Course Overview

This course shows how greenhouse gas emissions can result in a wide range of health effects, and provides you with a framework to trace pathways from emissions to health outcomes that emphasizes populations at risk. The course finishes with a consideration of how different sectors of society are working to meet the health challenges of climate change. The course is organized as follows:

Health: The Human Face of Climate Change Our introductory section. Learn why we're offering this course, find out how to complete edX assignments, and take the introductory survey.

Climate Science Mini-course Those who are newly learning about climate change should go through this short section to

Heat & Air Quality The most direct effects of climate change are in the temperature of our environment and the air we breathe. Learn what those effects are, how severe they can be, and strategies for mitigating the effects.

Infection Infectious diseases have a complex relationship with temperature. Learn more from an in-depth examination of malaria.

Nutrition More CO_2 may mean larger plants, but it also means less nutrition. Find out why in this section.

Migration Worsening conditions drive people from their homes. We'll tell you what the triggers are, as well as what the effects are.

Research Methods How do we know all this? What are the data sources, and how can we evaluate them? This section is intended for budding researchers who want a place to start and an overview of the field.

Solutions We know now that addressing climate change will lead to health improvements. So how do we do it?

Responses to climate change Our wrap-up section. Learn what people are doing to improve our world, find out where you can learn more, and take the post-course survey.

Introduction to Climate Science

This section is a quick introduction to climate science for those who aren't already familiar with the topic. If you don't know the role of greenhouse gases in our atmosphere, the major sources of greenhouse gases, or the amount of potential temperature increase over the next hundred years, we recommend you take some extra time in this section. If you're already familiar with this information, you can move on to the section on Heat and Air Quality.

This section is ungraded, and you can see the answers to each question after attempting them. Later in the course you may need to use up all your attempts (or get the problem right) before you can see the answers.

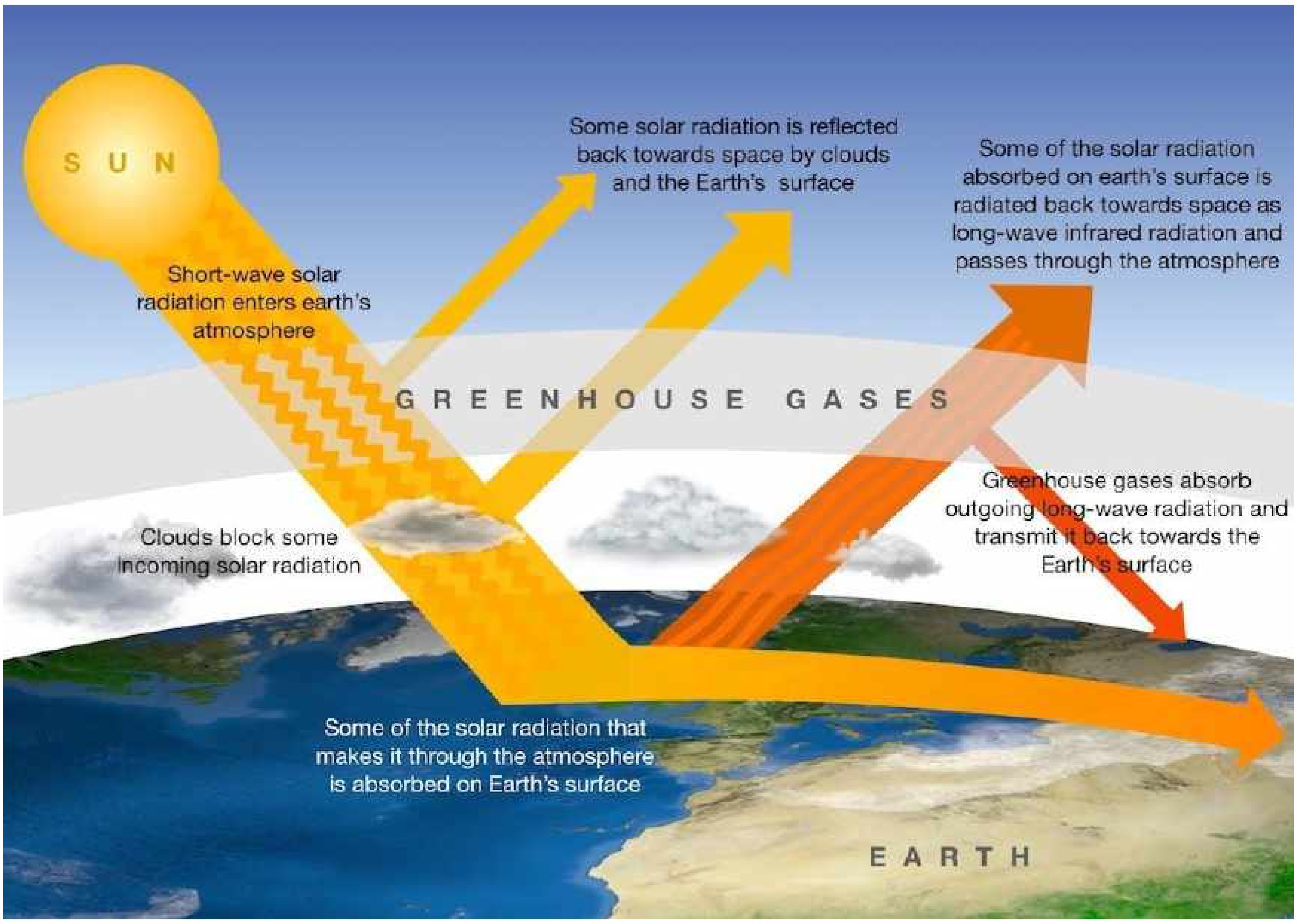
The Role of the Atmosphere

Why do we have missions to Mars but not to Mercury? Mostly because there's some prospect that Mars can support life whereas Mercury can't. On Mercury, daytime temperatures can get as hot as 430 degrees Celsius (806 degrees Fahrenheit), which is hot enough to melt lead. At night, the planet cools to minus 183 degrees Celsius (minus 297 degrees Fahrenheit), which is cold enough to liquefy oxygen. The vast swings in temperature are due to the combination of Mercury's proximity to the sun and its complete lack of atmospheric gases. Without gases in the atmosphere, all the heat energy the sun imparts to the planet are lost to space when the sun's rays are absent.

Earth has several gases in its atmosphere that trap heat, including carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). These three gases, and others, retain heat and make the climate of the earth what it is, and the one in which all life that exists depends on for survival.

The rays of the sun that make it through the atmosphere are absorbed on the earth's surface. They are then radiated back towards space with a longer wavelength than incoming solar radiation - what was visible light becomes infrared light. This lengthening of the wavelength is critical to the greenhouse effect: molecules of CO_2, N_2O, and CH_4 as well as other greenhouse gases are better able to absorb energy at the wavelengths of the radiation coming off the earth's surface and heading back to space than they are at the wavelengths of incoming solar radiation. You can see this in the diagram below. Click on the image for a larger version.

The Greenhouse Effect



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Other Contributors to Earth's Temperature

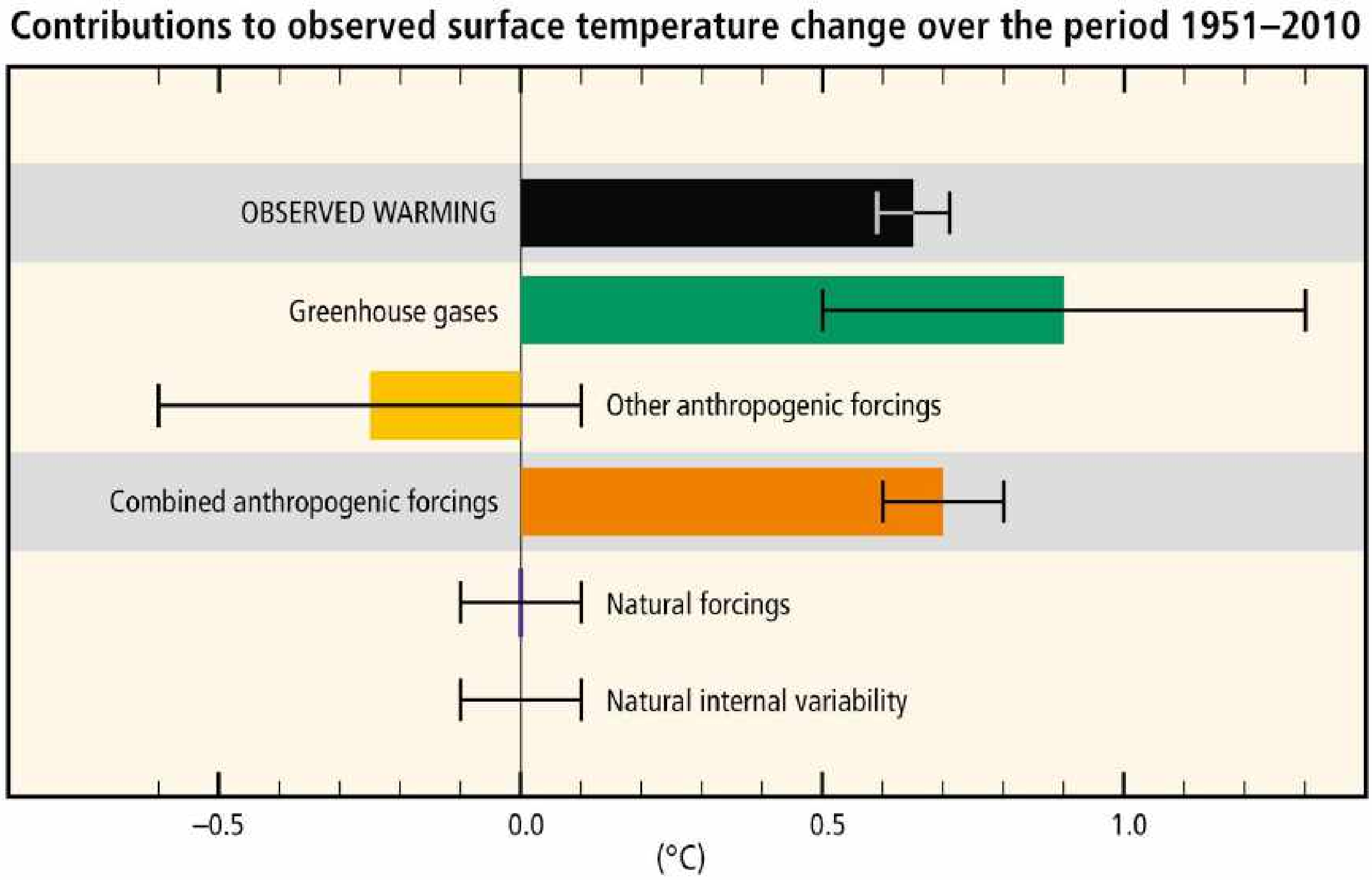
Many forces contribute to the Earth's average overall temperature, including...

- Its orbit around the sun, which is more elliptical than circular.
- How hot the sun is - its temperature varies over time.
- How reflective the Earth's surface is (white stuff, like ice caps, reflect light).

...but the temperature of our planet is most substantially influenced by the amount of greenhouse gas in the atmosphere.

This figure shows the contribution of anthropogenic (i.e. human) activities and natural forces to observed warming between 1951-2010. Notice that natural forcings (such as how hot the sun is) and internal variability (such as how far the earth is from the sun) are negligible contributors. Their effect is so small that you can't even see it on the graph. As with almost every image in this course, you can click on it to get a larger version.

Global Warming Factors



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Sources of Greenhouse Gases

Carbon dioxide is the most common greenhouse gas by volume, and though it may not be the most potent, the sheer amount of it has a large impact on our climate.

Most human-generated CO2 is generated by burning fossil fuels: coal, natural gas, and oil. Coal is the largest contributor. Some amount of CO2 is also generated via "direct emissions" - agriculture, mining, and forestry - but these activities also produce most of the methane (CH4) and N2O that humans release into the atmosphere.

A wonderful Sankey Diagram showing all this was created by ASN Bank / Ecofys , and you can use that to trace the amount from each particular fossil fuel to the greenhouse gas it creates.

Human-generated CO2 is only part of the CO2 exchanged with plants and the oceans each year. However, CO2 can take hundreds or thousands of years to leave the atmosphere. The CO2 that human beings are producing is therefore building up over time, and will take centuries to go away.

Heat, Floods, Droughts, and Sea Level Rise

Before you read this page, please answer the question below. This is an ungraded question, intended to help you learn, so if you don't know just take a guess.

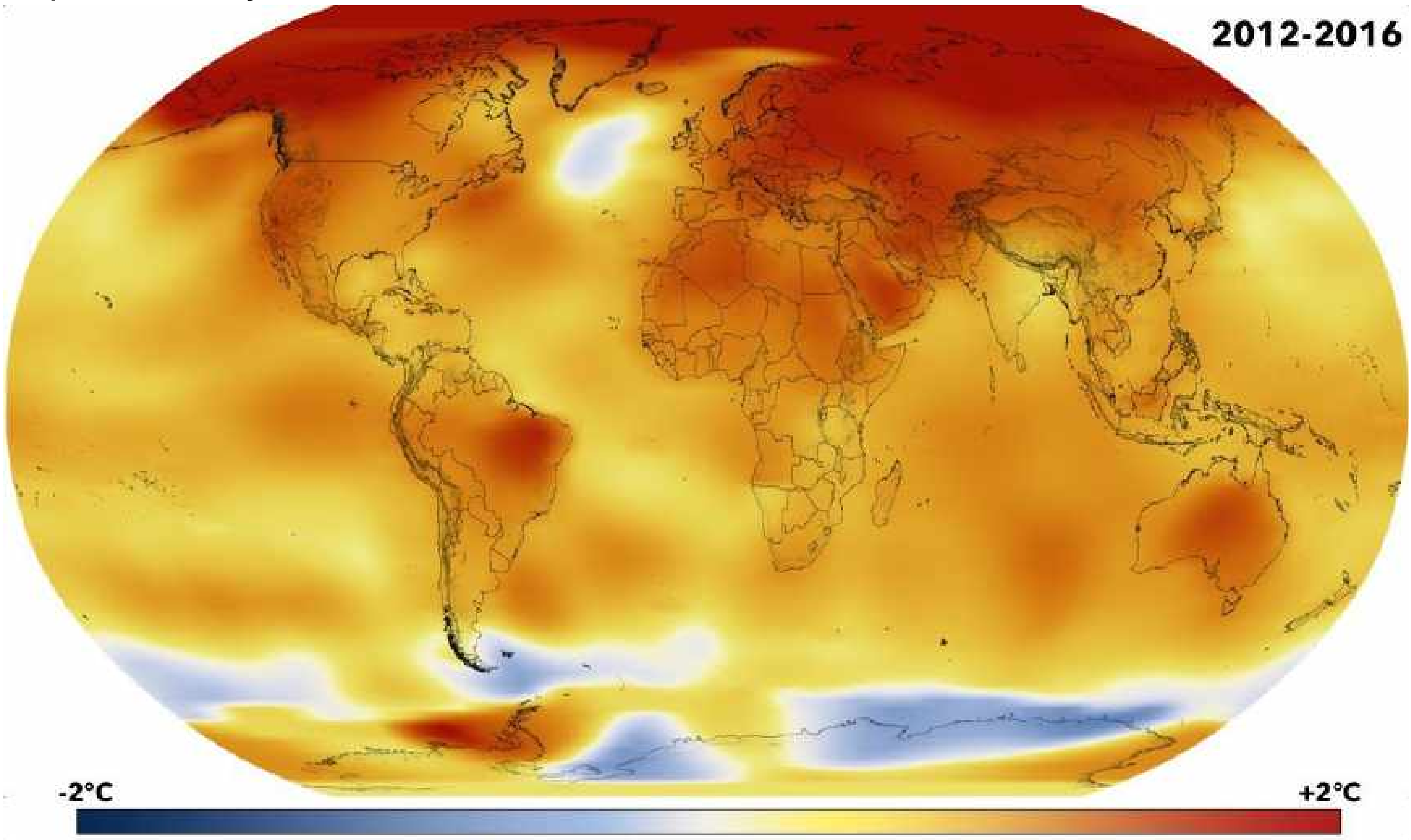
Temperature Rise

As concentrations of greenhouse gases increase, the amount of solar radiation that gets trapped also increases and the earth’s temperature rises but not equally everywhere.

The images below show maps of the temperature change, in degrees Celsius, from the 1890s to the 2010s. On average, the entire surface of the earth has warmed nearly 1 degree Celsius since the late 19th century. But this map makes clear that the northern parts of the planet are warming many times faster than the tropics. In addition, portions of Brazil, Australia and Antarctica have also warmed disproportionately.

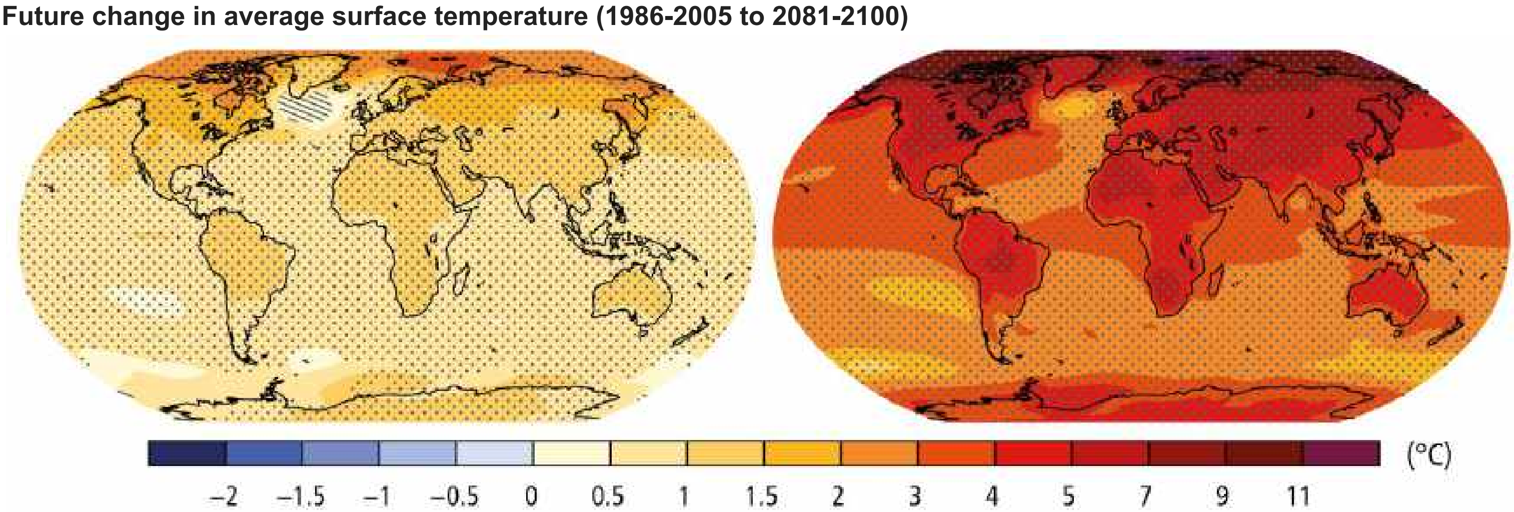
1892 to 1896 2012 to 2016

Temperature Anomaly, 2012-2016



After that change, what comes next? The maps below show two visions of how much warmer our planet may get by the end of this century as compared to its start. On the left, most places will warm only between 1 and 2 degrees Celsius. On the right, most places warm 4 or more degrees Celsius. The difference between these two futures depends heavily on how much more greenhouse gas gets added to the atmosphere as well as how reflective the surface of the earth is.

Future change in average surface temperature (1986-2005 to 2081-2100)



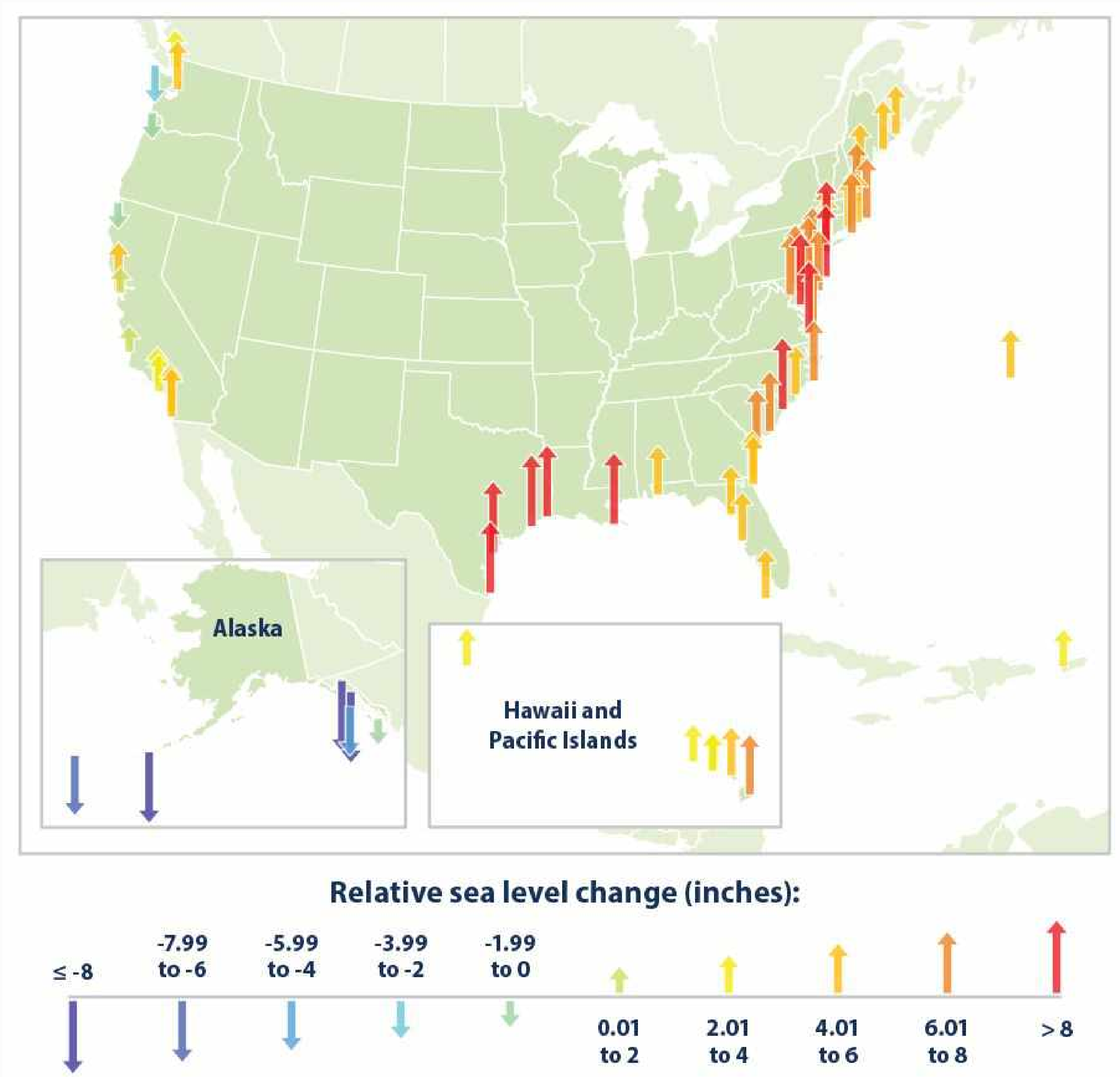
The difference between the world on the left and the world on the right is hard to know precisely. At the very least, with 4 degrees of warming, many if not most of the major cities on the coasts of the world may flood , and the heat in many places - and especially the Middle East - will be so extreme as to make it routinely hazardous to be outside.

The most important message of these two maps is: choices we make today will have major effects upon the world of our kids and grandkids. But the choices about where our energy comes from, and how we manage the earth's resources more broadly also carry immediate relevance to our health, all of which will be considered later in this course.

For more on the science that demonstrates that climate is changing and that greenhouse gas emissions are causing most of the changes, see the NASA website on climate change

Sea Level Rise

Sea levels have already risen substantially around the world by an average of roughly 90mm (~3.5 inches) since the early 1990s, but just as with temperature, rates of sea level rise vary from place to place. The map below illustrates variability along the coasts of the United States. You can see how sea level has changed around the world on this interactive map from NOAA.



Sea level rise in the past century was primarily due to melting land ice, including mountain glaciers and the ice sheets covering Antarctica and Greenland. Thermal expansion of water has been the next biggest contributor. The potential magnitude of further sea level rise has been the subject of some debate in recent years. The recognition that ice melt on land may be happening faster than previously thought has led to an upward revision of projected sea level rise in 2100. Previously, 1 meter (~3 feet) of sea level rise was thought to be the high end of possible sea level rise in 2100. But now with a better understanding of how ice melt happens with land ice, 1 meter may be the middle of the road estimate, with 2 meters possible . Again, some places may experience much more sea level rise, and others less.

You can explore what sea level rise may mean for flooding where you live using this interactive map . You also can get a better sense of the hundreds of millions of people at risk of sea level rise by exploring this interactive map of global population density . Note just how many of the world's largest cities are situated on the coasts. About a third of the world's population (or 2.4 billion people) lives within 100km (60 miles) of a coast.

Floods and Droughts

Warmer air holds more water. So, as air temperature rises with climate change, the atmosphere holds more water. And when that air with more moisture is ready to rain (or snow), it does so in greater amounts. Heavier downpours are already prevalent around the world (follow this link for more detail on the United States) and climate models indicate precipitation events are likely to get even heavier if greenhouse gas emissions are not substantially curtailed.

As a general rule, climate change will make places in the world that have recently had a trend towards more precipitation get more, and those places that have a trend towards less precipitation get less. In other words, places which are getting wetter recently will get wetter, and places getting drier will get drier . This effect of climate change needs to be distinguished from changes in the total amount of precipitation that falls in any given place, which may be small compared to the growing severity of individual rainfall events or the length of periods without rain. If the projections in the map are correct, each day it rains may see 50% more rainfall on average, presuming that the number of rainy days doesn't change. So in March, the wettest month, if it rains about 10 days each of those days may receive on average closer to 0.5 inches of rain in 2100 rather than 0.3 inches as is true today. How does intensification of the water cycle affect rainfall where you live? The health effects of water cycle intensification are many and will be discussed in the context of nutrition, infection and migration.

Warmer temperatures cause more evaporation and drying of land. If greenhouse gas emissions are not substantially reduced, climate models indicate that drought severity is likely to substantially increase over the course of this century. You may be interested in viewing an animation showing the potential increasing severity of drought conditions around the world, as assessed by the Palmer Drought Severity Index

The Direct Effects of CO2

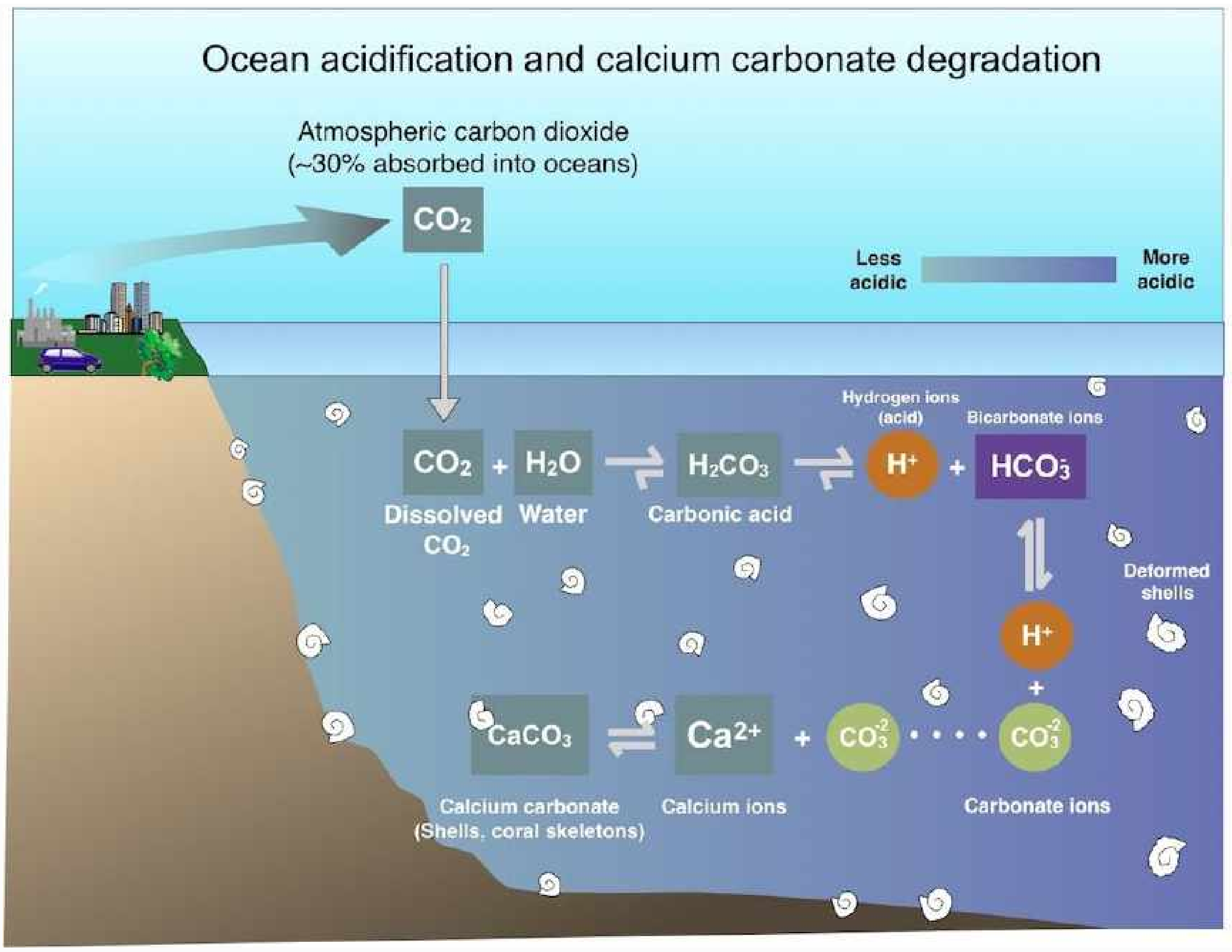
As we've learned, carbon dioxide is the greenhouse gas most responsible for changing our planet's climate. But carbon dioxide has other effects on our planet that may be just as important for our health as its effects on the climate.

Ocean Acidification

About 30% of the carbon dioxide released into the atmosphere from human activities, such as burning fossil fuels, is absorbed into the world's oceans. As it gets absorbed, it produces carbonic acid, which makes the world's oceans more acidic.

The higher concentration of acid in the oceans promote the breakdown of calcium carbonate, which forms the skeletons of animals such as corals, by depleting the ocean's carbonate ions. Without those ions, calcium carbonate and skeletons cannot form.

The illustration below is a simplified version of the chemistry involved in ocean acidification and how it puts at risk the skeletons of animals large and small in the ocean.



Carbon dioxide effects on plants

Plants breathe in carbon dioxide and breathe out oxygen. When concentrations of carbon dioxide in the air rise, plants change in ways that have consequences for health. These effects will be explored in the air quality and nutrition sections of the course.

Human Behavior

The largest modifier of the health impacts of climate change is human behavior, including the policies we create to protect health from climate change. It is important to understand the three main ways through which human action can reduce the effect of climate change on human beings:

1. **Through adaptation policies and actions to protect health from climate impacts (the black area in the graph below).**
2. **Through mitigation, such as reducing emissions in the first place (the dark blue area).**
3. **Through health co-benefits - reaping health gains from climate-friendly policies and individual behavior (the light blue area).**

Net health impact of climate change

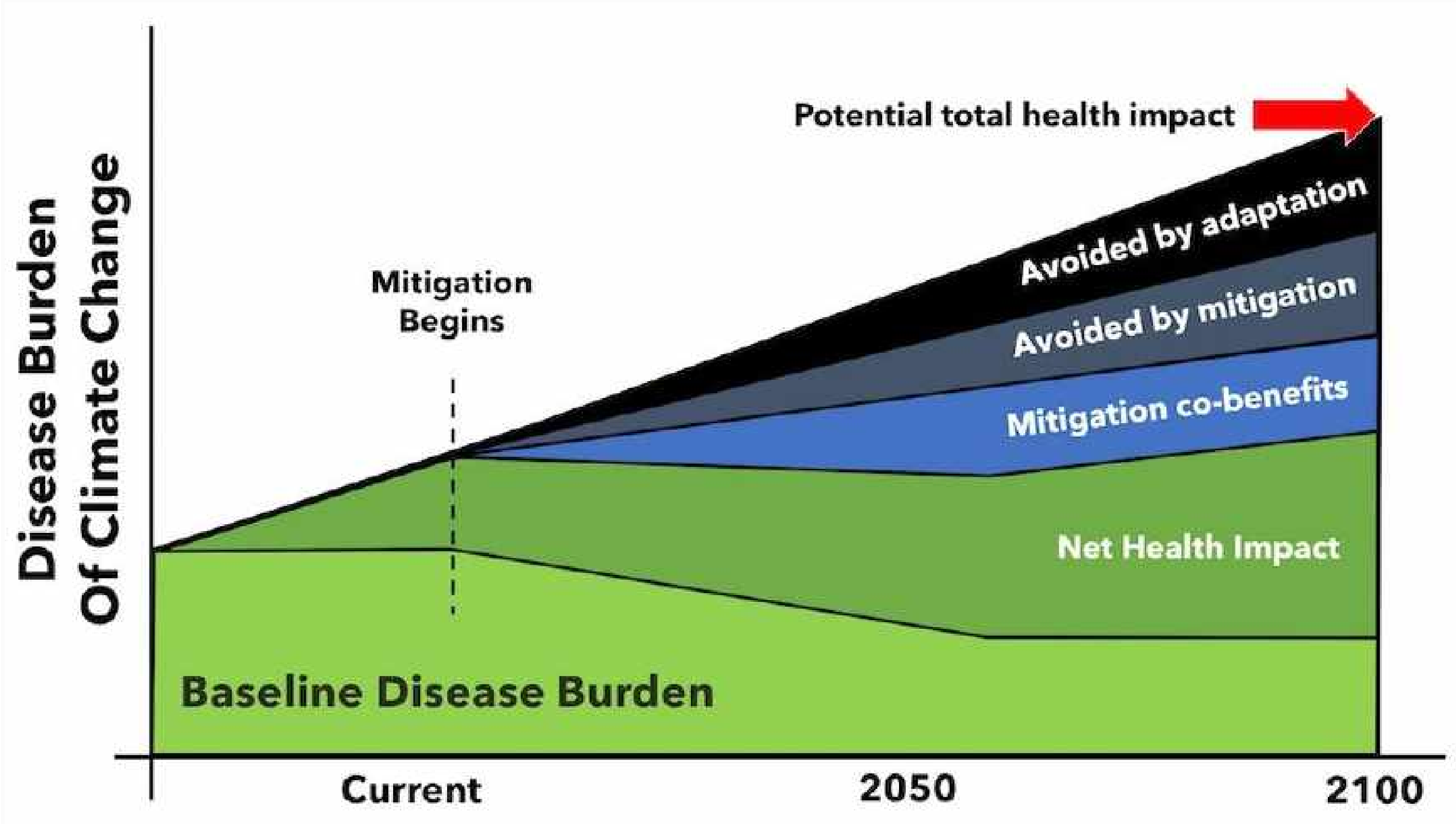


Figure courtesy of Harvard. Adapted from Climate change: present and future risks to health, and necessary responses , A. J. McMichael and E. Lindgren, Journal of Internal Medicine 2011

As climate change impacts human health, the disease burden increases. On the graph above, the amount of burden reached in the year 2100 is labeled as "Potential total health impact," in the right-hand upper part of the graph. This is the impact if we make no policies to limit or even acknowledge climate change. The effects of policies are depicted through the blue (mitigation) and black (adaptation) segments of the graph. Mitigation is designed to reduce greenhouse gas emissions and increase carbon sinks , while adaptation is designed to protect the health of populations from already-committed climate change.

Mitigation policies in and of themselves will attenuate climate change. This reduces the total impact. An additional reduction of the potential health impact can be achieved through adaptation.

In addition, we can even see a reduction in the *baseline disease burden* - shown in light green at the bottom of the graph. This improvement in our existing health will be achieved through *health co-benefits*. These denote health improvements from individual mitigation interventions (e.g. by using your bike instead of your car), or through public interventions (e.g. societies changing from fossils to renewables for energy generation).

From a research point of view, we strive to measure the net health impact: the darker green shade in the middle of the graph. As a first approximation, we will focus on the worst-case health impact. We are ignoring the policy/behavioral effect modifications of human behavior and policies, but we must stay aware of them, because they are our opportunities for improvement.

Intro to Heat and Air Quality

Overview

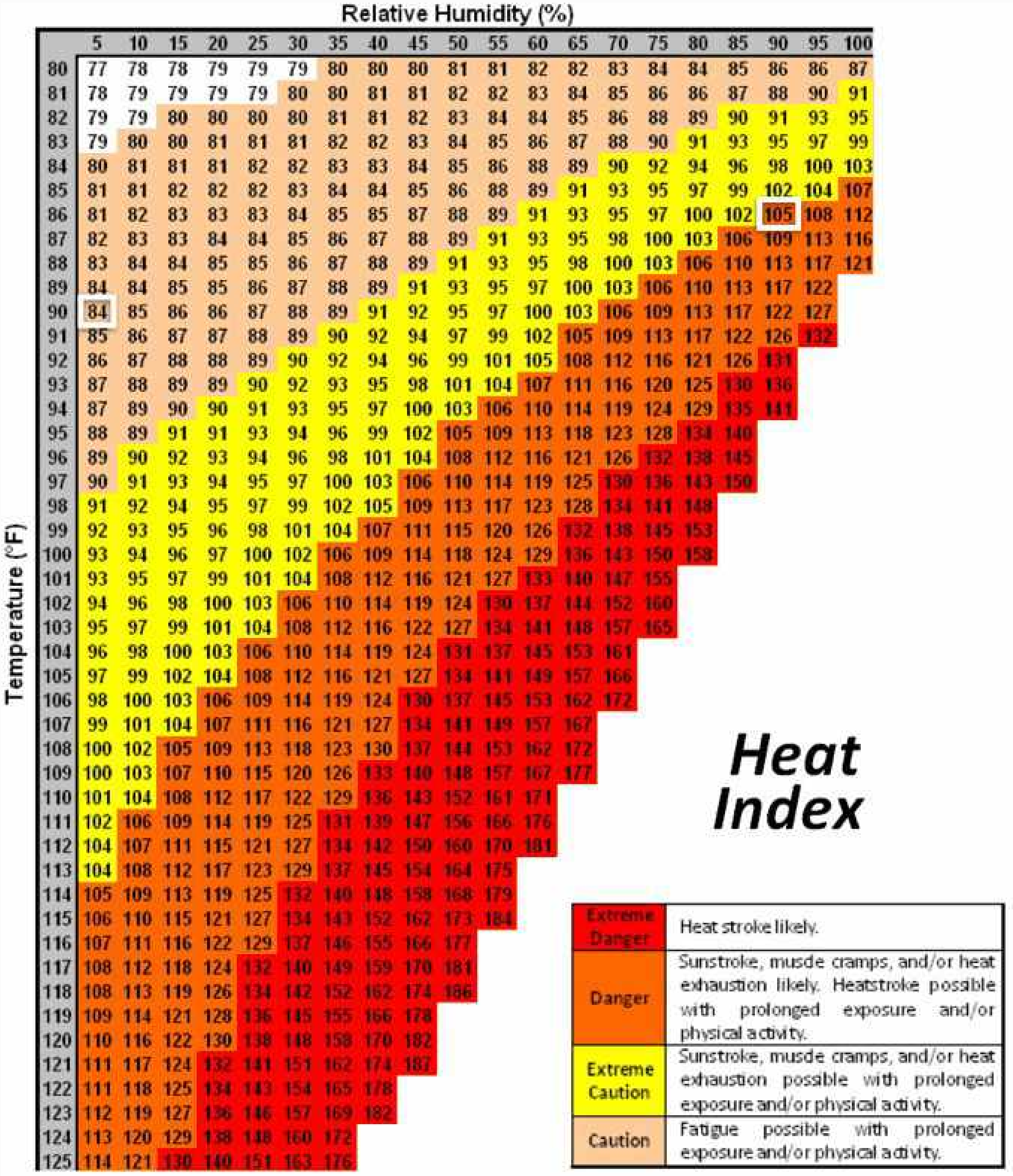
Let's begin our exploration of the pathways that connect greenhouse gas emissions to health through considering what they mean to the planet's temperature.

Most people enjoy a warm summer's day, but even for those who love sun and heat the most, very hot temperatures can be dangerous. In recent years, severe heatwaves around the world have led to the deaths of tens of thousands of people , either from the effects of heat itself or because of air pollution that heatwaves can generate. In the future, heat-related illnesses are likely to get even worse. What makes heat so lethal? Who is at risk and why? We'll explore these questions in this section of the course.

Heat Index

You may have heard a weather forecaster talk about the "feels like" or "real feel" temperature. Each of these is based upon what's known as the *heat index*. This combines the effects of temperature and humidity to give people a better sense of heat related health risk, because we know that heat + humidity is more dangerous than heat alone.

The heat index table below shows how a cooler temperature with higher humidity can produce conditions more hazardous to health. The orange zone in the middle means a danger of heat stroke, which begins around 114°F (45°C) at zero humidity. However, at 90% humidity, the same level of danger happens at just 86°F (30°C). Our two room scenarios from the question above are highlighted on the table.



Temperature (°F) \ Relative Humidity (%)	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100
80	77	78	78	79	79	79	80	80	80	81	81	82	82	83	84	84	85	86	86	87
81	78	79	79	79	79	80	80	81	81	82	82	83	84	85	86	86	87	88	90	91
82	79	79	80	80	80	80	81	81	82	83	84	84	85	86	88	89	90	91	93	95
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84	80	81	81	81	82	82	83	83	84	85	86	88	89	90	92	94	96	98	100	103
85	81	81	82	82	82	83	84	84	85	86	88	89	91	93	95	97	99	102	104	107
86	81	82	83	83	83	84	85	85	87	88	89	91	93	95	97	100	102	105	108	112
87	82	83	83	84	84	85	86	87	88	89	91	93	95	98	100	103	106	109	113	116
88	83	84	84	85	85	86	87	88	89	91	93	95	98	100	103	106	110	113	117	121
89	84	84	85	85	86	87	88	89	91	93	95	97	100	103	106	110	113	117	122	
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91	85	86	87	87	88	89	90	92	94	97	99	102	105	109	113	117	122	126	132	
92	86	87	88	88	89	90	92	94	96	99	101	105	108	112	116	121	126	131		
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96	89	90	92	93	94	96	98	101	104	108	112	116	121	126	132	138	145			
97	90	91	93	94	95	97	100	103	106	110	114	119	125	130	136	143	150			
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99	92	93	95	96	98	101	104	107	111	115	120	126	132	138	145	153				
100	93	94	96	97	100	102	106	109	114	118	124	129	136	143	150	158				
101	93	95	97	99	101	104	108	112	116	121	127	133	140	147	155					
102	94	96	98	100	103	106	110	114	119	124	130	137	144	152	160					
103	95	97	99	101	104	108	112	116	122	127	134	141	148	157	165					
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105	97	99	102	104	108	112	116	121	127	134	141	149	157	166						
106	98	100	103	106	109	114	119	124	130	137	145	153	162	172						
107	99	101	104	107	111	116	121	127	134	141	149	157	167							
108	100	102	105	109	113	118	123	130	137	144	153	162	172							
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122	111	118	125	134	143	154	165	178												
123	112	119	127	136	146	157	169	182												
124	113	120	129	138	148	160	172													
125	114	121	130	140	151	163	176													

Extreme Danger	Heat stroke likely.
Danger	Sunstroke, muscle cramps, and/or heat exhaustion likely. Heatstroke possible with prolonged exposure and/or physical activity.
Extreme Caution	Sunstroke, muscle cramps, and/or heat exhaustion possible with prolonged exposure and/or physical activity.
Caution	Fatigue possible with prolonged exposure and/or physical activity.

Heat Index
Figure courtesy of NOAA and the US National Weather Service.

Heat *exhaustion* is a moderately dangerous situation that should be addressed quickly. Heat *stroke* is a life-threatening medical emergency. For more on the difference between these and other heat-related illnesses, see the US Center for Disease Control's Warning Signs and Symptoms of Heat-Related Illness

Knowing what you know now, which hot room would you choose to suffer in? It turns out that a 90° F (32° C) room with near zero percent humidity will be effectively *cooler* than an 86° F (30° C) room with 90% humidity, You'll learn why on the next page.

How human bodies deal with heat

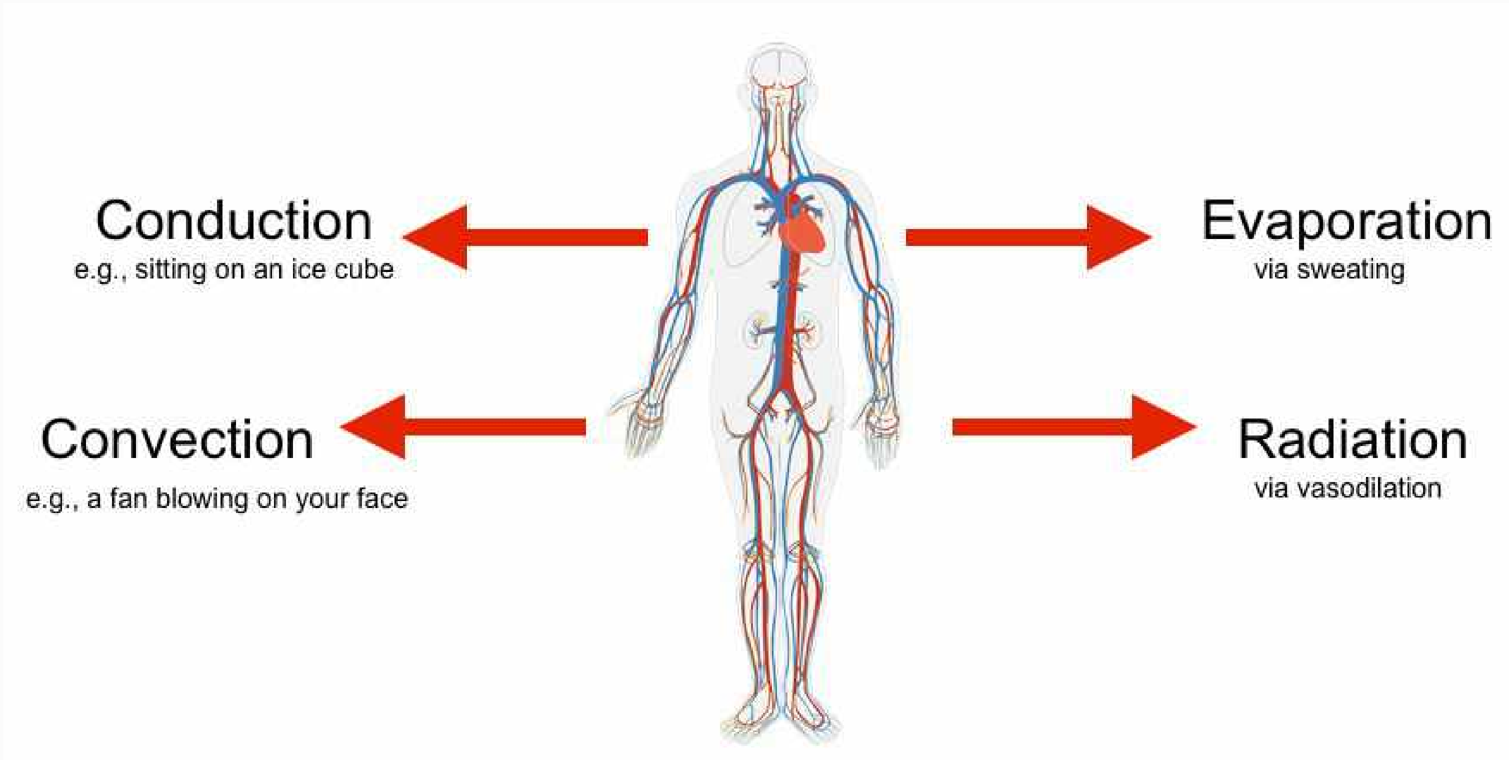
You saw on the last page that not all heat is created equal. Knowing why can be the difference between life and death. Our bodies are able to lose heat in four ways:

1. **Conduction involves losing heat through contact with something colder than our bodies. For instance, if you sat on a giant block of ice, your body heat would melt the ice and you would be cooled. But if you sat on a hot iron, conduction would convey heat into your body and possibly burn your skin.**
2. **Radiation is why the sun makes you feel warm - the electromagnetic radiation that the sun lets out warms our bodies and everything else from the outside. When it gets hot out, our blood vessels dilate and allowing greater radiation of heat from our bodies into the air and helps cool us down. When the temperature outside is warmer than our body (which is normally at around 98.6 degrees F / 37 degrees C), radiation increases our body temperature.**
3. **When you turn on a fan that blows across your skin on a hot day and you feel cooler, convection is at work. Cooling by convection only works well if the air outside your body is cooler than your body.**
4. **If the temperature outside is over normal body temperature, is overheating inescapable since conduction, radiation and convection won't help cool us much? Fortunately not. The fourth way our bodies lose heat is through evaporation. When it's hot, we sweat. The heat on our skin gets transferred to the sweat and it evaporates which results a net loss of heat for our bodies.**

Key point: when the temperature outside is higher than body temperature, sweating is the best way to lose heat.

The figure below summarizes the ways humans can cool down.

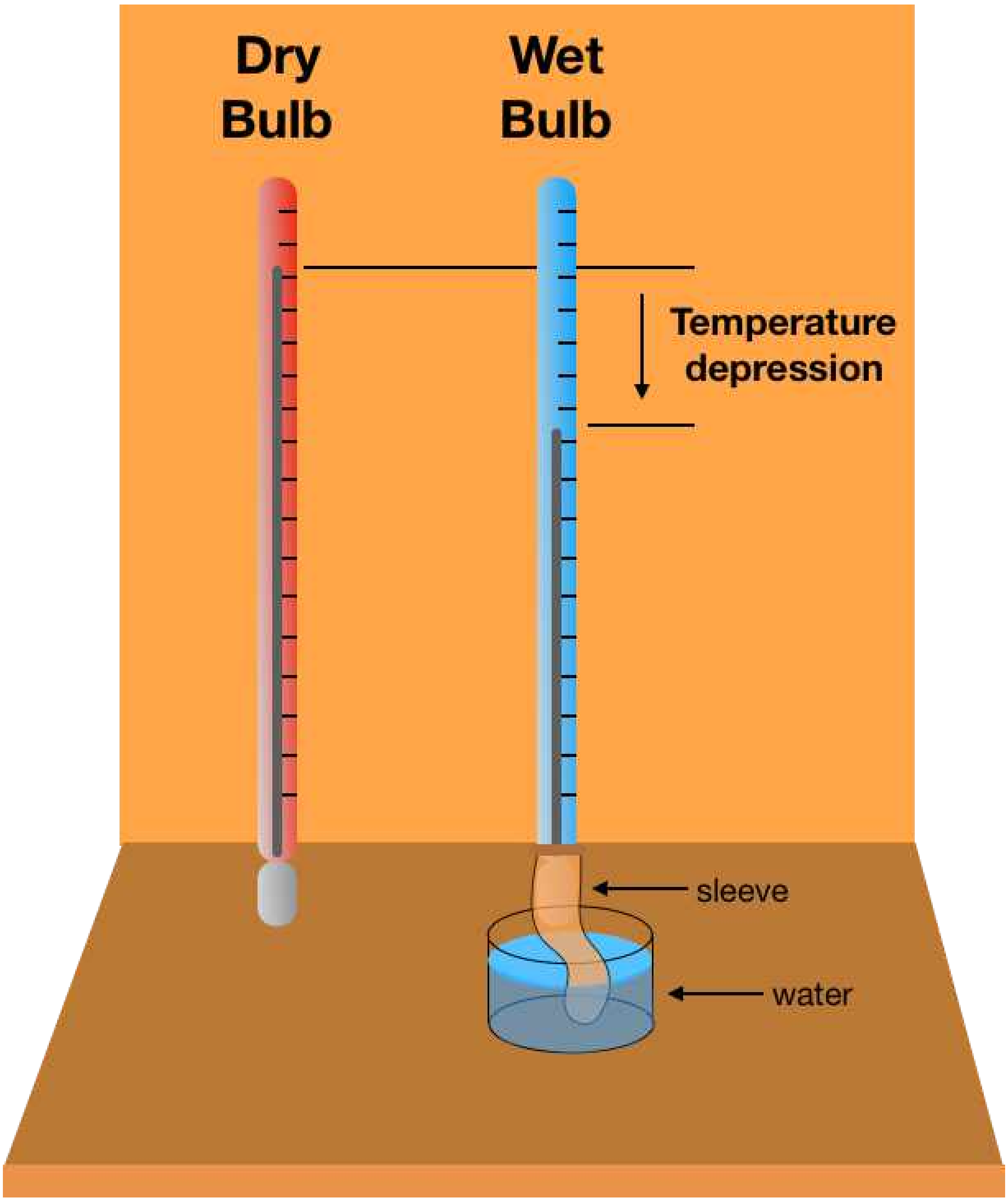
Human cooling mechanisms



Sweating is our body's best way to cool when temperatures soar, but even it has limitations. Evaporative cooling requires sweat (i.e. water) to evaporate off our skin. However, if it's humid, and there's already a lot of water in the air, evaporation doesn't happen as readily. This makes sweating less effective. That means that hot moist air is more dangerous than hot dry air, as the moisture in the air interferes with our body's best means to lose heat at high temperatures.

Wet Bulb Temperature

Wet Bulb Thermomenter



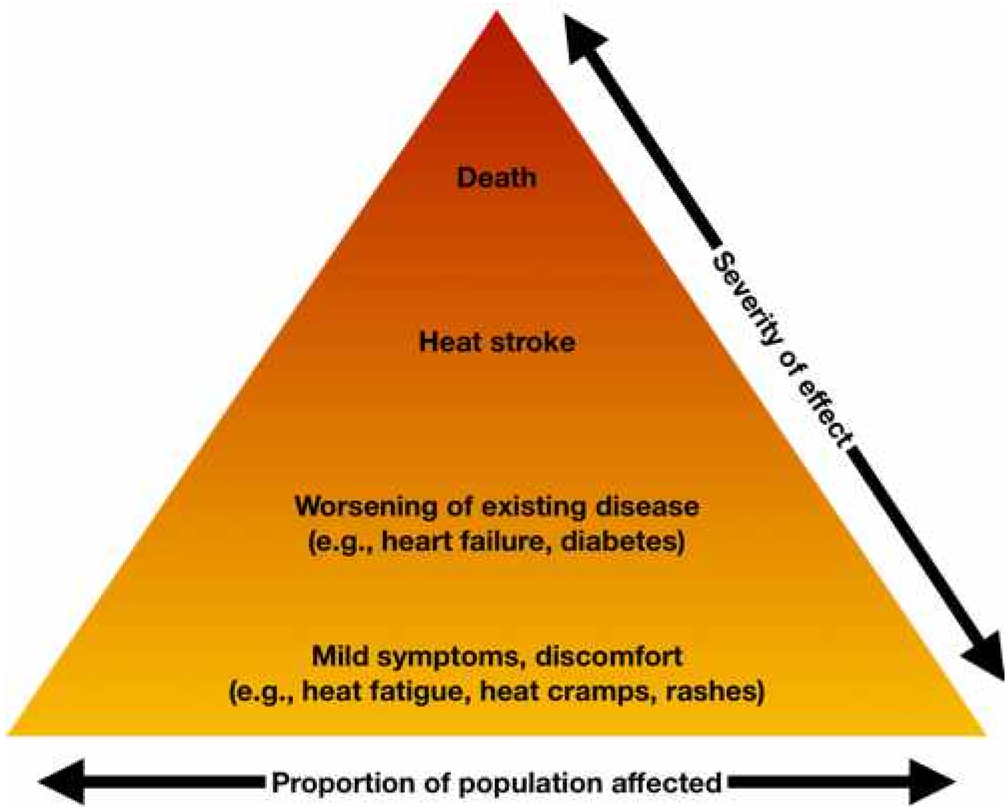
The heat index provides a more physiologically relevant measure of heat exposure as it accounts for the effects of radiation and evaporative cooling. But it doesn't account for convection. Another measure of temperature, known as the wet bulb temperature, integrates radiation and evaporative cooling with convection.

When you put a sock on the bulb of a thermometer and then immerse it in water, you've created what's known as a wet bulb thermometer. The temperature a wet bulb thermometer measures is usually *lower* than the temperature a dry bulb thermometer measures. Because the bulb is wet, it can lose heat through evaporation (just like our bodies). If the wet bulb temperature is the same as the dry bulb temperature it means that the air is so saturated with water that evaporative cooling isn't working for the thermometer and also won't work well for people. Moral of the story: if the wet bulb temperature is near the dry bulb temperature, watch out - heat related illness may be likely.

An important reminder: warmer air holds more water, and it's not uncommon for humidity to rise with temperatures in places near large bodies of water.

Health Effects of Extreme Heat

Heat exposure pyramid



Figure

Extreme heat and humidity can cause diseases such as heat stroke in which the body overheats and figuratively gets cooked. Heat stroke can result in permanent damage to brains and nerves (among other organ systems) as well as death. The heat exposure pyramid shown to the right shows a range of health effects caused by heat exposure and the proportion of a population that may be affected. The wider the pyramid is at the level of the specified health effect, the more likely the health effect.

Death from heat exposure is rare. More often, exposure to heat makes existing disease worse. Heat can promote dehydration which makes a wide range of diseases worse, including many heart and lung diseases such as asthma, chronic obstructive pulmonary disease, and heart failure, as well as diabetes. Heat also can make it harder to think and has also been shown to decrease productivity .

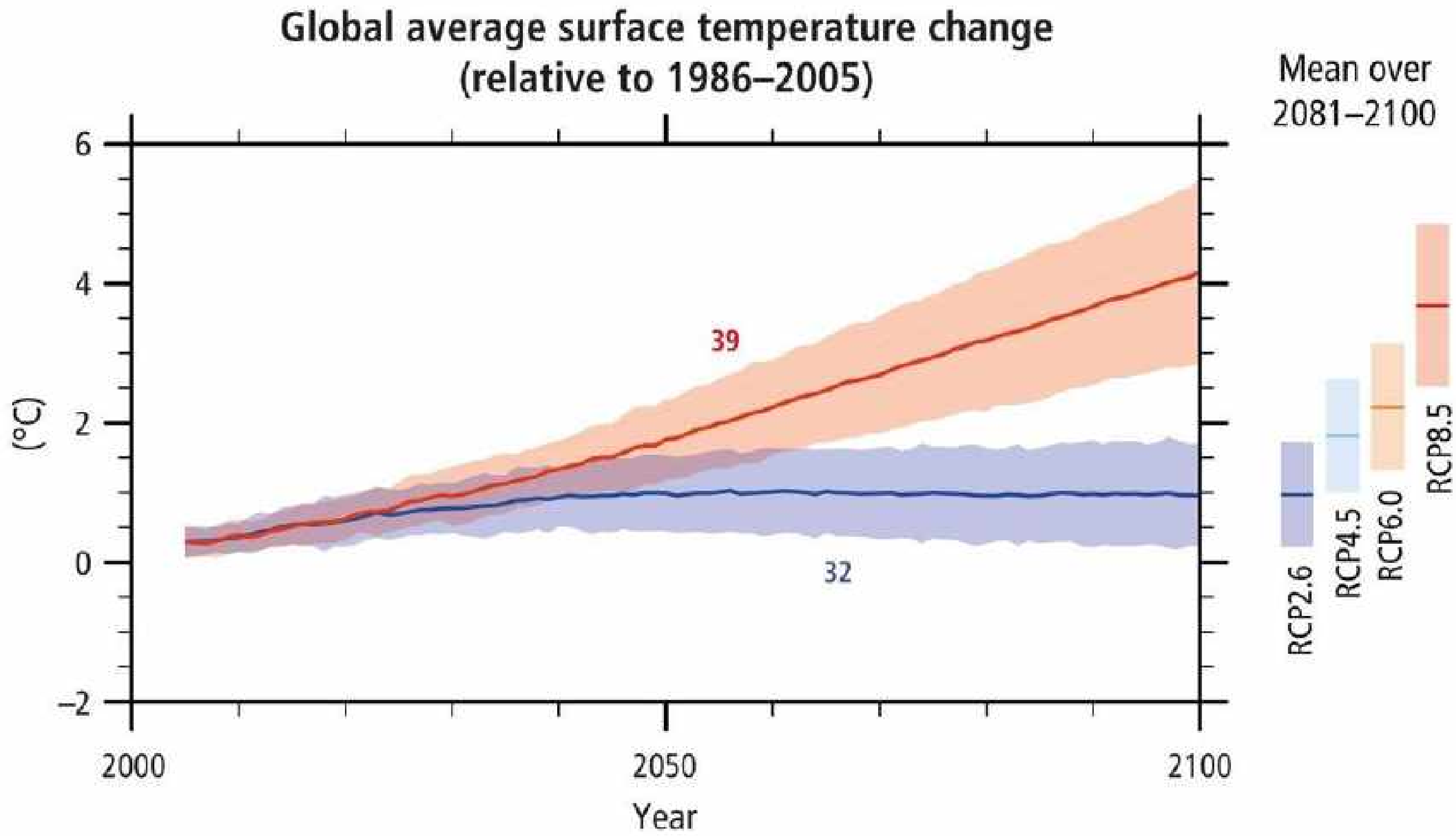
Heat waves can be fatal for many reasons. Hearts, brains, and lungs are all sensitive to heat stress and when they get overheated they fail. Higher mortality during heat waves has been attributed predominantly to failure of these organs . During heatwaves, emergency room visits rise for a variety of heat-related conditions such as heat exhaustion and heat stroke , heat cramps, dehydration and electrolyte disorders, cardiovascular and cerebrovascular diseases, respiratory disorders, acute renal failure, neurologic conditions, and mental illnesses. Also, fetuses born to women who were exposed to extreme heat may be at greater risk of neural tube and other birth defects . Several factors determine an individual's ability to dissipate heat. Age appears to be one of the biggest contributors, with older adults having markedly less ability to get heat out of their bodies. Pre-pubertal children also may have less ability to lose heat as compared to adults. Those who work outdoors, particularly in construction, may be at elevated risk in the coming century.

Heat waves in the near future

In our Climate Science Mini-course section, we addressed how the planet has already warmed under the influence of additional greenhouse gas emissions. What we didn't consider was how much *more* it will warm in the future, which of course matters when considering how many people may be exposed to extreme heat.

Climate models have been used to predict what the global average temperature will be throughout this century. (If you're unfamiliar with climate modeling, you can watch a video about climate models here .) The models are asked to consider different potential paths of action. Some of them model a world in which greenhouse gas emissions are substantially curtailed, deforestation is slowed and technologies to prevent warming are widely shared. Others model a path of business as usual with no substantial move off of fossil fuels and substantial population growth, for example. The graph below shows what the models tell us. In a best case scenario (labeled RCP 2.6), warming is held to about 1° C over the century. In a worst case scenario (labeled RCP 8.5), the planet warms on average more than 4° C. While three degrees may not seem like much of a difference, it may be the difference between life and death for a substantial fraction of the human population (at least where we are living today).

Possible Future Temperatures



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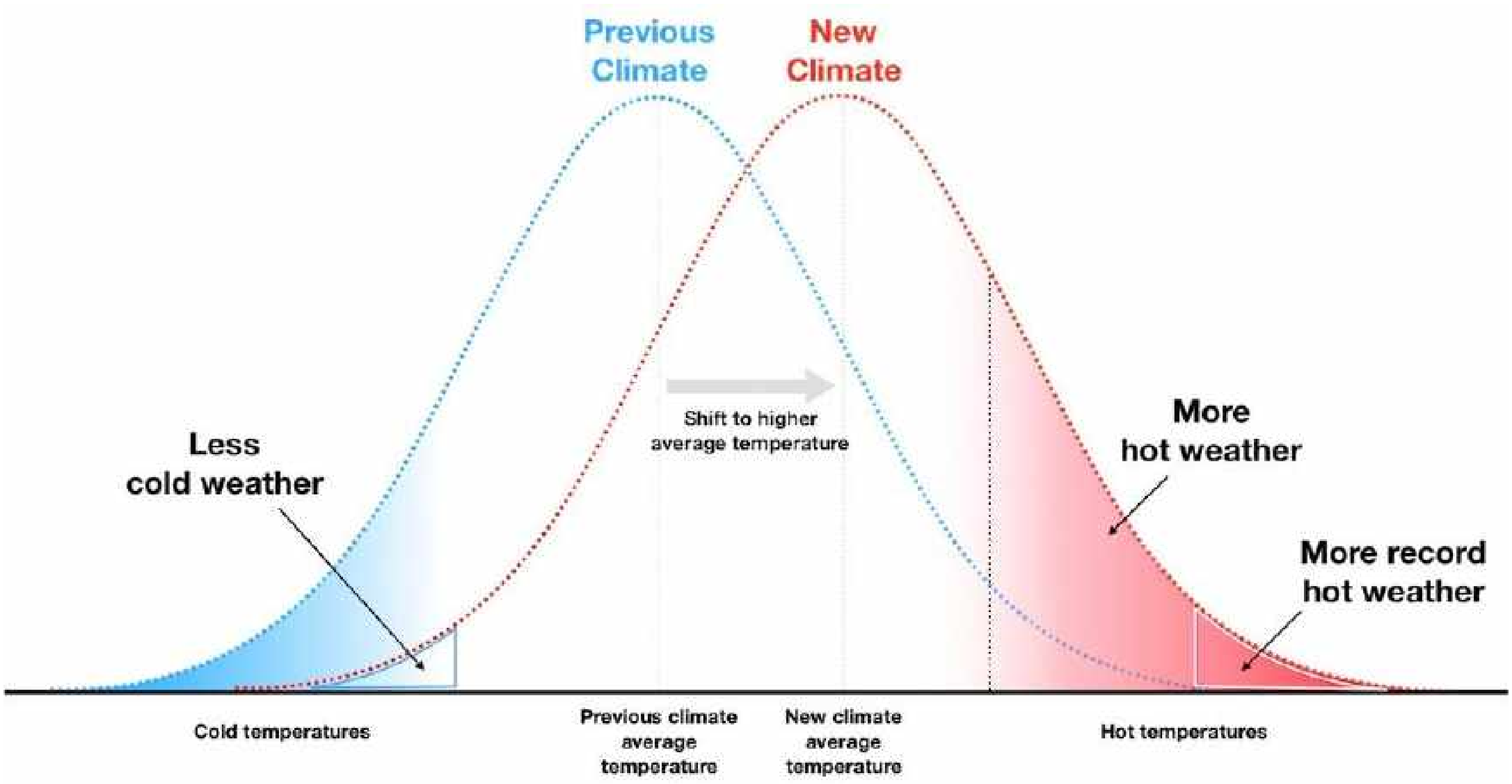
Research has indicated that climate change will increase the areas on the earth that experience lethal heatwaves such that nearly three quarters of all people alive may be affected by 2100 if we stay on the RCP 8.5/worst case scenario path)

The next graph illustrates how a small shift in average temperature can make a big difference in the number of days with hot weather. The blue bell-shaped curve labeled "previous climate" shows the distribution of days in a given place (e.g., a city) across a year. In this place, relatively few days are hot and relatively few days are cold (the height of the curve is a measure of how frequent the temperature is reached on a given day of the year). When the average temperature shifts upward, to create the red "new climate" curve, the number of days with hot - or record hot - weather increases markedly, with roughly 3 times more hot days and a whole set of days (the "record hot days") with unprecedented heat.

Effects of increasing the average temperature on temperature extremes



In other words, as the average temperature goes up, the frequency and intensity of heatwaves grows dramatically.

Ground-level ozone

You may have heard about ozone as a chemical in earth's stratosphere (the upper part of the atmosphere) that shields us from the sun's ultraviolet radiation, which can cause skin cancer. This is correct - ozone does play that role in the stratosphere. However, ozone at *ground-level*, where we can breathe it into our bodies, is a different story.

The above photo shows ozone smog blanketing Los Angeles. Inhaling ozone is bad for our lungs. When ozone contacts our lungs it causes inflammation that makes it hard to breathe for all people, but especially those with existing lung diseases such as asthma and chronic obstructive pulmonary disease (COPD).

The health effects of ozone on the human body

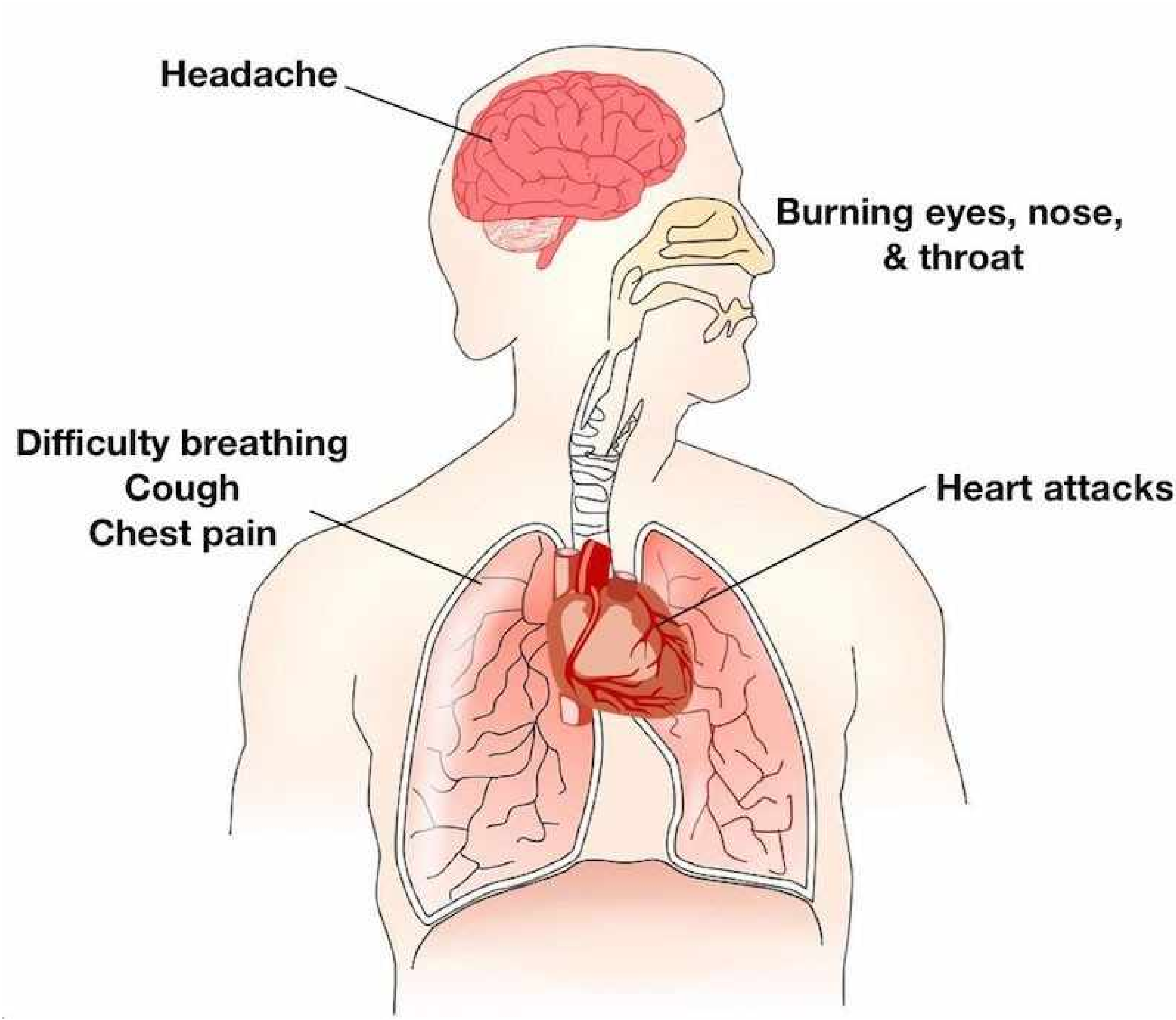
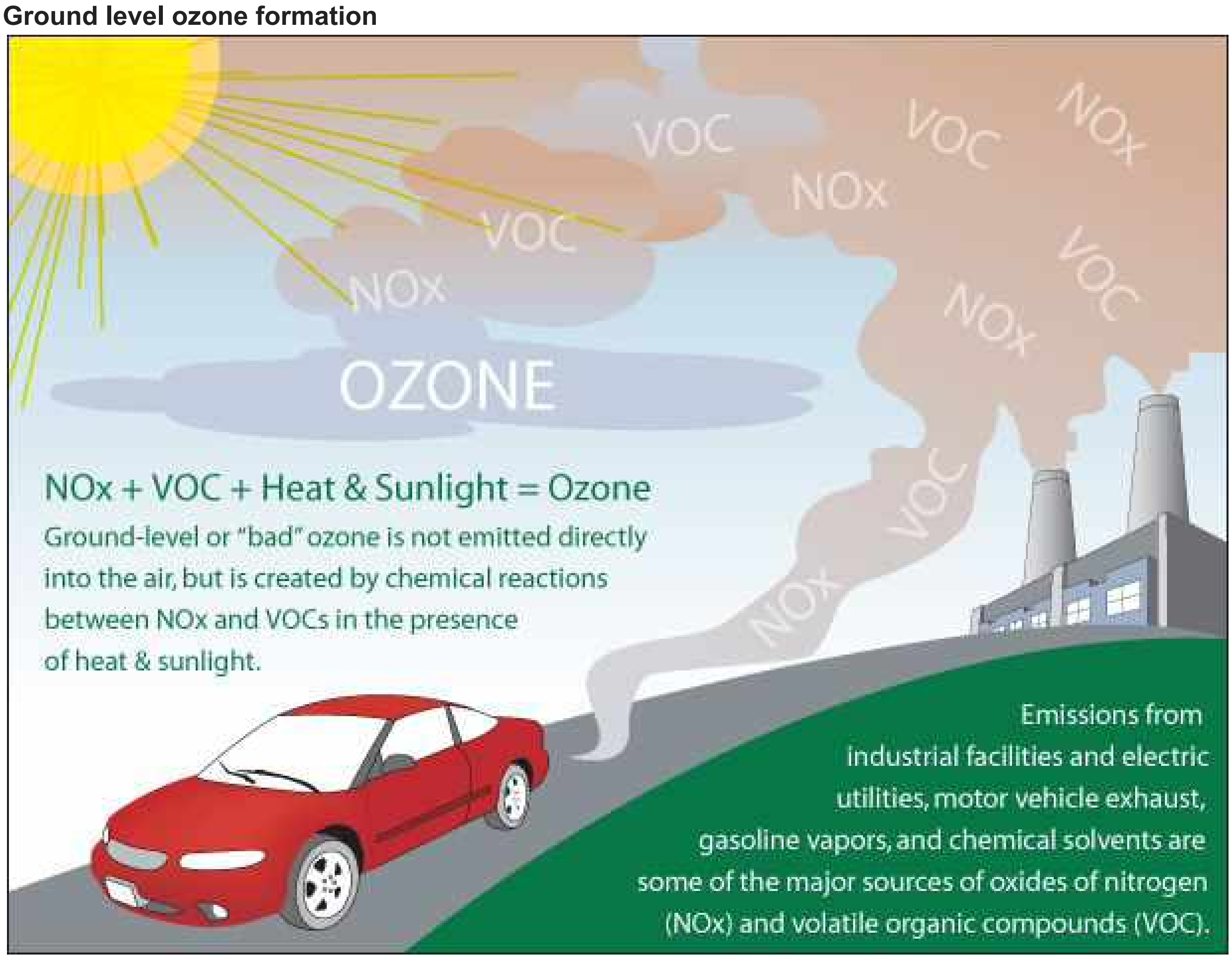


Figure courtesy of Harvard.

Ozone is formed when byproducts of fossil fuel combustion, including oxides of nitrogen (NOx) and volatile organic compounds (VOCs) are exposed to ultraviolet radiation from the sun, as is shown in the figure below.

Ground level ozone formation



More ozone forms in the summer because there's more ultraviolet radiation hitting the earth from the sun.

Scientists have tried to forecast how higher average temperatures may influence ground level ozone in the decades to come, but ozone prediction is difficult. Ozone formation happens more readily at higher temperatures, but one thing they've found is that at *very* high temperatures (over 90° F / 32° C), ozone formation tends to slow down . Even with this, mortality from ozone pollution is expected to grow in many places around the world as temperatures warm across this century.

With RCP 8.5 (the worst-case climage change scenario), ozone mortality will be most pronounced in India and China, with substantial worsening in the eastern U.S., much of Europe and southern Africa. All told , tens, and perhaps hundreds of thousands of additional lives may be lost . This can be seen in the map below.

The health effects of changing ozone levels

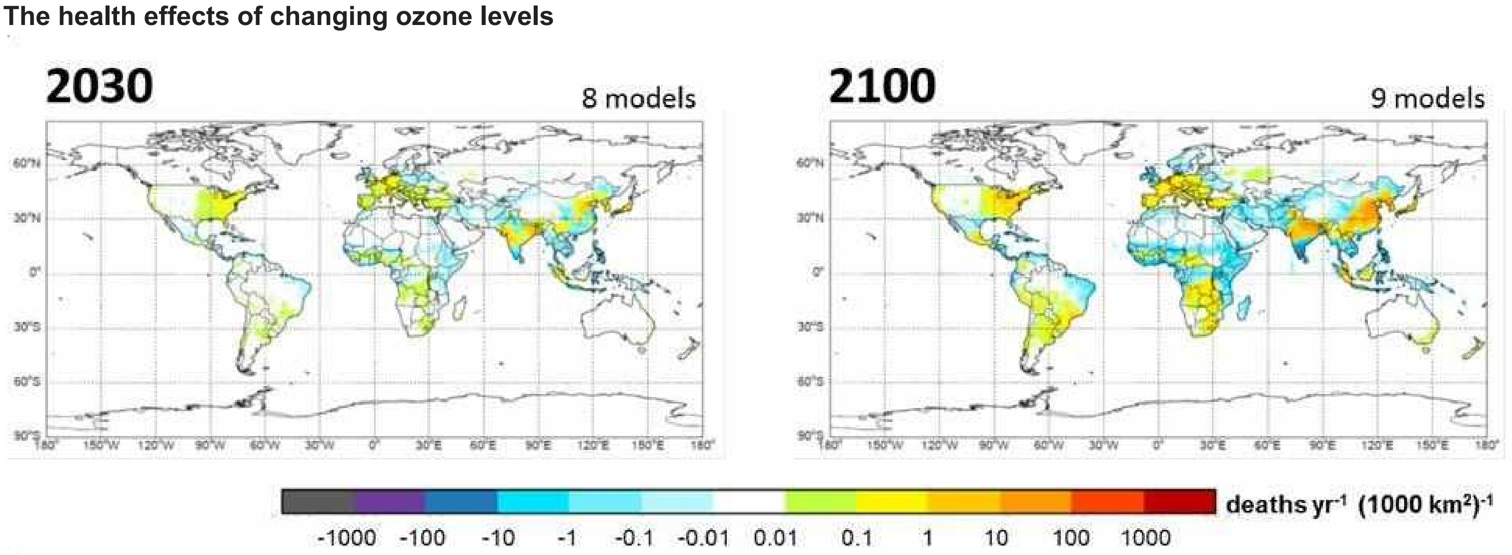


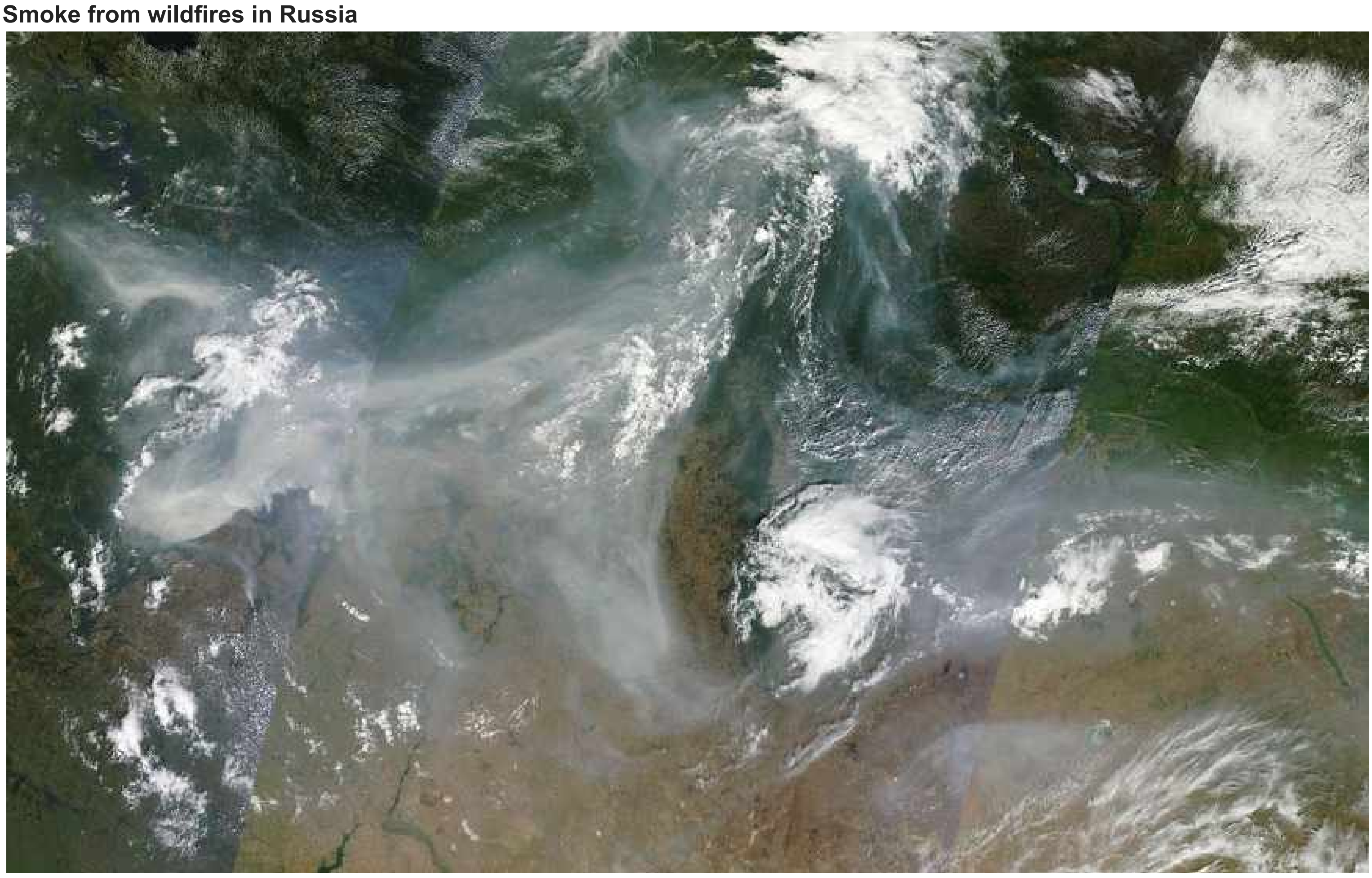
Figure from Future Global Mortality From Changes In Air Pollution Attributable To Climate Change

Ozone isn't just bad for people, it's bad for plants too. The consequences of higher ozone levels at ground-level for human nutrition will be considered later in the course

Wildfires and particulate matter

Because climate change causes heatwaves and more severe droughts, it creates conditions favorable to wildfires. During a particularly hot and dry spell in eastern Europe in 2010, thousands of fires burned an area of forest roughly the size of Indiana (38,600 square miles or ~100,000 square kilometers) burned. The smoke from the fires, however, would have stretched from San Francisco to Chicago. The air pollution produced by the fires killed tens of thousands of people. Below you can see an image of the smoke in Russia, taken from space.

Smoke from wildfires in Russia



Click for a *much* larger version. The stripes on this image are caused by satellites taking multiple photos on multiple passes over the territory, so the clouds on the left-hand and right-hand side of the stripe may not line up. You can see that the smoke is still present.

Toxic substances in smoke

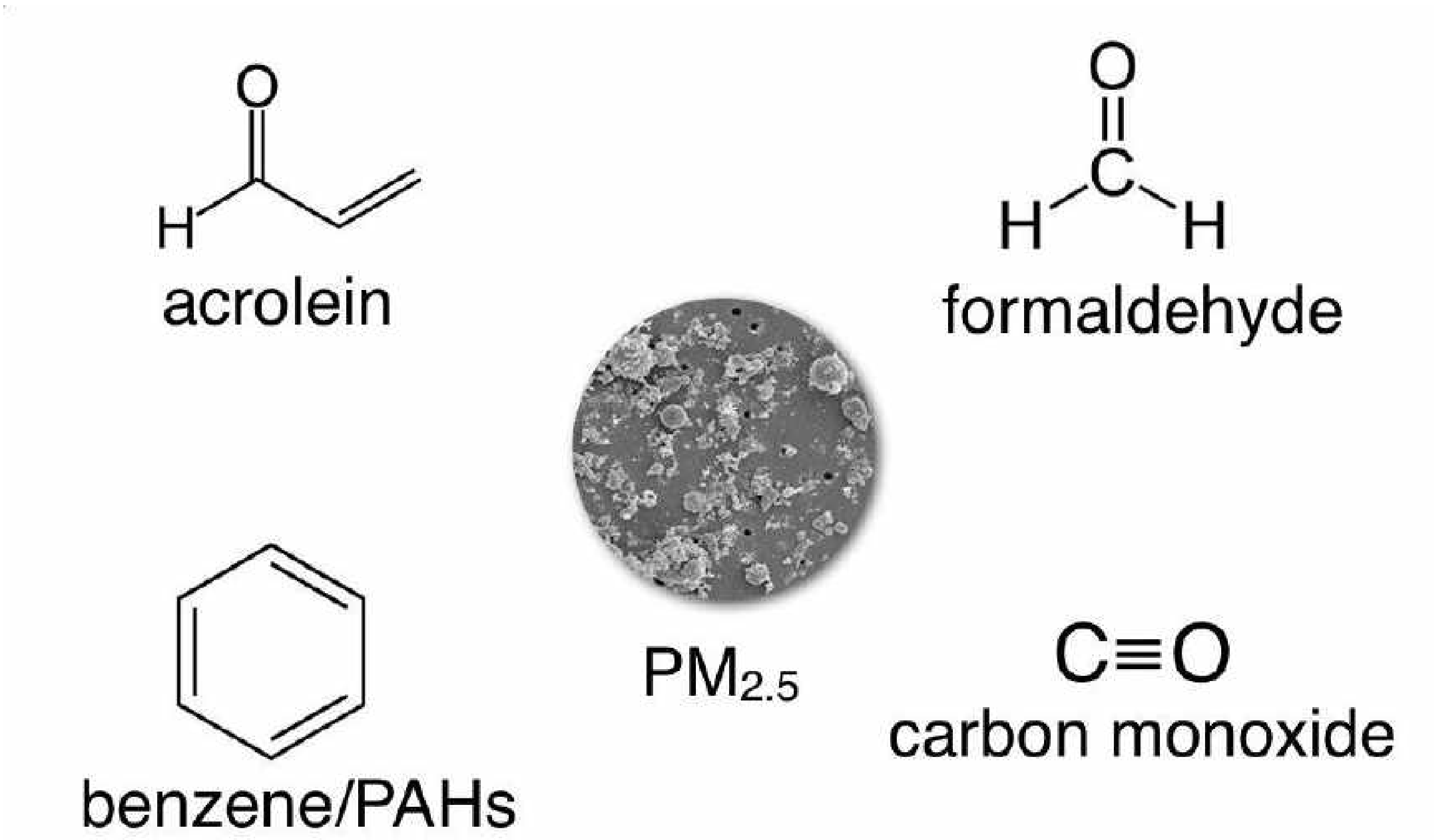


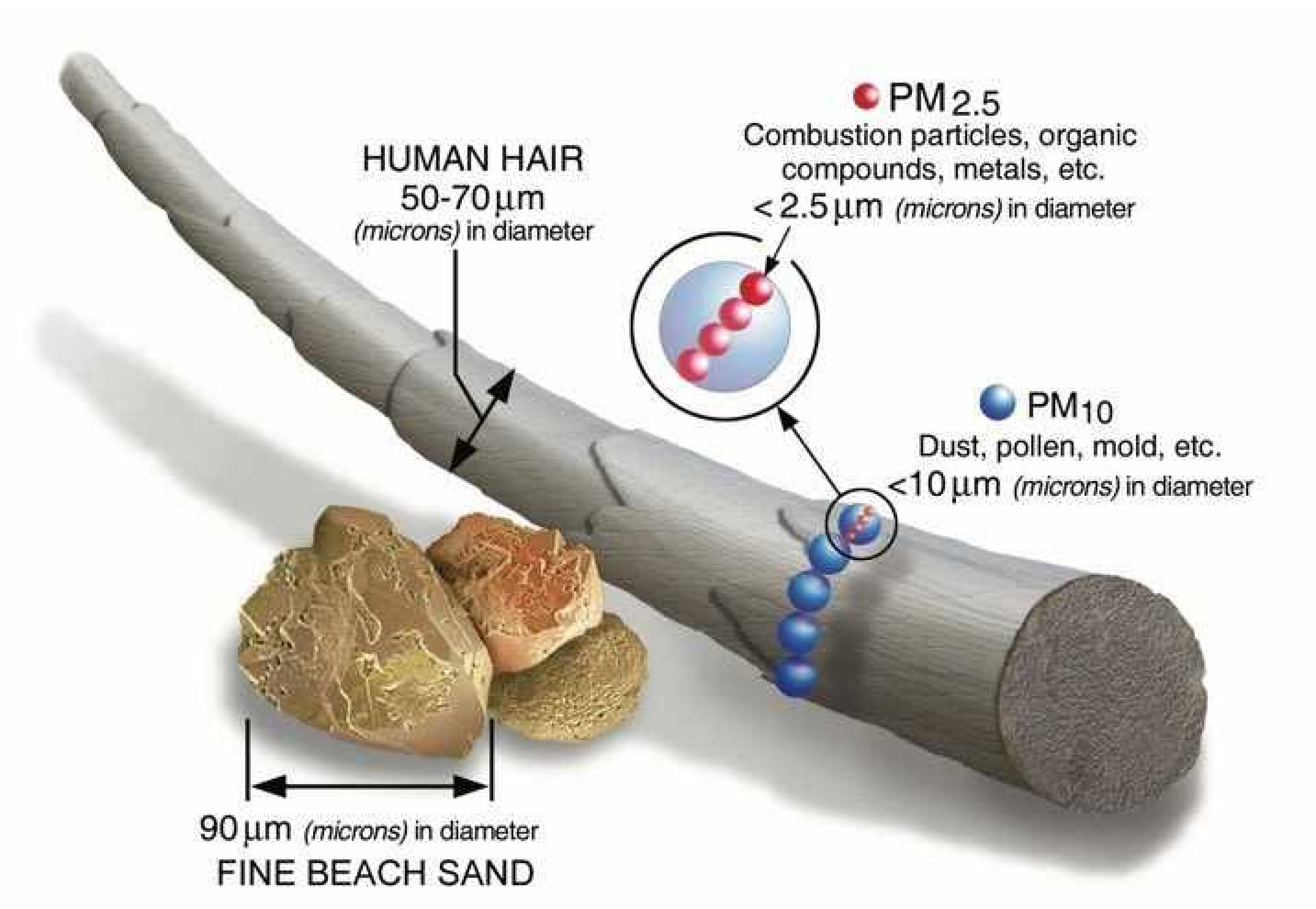
Figure courtesy of Harvard.

When forests burn, they produce smoke that is comprised of many toxic substances, as shown in the image to the right.

Harmful substances in smoke from wildfires includes acrolein (a lung irritant), carbon monoxide (which can be fatal at high concentrations); formaldehyde, benzene, and polyaromatic hydrocarbons, or PAHs (all of which can cause cancer); and particulate matter (PM).

PM2.5 refers to particulate matter that is 2.5 microns in diameter or smaller in size. You may also see references to PM10, 10 microns in size, which is considered less harmful but can still be dangerous.

Size chart



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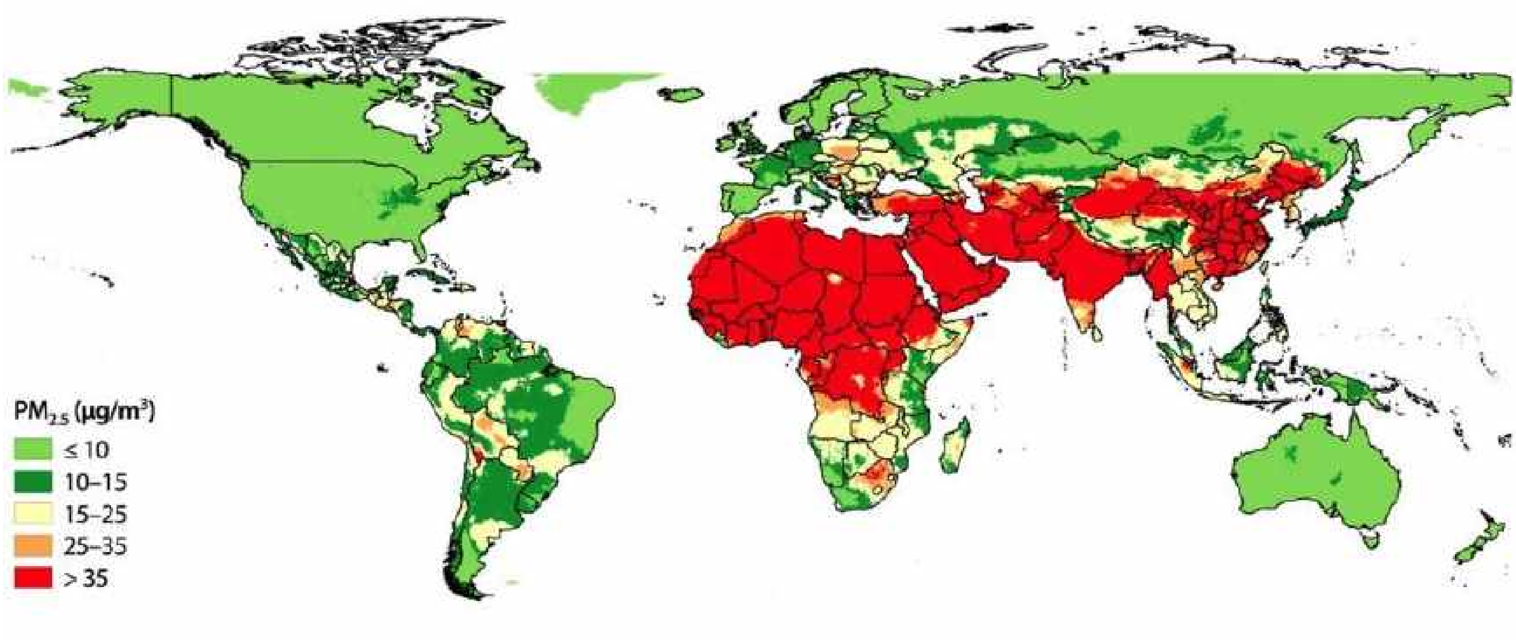
PM2.5 is about 1/20th the width of a human hair. Research on PM2.5 has clearly demonstrated that when people breathe it in, it can be deadly, particularly by causing heart attacks and strokes. World wide, PM exposures is responsible for millions of deaths each year . PM exposure has also been associated with preterm birth, lung cancer, and a host of other diseases . Exposure to air pollution is the 4th highest-ranking risk factor for death in the world.

Particulate matter around the world

The map below shows that PM2.5 is primarily a problem in Africa, the Middle East and south and east Asia. But particulate can come from a variety of sources besides fires. For particulate matter in outdoor air, combustion of fossil fuels, with coal and diesel fuel, make substantial contributions in most places.

PM2.5 worldwide



For an interactive view of particulate matter on Earth, check out https://www.airvisual.com/earth.

Finally, the table below illustrates the different sources of particulate air pollution - both indoor and outdoor - in countries around the world. Indoor particulate matter air pollution is just as dangerous as outdoor pollution but its sources are different: indoor PM mostly comes from burning fuels to cook and heat homes with.

Location	Traffic	Industry	Domestic fuel	Other human sources	Natural sources
Canada	15%	10%	6%	62%	7%
USA	24%	9%	12%	46%	10%
Brazil	34%	19%	*	25%	22%
Rest of the Americas	30%	8%	25%	16%	21%
Northwestern Europe	21%	13%	22%	23%	21%
Western Europe	25%	11%	15%	44%	5%
Central and Eastern Europe	19%	17%	32%	16%	16%
Southwestern Europe	35%	11%	12%	22%	20%
Turkey	14%	30%	*	42%	14%
Middle East	12%	27%	*	9%	52%
Africa	17%	10%	34%	17%	22%
India	37%	4%	16%	22%	21%
Southern Asia	34%	27%	13%	16%	10%
Southeastern Asia	36%	18%	19%	13%	14%
Southern China	18%	27%	21%	24%	10%
Northern China	15%	16%	15%	30%	24%

South Korea	23%	15%	5%	45%	12%
Japan	23%	34%	*	1%	42%
Oceania	26%	11%	13%	25%	25%
Global Average	25%	18%	15%	20%	22%

Data on this table is from Contributions to cities' ambient particulate matter (PM): A systematic review of local source contributions at global level , Karagualian et. al. 2015. If the table seems to cover a strange set of geographical locations, it is because these studies had simply not been done yet in many locations as of 2015. Items with an asterisk (*) were not included in that particular study. Domestic fuel includes wood, coal and gas fuel for cooking or heating. Industry includes emissions from oil combustion, coal burning in power plants and emissions from different types of industries (petrochemical, metallurgic, ceramic, pharmaceutical, IT hardware, etc.) and from harbor-related activities. Natural sources includes dust aerosolized from fields or soils (road dust was included in the traffic) and sea salt. The category labeled "unspecified sources of human origin" refers to air particles formed from chemical reactions in the atmosphere - so-called secondary particle formation. The precursors to these particles are often from fossil fuel combustion byproducts.

Curtailing fossil fuel combustion reduces the quantity of climate warming gases emitted, and also reduces disease and death associated with particulate matter and other air pollutants.

Allergies and Asthma

Pollen is a major contributor to seasonal allergies and can cause asthma attacks. Warming temperatures have substantially lengthened the season during which plants that produce allergenic pollen can survive. Over the past few decades, the ragweed pollen season has been extended by several weeks in parts of North America, as can be seen on the map below.

Days added to ragweed pollen season, 1995-2009

At the same time, higher carbon dioxide concentrations in the air are contributing to greater pollen output from ragweed plants.

Pollen Count and Production by Year

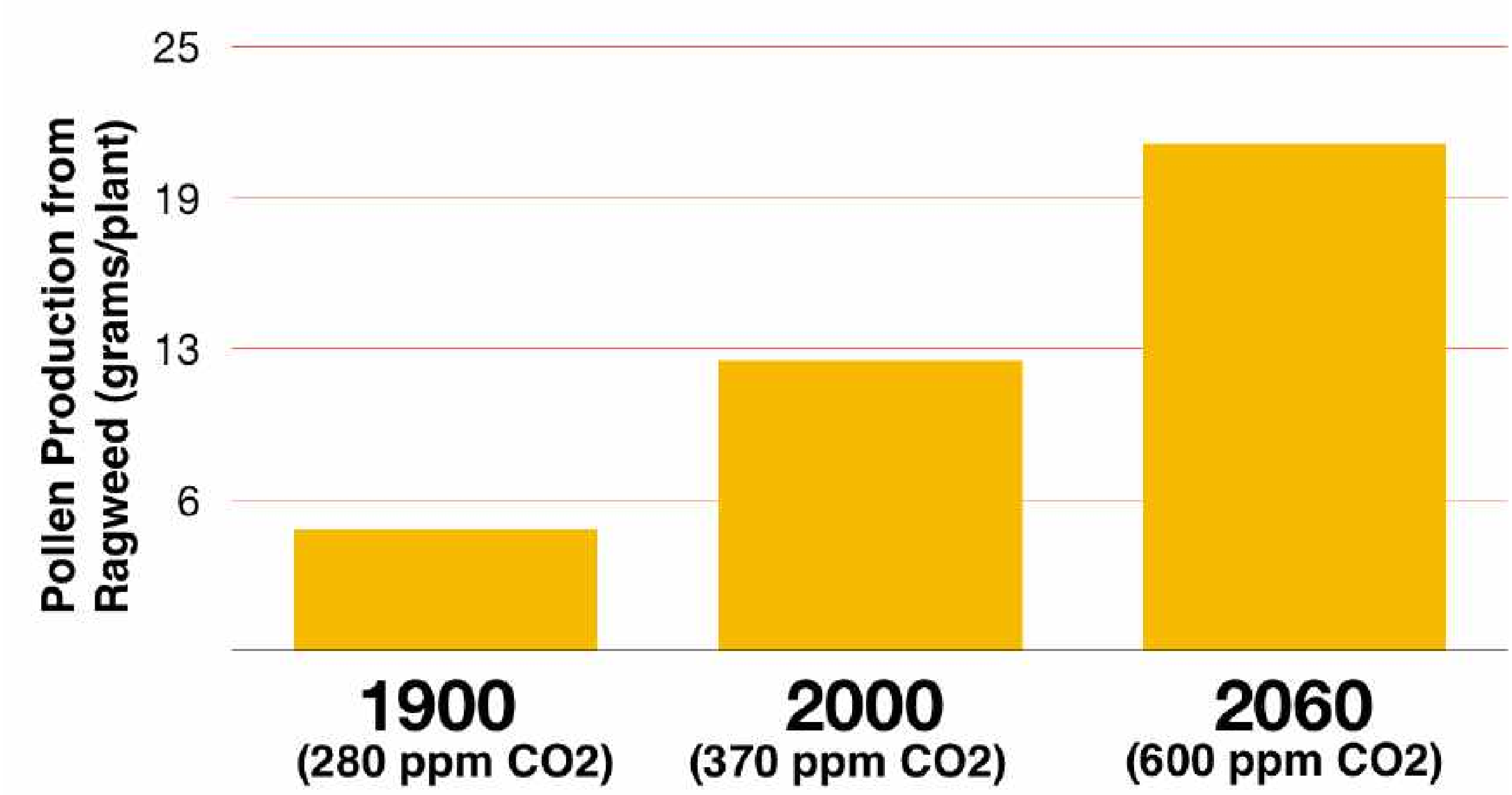


Figure courtesy of Harvard. Data from Rising CO2 and pollen production of common ragweed (Ambrosia artemisiifolia L.), a known allergy-inducing species: implications for public health.

The data shown in the graph to the right are based upon experiments in a lab in which ragweed plants were grown under different carbon dioxide concentrations (280, 370 or 600ppm). The higher the carbon dioxide concentration, the more pollen was produced. Remember, today the atmospheric carbon dioxide concentration is well above 400ppm, which means the amount of pollen produced by ragweed plants may be twice than that at the start of the 20th century.

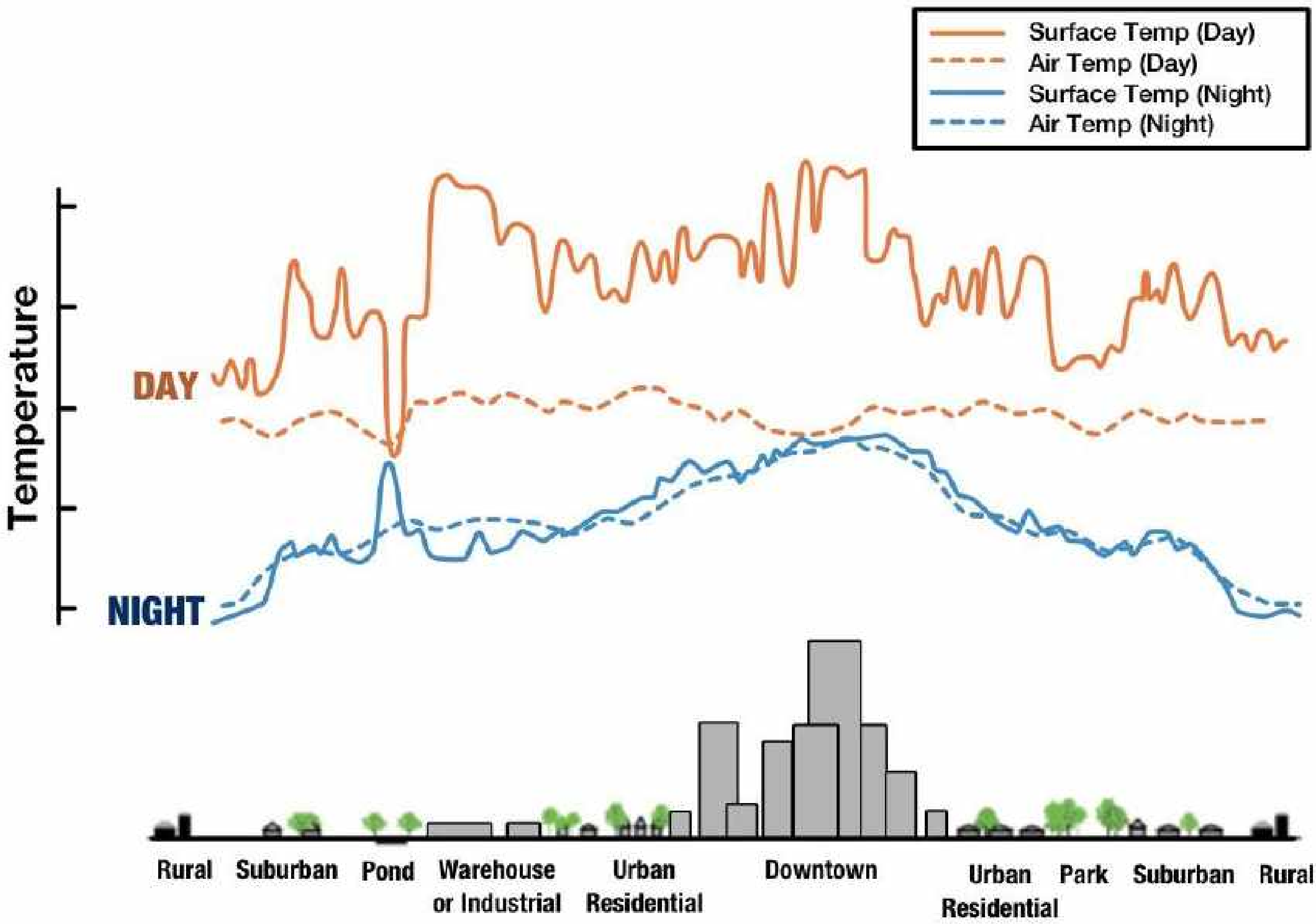
Other allergenic plants are influenced by elevated carbon dioxide, including poison ivy. Poison ivy has been shown to grow larger and produce more allergenic urshiol (the compound in poison ivy responsible for causing an allergic reaction) when grown under higher carbon dioxide concentrations

Cities and Local Temperatures

Cities are almost always hotter than surrounding areas. This has everything to do with how they are built. Dark surfaces absorb heat better than white or green ones, and cities are mostly draped in grey asphalt roads and dark roofs.

The illustration below demonstrates what is known as the *urban heat island* effect. Cities, because they absorb more heat, get hotter in the day - and stay hotter at night - than the greener areas that surround them. Heat islands have warmed cities around the world much faster than the effects of climate change. Lessening heat islands can go a long way toward preventing heat-related harms in cities.

The Urban Heat Island Effect



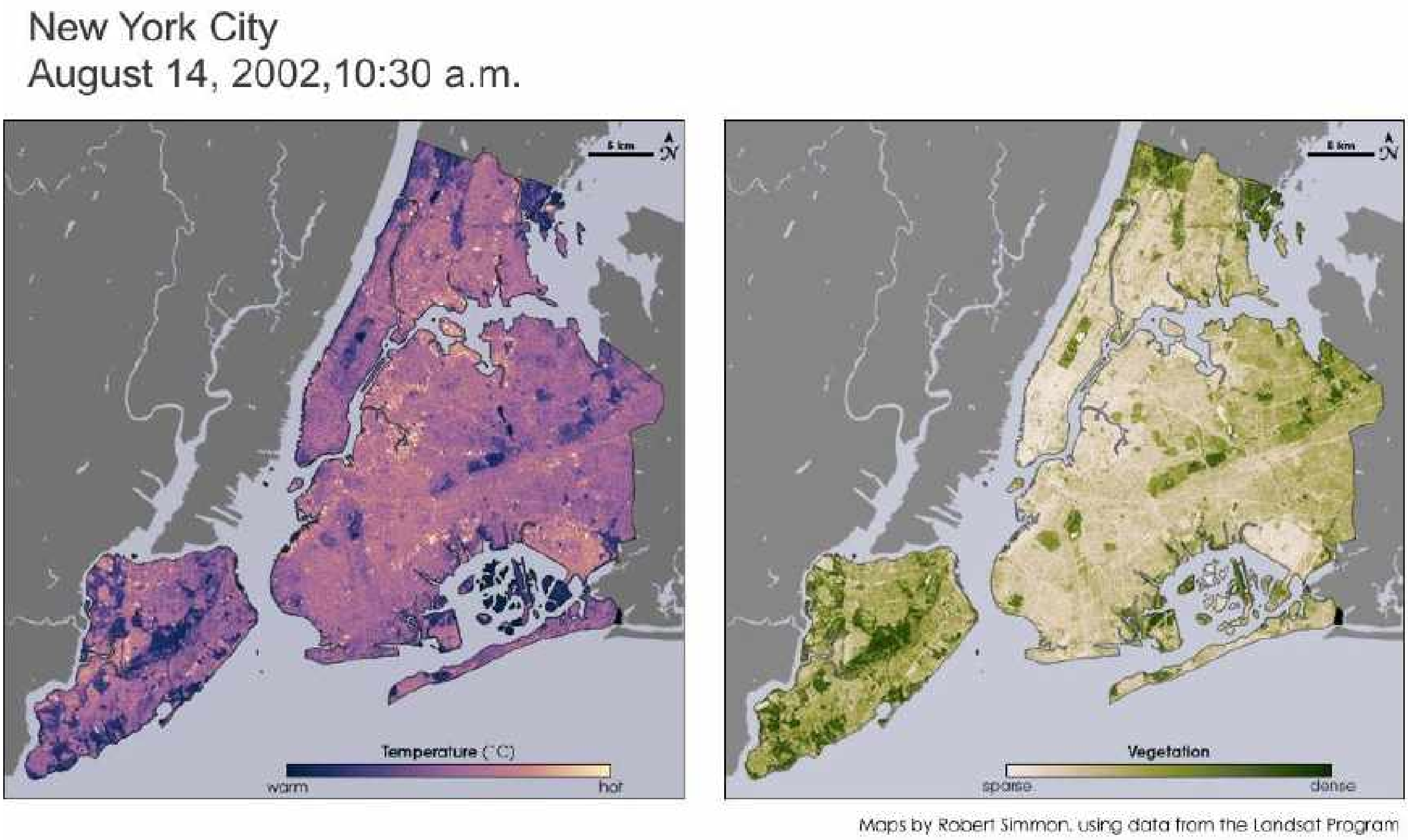
The urban heat island has produced substantial warming in recent decades. In many cities, the amount of warming over just the past 10 years exceeds the amount of warming that may occur due to greenhouse gas emissions by the end of this century. The table below shows 10 major cities in the United States with the fastest growing urban heat island effect per decade since 1970.

City	°F/decade
Columbus, Ohio	0.84
Minneapolis, Minnesota	0.77
Baltimore, Maryland	0.66
Louisville, Kentucky	0.65
St. Louis, Missouri	0.64
Wichita, Kansas	0.60
Birmingham, Alabama	0.58
New Orleans, Louisiana	0.56
Des Moines, Iowa	0.56
Oklahoma City, Oklahoma	0.55

Green Spaces and Temperature

These satellite images show New York City. On the left is the temperature gradient across the city with lighter colors indicating hotter temperatures. On the right is an image of where the green parts of New York are. Look at these two images - what can you infer about the relationship between green space in cities and heat?

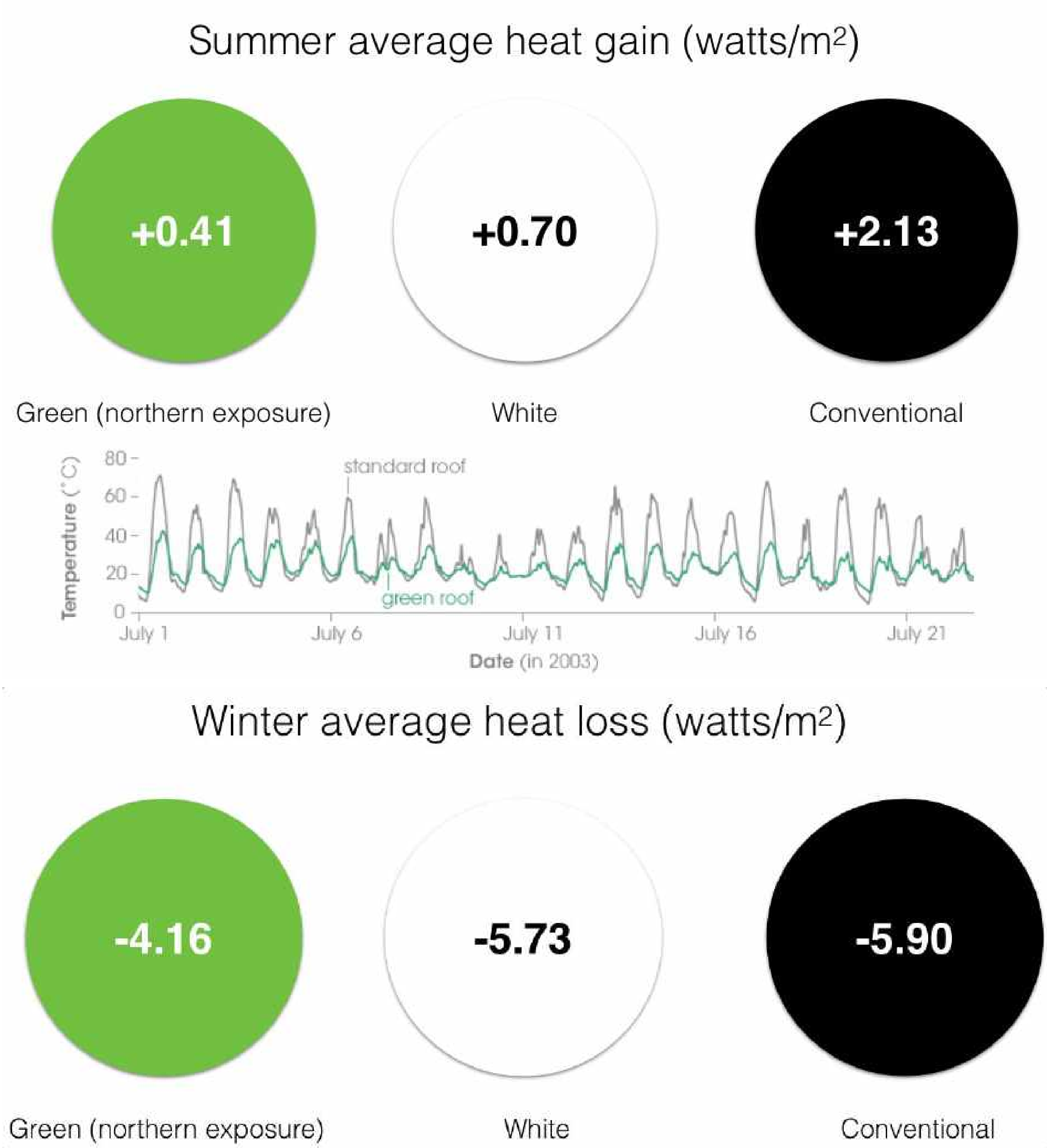
Temperature and vegetation maps



Urban green can substantially cool off cities. No surprise, then, that cities around the world have looked to increasing urban green space as a health intervention. In many cities, room to plant new trees is sparse so people have started to look at roof space, which is plentiful, as an alternative.

Green roofs, that are planted with vegetation, are more expensive and difficult to pull off than painting a roof white. However, on average they can confer greater benefits to the building's occupants in terms of the need for heating and cooling.

The Effects of Green Roofs



The above graphics show how green roofs are far cooler than their conventional (or white) counterparts in summer and also act to insulate in the winter (they have less heat loss). People who have to pay for energy in buildings will pay less when they have green roofs.

There's another important benefit to green roofs in cities: because plants absorb water and need soil which also absorbs water, green roofs prevent water runoff into storm sewers. Heavier downpours with climate change have strained sewer systems in cities around the world. When sewers overflow, it can set the stage for waterborne disease outbreaks. You can read about sewage issues later in the course, or you can move to the next page and continue with the final pieces of this chapter.

Introduction to Infectious Disease

Overview

In the last chapter, Heat & Air Quality, you learned about the pathways from greenhouse gas emissions to health effects related to heat and air pollution.

In this chapter we'll trace paths from greenhouse gas emissions to vector-borne and waterborne diseases. We'll take a close look at diseases, such as malaria and dengue, that are transmitted to people by mosquitos, since these diseases have received a lot of attention in recent years and sicken millions of people each year. We'll also look into the challenges that researchers and policymakers face when trying to predict how climate change will change where and when these diseases appear.

The Basics of Vector-borne Disease

As Erin Mordecai described in the video clip above, climate change matters to vector-borne diseases for many reasons. Insects, for instance, are cold blooded creatures (or "ectotherms"), and so must seek out warmer or cooler environments to regulate their body temperatures. The intensification of the water cycle with climate change is particularly relevant to mosquito reproduction which occurs in water. The parasites and viruses carried by insect vectors also are temperature sensitive.

Rainfall can substantially influence risk of vector-borne disease. Research on Dengue in Guangzhou China , Taiwan , and elsewhere documents that rainfall is associated with dengue outbreaks. Rain creates pools of water that can be breeding habitat for juvenile mosquitos. However, too much rain can wash away these pools, and with them, the developing mosquitos.

Somewhat counterintuitively, droughts may also promote vector-borne disease outbreaks. During droughts, people may be more likely to use containers to store water, and mosquitos can breed in these containers.

Warming combined with changes in the water cycle have raised concern about how climate change may influence the spread of vector-borne diseases. But as you heard in the clip above, predicting how climate change will change where and when vector-borne disease occurs isn't straightforward.

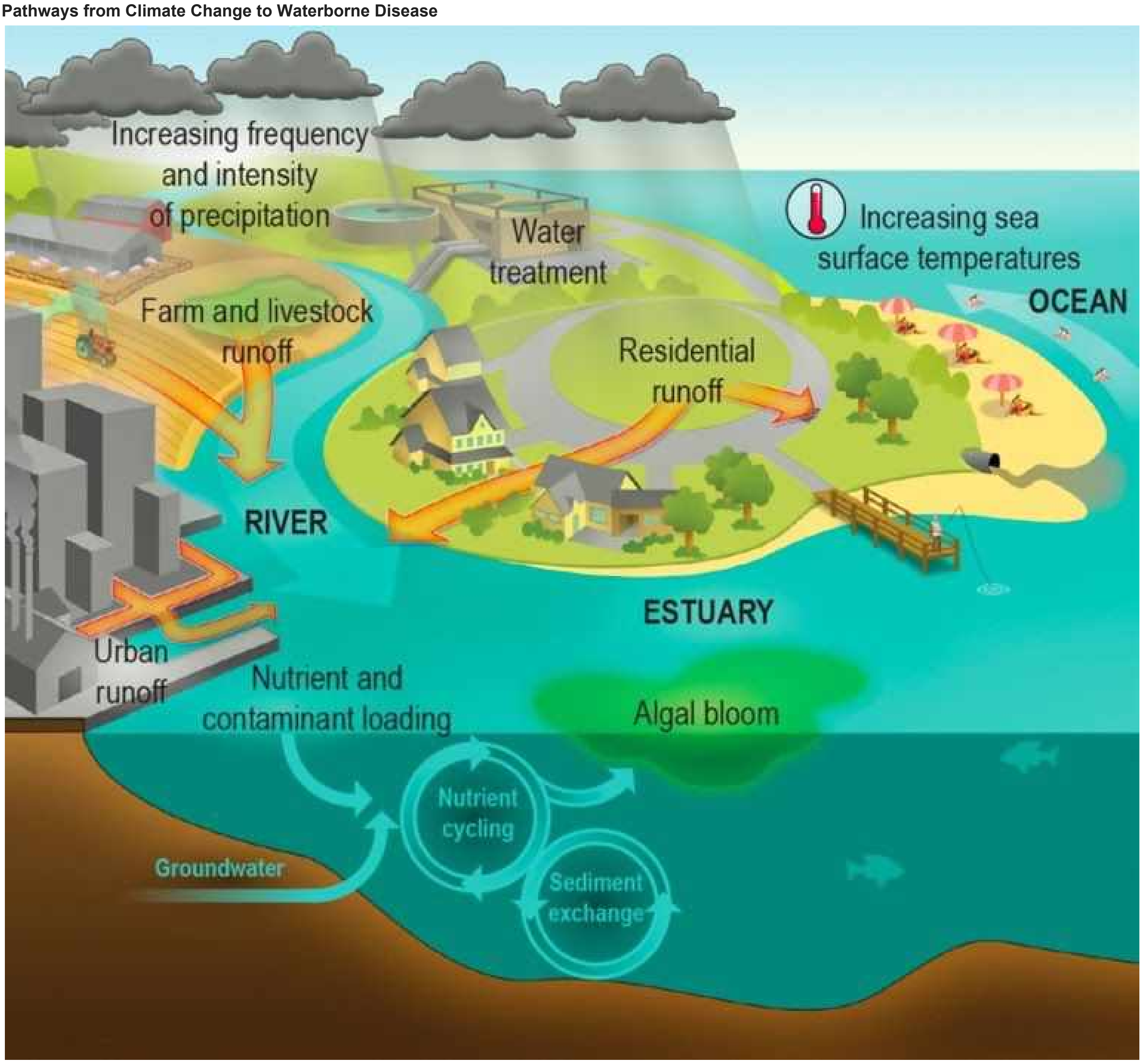
Our primary model to explore how climate change may affect vector-borne disease in this course will be malaria. We'll discuss infection and efforts to control it in much greater depth in the malaria section of this course. For now, however, let's move on to waterborne diseases.

Waterborne Disease

Greenhouse gas emissions arguably have equal if not greater relevance to the distribution and spread of waterborne diseases as vector-borne diseases around the world. From Vibrio bacteria that cause cholera and other diseases, to ciguatera fish poisoning and shellfish poisoning and harmful algal blooms, warming temperatures and more intense precipitation may favor waterborne disease outbreaks.

The graphic below illustrates how climate related events, such as heavy precipitation, can contribute to outbreaks of waterborne disease. Rainfall washes pathogens contained in animal and human excrement into sewer systems and eventually into local water bodies where water may be drawn from for drinking or crop irrigation. Warmer temperatures may promote growth of pathogens.

Pathways from Climate Change to Waterborne Disease



Causes of Algal and Cyanobacterial Blooms

Harmful algal bloom  **Figure courtesy of NOAA**

Algae and cyanobacteria behave like plants: they absorb carbon dioxide and release the oxygen that we need to survive on Earth. However, they can also produce toxins that are dangerous to wildlife and swimmers. Warmer ocean temperatures and heavier precipitation, which increases the delivery of nutrients such as nitrogen and phosphorous to coastal waters and lakes, can promote the growth of algae and cyanobacteria. When conditions are right, algal blooms occur like those seen to the right. For the purposes of this course, we'll define a harmful algal bloom as an instance where algae or cyanobacteria grow out of control and produce toxins.

One of the key ingredients for a harmful algal bloom is nitrogen. The map below shows where nitrogen is deposited across the Mississippi river basin in the United States. The heavy use of nitrogen based fertilizer to grow food, as well as highly concentrated livestock operations in the upper midwest, deliver nitrogen into the Mississippi river. There, it ultimately reaches the gulf of Mexico, where it can fuel harmful algal blooms. This scenario occurs wherever agriculture and rivers co-exist, which means it can - and does - occur on every continent except Antarctica.

Nitrogen in the Mississippi river watershed

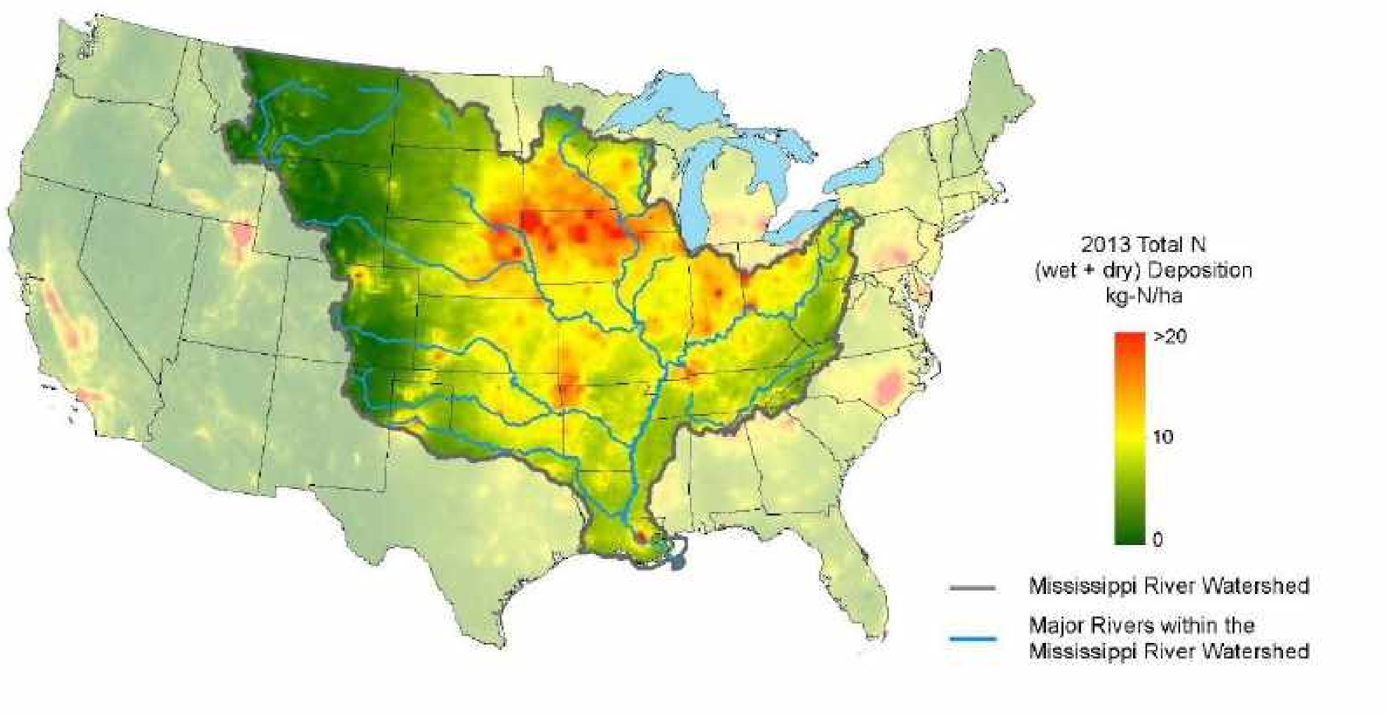


Figure courtesy of the National Atmospheric Deposition Program

Agricultural run off flowing into river basins and ultimately to the sea and fueling harmful algal blooms is occuring around the world

Malaria's Impact

Ever been bitten by a mosquito? Depending on where you were when that happened the bite could have been merely an itchy nuisance or the beginnings of a life threatening disease. Malaria, a parasitic disease transmitted through the bite of a mosquito, is a major global health challenge . Each year, more than 200 million people - mostly in lowland tropical areas - are estimated to contract malaria and more than 400,000 people, mostly children younger than 5, die. Almost half of the Earth's population currently live in areas where malaria can be transmitted.

The impact of many diseases is measured in DALYs: Disability-Adjusted Life-Years . The greater the DALYs, the worse things are. The map below shows the DALYs associated with malaria round the world.

Map: Malaria DALYs per 100,000 population

White: value is zero Grey: no data

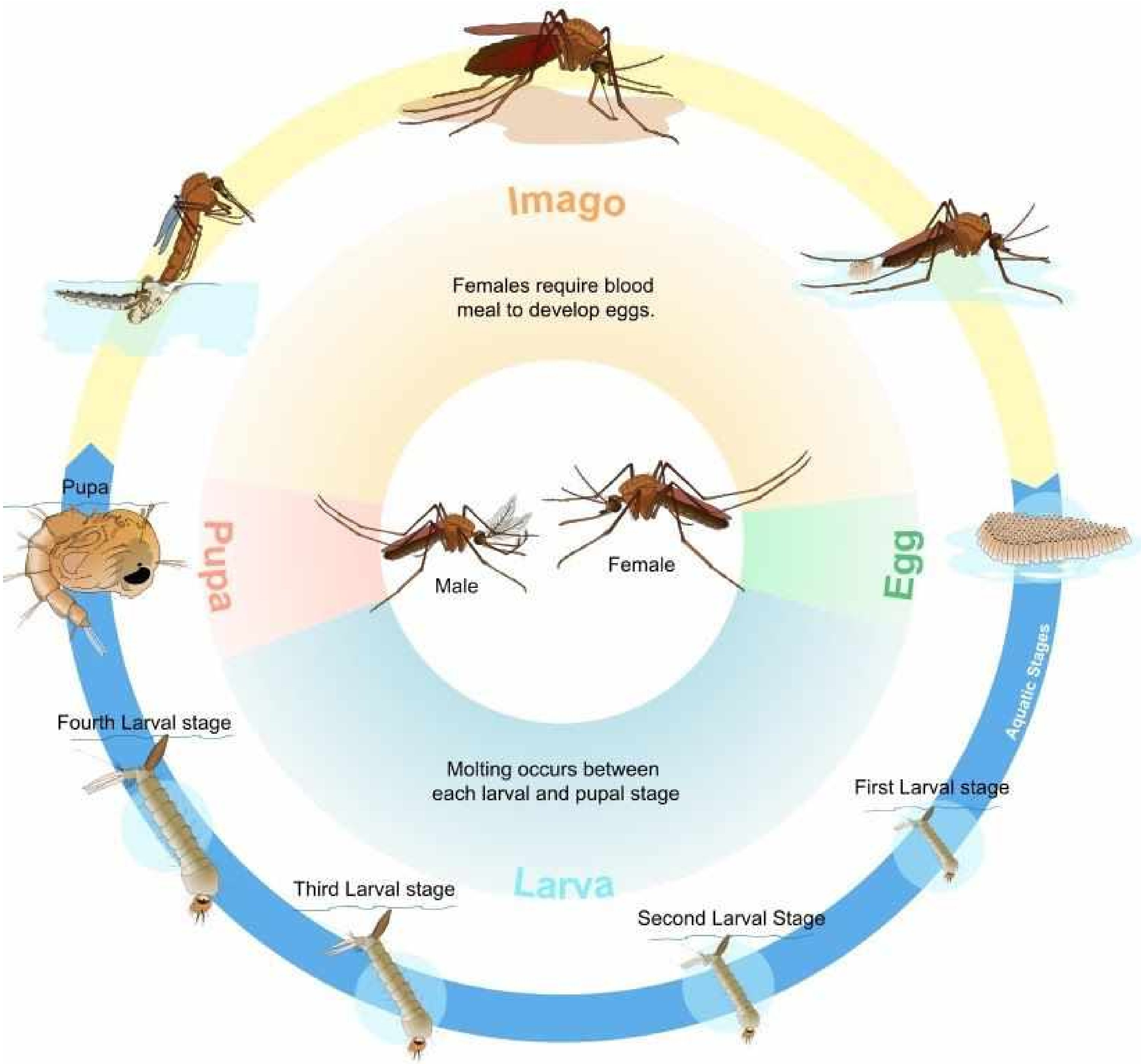
Fortunately, the incidence of malaria has been declining in many parts of the world in recent years, especially in Africa.

Much research has focused on the role of temperature and its effects on where the disease may occur. This relationship is complex, showing many nonlinear aspects.

The reproduction of malarial parasites involves stages in mosquitoes and in humans (including periods of time in liver cells and blood cells). You can see quick overviews of the mosquito and malaria life cycles below. Note that the mosquitoes lay their eggs in water. The parasites have a lifecycle that includes time inside the human body and inside a mosquito. The time the parasite spends developing in the mosquito,

where it is exposed to outdoor temperatures, is known as the extrinsic incubation period. Keep these in mind as we move through this section.

The Mosquito Lifecycle



Public domain image courtesy of **Wikimedia Commons user LadyOfHats**

The Malaria Parasite Lifecycle

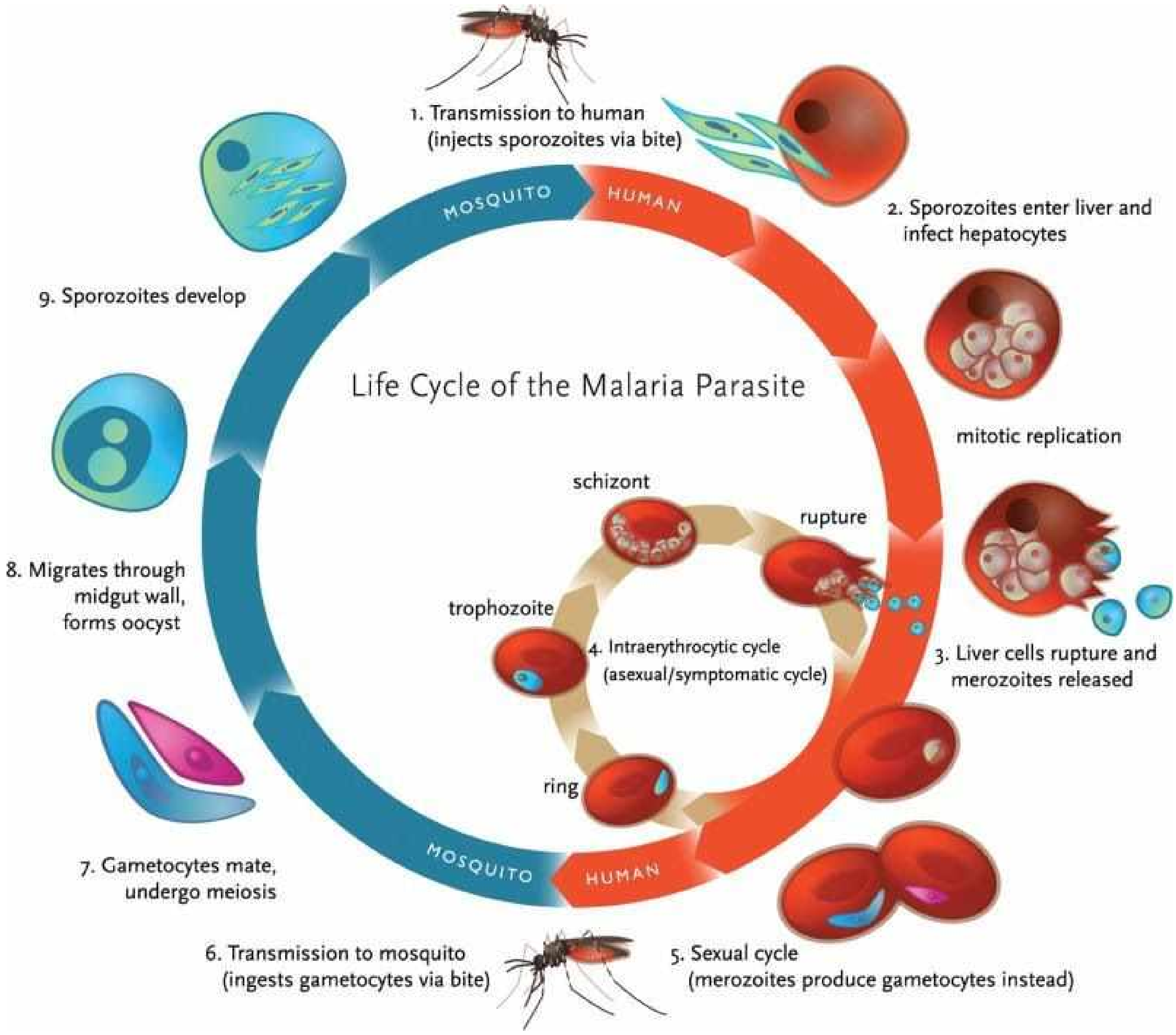


Image from Antimalarial drug resistance: a review of the biology and strategies to delay emergence and spread , E.Y. Klein, Int J Antimicrob Agents. 2013 Apr; 41(4): 311–317. Published online 2013 Feb 8. doi: 10.1016/j.ijantimicag.2012.12.007

Mosquitos and temperature

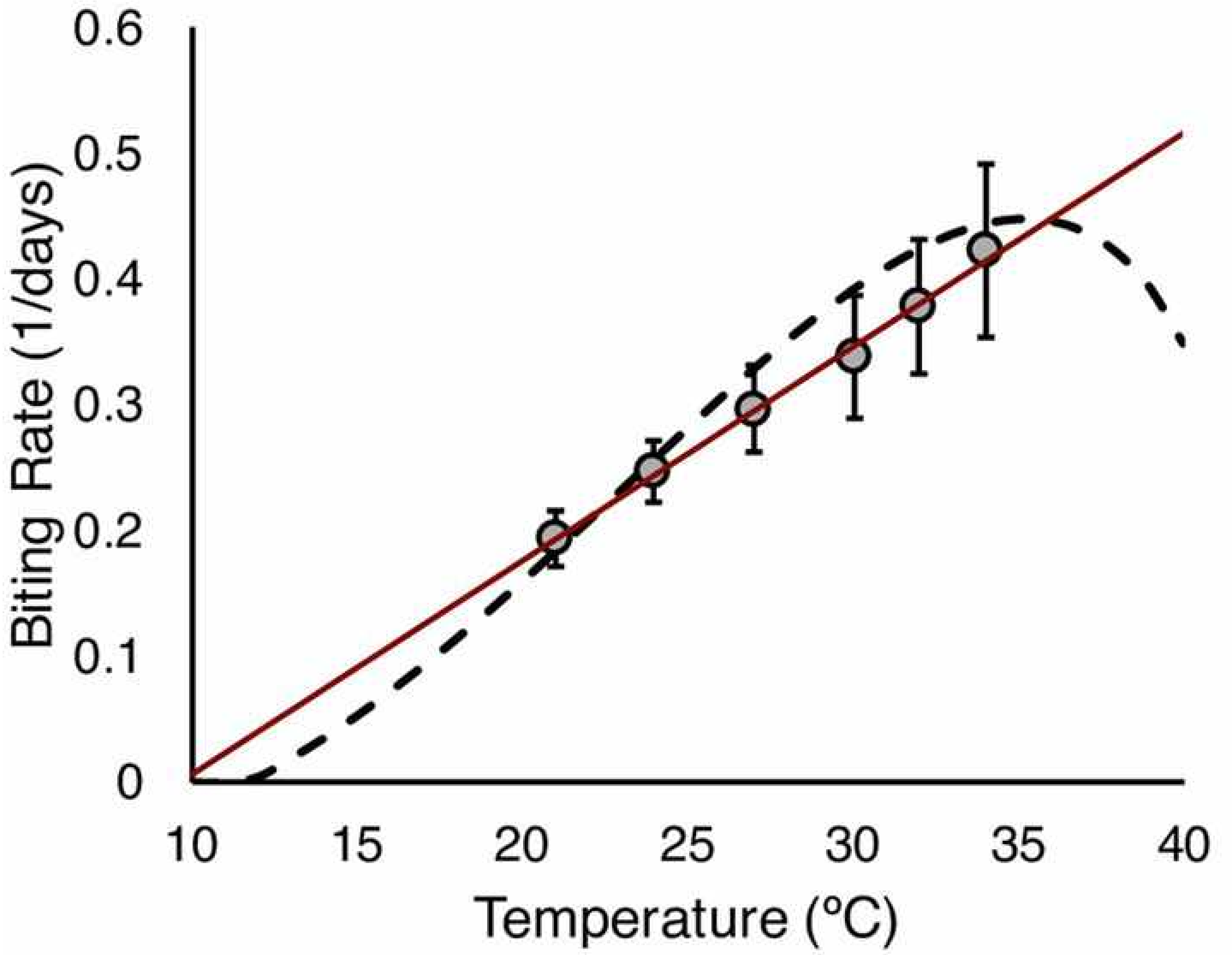
Where mosquitoes live depends on temperature as they are cold-blooded and cannot survive when temperatures get too hot or too cold. The rate of mosquito development also varies with temperature. Warmer temperatures accelerate development until temperatures are high enough to be lethal. Colder temperatures slow development until development stops because it's too cold.

Malarial parasites also are temperature sensitive, especially during the so-called extrinsic incubation period (see parasite lifecycle figure in the previous section), which occurs when the parasite is living in mosquitoes.

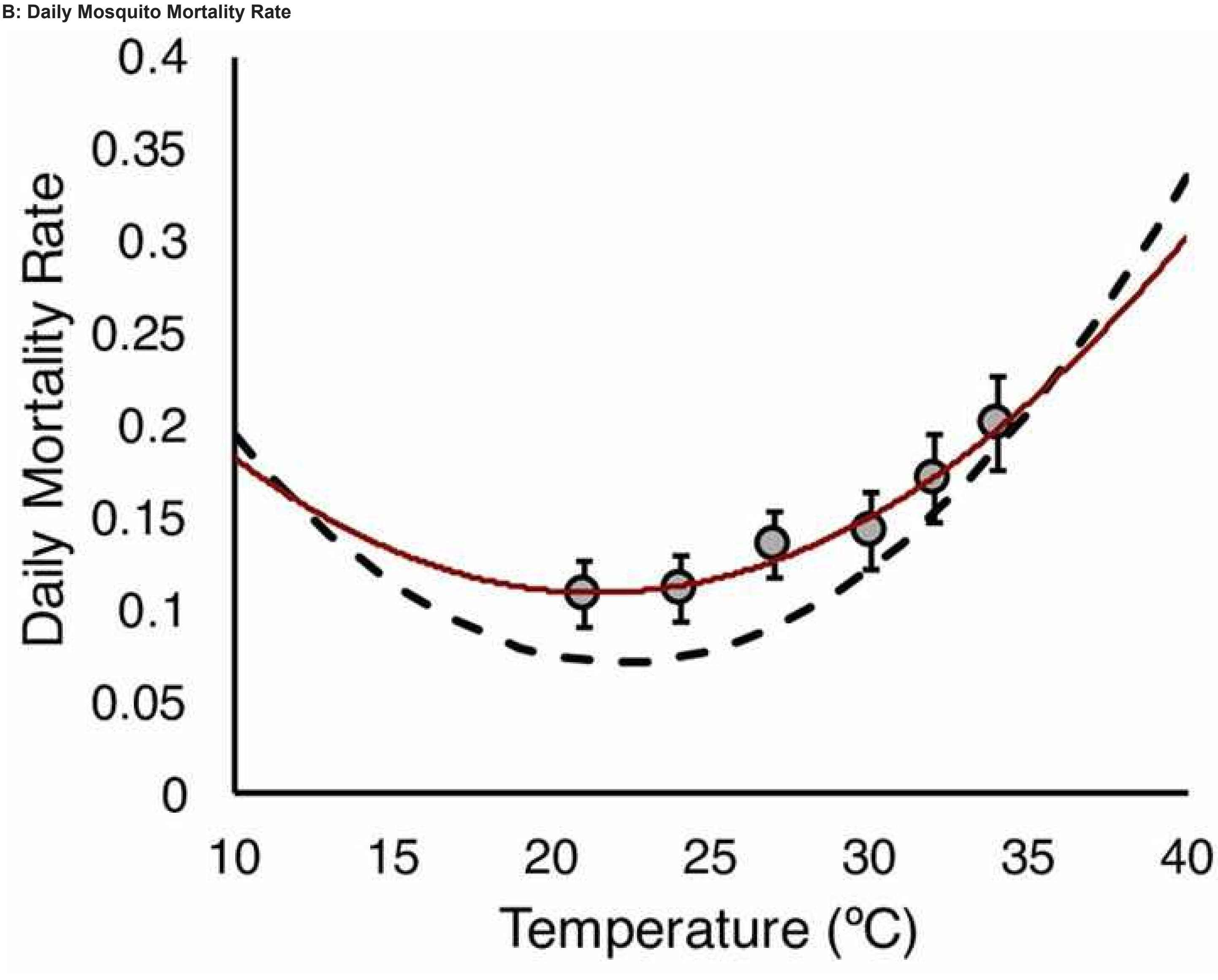
The first studies on the relationship between temperature and malaria examined how an increase in average temperature might expand the geographic range of disease. But subsequent research has shown that studying changes in average temperature may have overestimated how much malaria may respond to climate change.

The graphs below illustrate some of the effects of temperature on mosquitoes that transmit malaria and malarial parasites. As always, you can click to see larger versions.

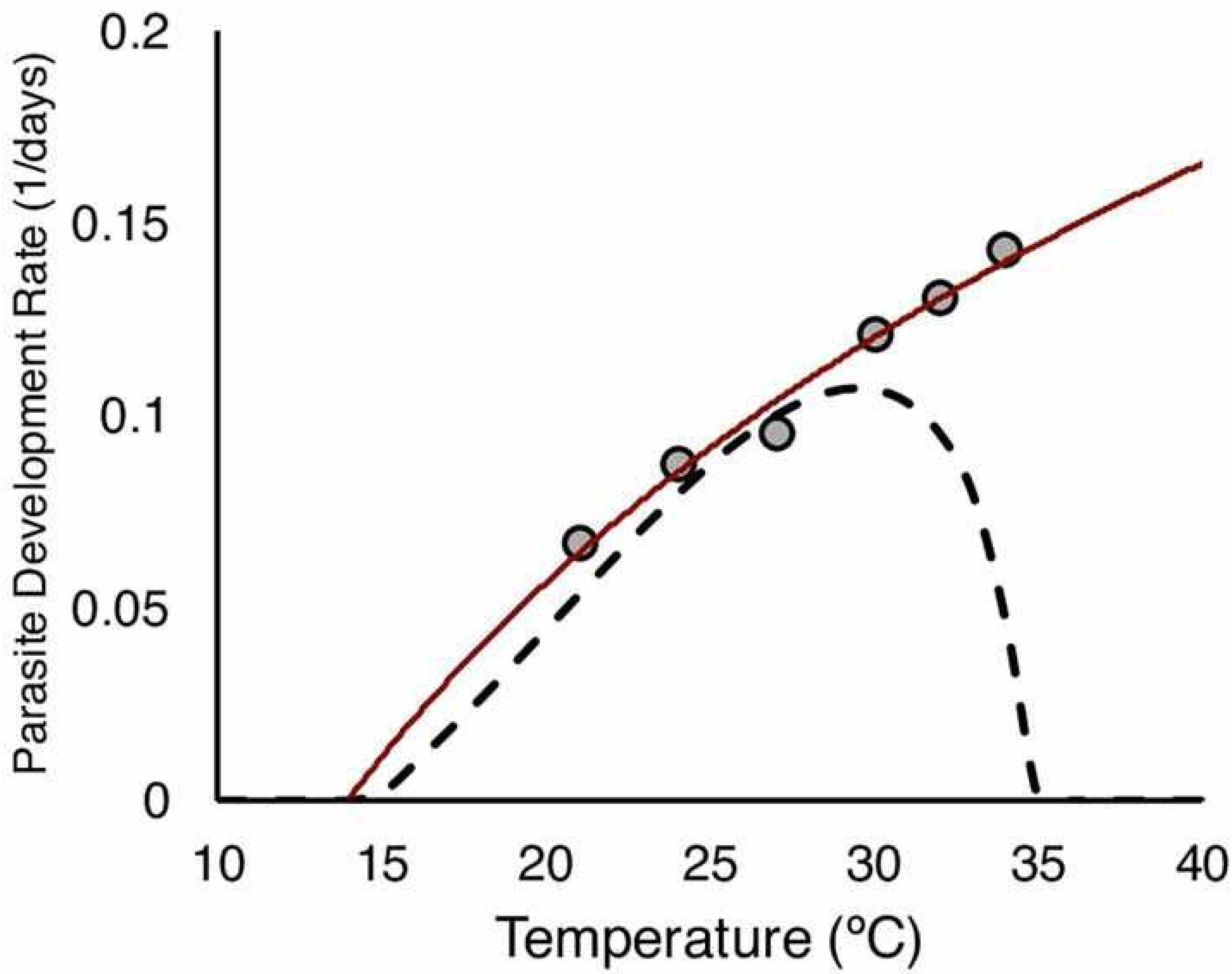
A: Mosquito Bite Rate



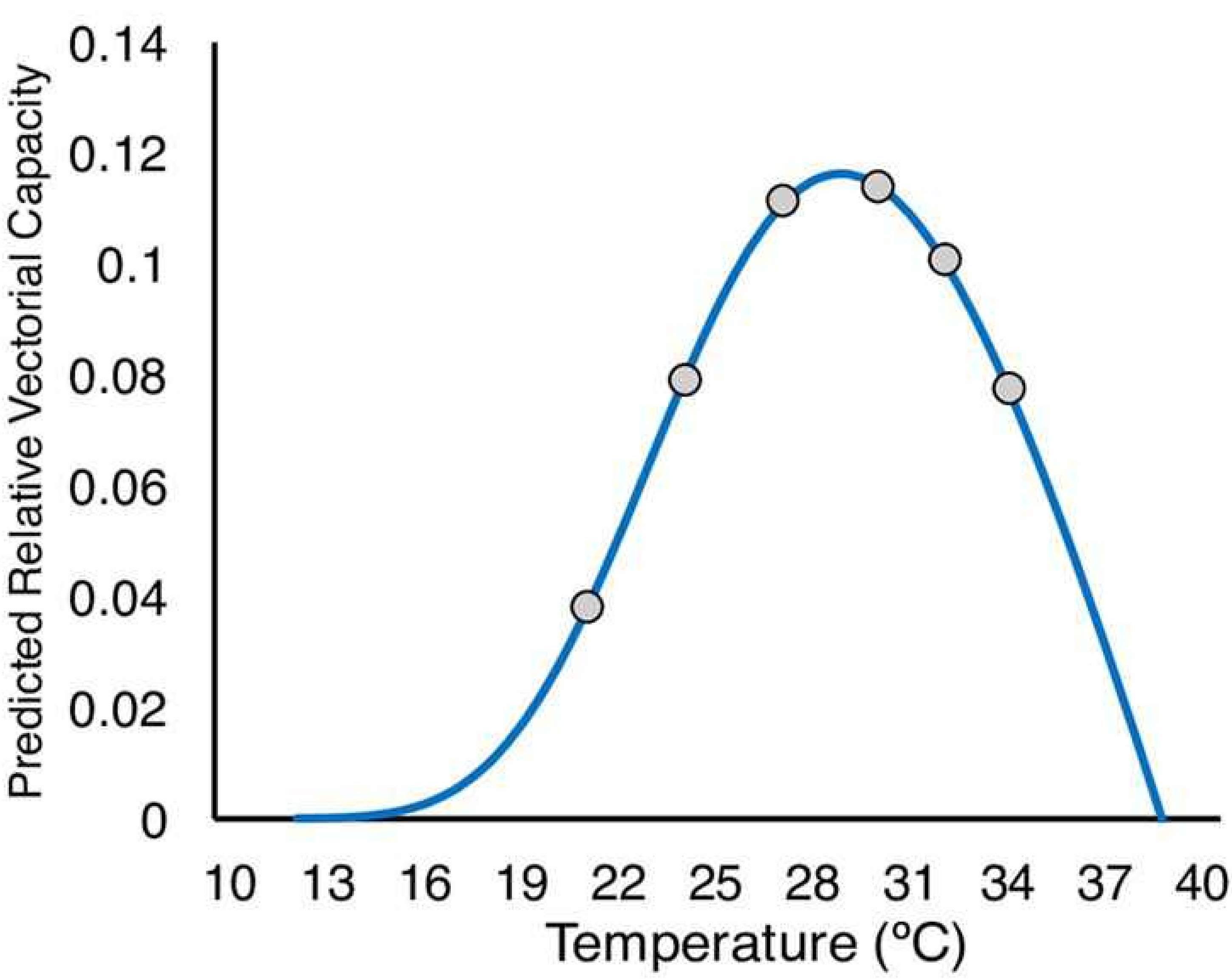
B: Daily Mosquito Mortality Rate



C: Malaria Parasite Development Rate



D: Predicted Vectorial Capacity



Figures from Shapiro LLM, Whitehead SA, Thomas MB (2017) Quantifying the effects of temperature on mosquito and parasite traits that determine the transmission potential of human malaria . PLoS Biol 15(10): e2003489. https://doi.org/10.1371/journal.pbio.2003489

The solid red lines are best-fit lines to the data in this study, while the black line shows predictions from a previous study from Mordecai et al . The blue line in graph D indicates that this is a prediction based on the data collected in this study.

Warmer temperatures promote higher biting rates and faster parasite development (note that graphs A & C show the biting and development rates as reciprocals - 1/days - so the higher the value the faster the biting or development rate). However, high temperatures also increase mosquito mortality (graph B). Mosquitoes live shorter times at significantly higher temperatures.

Graph D shows the predicted vectorial capacity (which is the rate at which a mosquito bites can transmit infection to a human following ingestion of an infected blood meal) based upon how temperature influences mosquitoes' and parasites' ability to spread malaria and shows that at low and high temperatures, mosquitoes are much less likely to transmit disease.

Temperature and Development

Daily temperature *variability* - not just the temperature, but its range over the course of a day - affects how fast the mosquitos that transmit malaria reproduce. But the same amount of temperature variability does not affect all mosquito vectors equally. Consider the graph below:

Mosquito development rate at constant and fluctuating temperatures

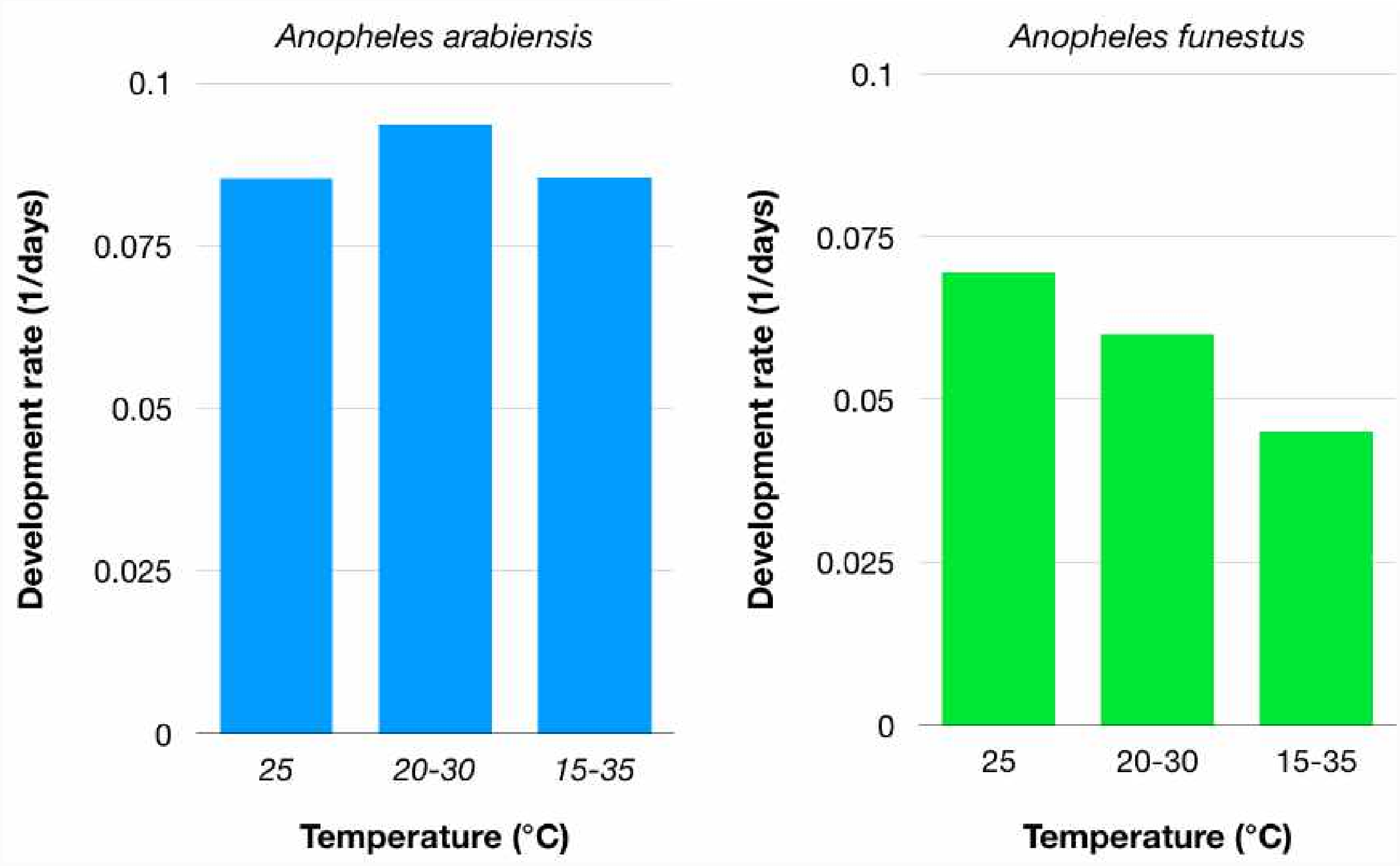


Figure adapted from Stable and fluctuating temperature effects on the development rate and survival of two malaria vectors, Anopheles arabiensis and Anopheles funestus

The above graphs show experiments with two malaria mosquito vectors, *Anopheles arabiensis* and *Anopheles funestus*. In this experiment, mosquitos were exposed to either a constant temperature (25°C) or varying temperatures (either from 20-30°C or 15-35°C).

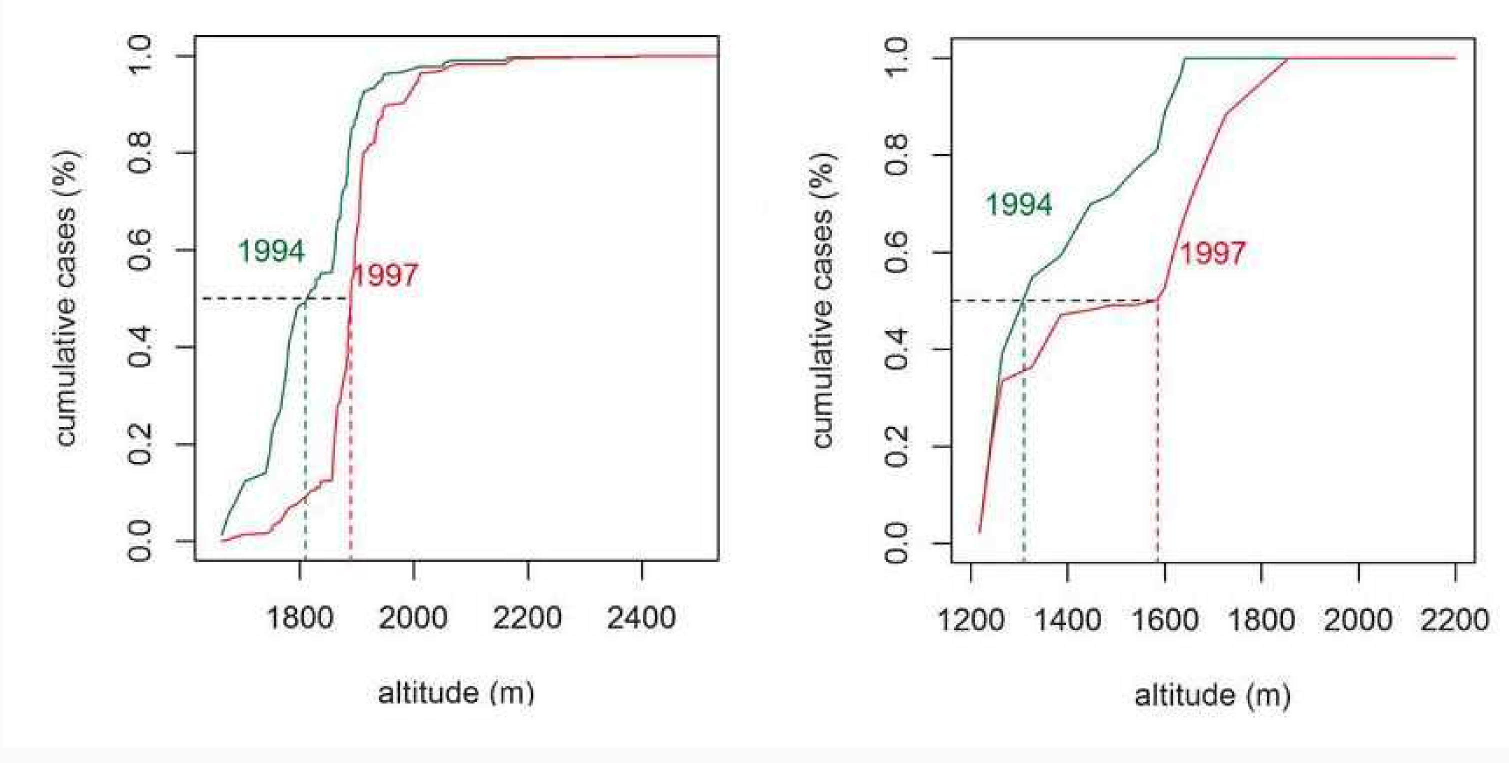
For *Anopheles arabiensis*, development rates did not change significantly across the three temperature conditions. However, for *Anopheles funestus*, development occurred substantially faster at 25°C than under the fluctuating temperature conditions. Temperature swings may harm *funestus* more than other mosquito types, which has implications for malaria transmission in the places where this species is common.

Temperature and Altitude

Despite the many moving parts involved in temperature effects on mosquitoes and malaria parasites as Professor Mordecai describes, some evidence suggests that it has been increasing its geographic range with warmer temperatures.

Temperature effects may be clearest when looking for the spread of malaria up mountainsides. As climate warms, it may facilitate the spread of malaria to higher elevations, which were historically too cool for the disease to gain a foothold.

Shifting altitudes of malaria cases (Ethiopia and Colombia)



Data from Stable and fluctuating temperature effects on the development rate and survival of two malaria vectors, Anopheles arabiensis and Anopheles funestus

The above graphs show that cases of malaria in Debre Zeit area of central Ethiopia and the Antioquia region in western Colombia have moved to higher elevations under the influence of warmer temperatures.

Many cities in mountainous regions

in the tropics were established at altitudes high enough to make them safe from mosquitoes and the diseases they carry. As temperatures warm, these cities - some of which have populations in the millions - may now or soon have suitable temperature regimes for vectorborne disease. The people in these cities may also be at risk of infection because they have never been infected with the diseases that may be coming their way, and so they lack immunity to them.

While some places may be getting warm enough for malaria, others may be getting too warm. Check out the video below for more information.

Malaria and Precipitation

Knowing that mosquitoes can't readily survive if temperatures are too warm can help predict where malaria may not occur as climate change unfolds. But other factors aside from temperature matter to malarial incidence, including rainfall.

The mosquitoes that transmit malaria (though not all mosquitoes) prefer standing pools of water to breed in. This makes rainfall a key determinant of when malarial outbreaks may occur and many studies (e.g. in China and Kenya) have shown that rainfall today may increase risk of malaria in people.

But the relationship between rainfall and mosquito breeding isn't as simple as "more rain = more mosquitoes." Too much rain, as has been mentioned, can wash out pools of water and the mosquito larvae developing in them. Soil moisture may be a better marker of malaria risk than precipitation itself. Saturated ground might be prone to flooding whereas dry compact earth could be perfect for development of small pools. Temperature and precipitation effects also interact to determine mosquito prevalence as the illustration of data below from Rwanda indicates. Population of mosquitoes in an area by temperature and daily rainfall

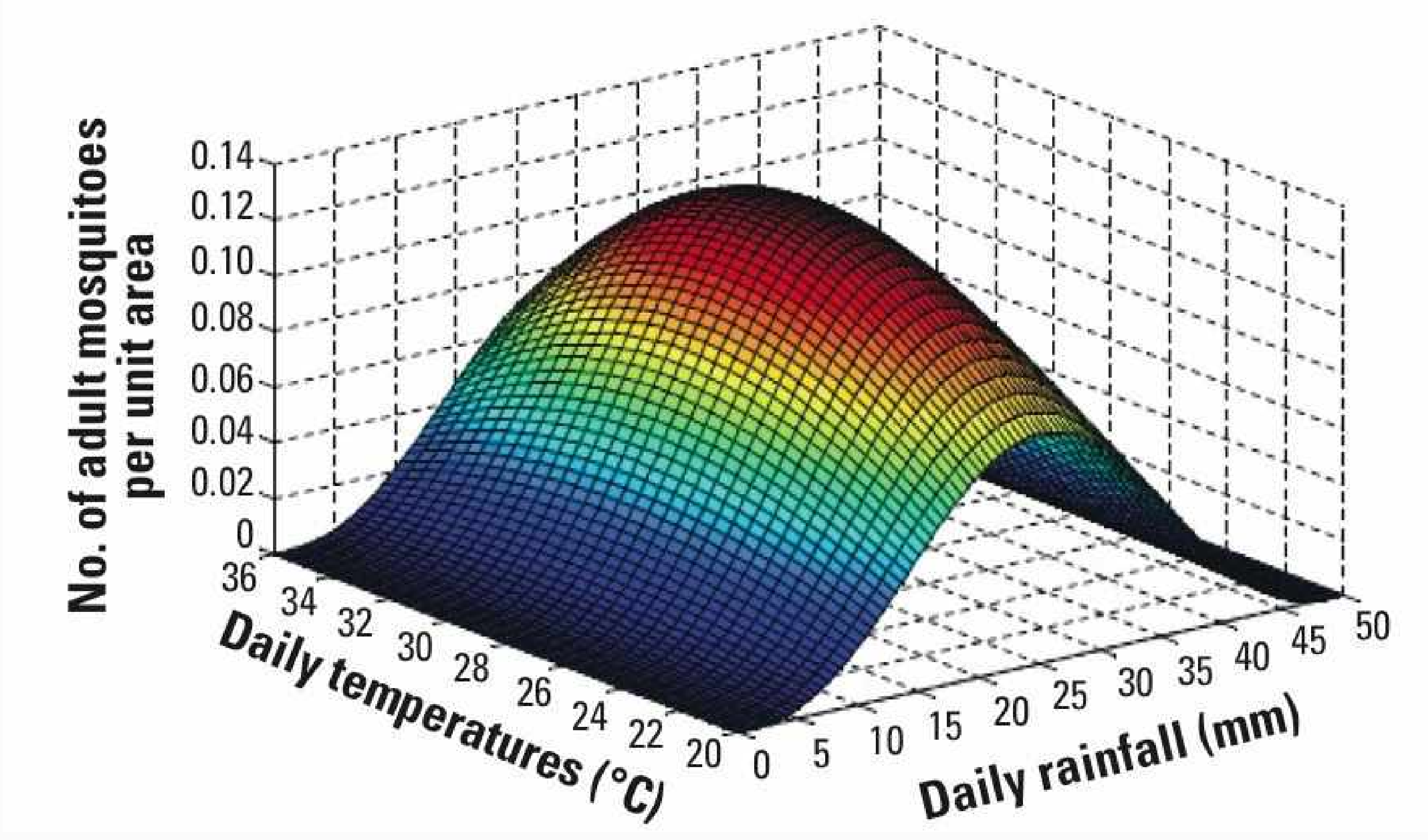


Figure from Modeling the Effects of Weather and Climate Change on Malaria Transmission

As the figure indicates, Rwanda sees a greater number of mosquitos at moderate temperatures and rainfalls, rather than at extreme values.

The Interplay of Natural Systems

In the material on vector-borne diseases you learned that pathogens and their vectors are sensitive to temperature. For example, warmer temperatures promote faster reproductive cycles in mosquitoes that transmit malaria and in the parasite itself. But what if the mosquito and parasite don't accelerate their reproductive cycles at the same rate?

Look again at the diagram (below) showing the malarial life cycle. If the mosquito's cycle accelerated faster than the parasites, then it might take a blood meal before the parasite had developed far enough to successfully infect a person.

The Malaria Parasite Lifecycle

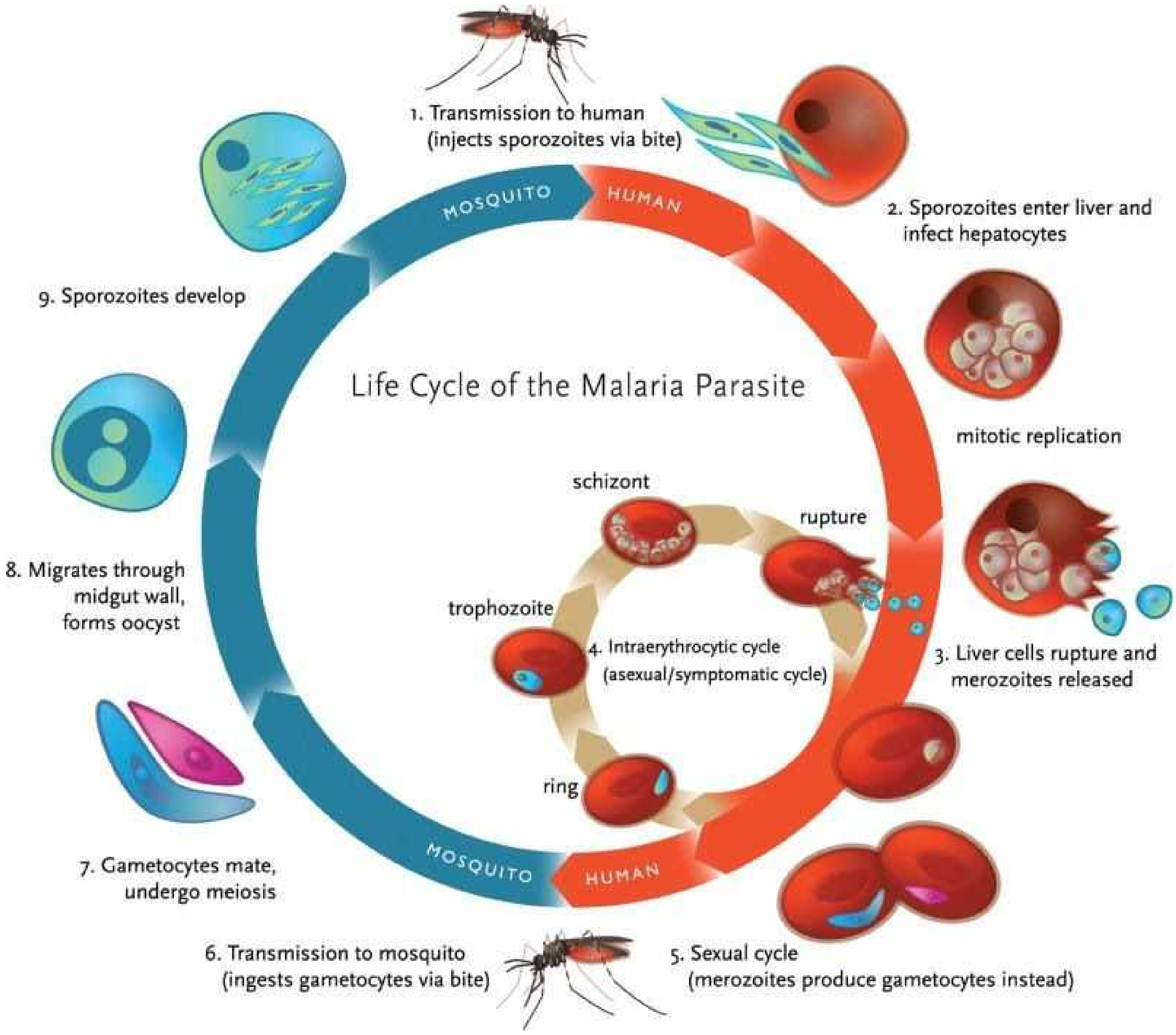
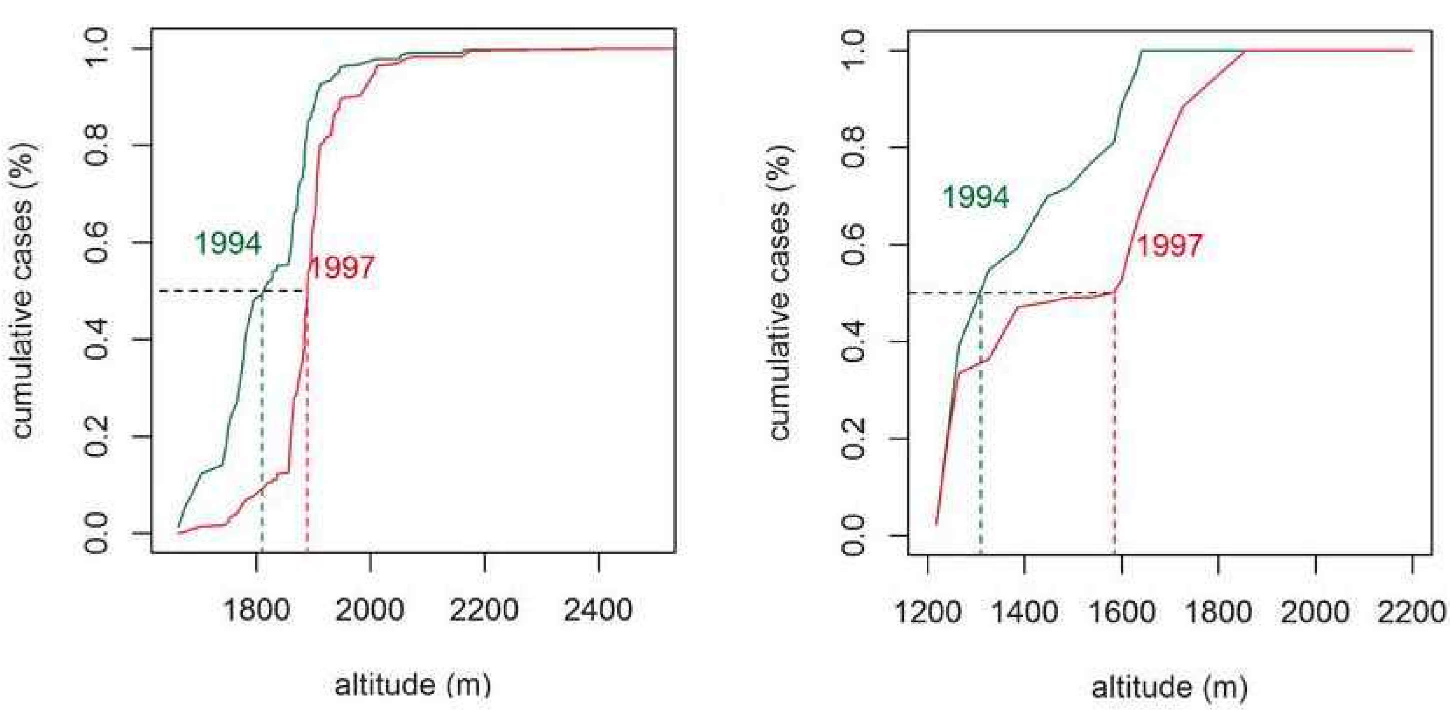


Image from [Antimalarial drug resistance: a review of the biology and strategies to delay emergence and spread]

Such a potential disconnect is one of many potential ways in which climate change - in this case, because of warmer temperatures - may not uniformly favor disease transmission because of an interplay between natural systems.

Can you think of other ways in which expected changes to precipitation and/or temperature might conspire to decrease the incidence of vectorborne disease? Look again at the data (below) showing the movement of malaria to higher elevations in Ethiopia and Colombia. If climate change forced drier conditions in these areas, that might prevent malarial spread as it would decrease habitat for mosquitos.

Shifting Altitudes of Malaria Cases (Ethioipia and Colombia)



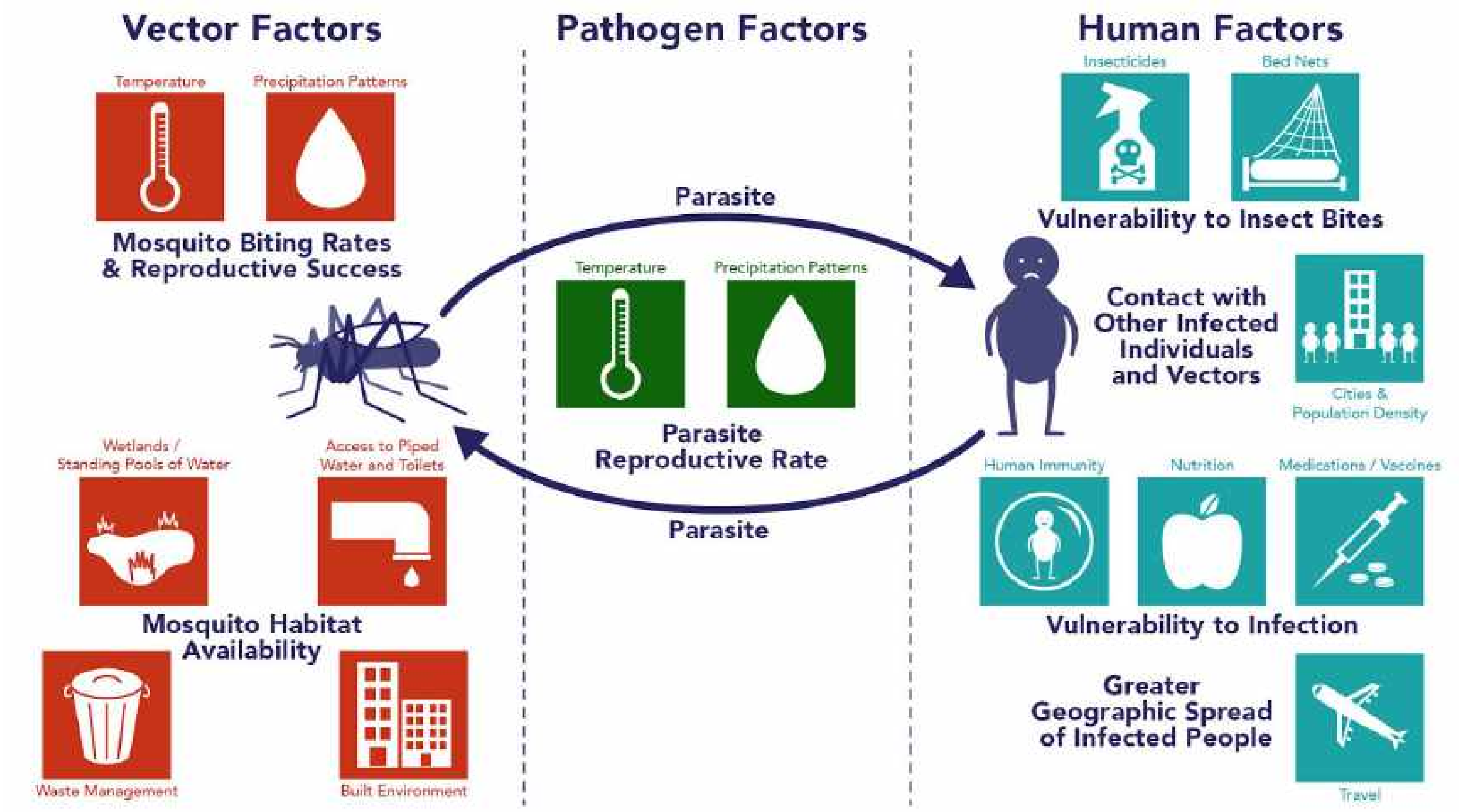
Data from Stable and fluctuating temperature effects on the development rate and survival of two malaria vectors, Anopheles arabiensis and Anopheles funestus

ust because modeling vector-borne diseases are not easy, and doing so under a changing climate is yet more difficult (as the above examples illustrate), there is still reason to believe that using models can and will yield valuable insights that may inform decisions about how best to manage climate-related disease emergence.

Human Intervention

The graphic below illustrates some of the connections between malarial parasites, vectors, and people. It also shows where people have been able to intervene to curtail malarial spread, either through the use of antimalarial drugs or through draining wetlands where mosquitoes may breed.

Malaria Transmission Factors

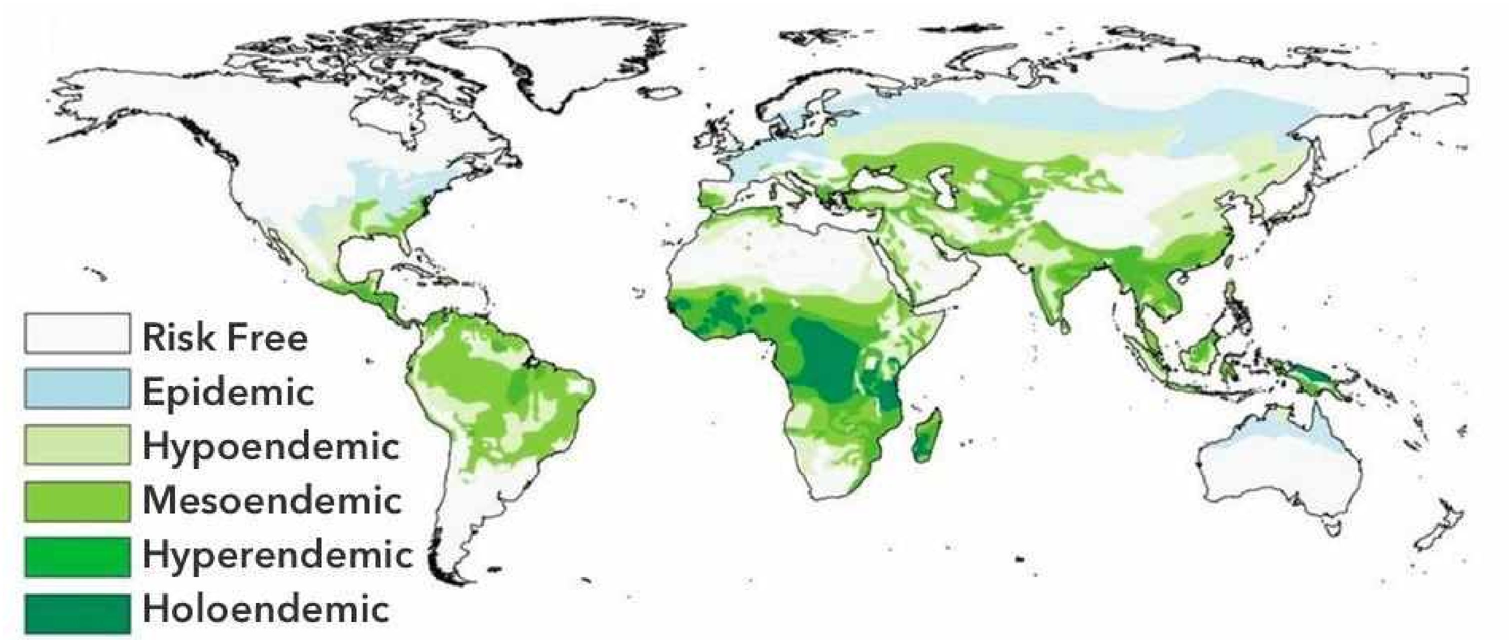


The right-hand side of the diagram shows factors affecting human beings, most of which we can control. We can reduce our vulnerability to insect bites via insecticide and bed netting, reduce our vulnerability to infection through nutrition and medicine, and control how much we come in contact with others. On the left-hand side are factors that affect the mosquito, some of which we can control directly (the presence of waste and standing water) and some of which we only control indirectly (temperature and preciptation patterns). The center of the diagram is for the malaria parasite itself, whose reproduction is affected by temperature and precipitation.

Malaria was much more prevalent in the world at the start of the 20th century than at the start of the 21st century. The maps below illustrate this point - far fewer places in the world had malaria in 2007 than in 1900.

1900 2007 Change

Malaria Endimicity Map, 1900



Figures from Climate change and the global malaria recession

The graph colors correspond to increasing prevalence of malaria from epidemic disease (meaning sporadic outbreaks of malaria) to holoendemic disease (meaning nearly everyone is affected). You can see that in 1900, malaria was prevalent across much of North America, Russia, mainland China, and Europe, whereas it is now almost unheard-of in those areas. Even in areas where malaria is now prevalent, there are far fewer cases than there once were.

What changed in that century? For one, vast areas of the world had wetlands drained , which deprived mosquitoes of habitat. For another, widespread use of insecticides, including DDT and antimalarial medications, such as chloroquine and its derivatives, have curtailed the prevalence of the mosquito vectors and parasites. The substantial and widespread decrease in malaria in the 20th century owing to human intervention suggests that predicting future malarial incidence based upon the effects of climate change alone may prove difficult.

Case study: *Aedes* mosquitoes

Many other diseases have mosquito vectors. Dengue all are transmitted by species of Aedes mosquitoes, which, in contrast to the mosquitoes that transmit malaria do particularly well in urban areas and bite indoors. Historically, these mosquitoes bred in natural pools of water, such as treeholes, but with urbanization, they have adapted to breeding in used tires and water containers.

Their ability to thrive in cities raises concerns for increased disease spread with the growth of cities, particularly ones without adequate piped water, sanitation, and waste management.

From Global to Local Disease Forecasts

Climate models provide forecasts for temperature and precipitation at large spatial scales decades into the future. This temporal and spatial resolution may not be particularly helpful to understanding infectious disease risk in a city this year. Marrying climate forecasts with infectious disease models provides another complication when it comes to predicting what climate change will mean for infectious disease in the future.

Overview

In the last chapter, Infection, you learned how the landscape of diseases might change in the coming years. However, we also need to make sure people start healthy and stay healthy, so that they can fight infections better. Proper nutrition is the key to that.

In this chapter we'll talk about the current state of nutrition around the world, how it's likely to change, and what specific sources of nutrition will be at risk.

Learning Objectives

By the end of this chapter, you should be able to:

- **Describe the pathways by which changes in our climate will impact crop yields and nutrition**
- **Identify the populations at greatest risk in the coming century**
- **Estimate how a particular nation's diet is likely to change**
- **Associate particular dietary changes with the health risks they carry**
- **Identify the areas where potential interventions might have the greatest benefit**
- **Distinguish between topics in this area that are certain and those that are uncertain**

Nutritional Diseases

Nutritional diseases are conditions that affect the human body due to its food intake. Their strongest and most widespread effects are on children, the elderly, and women of child-bearing age. Each nutrient has a different set of diseases that can be induced by over- or under-consumption; see "Macronutrients" and "Micronutrients" below for examples.

Nutritional diseases are sometimes referred to as nutritional deficiencies or malnutrition, but this overlooks the (comparatively new) issue of *overnutrition*, which can lead to obesity.

Macronutrients include carbohydrates, fiber, fat, essential fatty acids, and protein. In this course we focus primarily on protein. Protein deficiencies can lead to a variety of issues, from kwashiorkor to birth defects. An excess of protein may lead to increased kidney stone formation

Micronutrients are primarily vitamins and minerals. Many have well-documented and specific effects caused by deficiency: low vitamin C causes scurvy . Others have broader effects: low zinc intake can result in a broad variety of issues from depressed growth to skin lesions to diarrhea. There are often connections between various nutrients: for instance, it is difficult for the human body to absorb calcium without vitamin D.

Some micronutrients (like vitamin C) can be tolerated in doses much larger than what is needed by the body. Others (like iron) can cause severe issues in overdose , especially in children. Taking in more micronutrients than the minimum the body needs does generally not show any health benefits.

A New Era for Nutrition

Climate change is unfolding during an unprecedented era in human nutrition: for the first time in human history, more people are dying from too many calories than too few. While climate change has most often been seen as a risk for greater undernutrition, it also may push people toward diets that promote weight gain because of its effects on food security.

The causes of over- and under-nutrition are many. For overnutrition see this World Health Organization fact sheet and this Nature review of global obesity

In this part of the course we will also consider the direct effect of higher greenhouse gas emissions on the nutritional content of food. Higher carbon dioxide concentrations substantially reduce nutrients such as protein, vitamin A, and folate, which are already in short supply for hundreds of millions of people worldwide.

Let's start with an overview from Chris Golden, Associate Director of the Planetary Health Alliance, who will describe the changes in food sources that will happen over the next hundred years.

Measuring Bodyweight

Having too much or too little nutrition can be defined in many ways. One common method is to use body-mass-index, or BMI, which is calculated by taking weight in kg and dividing by height, squared:

$$BMI = \frac{weight\ in\ kg}{(height\ in\ m)^2}$$

Most health organizations, including the World Health Organization (WHO) and U.S. Centers for Disease Control and Prevention (CDC), define the underweight and overweight ranges for adults as follows:

Underweight	**< 18.5**
Normal range	**18.5 - 24.9**
Overweight	**≥ 25**
Obese	**≥ 30**
Severe obesity	**≥ 35**

The following maps display the prevalence of underweight and obesity for adults and children around the world. You can click each map to see a larger image. In general, you will notice that underweight individuals are more common in India, southeast Asia, and central Africa. Overweight and obese individuals are more common across the rest of the world, but especially in Argentina, the United States, the Middle East, and northern Africa.

Children

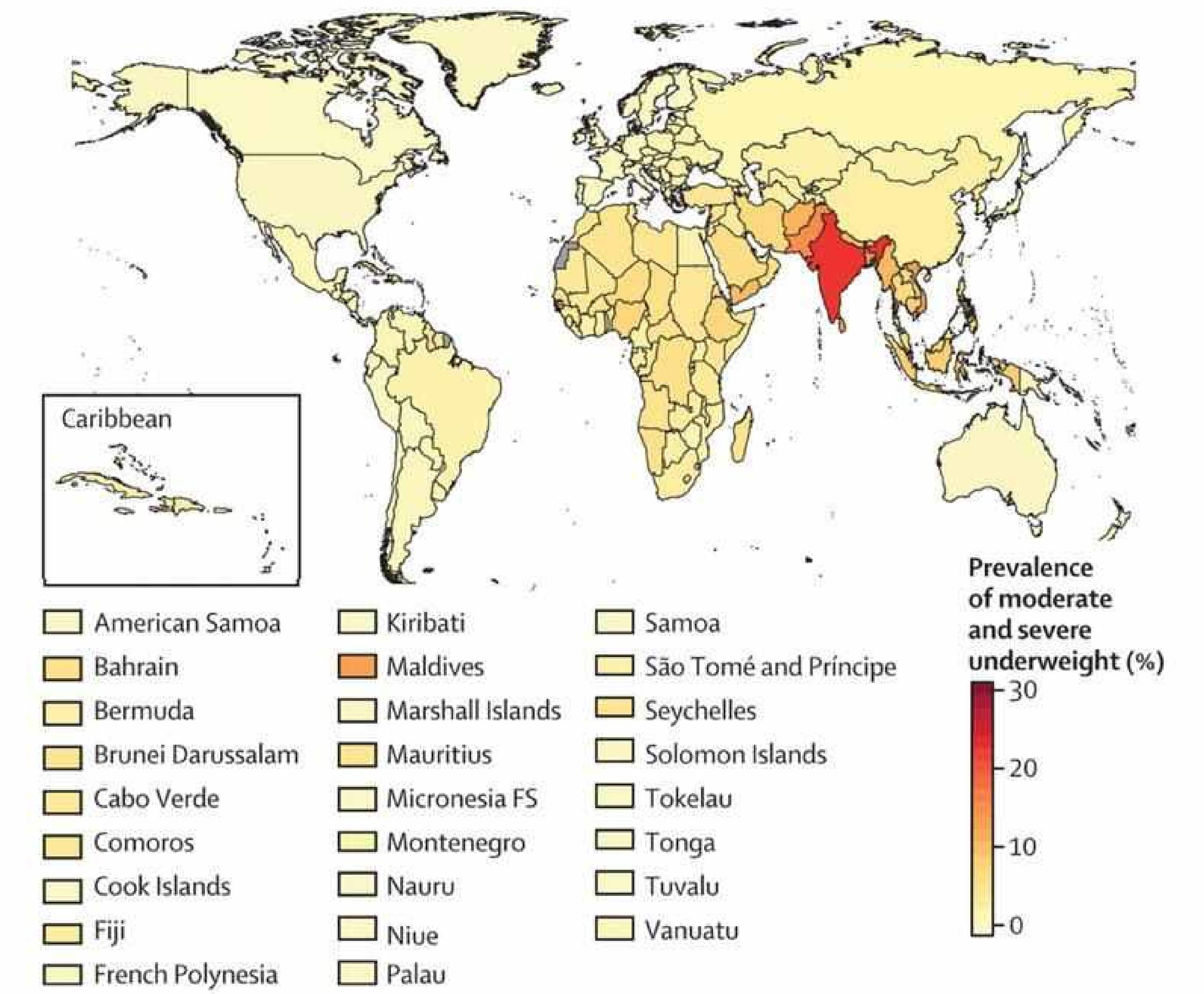
Adults

Female

Male

Underweight

Overweight or Obese



Images from *Worldwide trends in body-mass index, underweight, overweight, and obesity from 1975 to 2016: a pooled analysis of 2416 population-based measurement studies in 128·9 million children, adolescents, and adults*, NCD Risk Factor Collaboration (NCD-RisC). Published in The Lancet, Volume 390, No. 10113, p2627–2642, 16 December 2017. DOI https://doi.org/10.1016/S0140-6736(17)32129-3

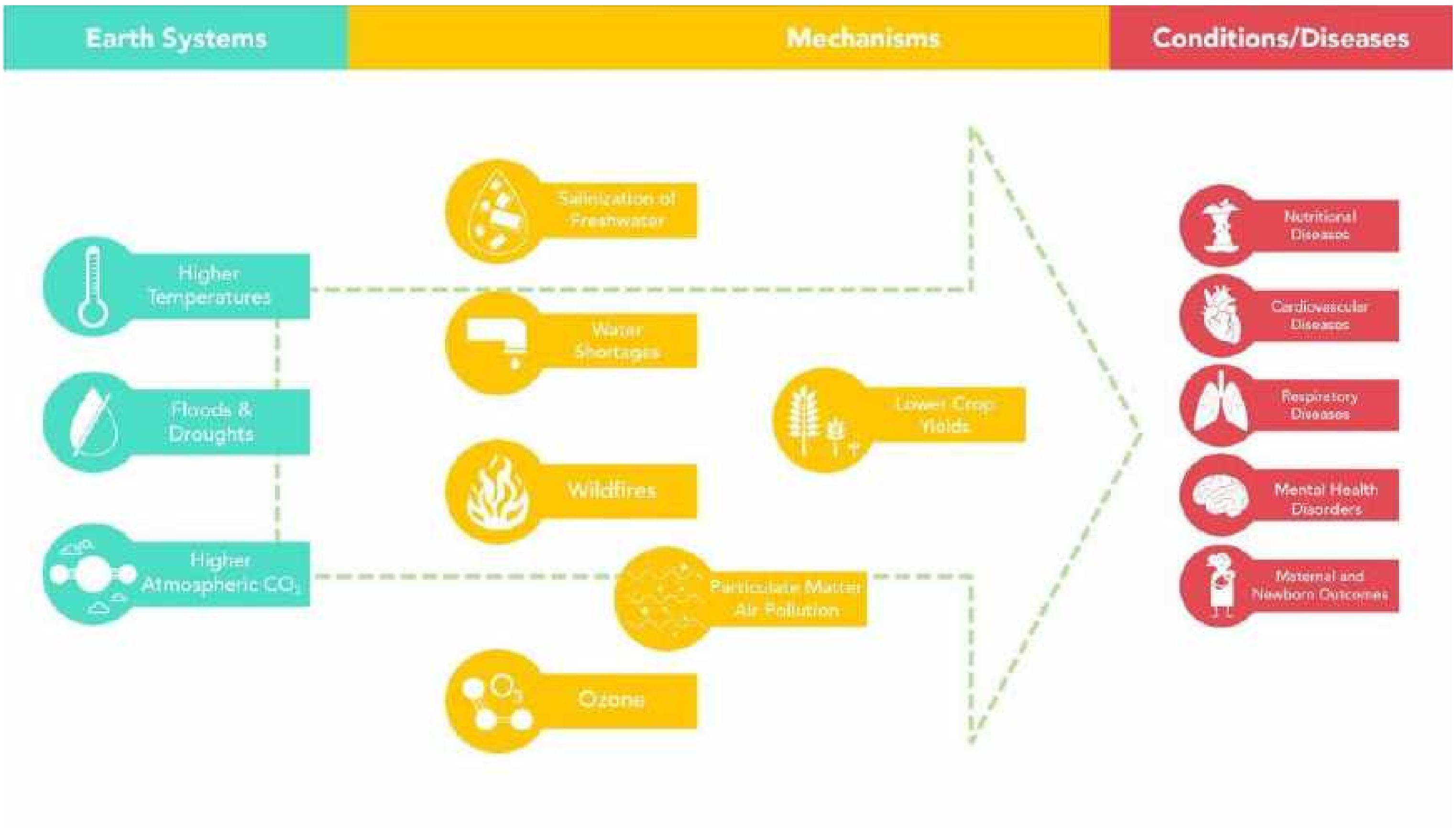
The locations where over- and undernutrition are prevalent in the world today are places of particular relevance to understanding the effects of climate change on human nutrition.

Pathways from Greenhouse Gas Emissions to Crop Yields

Changing Nutrition

In the last section, you got an overview of the current state of world nutrition, especially in areas of over- and under-nutrition. Here we'll look more closely at the factors that impact our food supplies: heat, ozone, rainfall, salinization, and insects (both pests and pollinators).

Lower Crop Yields Flowchart



The Effects of Heat on Crops

As described earlier in the course, heat and ozone are harmful to people. They're also harmful to plants. Have a look at the graphs below.

Corn and Soybean Crop Yields (log scale)

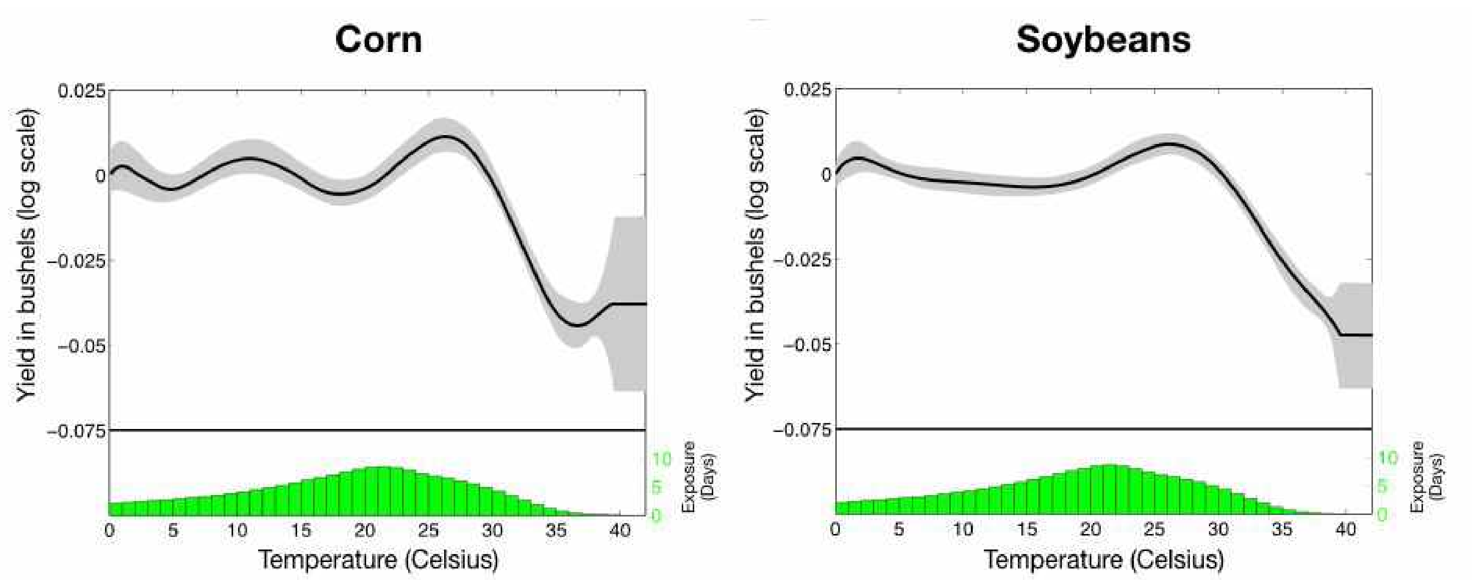


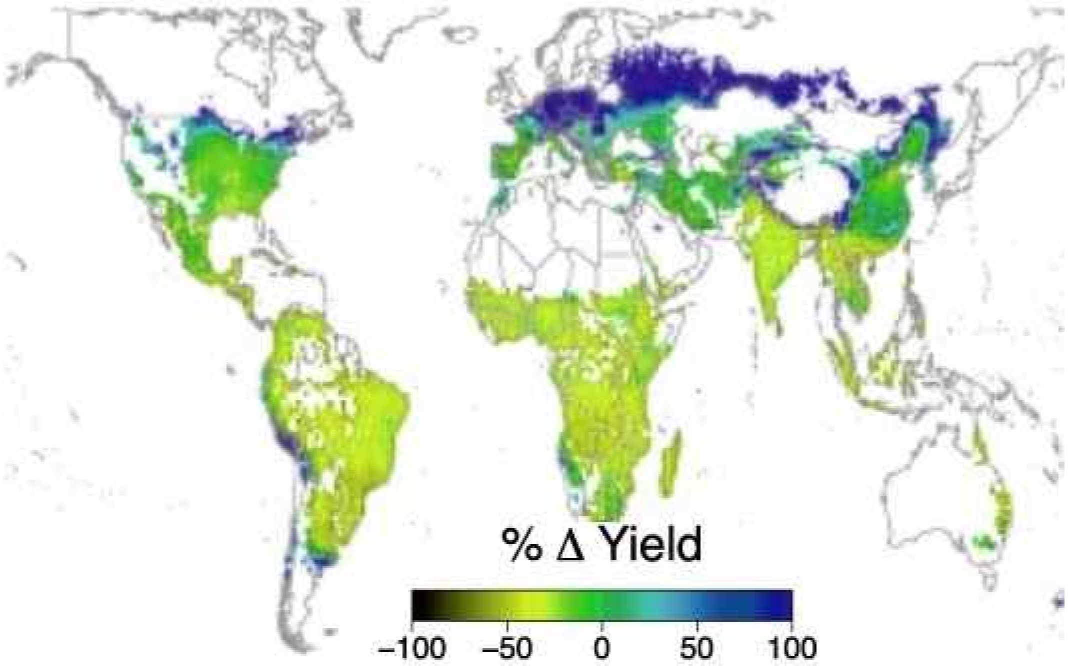
Figure created at HarvardX using data from Nonlinear temperature effects indicate severe damages to U.S. crop yields under climate change

The above graphs demonstrate how yields for corn and soybeans respond to increasing heat. As temperatures warm, crop yields increase slightly. But then, at around 27° C for corn and a bit cooler for soybeans, yields drop off quickly. The green bars at the bottom of the graphs show the number of days the temperature reaches the specified value in the counties where these crops are grown in the United States - you can see that most counties are currently between 15 and 25 degrees on average, but many are warmer or colder.

Plants, like people, can only tolerate so much heat stress before they wilt. The increasing likelihood of extreme heat events in coming decades, as described earlier in the course (in Heat, Floods, Droughts and Sea Level Rise), have particular relevance to crop yields and human nutrition.

Heat and CO2

Heat stress on crops won't occur in isolation. CO2 tends to have a fertilizing effects on plants. The maps below show the percent change in yield for maize, wheat, and soy, between 1980 and the 2080s assuming little is done to reduce greenhouse gas emissions in this century. Wheat appears to overall fare relatively well (even if production shifts poleward), whereas soy and corn have at best mixed results, even with potential benefit from carbon dioxide fertilization. Note a large swath of the United States, where the bulk of soy is grown worldwide, becomes inhospitable to soy plants.



Corn Yield Map **Figure from** ***Global crop yield response to extreme heat stress under multiple climate change futures***

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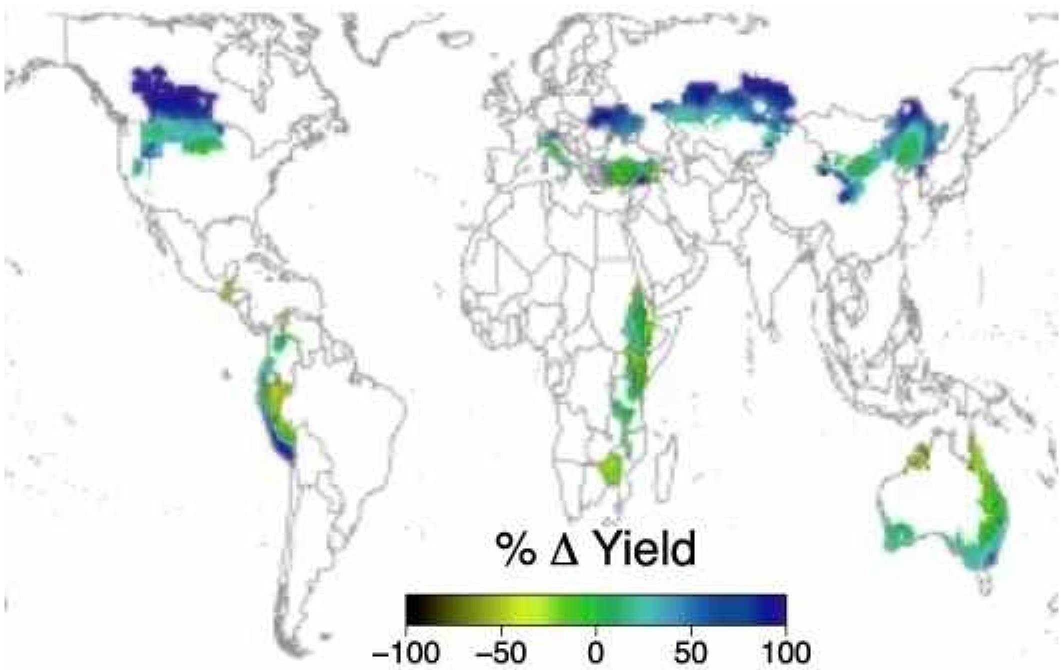

Wheat Yield Map **Figure from** ***Global crop yield response to extreme heat stress under multiple climate change futures***

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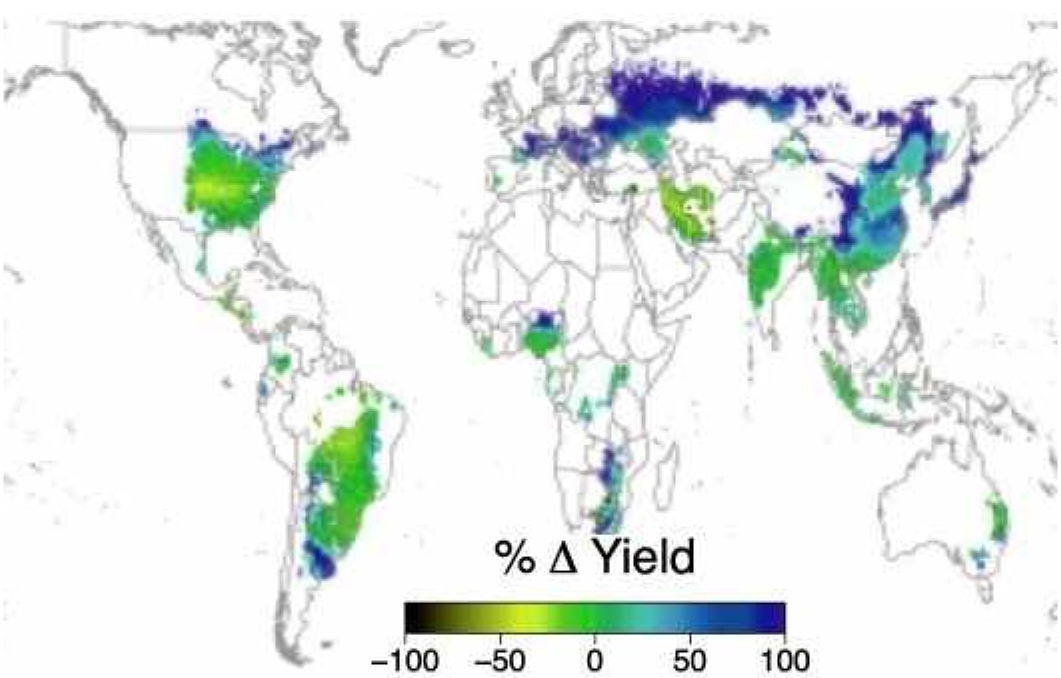


Soy Yield Map **Figure from** ***Global crop yield response to extreme heat stress under multiple climate change futures***

Precipitation Change

As described previously, higher atmospheric greenhouse gas concentrations will raise sea levels and influence the global water cycle. This will likely result in more droughts and floods around the world.

The maps below show potential changes for annual average precipitation across the globe by the end of this century under two different scenarios. The left depicts a best case scenario (RCP 2.6) and the right a worst case scenario (RCP 8.5) for greenhouse gas mitigation.

Change in Precipitation

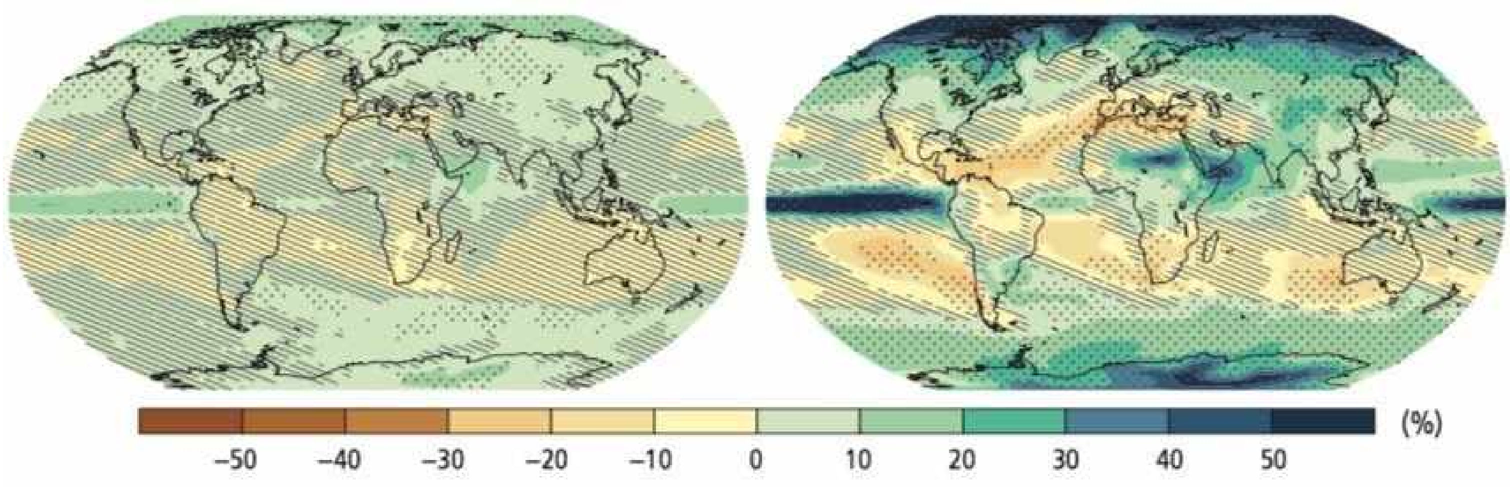


Figure from the IPCC, 2014: Climate Change 2014: Synthesis Report

The maps below demonstrate the use of climate models that assess effects of temperature and precipitation, as well as nutrients and carbon dioxide, to predict changes to yields towards the end of the century. Note how different these results are from those that consider temperature effects and carbon dioxide alone. Here, wheat appears to be the most adversely affected. Also, these maps indicate that regions further north and south may become more suitable to growing food.

Change in Crop Yields: Combined Models Map

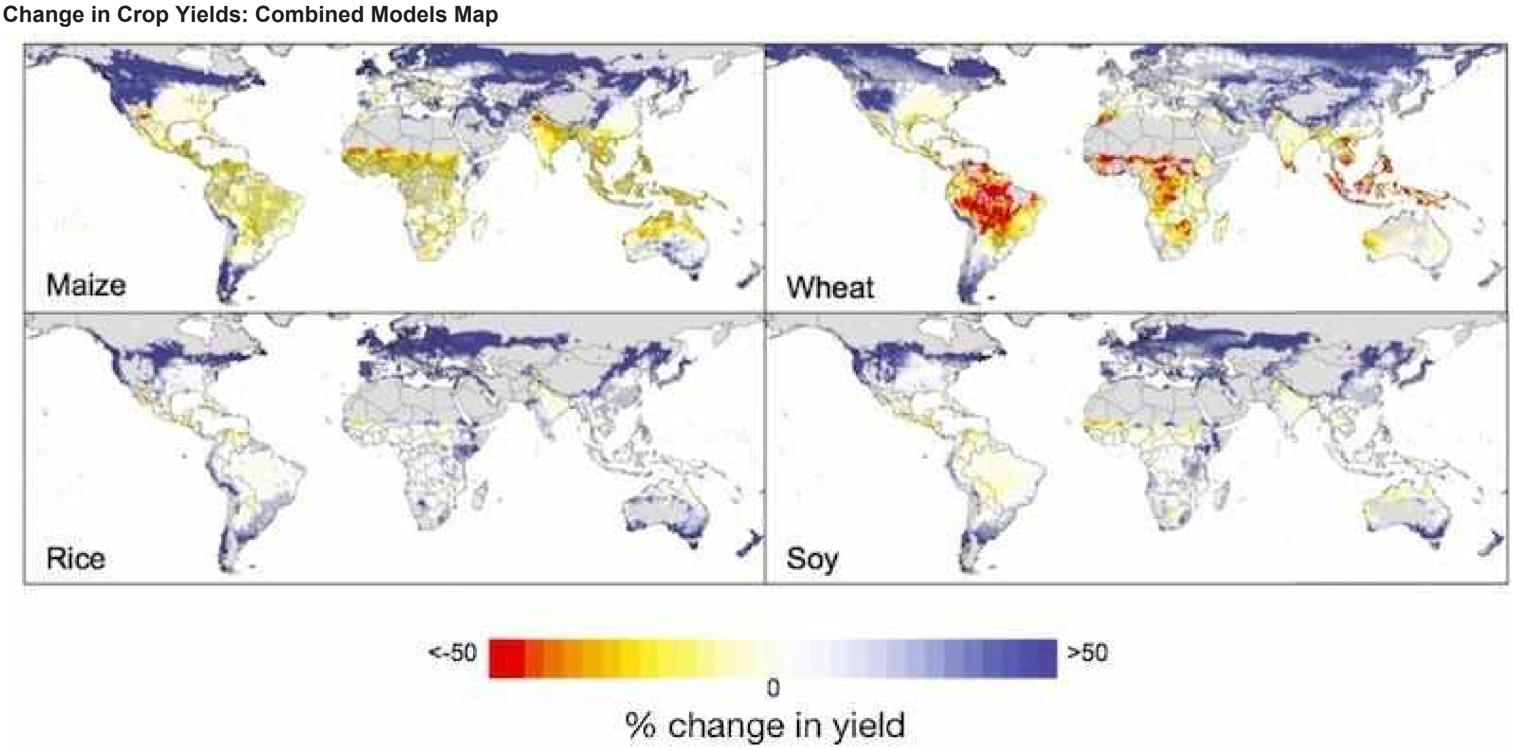


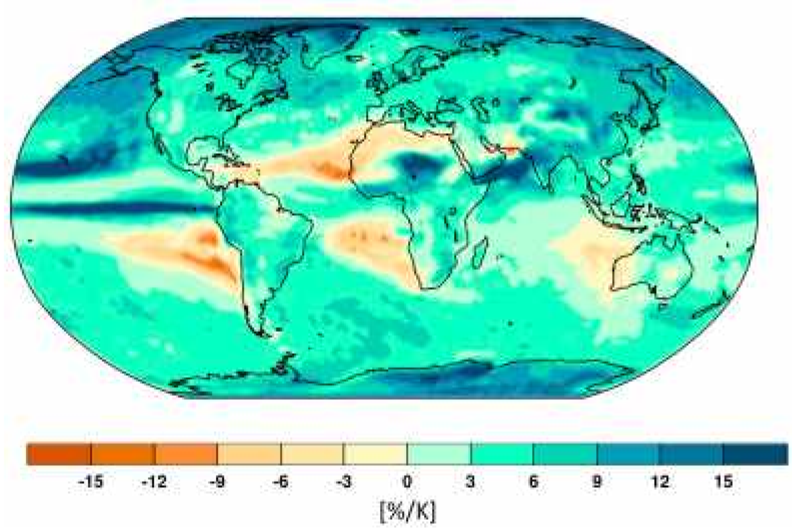
Figure from Global multi-model crop-climate impact assessment , C. Rosenzweig, et al. Proceedings of the National Academy of Sciences Mar 2014, 111 (9) 3268-3273; https://doi.org/10.1073/pnas.1222463110

More relevant to food production than changes to the overall amount of precipitation are changes in the extent of individual precipitation events as well as periods of drought. Research in many countries has shown that *both* outcomes are more likely.

In the United States, the likelihood of extreme rainfall events may increase 4-fold in many places

by the end of the century and the amount of rainfall in these events may rise 70% such that a 2-inch rainfall today would be 3.5” by 2100.

Globally, climate models suggest that rainfall will become more intense over most land areas throughout this century as illustrated in the figure below. This map indicates that North America, Europe and Asia may see the greatest increases in heavy downpours.



Percent Change in Rainfall Intensity per Degree **Figure from Fischer, E. M., J. Sedláček, E. Hawkins, and R. Knutti (2014), Models agree on forced response pattern of precipitation and temperature extremes**

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Sea level rise

Flooding can also occur due to sea level rise which increases the chances of severe storms, including hurricanes, to flood coastal lands and also through the effects of sea level rise on raising coastal water tables. As sea level rises, it exerts force upward upon coastal groundwater aquifers and can promote flooding on land

Drought, Water Scarcity, and Crops

Too much water makes growing crops difficult. So too, of course, does too little water. A recent analysis found that between 1964 and 2007 droughts may have contributed to a 10% loss of agricultural output globally . Forecasting drought likelihood and intensity with climate change has proven challenging. Drought datasets, metrics, and drought indices all have been sources of uncertainty . With that said, climate change makes the planet warmer and this warmth promotes drying. This will likely promote quicker onset of drought and may make droughts longer and more intense when they do occur. It is unclear whether climate change will influence drought frequency.

Groundwater Recharge Rates (mm per year)

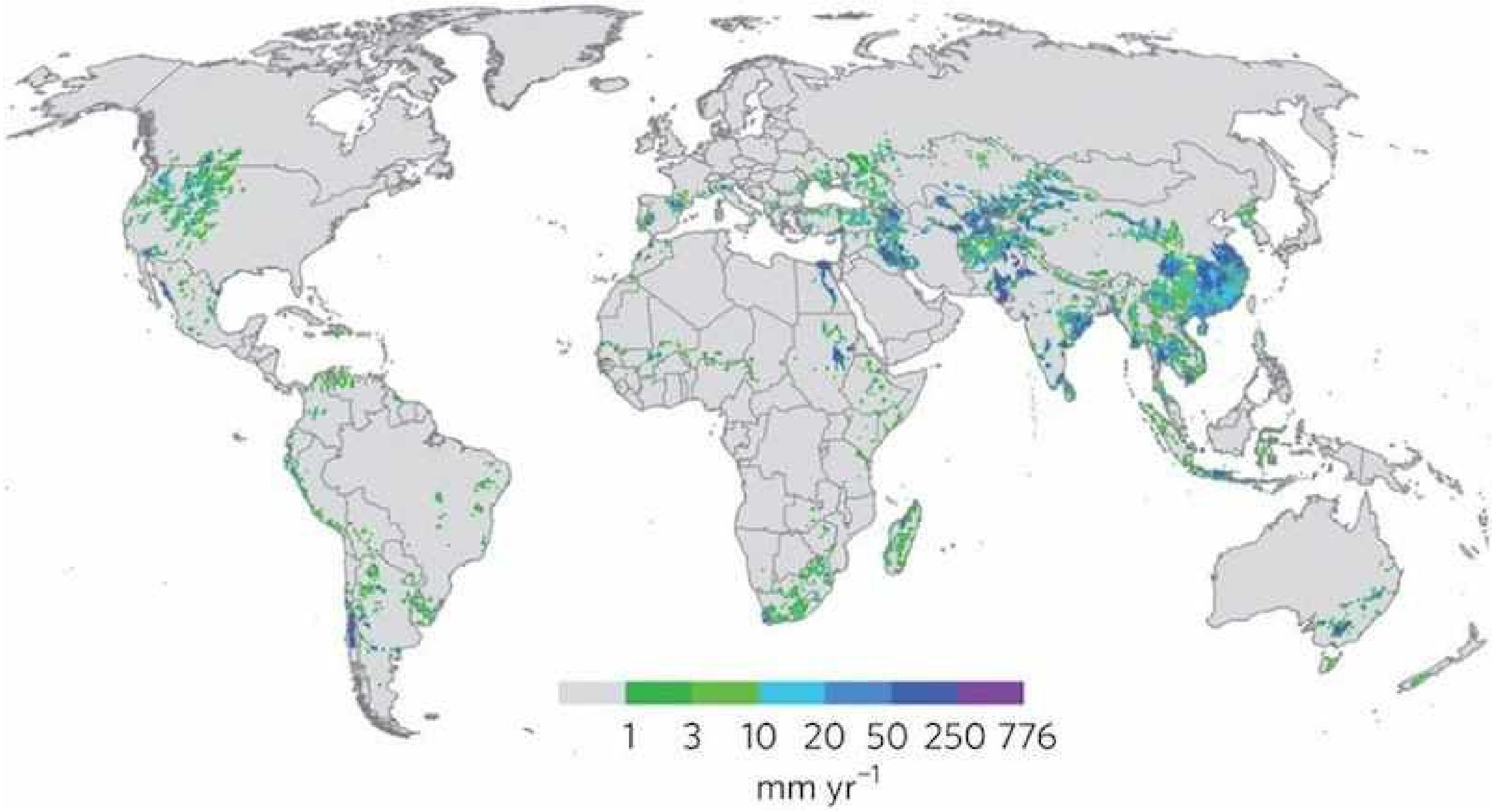


Figure from ***Ground water and climate change***

Current water use and scarcity influences the possible impact of drought on water quality and quantity. The map to the right illustrates rates of groundwater recharge. Where groundwater recharge is higher, the use of groundwater for irrigation is often high as water pumped from aquifers to feed plants drains back into aquifers. Climate change may increase demand for groundwater withdrawals as higher temperatures promote water evaporation Existing water scarcity can be measured in many ways that account for water consumption, rainfall, political risks (related to, for example, infrastructure maintenance), drought and flood risk, and other factors. The map below illustrates an approach that assesses water scarcity by comparing blue water consumption to availability. ("Blue" water is fresh water than can be used for drinking or growing food.) In this analysis, 2 of 3 people on earth live in areas where water consumption is twice as great as availability   Almost half of these people live in China and India. ***Half a billion people face this extent of scarcity every month of the year.*** **Number of months/year when water consumption exceeds availabiltiy**

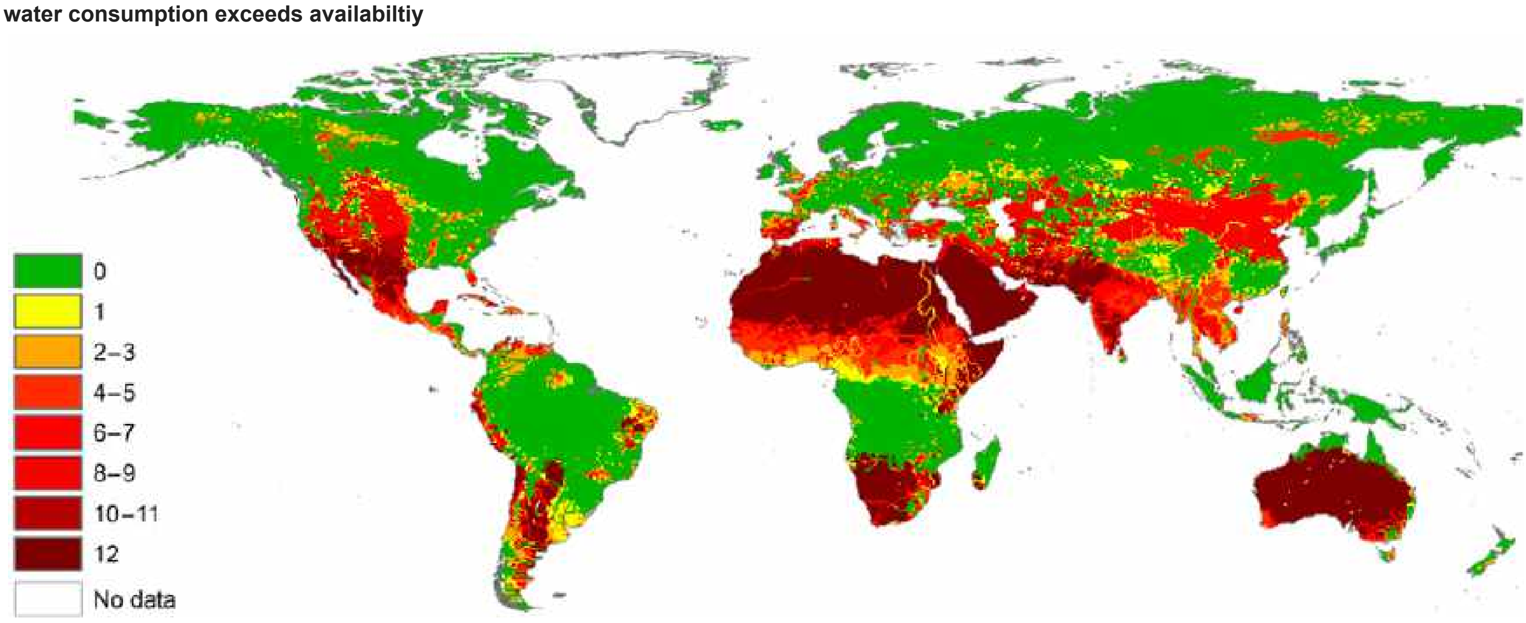


Figure from ***Four billion people facing severe water scarcity***

Salinization of Coastal Groundwater

Sea level rise makes salinization of coastal groundwater more likely. As sea level rises, the pressure of salt water to intrude through rock and earth into aquifers rises, which drives salty water into fresh water.

How sea water rise salinizes ground water

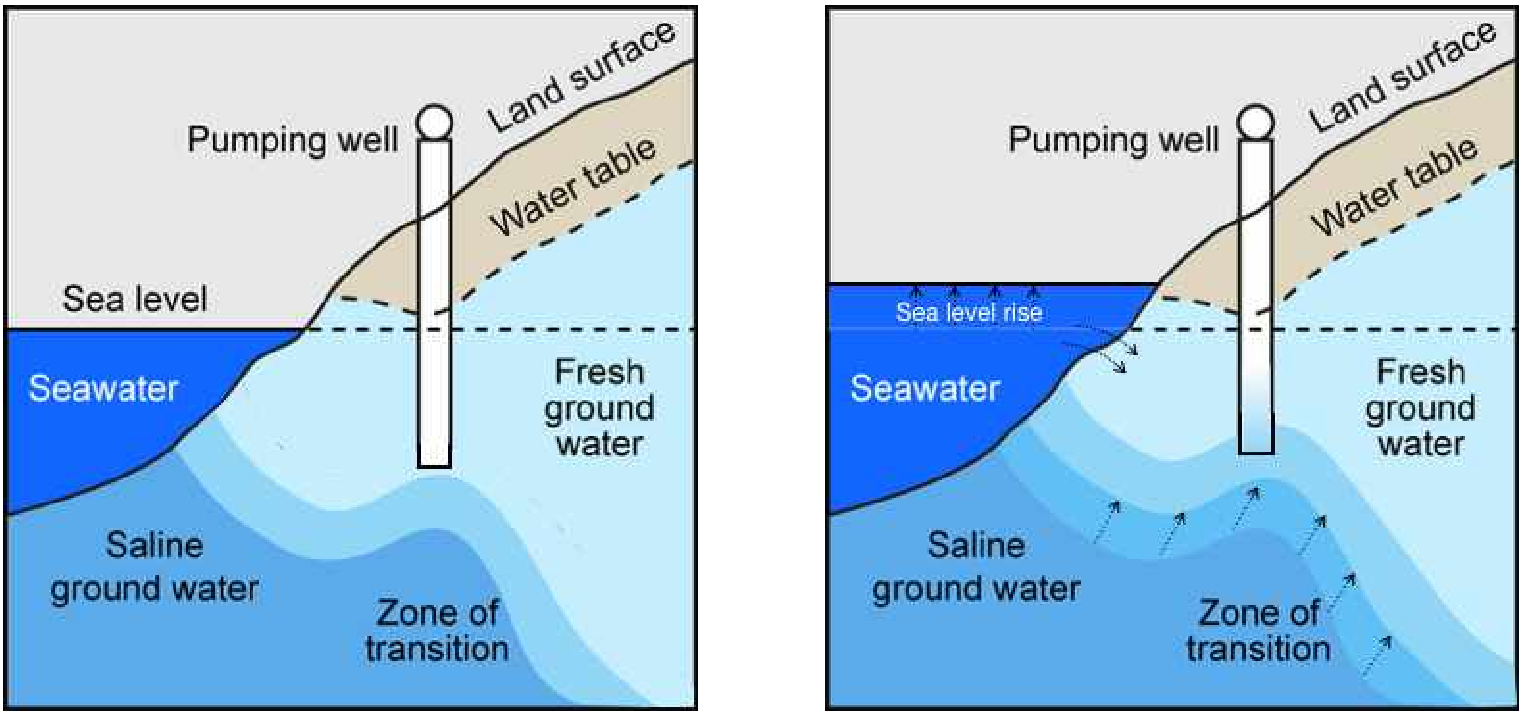


Figure adapted from Climate Adaptation and Saltwater Intrusion

At the same time as sea levels are rising, withdrawals of groundwater are growing worldwide and especially on the world's coasts where population growth is fastest. More groundwater withdrawals cycles water faster through aquifers and this may further add salt to them as soils above aquifers may contain salt.

Growing food requires fresh water (i.e. water without salt). Irrigation provides water to 20% of all agricultural lands globally, but this fraction of land produces 40% of the world's agricultural output . As demand for water grows in the coming decades, to provide directly for drinking water and to grow food, the risks of groundwater salinization are also likely to grow.

Temperature and Reproduction

Weather clearly matters to crop pests and pathogens. Current forecasting for crop disease spread relies on knowledge of temperature, precipitation, humidity and wind, among much else. Warmer temperatures prolong the season during which pests may be active and have already been shown to increase the chances that pests may have multiple reproductive cycles during a warm season (eg spring, summer and fall). Codling moths, which feed on apples, as well as other fruits and nuts, are expected to have two reproductive cycles every warm season towards the end of the century in climates where they today typically only reproduce once in that season.

Codling Moth reproductive timeline

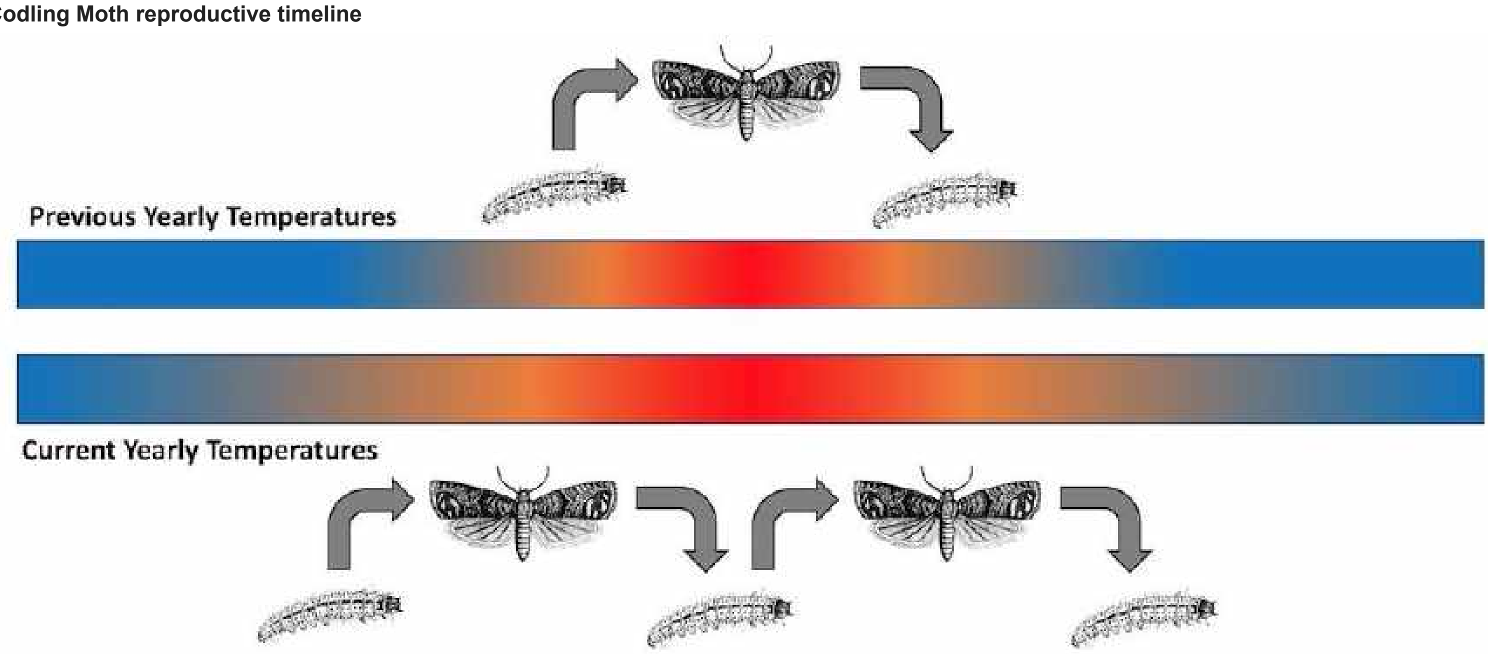
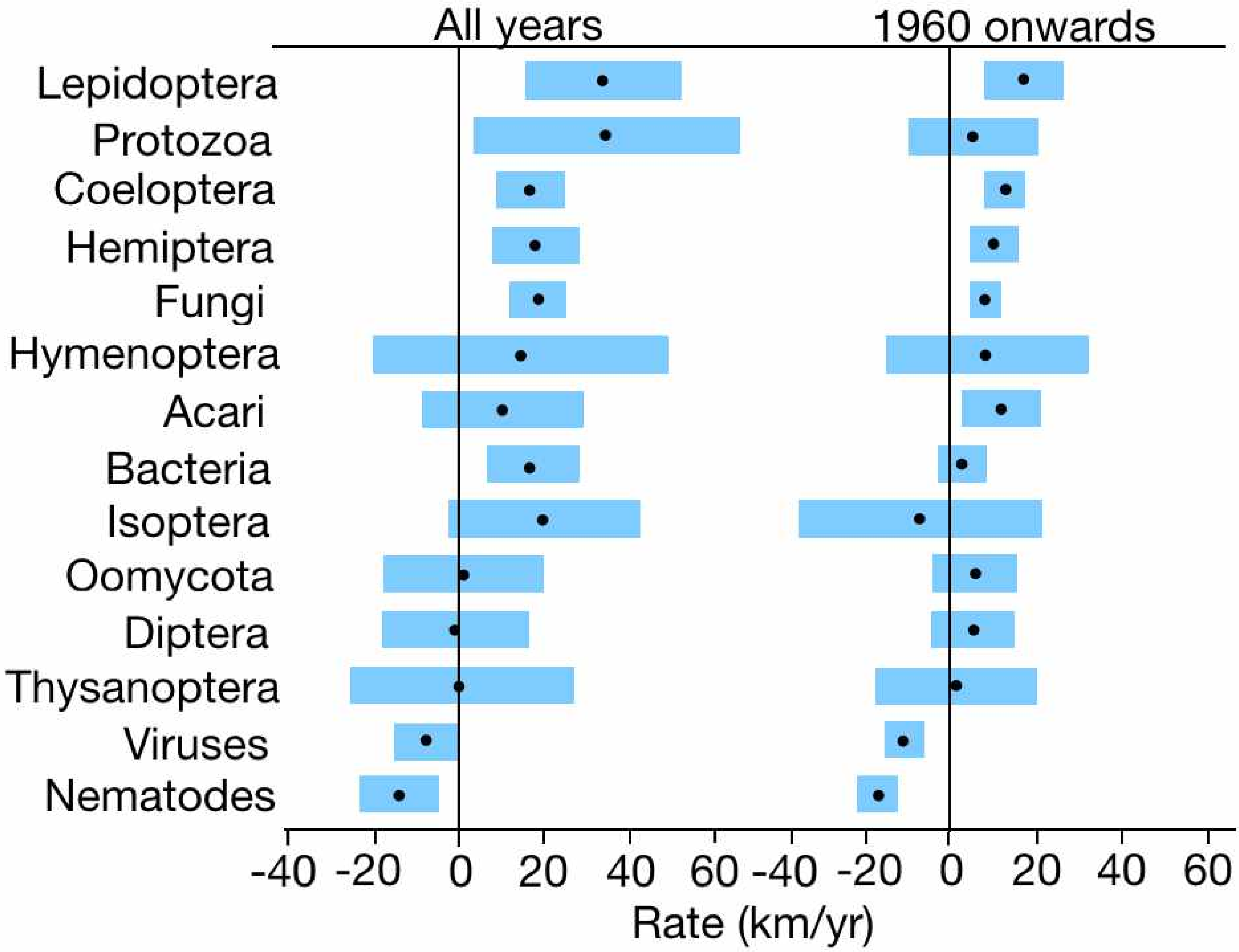


Figure by HarvardX, adapted from Jeffry B. Mitton and Scott M. Ferrenberg, "Mountain Pine Beetle Develops an Unprecedented Summer Generation in Response to Climate Warming.,"

Pest Migration

While proving pest or pathogen movement due to warming temperatures is difficult, warmer temperatures may enable the spread of plant diseases and pests to higher elevations and poleward and some may have done so already based upon observations over many decades such as those presented in the graph below.

Yearly Latitude Shift for Pests and Pathogens



Graph by Aaron Bernstein. Data from Crop pests and pathogens move polewards in a warming world , Daniel P. Bebber, Mark A. T. Ramotowski & Sarah J. Gurr, Nature Climate Change volume 3, pages 985–988 (2013)

Even if pests and pathogens are on the move, plants can adjust their defenses to pathogens as temperatures warm , and in some cases may be able to protect themselves from new or more aggressive diseases or insects.

Some pests and pathogens attack plants when they flower. If warming makes a pest or pathogen arrive before, or after, the flowering window of opportunity closes, they may not affect their host plant. The differential effects of warming on flowering time and pest and/or pathogen arrival make it difficult to understand how warming may influence such diseases and insects.

Bark Beetles

Bark beetles infest a forest

Nutrition isn't the only thing at risk from pest expansion. Warmer temperatures at higher latitudes have favored range expansion of bark beetles that devour stands of trees. Much like the codling moth, bark beetles now also have two reproductive cycles per summer season instead of one.Forests with bark beetle infestations have more dead wood, and may be more prone to fires. The image to the right shows stands of dead trees killed by bark beetles.

Combined Effects

Whether food crops may be more or less vulnerable to pests with higher ambient carbon dioxide concentrations in conjunction with warmer temperatures is likewise unclear. For instance, higher carbon dioxide exposures can impair innate defences of soy to corn rootworm and Japanese beetle infestations . However, the Asian corn borer may be less successful at damaging crops than anticipated with higher carbon dioxide as the nutrient content of the corn it eats is lesser owing to higher carbon dioxide levels. In some instances, pests may respond to lower nutrient content of the plants they eat by eating more of them .

To make matters still murkier, experiments that have investigated how temperature, carbon dioxide and pollutants such as ozone may jointly influence pest or pathogen success have yielded unexpected results. Take the susceptibility of barley, for instance, to powdery mildew and blotch spot disease. Elevated temperature or ozone appears to decrease powdery mildew growth but *accelerate* spot blotch fungus disease. Higher carbon dioxide levels may promote powdery mildew infection but *not* spot blotch disease. When all three exposures were combined (ozone, high temperature and high carbon dioxide) the net effect was not additive , and spot blotch disease slowed while powdery mildew spread more quickly.

A More Complete Story

In the last section, you learned about crop yields and how rising CO2 will change not only how much we can grow, but where we can grow it. Crop yields are important, but they're only part of the story. In this section we'll look at changes in the nutritional value of our crops. We'll start with the basics: photosynthesis.

Photosynthesis Strategies

Using sunlight, water and minerals, plants convert carbon dioxide into sugar and release oxygen as a byproduct. You can see a quick visual overview of this to the right. Click the image for a larger view.

Plants have evolved 3 strategies to capture carbon dioxide from air. The first takes carbon dioxide and fixes it into a molecule with three carbons. Such plants are knowns as *C3* plants. About 85% of plant species are C3 including, wheat, rice, barley, and oats. Peanuts, spinach, and soybeans (and most trees) are also C3 plants. The second pulls carbon dioxide into a 4-carbon molecule. These are known as *C4* plants including corn, sugar cane, millet and sorghum. The final strategy is known as crassulacean acid metabolism, or *CAM*. C3 and C4 plants respond differently to elevations in atmospheric carbon dioxide, as shown below:

Typical photosyntheis per leaf area by CO2 concentration

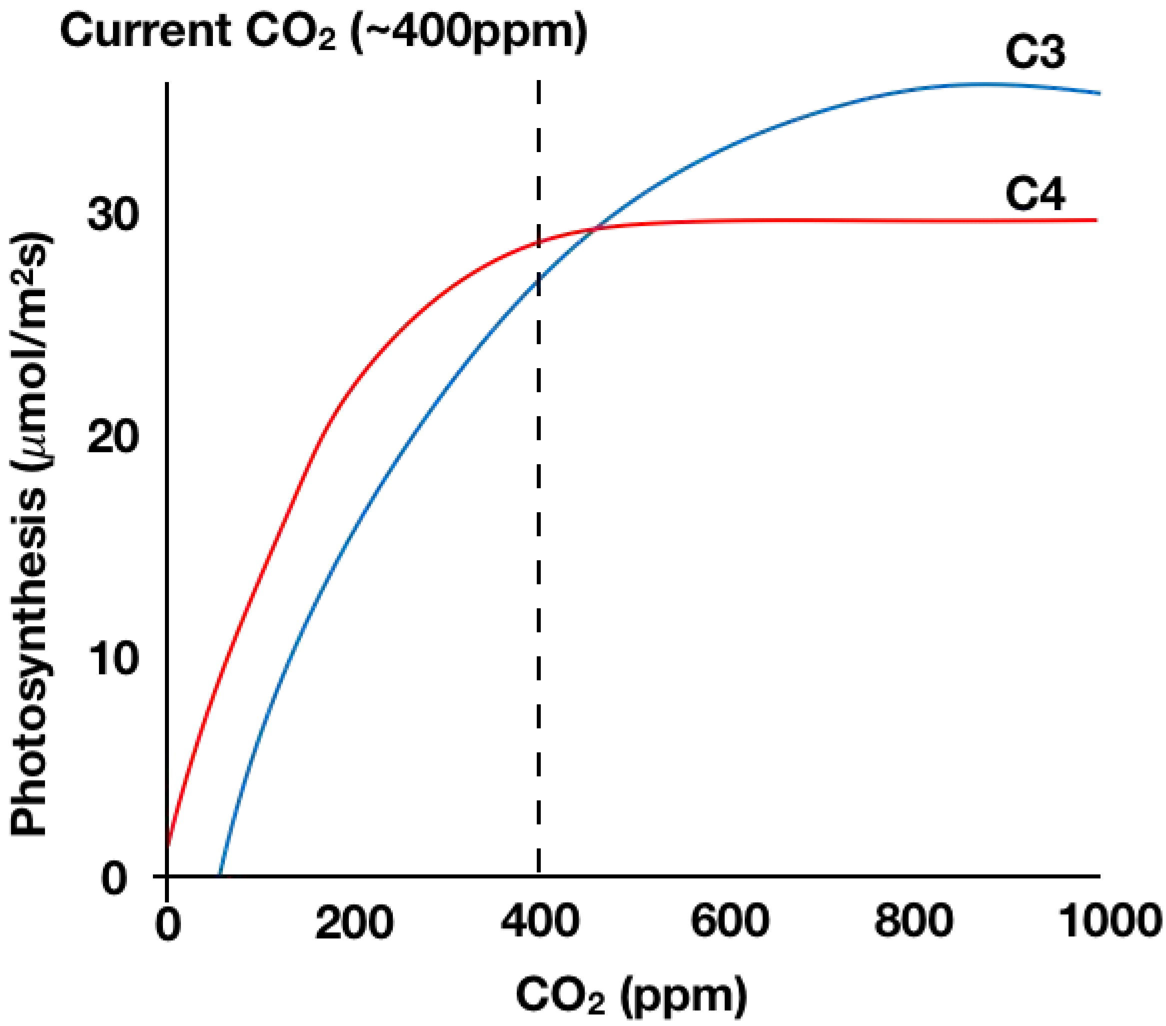


Figure adapted from

Wolfe, D.W. and Erickson, J.D. 1993. Carbon dioxide effects on plants: uncertainties and implications for modelling crop response to climate change. In: Agricultural Dimensions of Global Climate Change

The graph above illustrates that C3 plants increase their photosynthetic activity and fix more carbon dioxide as ambient concentrations of carbon dioxide increase, whereas C4 plants do not.

CO2 and Crops

Experiments have demonstrated that exposure to elevated carbon dioxide levels can substantially decrease the nutrient content of staple crops .

1.4 billion children aged 1-5 and women of childbearing age live in countries where iron deficiency prevalence is >20%. In these countries, the iron supply could fall by 3.8% based upon the foods consumed in their current diets and the detrimental effects of higher carbon dioxide levels on iron content of crops, as illustrated below.

Percent Change in Plant Nutrition between 380ppm CO2 and 550ppm CO2

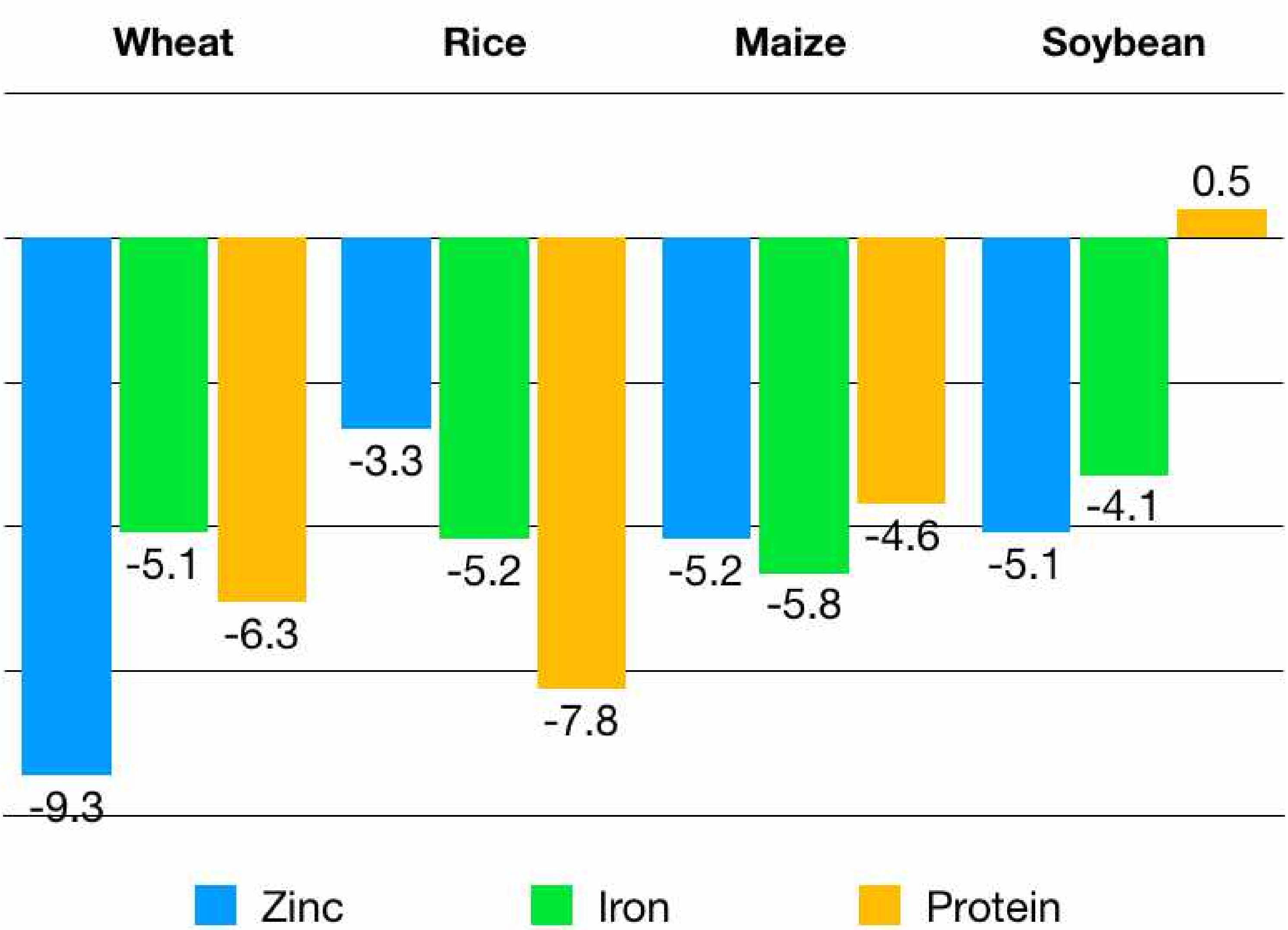


Figure by Harvard, using data from Increasing CO2 threatens human nutrition

76% of all people get most of their protein from plants. In low and middle income countries, the percentage is higher. Protein sources worldwide (grams per person per day)

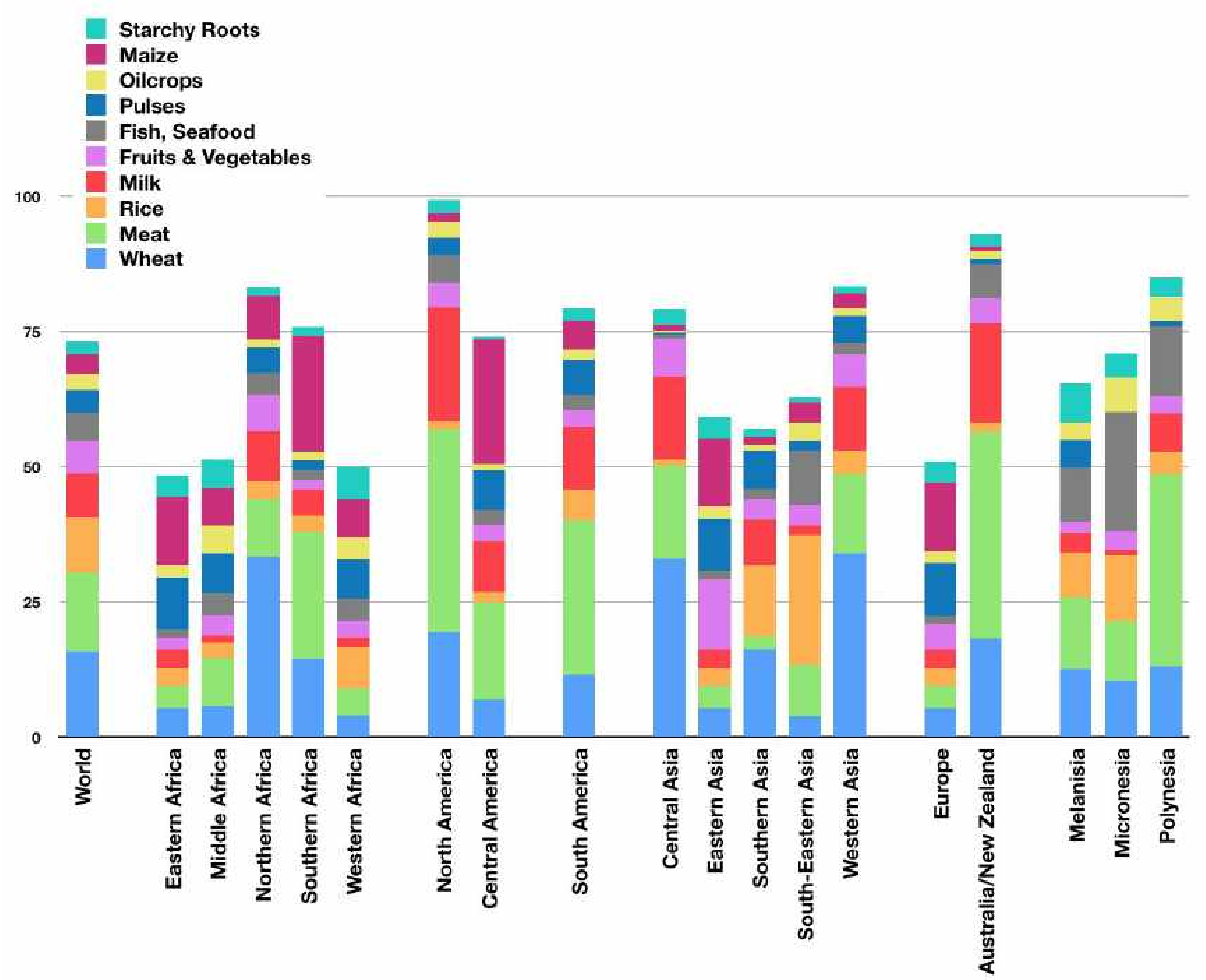


Figure Adapted from The Influence of Climate Change on Global Crop Productivity

The map below illustrates decreases to protein intake with crops grown at 550ppm carbon dioxide. Decrease in protein intake due to less nutritious plants

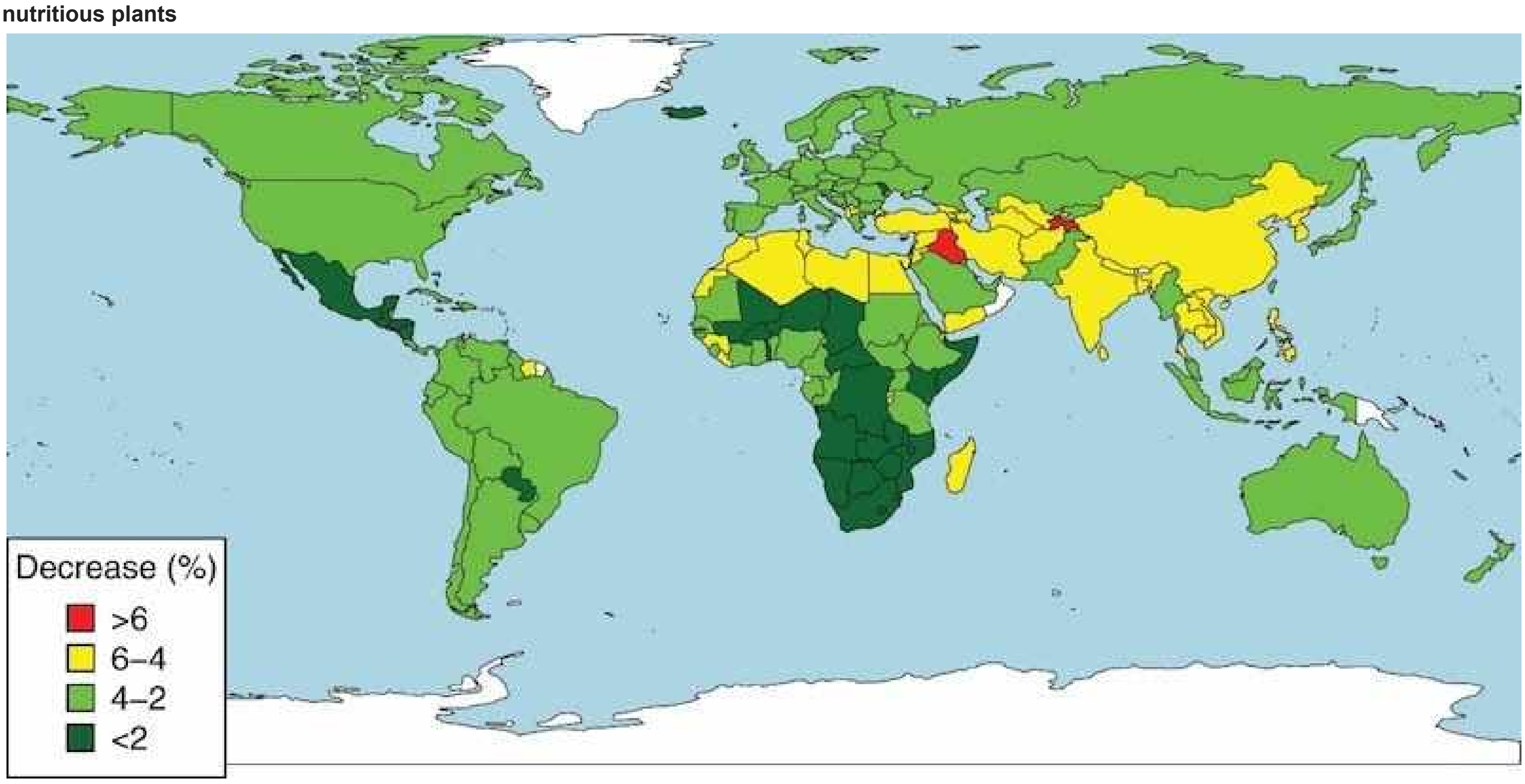


Figure 1 from Estimated Effects of Future Atmospheric CO2 Concentrations on Protein Intake and the Risk of Protein Deficiency by Country and Region

The map displays data on changes to protein intake that reflect current dietary food choices in each country as a baseline, and then computing decreases in protein intake based upon observed changes in plant protein content when plants were grown with elevated carbon dioxide concentrations.

Populations at Risk

These decreases in protein intake translate into nearly 150 million people newly at risk of protein deficiency: Population at risk worldwide (protein, raw numbers)

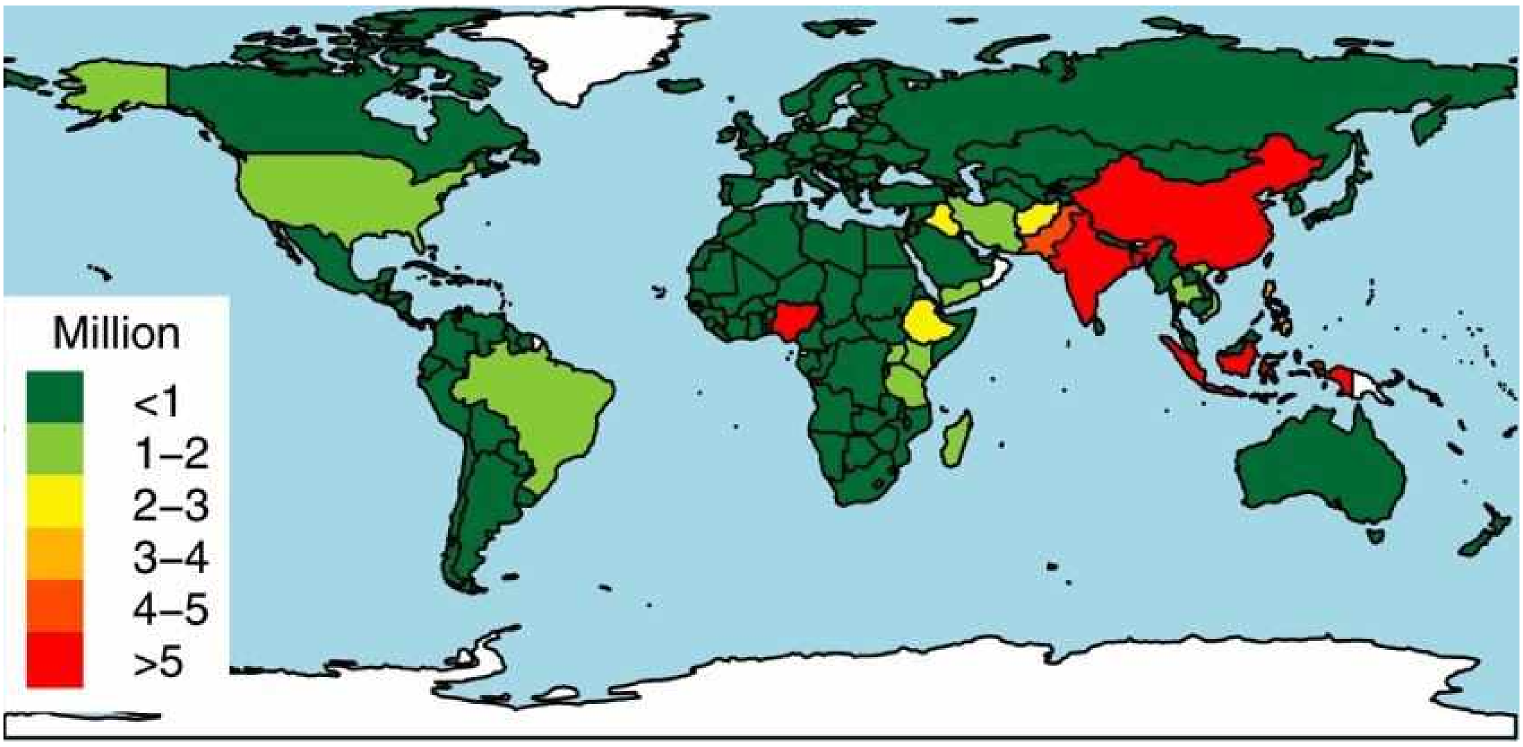


Figure 3 from Estimated Effects of Future Atmospheric CO2 Concentrations on Protein Intake and the Risk of Protein Deficiency by Country and Region

As the above map illustrates, effects of protein loss will be most acute in southern and southeast Asia. Effects will likely be most pronounced for the poorest in each country who are least able to afford animal protein.

Reduced zinc content of food crops also will place an additional 140 million people at risk of deficiency with 500ppm carbon dioxide levels in the atmosphere:

Population at risk worldwide (zinc, percentages)

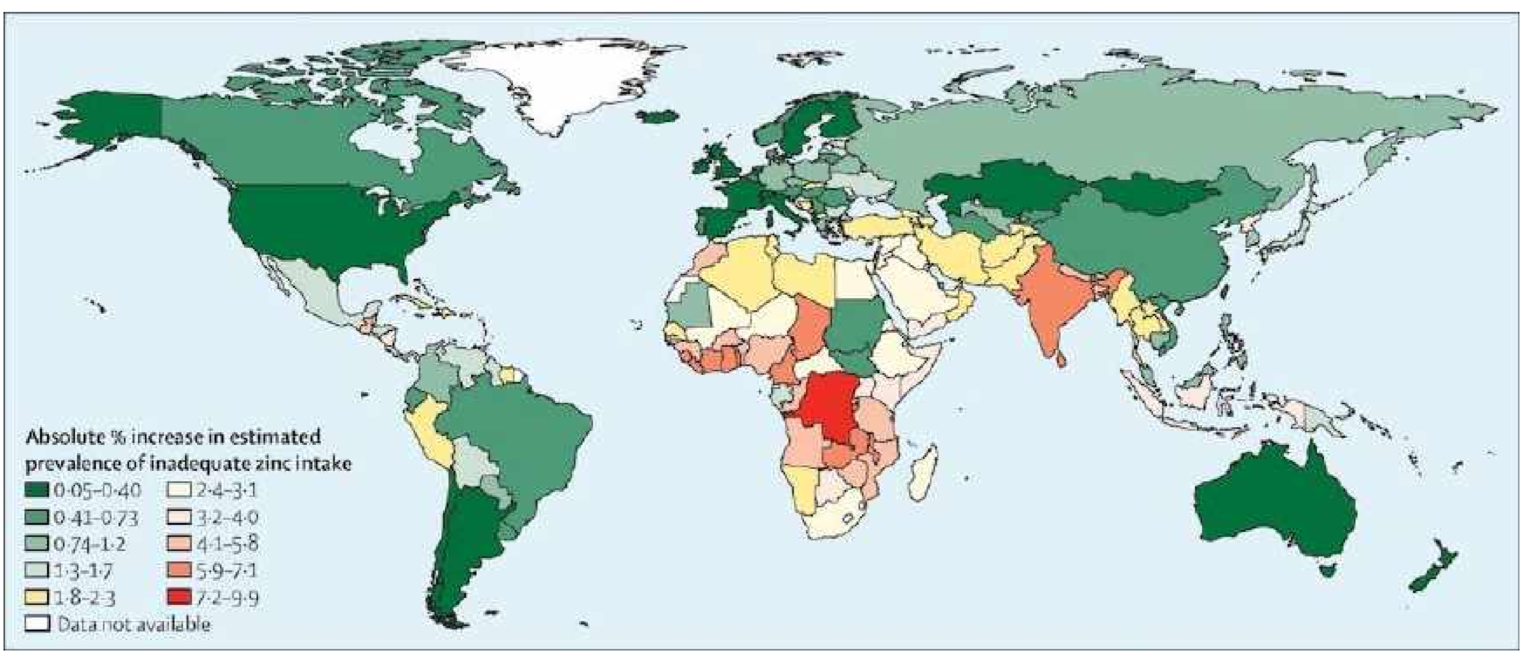


Figure 1 from Effect of increased concentrations of atmospheric carbon dioxide on the global threat of zinc deficiency: a modelling study Myers et al, The Lancet Global Health, Volume 3, Issue 10, e639 - e645. DOI: https://doi.org/10.1016/S2214-109X(15)00093-5 New risk for zinc deficiency has greater prevalence in sub-saharan Africa, the middle east and India as illustrated above.

CO2 and Fish

So far we've been talking about the impact of CO2 on plants. While plants are certainly a major part of the human diet worldwide, they aren't the only source of nutrition. Animal proteins are important to a large percentage of our world as well. Fish, especially, play a significant role in the nutrition of coastal and tropical regions. This section describes the current status of fish stocks, the effects of CO2 on the ocean and its wildlife, and how this might change what people eat in different regions.

The Decline of Fisheries

Seafood provides a generally favorable set of nutrients, with healthier fats, protein, and vitamin D, among other micronutrients. About 3 billion people get 20% of their animal protein intake from seafood . In coastal regions of developing nations and small island states, 50% of animal protein may come from fish.

Unfortunately, global fisheries are largely in decline due to overfishing.

Stock Status of Global Fisheries

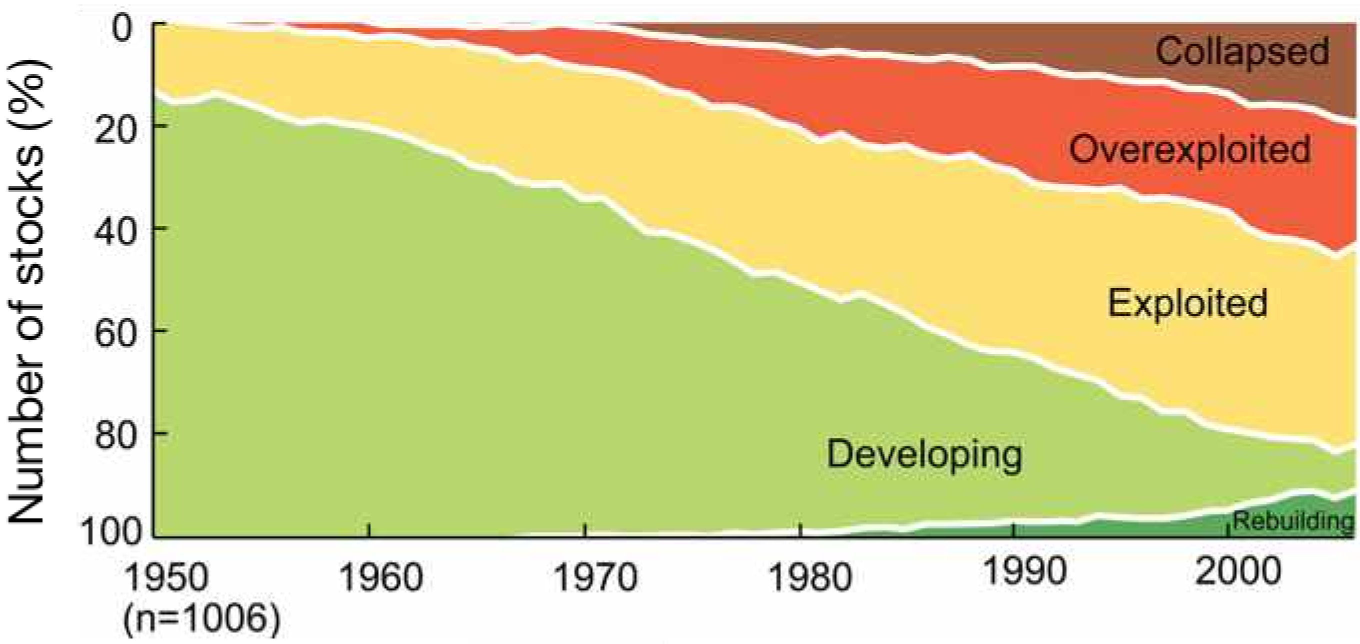


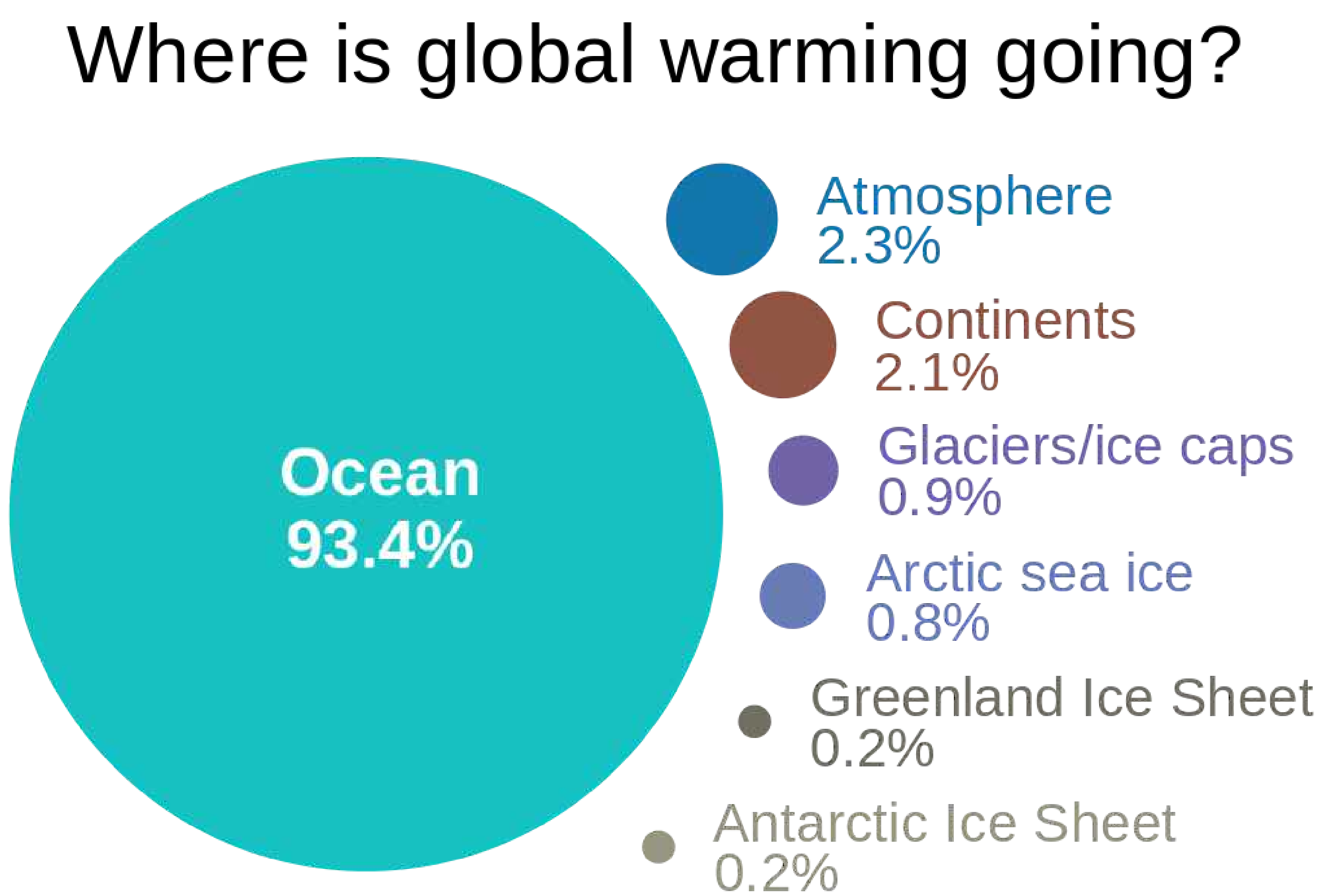
Figure from

Comments on FAOs State of World Fisheries and Aquaculture (SOFIA 2016) Daniel Pauly and Dirk Zeller, Marine Policy Volume 77, March 2017, Pages 176-181 https://doi.org/10.1016/j.marpol.2017.01.006

As the above graph demonstrates, 90% of global fisheries are fully or overexploited, meaning that given current fishing practices they will be entirely consumed, perhaps as soon as 2050

Warming Oceans

When people talk about warming that comes with climate change they most often are talking about warmer air. But about 90% of the excess heat trapped by greenhouse gases is being absorbed into the world's oceans.



This added heat is making regions of the tropics too hot for the fish and other sea creatures to live there and so they are migrating towards the poles.

Coral Reefs and Nutrition

Coral reefs alone supply more than 500 million people with food, income, coastal protection, and a range of other services **Particular for those who subsist on seafood captured just offshore in the tropics, coral reefs provide vital habitat for spawning and rearing fish and other seafood. Coral reefs are particularly important to the world's poor.** Nearly two-thirds of the roughly 400 million people who live within 100km of coral reefs worldwide live on less than $5000 per year **, and are likely to depend heavily on seafood (and other goods and services) from reefs.**

Coral reefs face a variety of threats including damaging fishing practices and pollution, but carbon dioxide which drives ocean acidification and warming is perhaps the biggest. We'll consider these in the sections that follow.

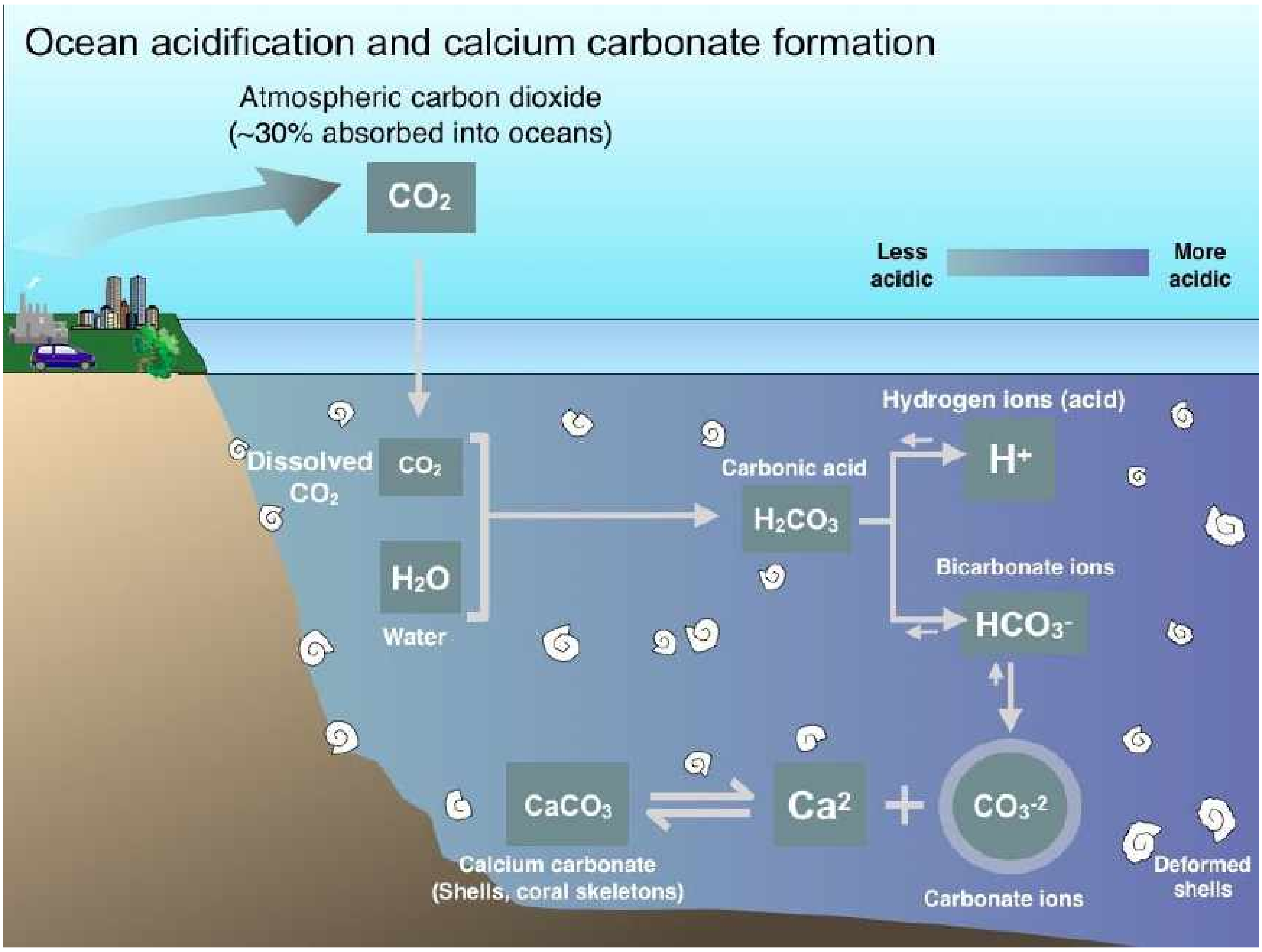
Coral Bleaching

Corals are at risk from warmer ocean temperatures that promote coral bleaching, illustrated below. When ocean temperatures are too warm, the algae that live on corals get stressed and leave the coral. This deprives coral of food which the algae help provide and corals bleach. Once bleached, corals are at high risk of infection from opportunistic pathogens.

Ocean Acidification

As carbon dioxide enters the oceans, it dissolves and makes the oceans more acidic. Since The Industrial Revolution, the oceans have already become more acidic under the influence of elevated atmospheric carbon dioxide concentrations.

How CO2 Acidifies the Ocean



More acidic oceans dissolve the calcium carbonate that forms coral skeletons, eating away at reefs.

Reefs near American Samoa

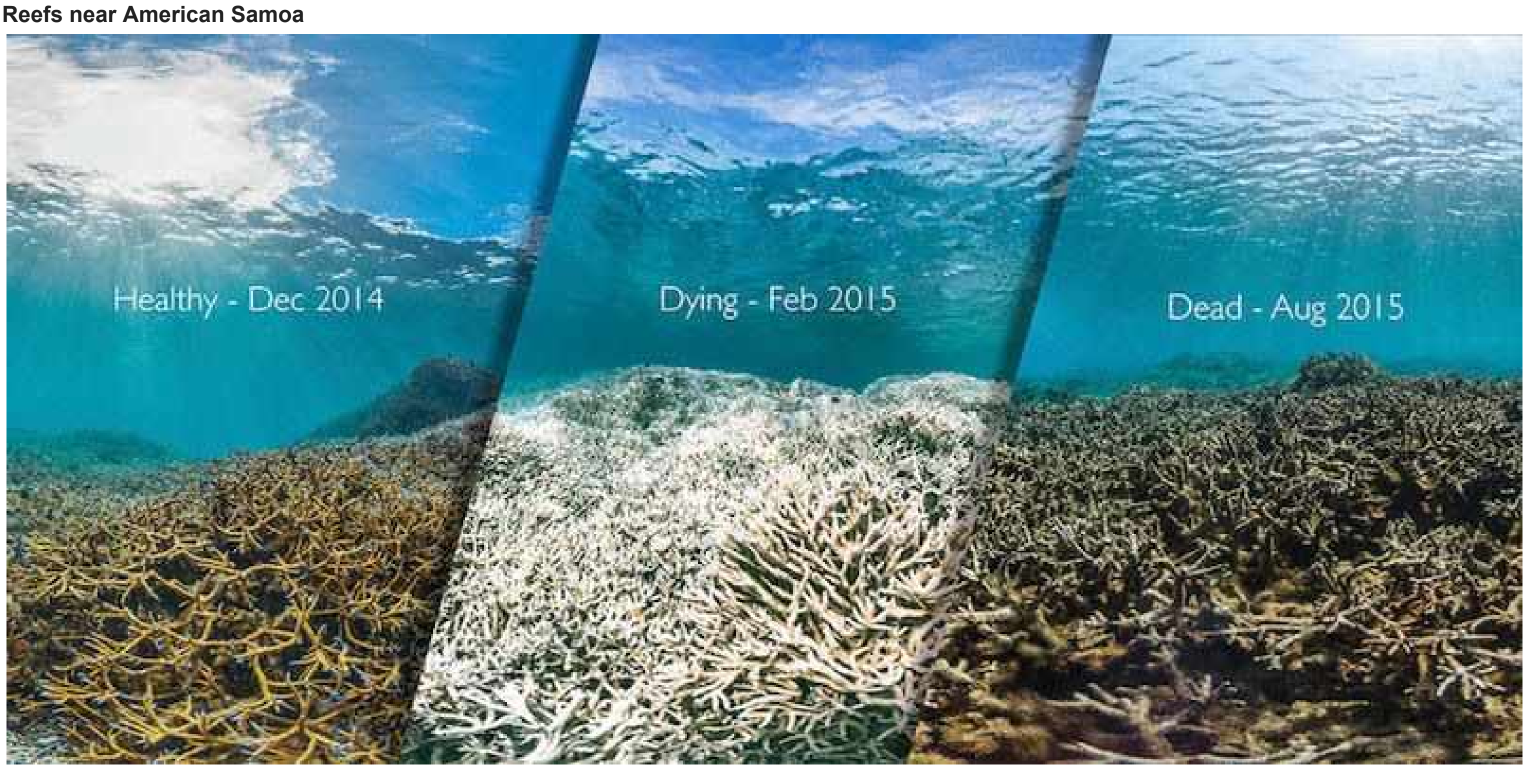
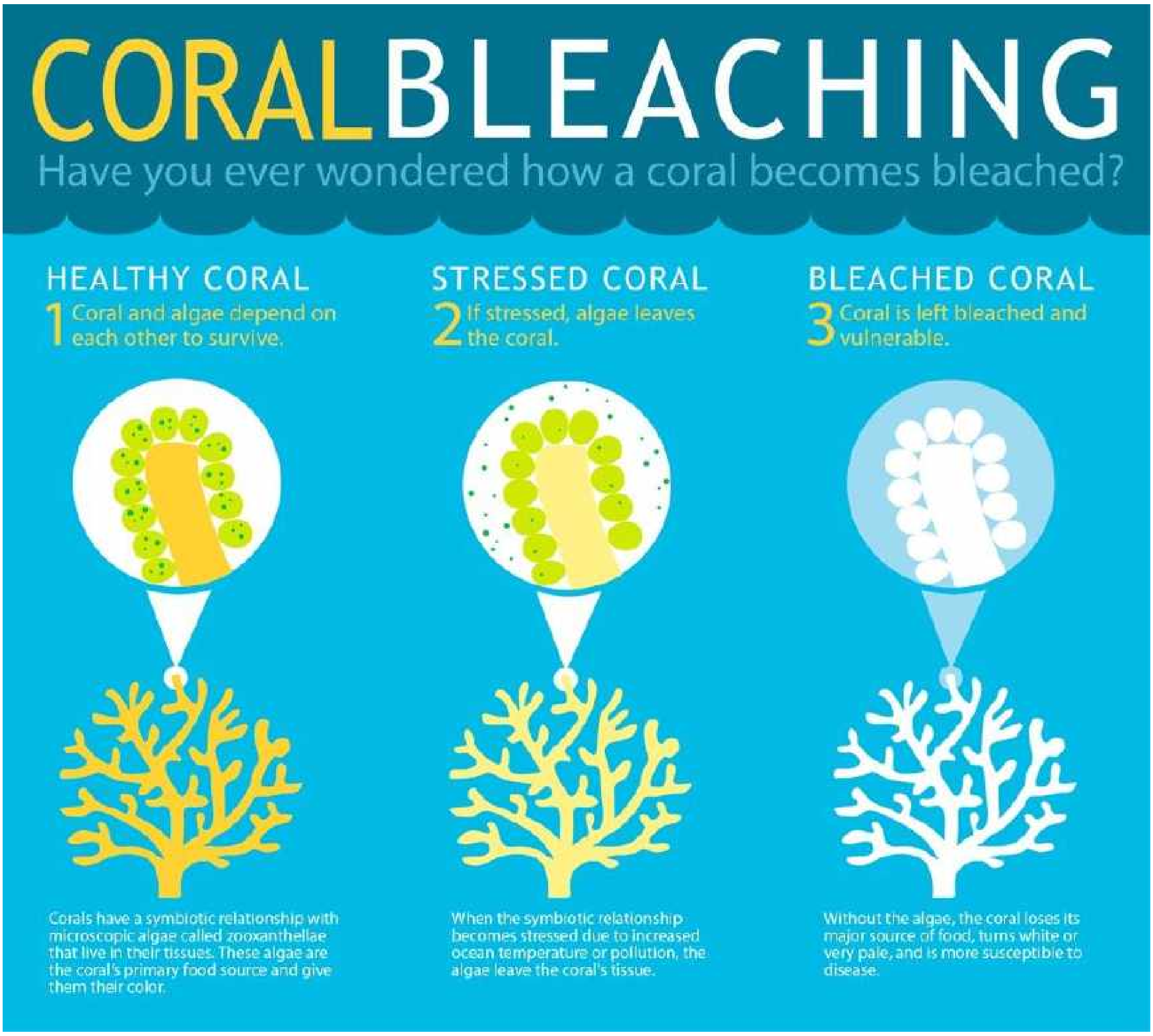


Figure from http://www.globalcoralbleaching.org/ . This image is from reefs near American Samoa, which show the progression from healthy coral (left) to bleached (middle), and then dead coral over the span of 9 months.

Evidence from the earth's distant past - millions of years ago, when the oceans were more acidic and there was also a lot more CO2 in the atmosphere - demonstrates that higher ocean acidity can dramatically affect what lives in the oceans.

Coral Bleaching



Widespread and severe bleaching events were unheard of prior to the 1980s. Recent research indicates that major reef ecosystems may bleach as often as every 6 years, while recovery from severe bleaching takes 10-15 years This is an issue because coral reefs serve as habitats for many fish at some point in their lifecycles. As the reefs disappear, the fish we eat (or the fish that *they* eat) lose their habitats. For more, see the Reef Resilience Network

Dietary Shifts

The many pressures on reefs and fisheries around the globe are forcing the coastal poor to find alternative food sources. Among inhabitants of small island states, the next available option may be highly processed and caloric foods typical of Western diets that have spurred the global rise in obesity.

A Small Island Nation Confronts Dietary Change

We were fortunate to speak with Tiene Took Kanoua, the Permanent Secretary of Health in Kiribati, a nation of 32 small islands atolls and reef islands with over 100,000 residents in the South Pacific. In the clip below she speaks about how the nation is working to address unhealthy changes to diet while at the same time building resilience to climate change.

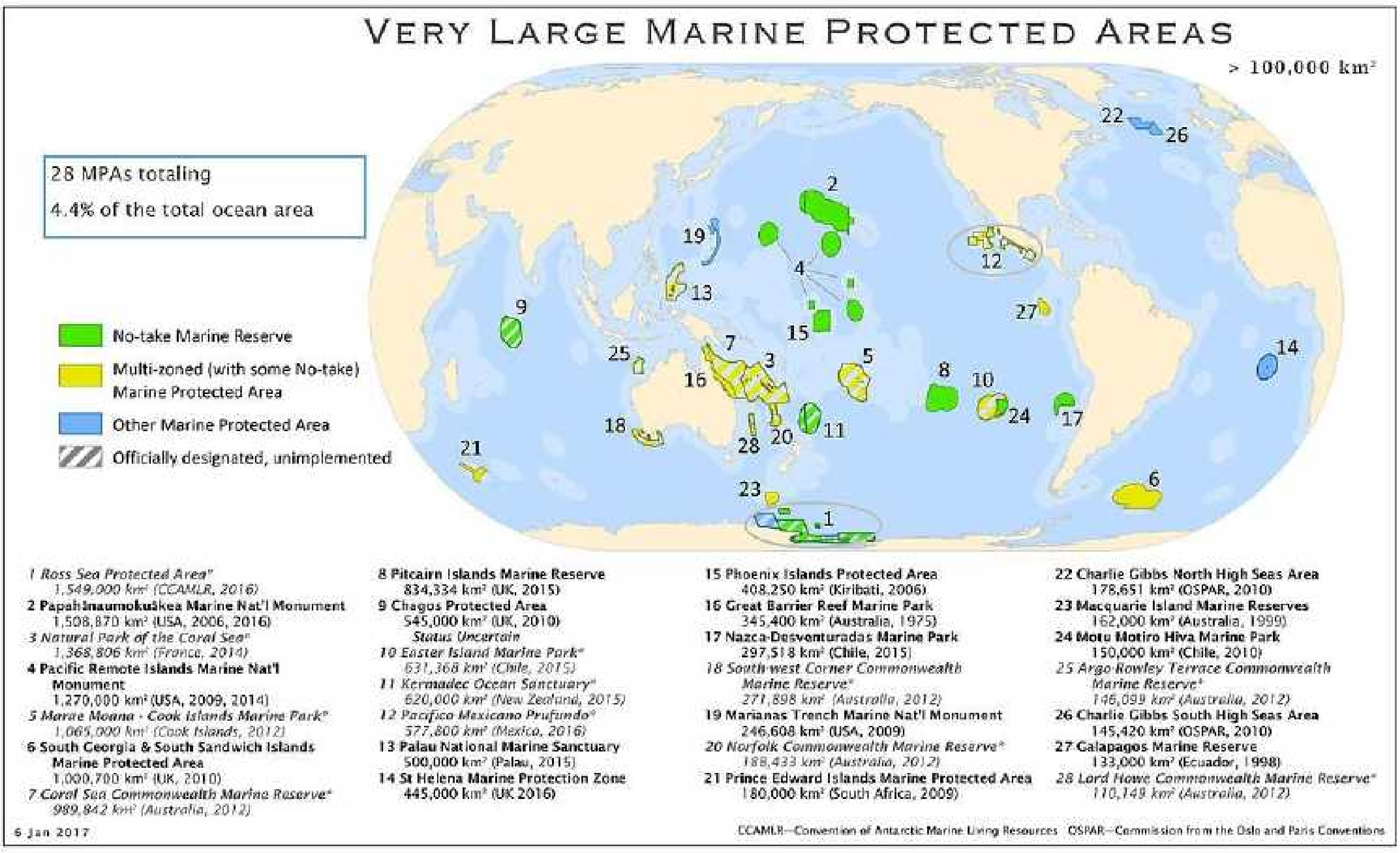
Ways to Protect Seafood

Overfishing the oceans along with ocean acidification and the loss of coral put at risk the fisheries that supply a major component of the diet to hundreds of millions of people worldwide.

Aside from limiting further greenhouse gas emissions, perhaps the best approach to protecting the oceans, the organisms that live in them, and human food security is to further embrace marine protected areas (MPAs) . MPAs are regions that have excluded fishing and other activities to protect the ecosystems within them. By protecting relatively small areas, fisheries and the ecosystems that support them can be buffered from the damaging effects of climate change and overfishing.

This map displays current MPAs around the world.

Very Large Marine Protected Areas



Overview

In the last few chapters, you learned about hardships faced by human beings due to climate change: heat-related conditions, infectious diseases, and nutritional issues.

In this chapter, we'll look at one of the results of these hardships: human migration.

Learning Objectives

By the end of this chapter, you should be able to:

- **Describe the ways in which the Syrian civil war is or is not typical of climate-induced migration issues.**
- **Construct pathways from greenhouse gas emissions to migration.**
- **Explain the short-term and long-term consequences of migration.**
- **Describe things that can be done to mitigate harm from migration.**

Human Migration - Human migration can happen for a number of reasons. Some people will be moving to escape sea level rise; others will face severe water shortages that will drive them from their homes. This is especially concerning for maternal and newborn health, as well creating heart strain and mental and emotional hardships for those who must migrate.

The Beginning of the Syrian Conflict

War has been ongoing in Syria since 2011. Many factors contributed to the war, including a history of sectarian conflict, unstable governance, changes to agricultural policies, and an unprecedented drought. For an in-depth look at the conflict in Syria, we recommend starting with Al Jazeera's article, Syria's civil war explained from the beginning . For a summary of the lead-up to the conflict, let's start by taking a look at the image below:

Before Syria's Civil War

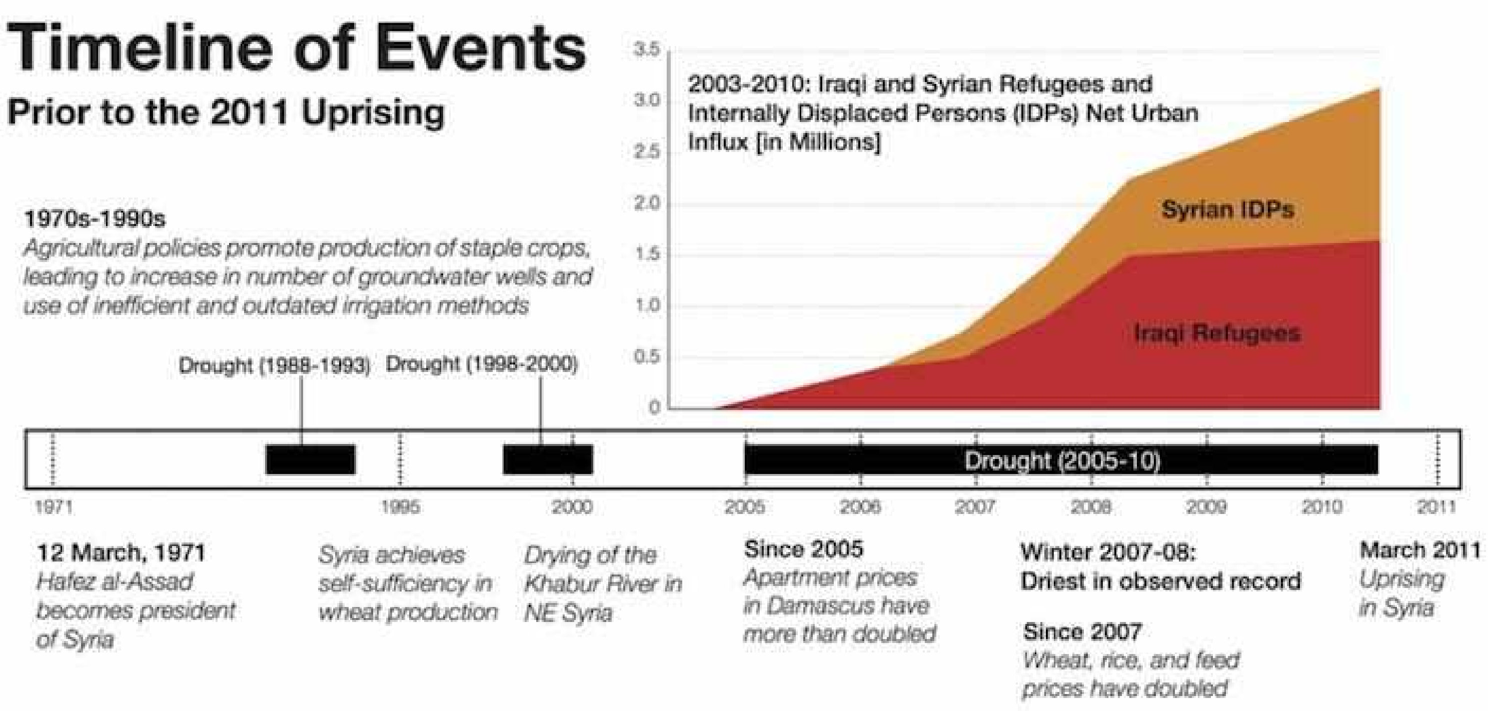
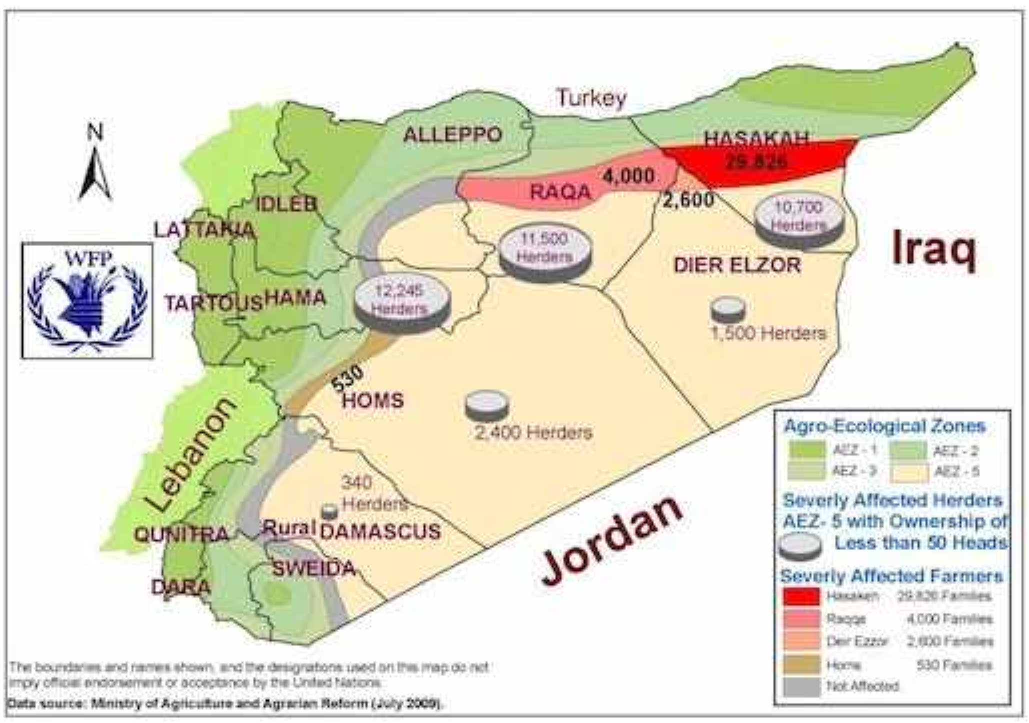


Image from [**Climate change in the Fertile Crescent and implications of the recent Syrian drought**]

Note that in the above timeline, the drought marked in black on the lower right preceded a major migration into Syrian cities that were already dealing with hundreds of thousands of refugees from the Iraq war.



Severely Drought-Affected Populations

This drought was one of the **worst in the past 900 years** **. In addition to marked declines in crop yields, the drought particularly affected herders in Hasakah Governorate who lost much, if not most, of their herds, and with them, their livelihoods. A migration of people from Hasakah to the cities in western Syria ensued. These internally displaced Syrians did not share a common heritage with the urban populations they joined. Tensions in these already overcrowded and under-resourced settings grew.**

Destinations of Syrian Refugees

Some 6.5 million people are now thought to be internally displaced from their homes within Syria, and 5.5 million have migrated out of the country, predominantly to Turkey. The map and table below show their destinations, with approximate numbers.

Before Syria's Civil War

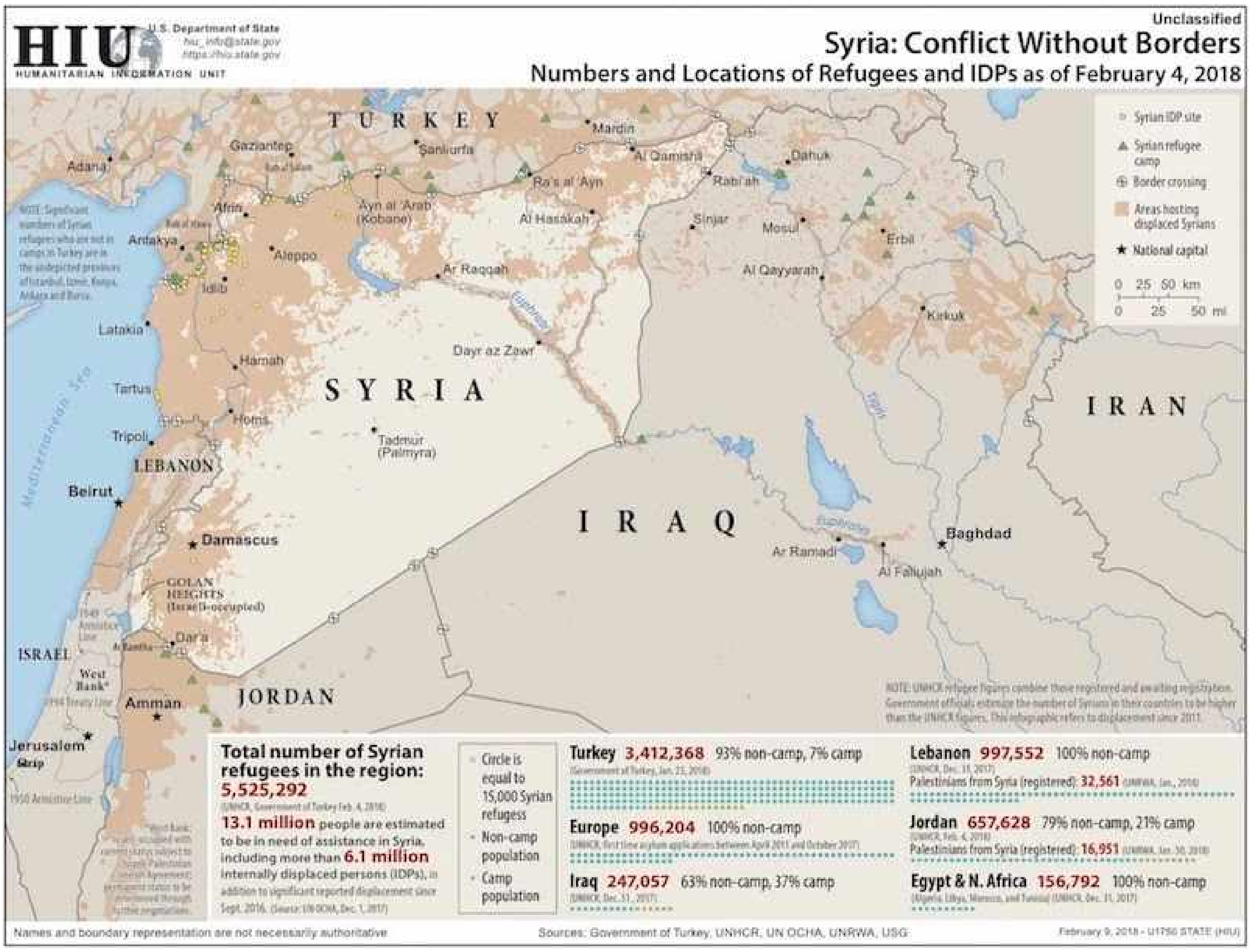


Image courtesy of the United States Dept. of State Humanitarian Information Unit , 2016

Location	% of Refugees	Number of Refugees
Turkey	64%	3,500,000
Lebanon	18%	1,000,000
Jordan	11%	600,000
Iraq	4.5%	250,000
Egypt	2.3%	125,000
Other (North Africa)	0.6%	33,000

While our climate was not the only cause of the conflict in Syria, it is certain that decreased food supply, increased prices, and higher temperatures did not help to improve matters. On the next page we'll discuss some of the pathways that led from climate change to this mass migration event.

Pathways to Migration

The Syrian refugee crisis provides a stark example of how an extreme drought can destabilize an entire nation. It increased tensions across many continents owing to mass human migration. However, drought is just one climate change-related event that can trigger forced migrations.

All paths that stem from greenhouse gas emissions can be seen to merge into a final common pathway, leading to population migration. Be it water scarcity, food insecurity, sea level rise, extreme weather events, or others - greenhouse gas emissions are forcing people to move against their will.

The Pathways to Population Migration

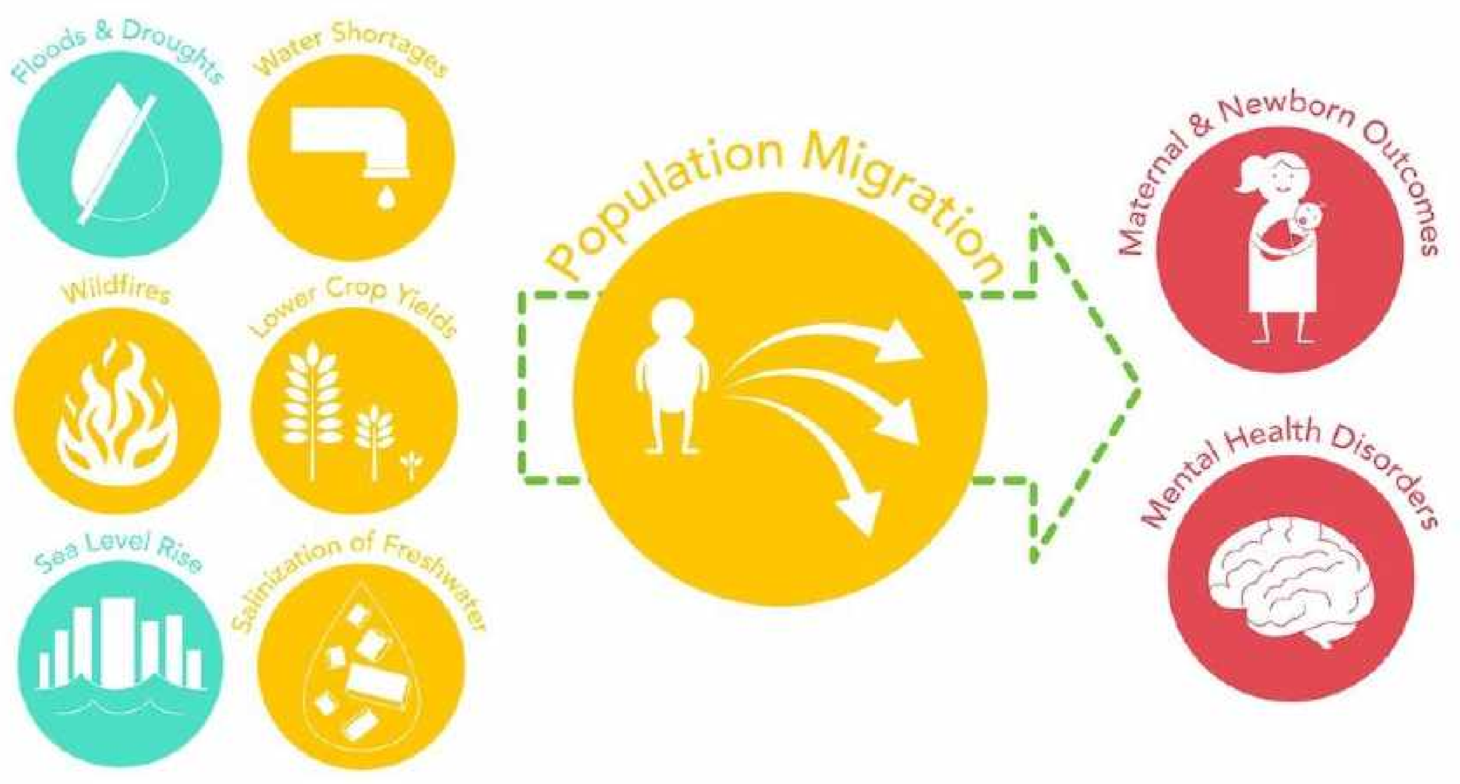


Image created at HarvardX

The United Nations estimates that an unprecedented number of people - more than 65 million - have currently had to move against their will from their homes. About 22 million have moved outside their home countries and are refugees and the vast majority are hosted in developing nations . About 40 million are internally displaced within their home countries, and are so called "internally displaced persons" or IDPs. Each year since 2008, more than 20 million people have been forced to migrate due to extreme weather.

Populations at-Risk

Because so many climate change pathways can result in population migration, many people may be at risk. Among those at risk, residents of small island developing states (SIDS) in the South Pacific may be *most* at risk. Just over 2 million people live on islands in the South Pacific, all of whom are endangered by sea level rise.

While severe drought may have contributed to migrations from Syria and elsewhere, sea level rise establishes another pathway to migration that is evident in small, low-lying island nations. We have been fortunate to obtain interviews with the Permanent Secretaries of Health for Tuvalu and Kiribati, where pressures of climate change on migration are perhaps greater than anywhere else on the planet. In this section, we'll use the present-day situations of Kiribati and Tuvalu as examples that will help us understand the possible fates of many other nations.

Near-Term Consequences

Migration has consequences - some of them are immediate and short-term; some are longer-lasting. In this page we'll discuss the short-term consequences.

Anyone who has moved will tell you it's difficult. Moving when you don't want to is more difficult, more stressful, and often must happen very quickly. Distressed migrants often have substantial health burdens caused by nutritional deficiencies, trauma, infections, mental illness, and pollution exposure.

Nutrition

Some evidence suggests that access to nutrition in refugee camps has improved in recent decades owing to better preparedness and delivery of nutrition. Nevertheless, nutritional deficiencies are commonplace among those forced to move from their homes against their will.

Infection

Overcrowding and lack of basic sanitary infrastructure including running water and toilets makes refugee and internally displaced person camps prone to infectious disease outbreaks. Waterborne and vectorborne diseases, such as cholera and malaria, respectively, can also be prevalent as water scarcity leads to bacterial water contamination and open water storage where mosquitos may breed.

Trauma and Violence

Such camps often lack governance, and interpersonal violence, including rape, is often reported . Trauma, both physical and emotional, are common among distressed migrants and have been associated with incidence of post-traumatic stress disorder and depression People forced to migrate can face a variety of health problems as you've learned. But even before migration occurs, people who face the prospect of migration, such as those living in small island states like Tuvalu and Kiribati can have substantial anxiety about their future. The above examples reveal health concerns that are common and somewhat expected with forced migration resulting from natural disasters and conflicts that may arise from natural disasters.

In the video clip below, Paul Farmer, Kolokotrones University Professor of Global Health and Social Medicine at Harvard and the founder of Partners in Health describes another kind of forced migration that occurs when people must move to find work. In some cases, this may occur when natural disasters or other climate related events lead to people seeking a livelihood elsewhere. (Syria is a good example in which rural herders lost their livestock due to a drought and migrated to coastal cities.)

Dr. Farmer speaks to circumstances in which patients that have received initial drug therapies for HIV and tuberculosis, as examples, may lose access to those critical medications when they leave home for work, often across international borders.

Long-Term Consequences

While forced migration fosters ill health as it occurs, harms may unfold for decades, if not for generations. Some research suggests that refugees may have mental health disorders as well as higher mortality rates years after they have resettled.

Preventing Migration

The best way to prevent harms associated with migration is to prevent migration in the first place. Improving climate resilience with critical infrastructure provides a means to increase the chances that populations at risk may be able to stay put, especially when other forces, such as conflict, are not present. In low lying island states, such as Kiribati and Tuvalu, losing freshwater to salinization may be the most likely pathway to force migration. Secretary Kanoua describes measures being taken in Kiribati to protect freshwater supplies.

Options for Direct Help

Looking at the pathways that can be traced from greenhouse gas emissions to population migration provides insights into actions that can forestall migration. Addressing food and water insecurity, improving current population health, bolstering infrastructure to guard against flooding, and other steps can be taken.

Programs to adapt to climate change have taken shape and encompass a wide swath of potential risks from food and water security, to infectious disease risk and more.

Climate Refugees

Adaptation to climate change has it limits. While it carries the potential to prevent some forced migration related to climate change, large scale population migrations related to climate change are expected in decades ahead. The World Bank recently estimated that 143 million people may become internally displaced by 2050 At present, international humanitarian law does not clearly provide protections for those that have been displaced by climate change, whether within their home countries or beyond their home nation's borders. Legal refugee status can only be granted once an individual has left their home country. Furthermore, those individuals who may be forced to leave their home countries due to, as examples, extreme weather events or sea level rise associated with climate change, may not be eligible for refugee status.

Recently, the United Nations, regional organizations, and individual nations have sought to provide greater protections to people forced to move because of extreme weather events and other climate related disasters. The Kampala Convention of the African Union provides one such example that specifically addresses internal displacement owing to climate change related events.

Monitoring Migration

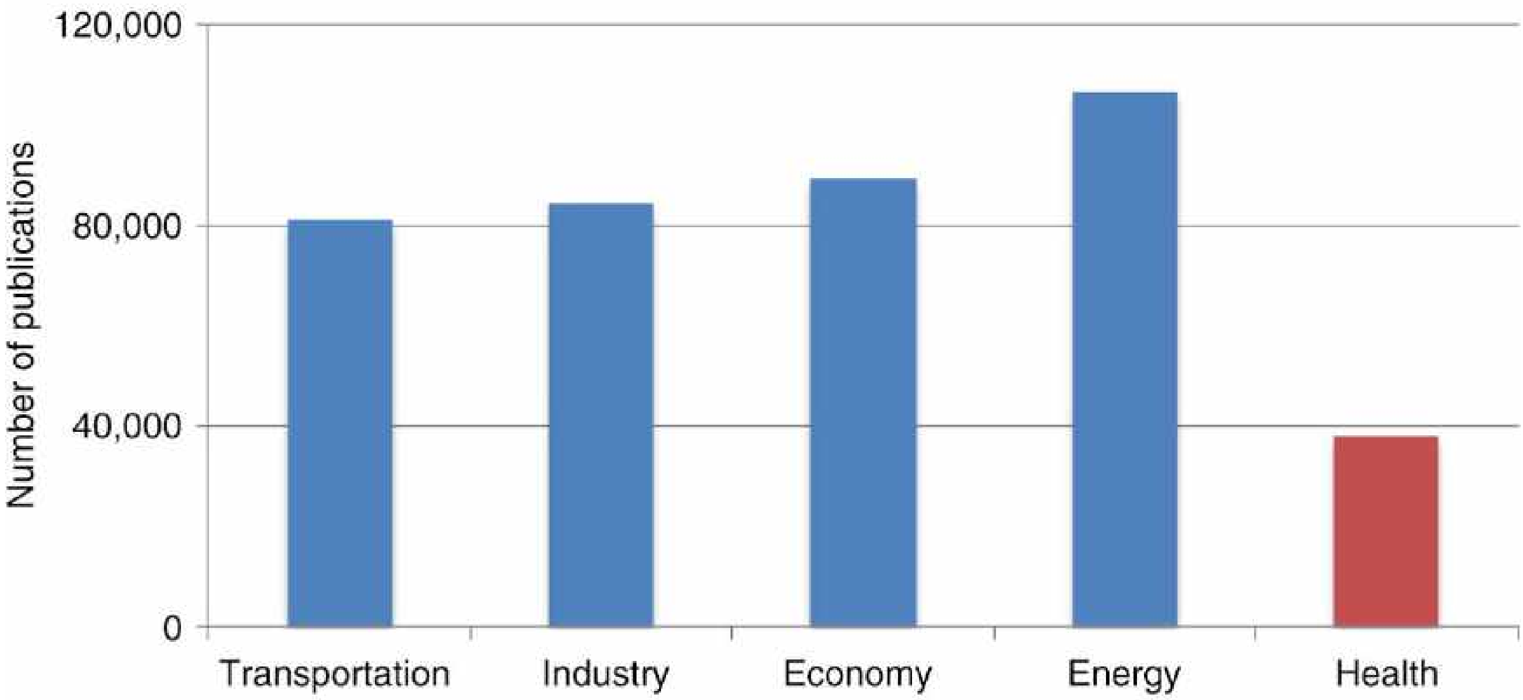
Without adequate population census, determining needs around migrations is impossible. With many more forced migrations on the horizon, investments in demographic data collection may be particularly valuable.

Overview

How do we know what we know about our climate? What data sources do we rely on? What are the challenges in understanding that data and relating it to human health?

This section aims to provide you with both factual knowledge and some basic skills regarding data sets and analytic methods. The motivation for including a module on research in this MOOC is twofold. First, Harvard is a prime generator and disseminator of research, and second, health scientists have largely sidelined the topic of climate change, as reflected in the sorry state of output in this field. The production of research papers on health and climate change is roughly half that of in other sectors impacted by climate change, such as agriculture, forestry etc.

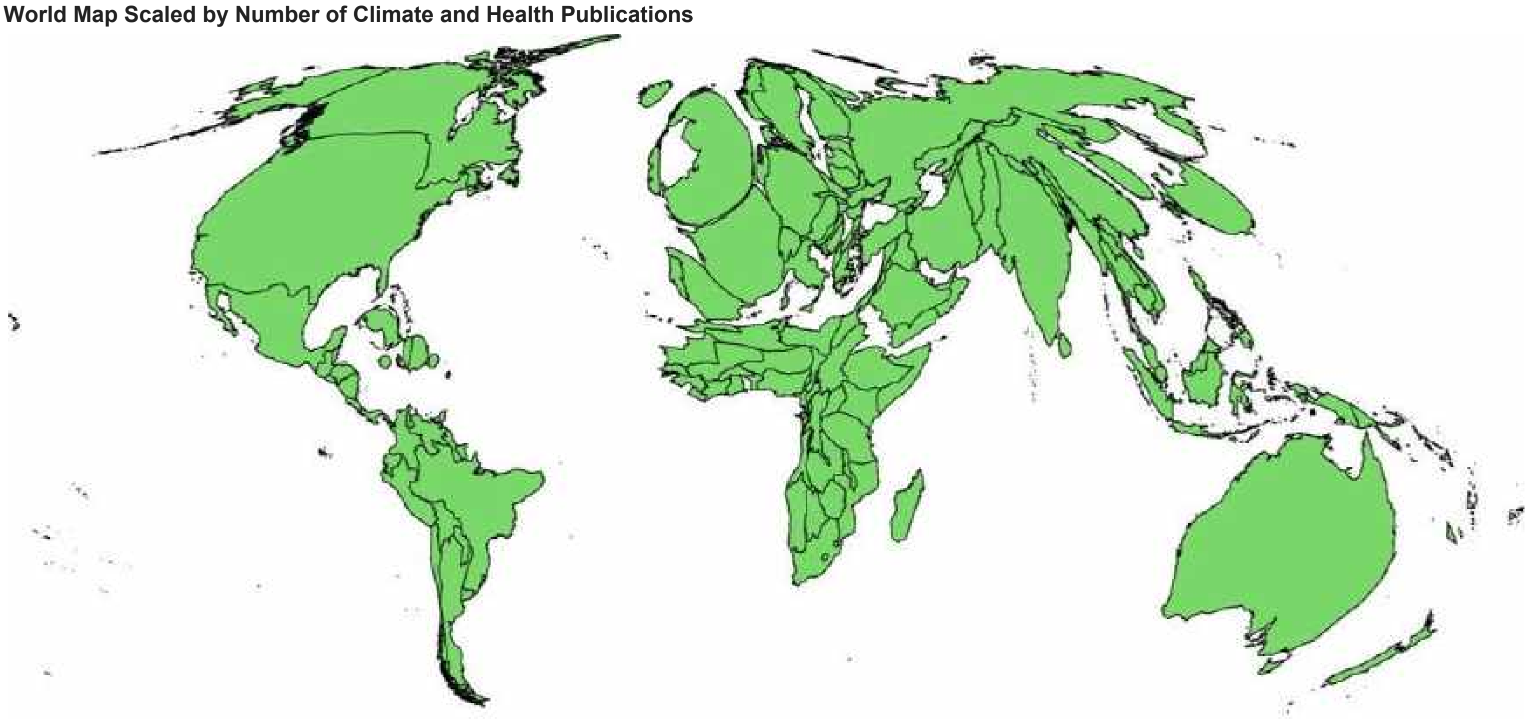
Climate Change Research Publications by Sector



Data source: Science Direct 1990–2014. Image from Health in climate change research from 1990 to 2014: positive trend, but still underperforming

Worse still, scientific evidence on health impact functions or on climate adaptation strategies to protect population health, or even on co-benefits, is extremely biased in favor of the Global North . This is unfortunate, as populations in the Global North are not as vulnerable to climate change and its health effects as those in low and middle income in the Global South.

World Map Scaled by Number of Climate and Health Publications



Data source: PubMed, 1990–2014. Image from Health in climate change research from 1990 to 2014: positive trend, but still underperforming . The depicted size of each country was altered to reflect the number of publications in those areas proportional to their population.

We hope to shine more light on this underserved population in this section, and in future research.

Deep Dives and Optional Material

> **We make extensive use of outside resources in this section: published papers, how-to guides, other MOOCs on the topic, and further multimedia materials. You can "deep-dive" into these materials as you wish, guided by your own interests.**
>
> **Those looking for introductory papers on climate change and health in general should examine the following material:**

Means, Variances, and Extreme Events

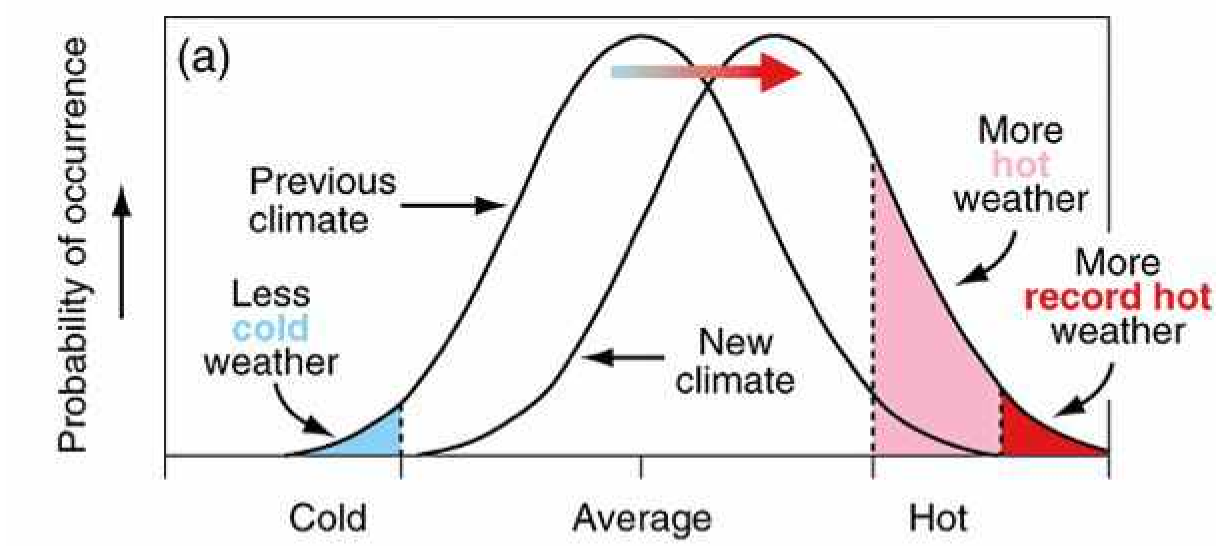
Weather and climate share the same key variables. The only difference, but a crucial one, is that weather measures the *current state* of the atmosphere of a given point in time and location, like a snapshot. Climate is the *average* state of the atmosphere, taken typically across 10 years. Time horizons for weather predictions are typically on the order of 10 days. Typical time horizons for projections of climate impact, including health, are 2030, 2050, or 2100.

Climate change will move the "needle" of these variables in a certain direction, in the case of temperature towards higher degrees ("global warming", Fig 2a). You've seen us discuss this before, in our page on Climate Change and Heat Exposure. However, in addition, it will make

the distribution of weather flatter (see Fig. 2b), with fatter tails, pointing to a greater number of extreme weather events. The figure below exemplifies the point using temperature e.g. global warming and heat waves as illustration.

Mean	Variance	Both

Increase in Mean Temperature



Images courtesy of Harvard.

Climate change moves the average of climate variables (here exemplified by temperature), while at the same time making the distribution wider. The combination of increasing average temperature with more extreme events (dark red equals heat waves) constitutes a double threat to health.

We can see from this set of figures that the distribution of weather/climate variables becomes wider when the averages of these variables move during climate change, which means that we see more extreme events.

Where in our atmosphere?

Human health is mainly affected by developments in the lowest part of the atmosphere, called the troposphere (up to 10 km above sea level). That's also where three quarters of the atmosphere's mass and 99% of its water vapor and aerosols are concentrated, and where the largest percentage of greenhouse gases are located (CO2, methane, and N2O especially). Further, that's where the short-lived climate-related pollutants are found, such as particulate matter, black carbon, and ground-level ozone that causes smog. All short-lived climate active pollutants have an influence on human health (Woodward et al, 2015).

Connecting the Past and the Future

Retrospective versus Prospective

How can we measure climate change, which spans at least 2 decades? Few funding agencies are willing to dedicate money to such long-term efforts. There are also few doctoral students willing to accept the idea of working for decades on such a topic.

Fortunately, we do not need to empirically study health impacts *prospectively*, as climate change evolves in future decades. Rather, we can look backwards in time, *retrospectively*, at how weather variables like rainfall and temperature influenced health outcomes during the past decades. Dr. Tony McMichael phrases this approach as follows: measure the past, observe the present, and project to the future.

Empirical data-based studies		Scenario-based future health risk assessment
Past	Present	Future
Measure: learn the relationship between climate change and human health	Observe: detect impacts and estimate current burden	Project: build predictive models for estimating future effects

To do this, we need population-based, continuous and long-term data sets on health outcomes, which have both spatial information and a date stamp. While this is relatively easy in the Global North (insurance data sets, death registration etc.), it is a challenge in low and middle-income countries in the Global South, whose populations are most vulnerable to the health effects of climate change. Later on we will discuss which suitable data sets exist in such countries and how you can access them at no cost.

Additional Burden

There are about one hundred diseases which are "climate sensitive", meaning that they are likely to increase in frequency and severity due to changes in climate variables. These climate-sensitive diseases have been in existence for quite some time, potentially giving us a long baseline of data. Our goal is to look at the current health burden from these diseases and identify the amount of *extra burden* added due to the effects of climate change. (For an excellent introduction to disease burden statistics, see Burden of Disease at Our World In Data.)

Although most people think of infectious diseases when they consider climate-sensitive diseases, you've seen in this course that non-communicable diseases and malnutrition are equally important. The additional disease burden from climate change impacts everything from malaria to asthma to even injuries and drowning (as higher temperatures make people more likely to become light-headed).

As policymakers tend to be interested in the *overall* added burden of diseases from climate change, it would be optimal to use aggregate health metrics, such as "DALYs from climate change by the year 2050". This has the additional advantage of including both deaths from these diseases (mortality), which can be attributed to climate change and diseases, measured here in years of life lived with a disease (morbidity).

Pathways

The Climate/Health Framework, indicating the causal relationships from the components of climate change to impacts on large disease groups, provides a glimpse of the complexities of this problem.

Climate/Health Framework

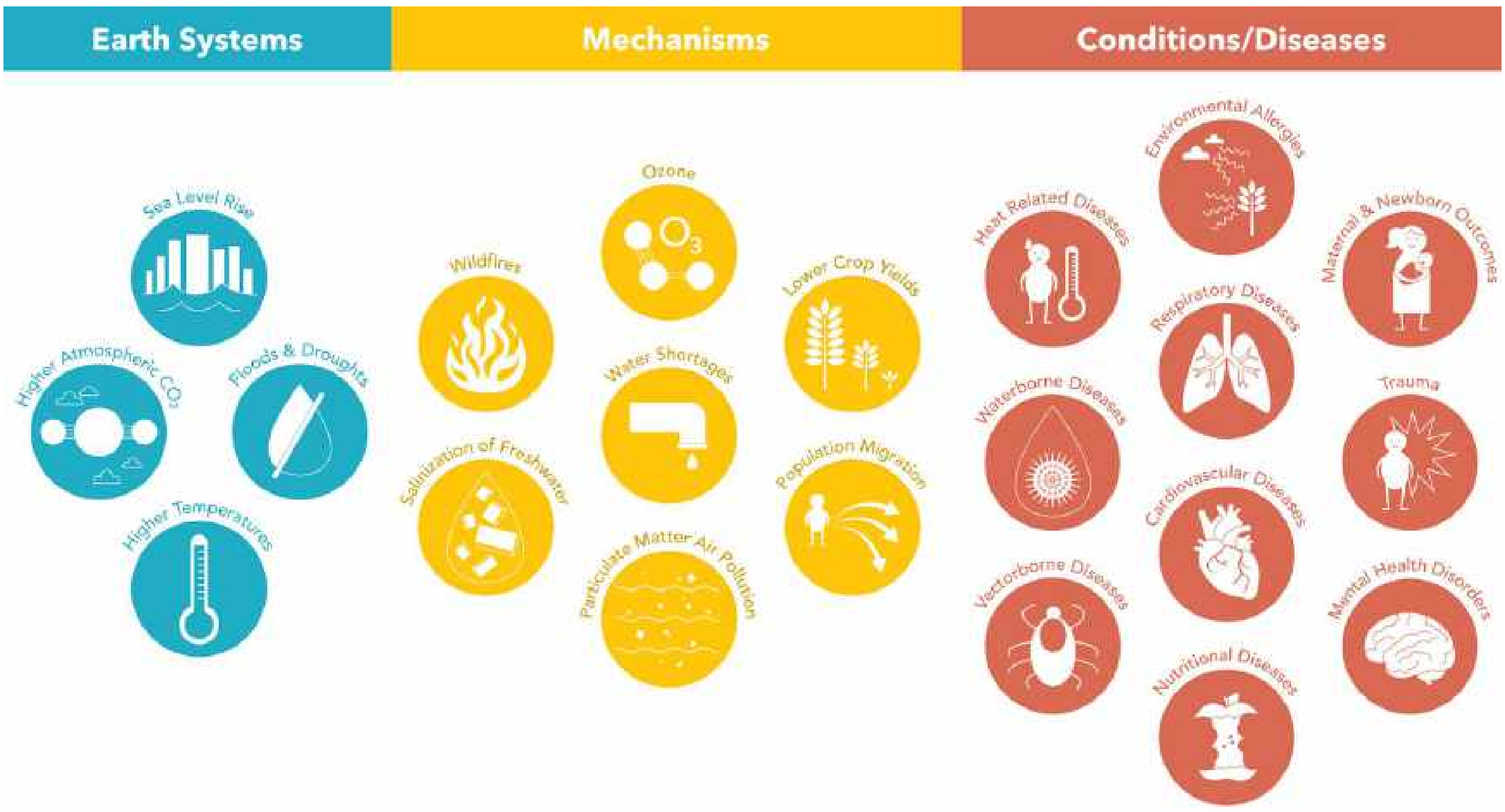


Figure courtesy of Harvard.

There are six components of climate change: Temperature increase, altered rainfall patterns, sea-level rise, ocean acidification, extreme weather events and climate-active pollutants. Each of these has its own distinct, but often linked pathways to the major adverse health outcomes.

Within each of the impact groups, e.g. infectious diseases, there is a wide range of disease entities which are likely to be affected by climate change, each with its own transmission mechanism. We estimate that there are at a minimum 100 climate-sensitive diseases. This calls for a focus on a few major groups: malnutrition, diarrhea, cardiovascular, respiratory and vector-borne diseases. Mental disorders are also a long-term consequence, one hardly touched by current research efforts.

To make the plot even thicker, all climate sensitive diseases have been and will continue to be strongly influenced by social determinants, many of which are not included in our framework: loss of habitation, loss of productivity, poverty, mass migration, and violent conflict.

Scale Overview

The image below shows the rough scales for events in the study of climate and health. Notice the logarithmic scale of the axes: times range from hours to millennia, and distances range from just a centimeter to the size of the entire Earth.

Time and Space Scales for Climate and Health

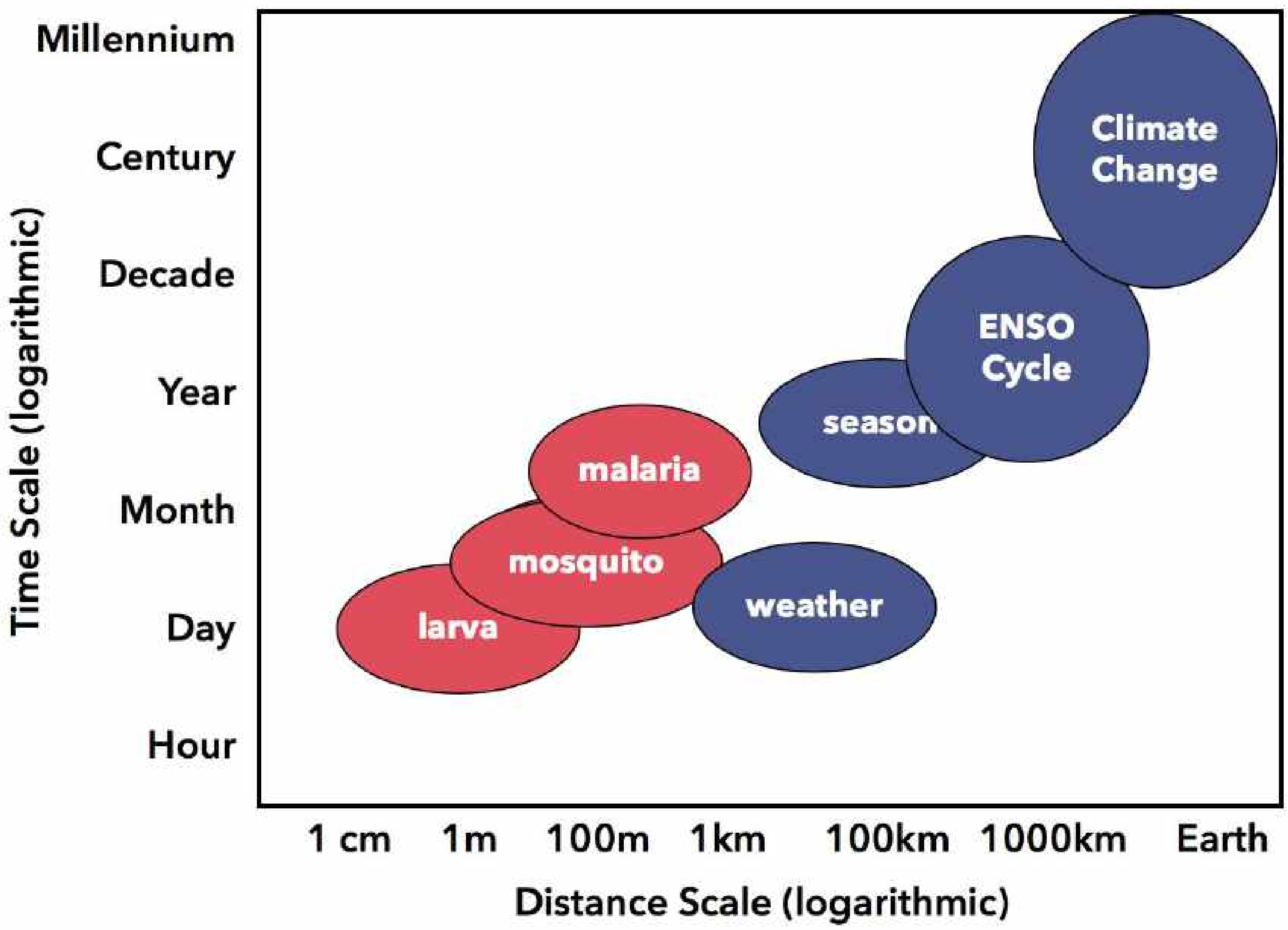


Figure courtesy of Harvard. Disease transmission factors are in red, while climate change factors are in blue.

Timescales

Many climate-sensitive diseases evolve on a small scale, both time-wise and space-wise. As an example, malaria-transmitting mosquito larvae take just under 2 weeks to develop in surface water. The adult Anopheles mosquitoes fly around 500 meters to find their blood meals. The mosquito stage, too, has a life span of about 2 weeks. Once Plasmodium parasites have been inoculated, they, in turn, require a bit more than a week to multiply to cause symptoms.

Climate, on the other hand, evolves over decades. Fortunately there are climate "analogues" of smaller scale resolution: weather (days), seasons (months), Inter-annual atmospheric changes, e.g. the El Nino oscillation or ENSO (El Niño-Southern Oscillation). We can use time series data of weather variability as it affects subsequent health outcomes and derive, for example, temperature-stroke impact functions as a proxy for climate impact on stroke. There is no other way.

Spatial Scales

Science has made large strides in the past decades when it comes to the spatial resolution of climate models. While the resolution of climate models is typically on the order of 300 by 300 km, they can be cleverly downscaled to a finer grain, for example 30 by 30 km. This allows local health impact functions to be coupled with local climate models of similar resolution. This is key for making meaningful estimates of the health impact of the local climate on local populations, from whom the climate health impact functions were derived.

The Impossibility of Randomized Control Trials

Epidemiology using statistical inference is predicated on estimating summary statistics (e.g. mean, median etc.) and their dispersion from samples of a source population (e.g. prevalence of type II diabetes in a given population). Invaluable contributions have been made possible through teasing out the contribution of risk factors (exposure) to population health (outcomes). Further, trusted methods have been developed to compare outcomes in the exposed and the non-exposed through case-control and cohort studies.

By randomly assigning comparable groups of patients to an intervention and a control arm in randomized controlled trials (RCT), preferably performed "double blind ", we have been able to demonstrate that drugs, vaccines, even health policy interventions are indeed effective (if everything else is equal). We forget, however, that the majority of medical procedures, operations and policies have proven effective without the badge of proof of an RCT. Sometimes this is because it would be unethical to "prove" their effectiveness; other times, because the empirical success record of the procedure was overwhelming in the absence of an RCT proof. The journal BMJ even presented a parody article, entitled *Parachute use to prevent death and major trauma related to gravitational challenge: systematic review of randomised controlled trials* , jokingly lamenting the lack of RCTs in determining whether parachutes actually save people from dying.

This prologue was to prepare the medically trained reader for the fact that in climate change impact research these classical epidemiological designs are *impossible by nature.* There is no control group, no control Earth that is not experiencing climate change. Therefore, p-values and confidence intervals *cannot and should not be demanded as a proof of evidence.* The absence of statistical evidence therefore does not serve as proof of the absence of an association between an exposure and an outcome. This is important to keep in mind in estimating future health impacts of climate change.

While this is true for the projection of health impacts through coupling with climate models, we are still on firm statistical ground when observing retrospective time series of exposure and health data. Here the exposure is a weather variable (rainfall, temperature) or associated climate active pollution variables (fine particles, ozone, NOx, black carbon) and its ups and downs over days and years. The outcome variable is an incident case of a climate-sensitive disease case or an associated death. Looking backwards in time, we can therefore apply our statistical/epidemiological tools, such as population-level attributable risk/attributable burden of disease. We can also run time series analysis, a type of regression which captures the time difference (lag) between exposure and outcome. While the former is the stuff of standard epidemiology textbooks and will not be dealt with here, we will go to some length in later sections to guide the reader in the use of time series analysis, particular its advanced form of "Distributed lag non-linear models" (as in Gasparrini et al. 2010)

Statistical Methods

Time Series Studies

Time series regression allows researchers to study the impact of time-variant exposures on outcomes, taking into account the lag (time difference) between the exposure and the outcome. As the outcome here is a count variable, the modeling should use a Poisson regression .

Sequences of exposure and outcome measurements are recorded at regular time intervals. As the base of time-series analysis, the exposure and the outcome variables as well as the potential confounders should be known and captured in a clear research hypothesis. Examples for exposures are variables such as atmospheric variables i.e., temperature, precipitation, carbon dioxide, methane, ozone and aerosols, among others. Examples for health outcomes are health effects of heat (such as heat stress outcomes comprising cardiac output, heart rate, stroke, etc.) or health effects of ozone.

Following the study of Bhaskaran et al. (2013) , one might formulate this research question with the exposure to ozone and the health effects of ozone: are day-to-day changes in mortality related to daily ozone levels? A dataset to answer this question needs to contain daily levels of environmental variables – in this case daily ozone levels – and the daily number of deaths.

Bhaskaran et al. (2013) define four key steps that should be taken into account for time series regression studies:

1. **Data exploration with simple data visualization,**
2. **Controlling for seasonality and long-term trends,**
3. **Modelling the exposure-outcome association with regards to immediate and delayed effects, and**
4. **Checking the implemented model for the respective data.**

Data exploration, the first step of the time series analysis, serves as the researcher's first orientation to the data and its features. If you would like to see an example where you can follow along, you may want to refer to Bhaskaran et al. (2013) Raw data is often dominated by long term and seasonal patterns, as well as comprising irregular short-term fluctuations. It is difficult to detect short-term associations that are based on, for example, a daily ozone level. Methods for seasonal adjustment can remove seasonal and systematic influences to uncover non-seasonal associations, based on an estimation.

As each observation of the time series should be independent of each other, there should not be any correlation between observations. However, observations close in time are likely to be more similar than those separated by time. Therefore data should be checked and controlled for autocorrelation. Similarly, over-dispersion in a Poisson distribution needs to be adjusted for, as it may be the case that the observed variance of the outcome counts is higher than predicted.

The next step is the modelling of exposure-outcome associations, whereby there are two main choices of model available: linear and non-linear. The model should incorporate delayed or lagged effects. For the ozone example, yesterday's ozone level may potentially be a better predictor for today's mortality risk than today's ozone level.

The last step consists of model checking. This consists of checking residual plots and carrying out sensitivity analyses, such as changing the amount of control for seasonality and long-terms trends, as well as specifying the exposure and confounder variable in different ways.

More Sophisticated Analysis

A further sophistication of time series analysis is the "Distributed lag non-linear model (DLNM)" recently developed by Gasparrini et al. (2010). The DLNM addresses delayed exposure-outcome effects that enables a modeling of the distribution of effects over time. It is particularly well suited to study the time relationship between exposures and different lags. It simultaneously describes non-linear and delayed dependencies, termed as exposure-lag-response associations. Furthermore, the DLNM allows for non-linear exposure-effect relationship, that addresses the harvesting effect and is able to address seasonality and long-term trends. The DLNM is compatible with cohort, case-control or longitudinal analyses.

While the interpretation of the simpler DLM is straightforward, the results of a more complex DLNM with smoothed non-linear dependencies are harder to summarize. One solution is to build a grid of predictions for each lag and for suitable values of exposure (see Bunker et al 2017), using three-dimensional plots to provide an overall picture of the effects varying along the two dimensions. However, this is beyond the scope of this introductory module.

Generating Health Projections

Linking Health Science and Climate Science

This page discusses how health scientists can work with their colleagues in the climate sciences in order to answer the following central questions:

1. **What is the size of the health impact of climate change? How does this impact differ by type of disease, vulnerable populations, and time horizon?**
2. **What approaches to adaptation are effective? What are their individual or societal costs?**
3. **What is the size of health co-benefits of mitigation?**

As we laid out earlier in this chapter, the key is to link retrospective empirical evidence with climate projection models. The challenge is building the health impact function from, on the one hand, a careful analysis of retrospective longitudinal data on health outcomes and its non-climatic co-variates, and on the other hand, the ups and downs of weather variables. This requires appropriate data sets for populations from all parts of the globe, particularly those in the Global South, which we expect to be the most vulnerable due to a combination of high exposure and low adaptive capacity.

Health scientists can generate empirical health impact functions (also referred to as "dose-response functions"), which our climate science colleagues need to get in order to incorporate the health dimension in their climate projections. Once this is achieved - and it requires intense and innovative cooperation between the hitherto separated fields of health and climate science - the models allow one to evaluate the protective impact of adaptation policies. This is possible through a recent climate model feature, known as Shared Socio-economic Pathways (SSPs). These allow one to test - within the model - which policies would reduce the impact of climate change by which amount, in great detail. Even better, SSPs can be downscaled to a district, country, region, in much the same way that climate models can be downscaled. This adds a modicum of realism to our "in silico" evaluation of the effectiveness of adaptation policies/interventions.

The rub is that the costs and effectiveness of interventions need to be tested in the present-day "real world". For example, to protect a population against climate-induced (or climate-aggravated) malnutrition, we might test a range of interventions: drought resistant crops, market-based interventions (prices, incentives), crop insurance, nutritional interventions for kids, keeping kids' infectious disease low through prevention and detection with prompt treatment, keeping calorie losses from diarrhea low, etc.

Any climate change impact, including effects on population health, will obviously depend on the which climate path the world chooses to follow. While the Paris Agreement of 2015 gave us hope that the world would stay below a 2 degree ceiling for global warming by 2100, the world has not lived up yet to its promises. In addition, in 2018, the IPCC released a special report highlighting the health-significant consequences at even 1.5°C above pre-industrial levels.

Data Challenges in Global South

The largest current burden of the major climate-sensitive diseases is suffered in the Global South, with which we mean those populations living closer to the equator: between the latitudes 37.5° north and 37.5° south. Furthermore, the political and health systems of most countries located in this swath of the globe currently have a low capacity to adapt to the additional health effects of climate change. The combination of high exposure, high pre-existing prevalence of climate-sensitive disease, and low adaptive capacity leads to the highest health vulnerability from climate change.

Data is a crucial component not only for research, but for health planning and policy development. If we want to empirically study the impact of climate change in past decades, we need to look at continuously recorded health data. This is relatively easy in high-income countries. However, in the Global South, vital event registration is unreliable and patchy. So is facility-based data, on which most health statistics are based. The data is not population-based, as only a fraction (and not a representative fraction) of the population in these countries use health services when ill.

The INDEPTH Network

This is where the INDEPTH network comes in. INDEPTH stands for International Network of field sites with continuous Demographic Evaluation of Populations and Their Health. It was founded as a quality assurance and comparative study-generating umbrella for dozens of research centers in Africa and Asia, which had been founded with the aim of providing accurate data on deaths by cause, births and migrations. The standardized method to collect theses data is called Health and Demographic Surveillance System (HDSS). The ultimate goal of the sites and the network is to scientifically test interventions and policies in order to improve peoples' lives, as well as to inform and influence policy (see Sankoh and Byass 2012). The figure below shows the countries with the current HDSS member sites. They lie exactly in the tropical and subtropical parts of the globe, whose populations are most vulnerable to climate change.

Nations with INDEPTH network member sites

- **Africa**
  - **Burkina Faso**
  - **Cote d'Ivoire**
  - **Ethiopia**
  - **Gambia**
  - **Ghana**
  - **Guinea-Bissau**
  - **Kenya**
  - **Malawi**
  - **Mozambique**
  - **Nigeria**
  - **Senegal**
  - **South Africa**
  - **Uganda**
- **Asia**
  - **Bangladesh**
  - **India**
  - **Indonesia**
  - **Malaysia**
  - **Vietnam**

INDEPTH provides (via HDSS) a network for longitudinal demographic and public health data within communities in Africa, Asia and Oceania. The HDSS sites within the INDEPTH network currently cover around 4.5 million individuals representing a total of mind-boggling 91.5 million person-years observed.

In the absence of reliable vital event registration, this network with high-quality data on cause-specific deaths and other population demographics is a treasure trove for the analysis of decade-long time series of health outcomes and their relationship to preceding weather variability in those countries whose population health is most vulnerable to climate change.

The figure above shows why these data rich populations are most suitable for retrospectively studying the relationship between weather variability/climate change and health: the enormous length of observation with an average of 25 years, ranging from 55 to 2 years. The population and health data are publicly available through the INDEPTH iShare website . This data repository comprises datasets with key demographic and health indicators extracted from the longitudinal database that contains events ranging from household dynamics to fertility and mortality, migration and livelihood as well as on causes of death, following a retrospective method to determine cause of death called verbal autopsy. The micro-data of respective HDSS sites is available to researchers, upon request.

Accessing Meteorological Data

When it comes to research on climate and health, it is a major challenge to collect high quality, continuous (daily), and long-term (> 20 years) health outcome data on a variety of variables. However, it's comparatively easy to find the corresponding "lagged" values of key weather variables, such as temperature or rainfall.

We are lucky, as today we can download with a mouse click more than 10 meteorological and air pollution variables - for every location on the planet (over land) and for every day for the past 30 years. The network of actual measurement stations is by far more dense in the Global North, but satellite data is rapidly filling the gaps in the Global South.

Meteorological data sources and points of access encompass different sources, including:

- **The National Oceanic and Atmospheric Administration (NOAA**
- **). NOAA provides worldwide data on daily rainfall, temperature, and other meteorological data for most national weather stations within countries.**
- **ClimateCHIP**
- **. The ClimateCHIP is another means to access the NOAA weather in a more accessible way, as the data is available processed and in a more user-friendly format.**
- **The Tropical Rainfall Measuring Mission (TRMM**
- **) by NASA and the Japan Aerospace Exploration Agency (JAXA). The satellite-based TRMM data provides daily – and even hourly – precipitation data on a finer geographical scale with various resolutions, but the satellite was depleted in early 2015. Processed data is available from the IRI/LDEO Climate Data Library**

Available Time Series Data

Type of data	Measurements	Global North	Global South
Meteorological	Daily temperature, daily rainfall, annual rainfall	NOAA and NASA databases, dense network of local weather stations	NOAA and NASA databases, coarse network of local weather stations
Meteorological	Rainfall distribution pattern	Needs data processing and modeling	Needs data processing and modeling
Air quality	Fine particles, PM5, PM 2.5, NOx, Ozone	Dense network of local weather stations, satellite based data	Very thin network of local weather stations, satellite based data

Health outcome	Global North	Global South
Cause specific mortality	Vital event registration	INDEPTH/HDSS
Morbidity	Various health insurance/provider data sets	Selected household panel surveys
Population burden of disease (both mortality and morbidity)	Not systematically available in retrospective long-term time series	Starting to be collected in some INDEPTH sites
Health care utilization	Multiple insurance and provider datasets	Sparse data of longitudinal nature

Both vital event registration systems and HDSSs also provide data on migration. The climate-related portion of emigration has yet to be established numerically; ditto for ill health and food insecurity from climate change.

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Deep Dives

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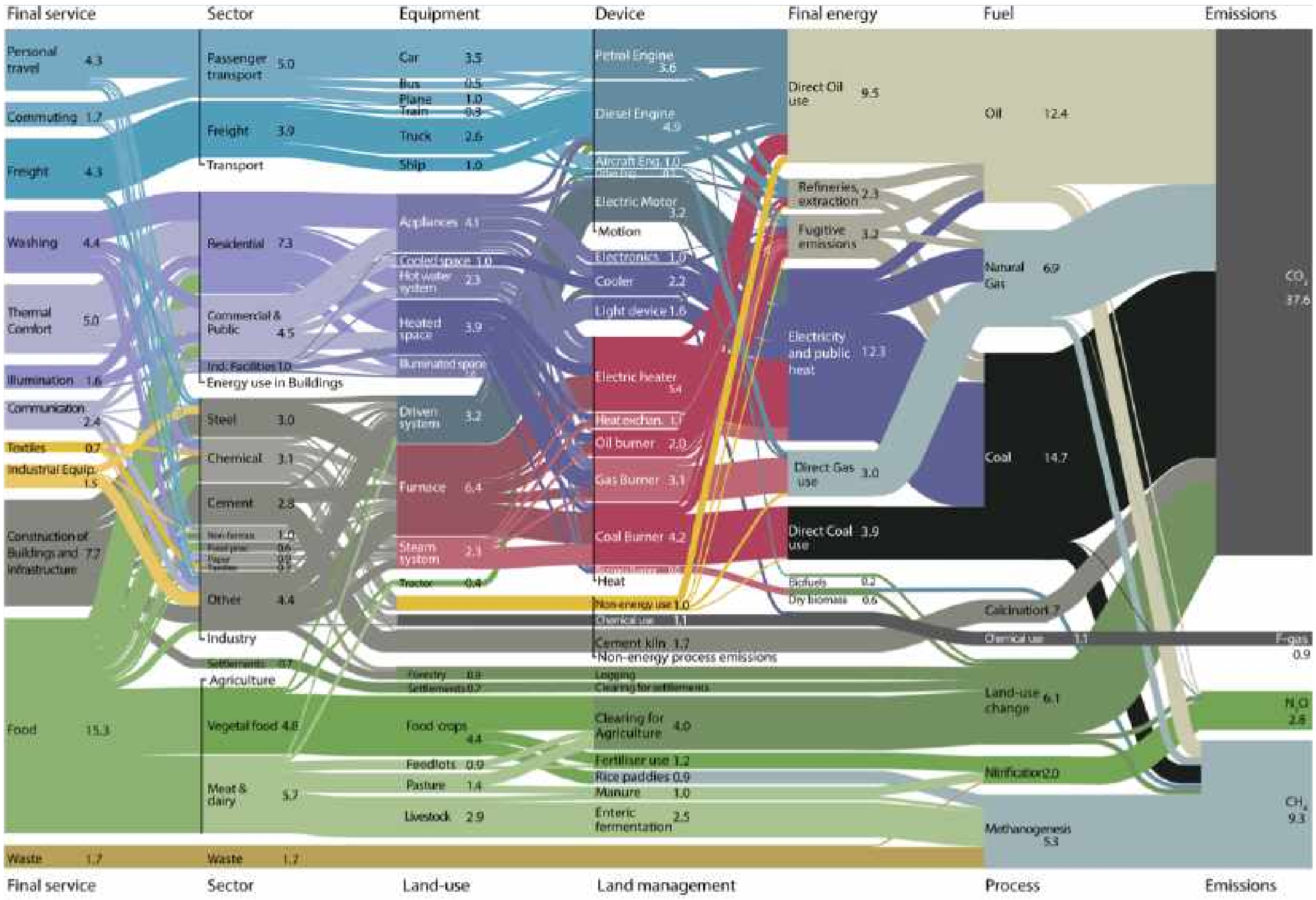
Reducing carbon pollution from its sources

Worldwide, most greenhouse gas emissions result from burning fossil fuels for heating, transporation, food production, and electricity. Spend some time tracing greenhouse gas emissions from the “final service” to “emissions” in the diagram below. Do any flows seem surprisingly large, or small?

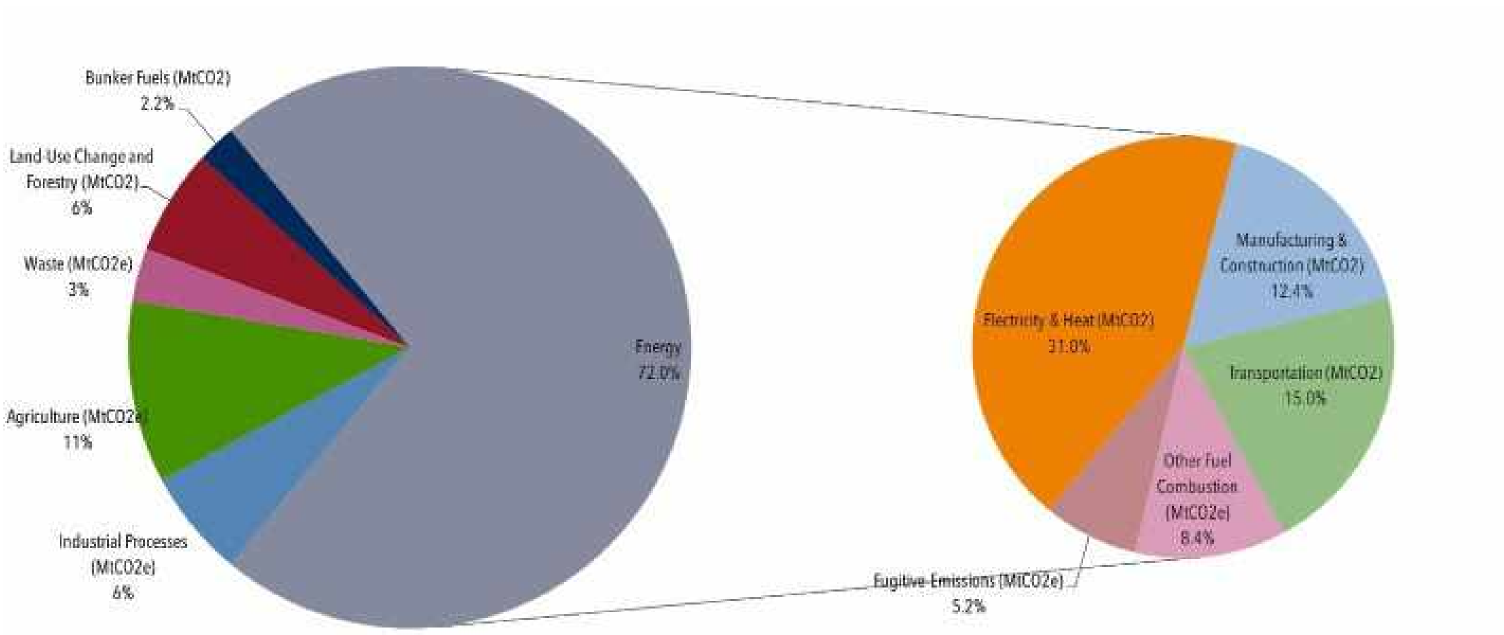
Overview of Global Greenhouse Gas Emissions 2010

(Gigatons CO_2 equivalent)



Source: Bajželj, B., Allwood, J.M. and Cullen, J.M., 2013. Designing climate change mitigation plans that add up. *Environmental science & technology*, *47*(14):8062-8069. Use by CC-BY license, American Chemical Society.

Bajzelj, B., Allwood, J.M. and Cullen, J.M., 2013. Designing climate change mitigation plans that add up. Environmental science & technology, 47(14):8062-8069. Use by CC-BY license, American Chemical Society.



"Global Manmade Greenhouse Gas Emissions by Sector, 2013" Graphic by Center for Climate and Energy Solutions, https://c2es.org/content/international-emissions/ , data from World Resources Institute.

Later in this section of the course, we'll consider ways to decarbonize major emissions sources and how these actions matter to health.

Climate change "mitigation" refers to actions that reduce the sources of greenhouse gas emissions. While mitigation itself will stave off harms well into the future by reducing harms associated with climate change, it also can result in *health co-benefits*. These are the near-term and often local health gains that accrue along with greenhouse gas emission reductions. Co-benefits derive from many types of interventions, including shifts from fossil fuels to renewable energy sources for electricity generation; shifts in diets from red meat consumption to legumes, fruits and vegetables; more active transit; and greater energy efficiency in buildings.

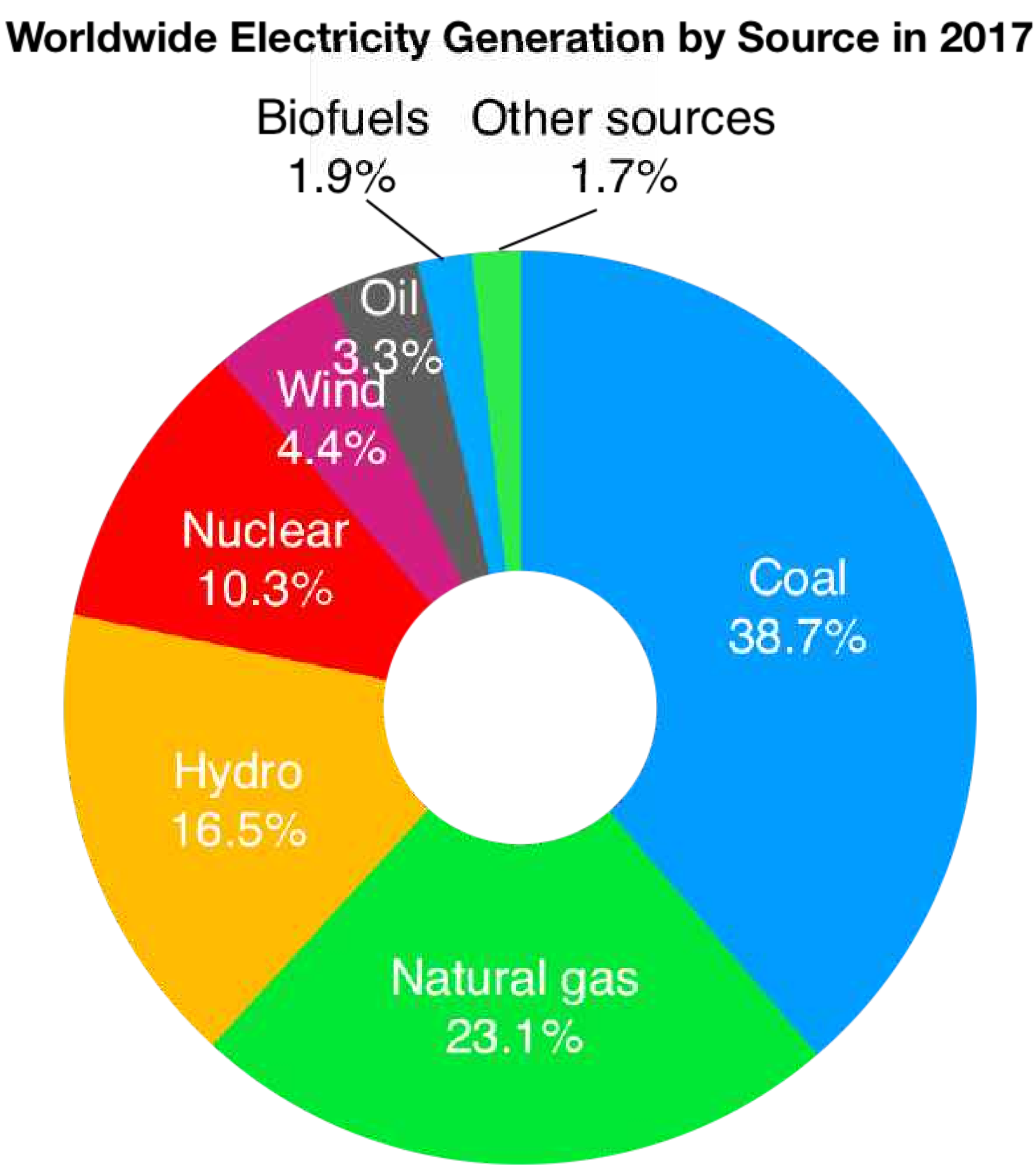
Shifting from...	...to...	...results in...

Fossil fuels	**Renewable energy**	**Less air pollution, which means fewer premature deaths, fewer heart attacks, less lung cancer**
Diets with meat proteins	**Diets with more vegetable protein**	**Fewer premature deaths, less colon cancer**
Driving	**Bicycling**	**Less heart disease, better mental health, reduced obesity and diabetes**
Uninsulated buildings	**Better-insulated buildings**	**Less energy consumption, which means cleaner air and all its associated benefits**

Air pollution associated with reliance on fossil fuels leads to roughly 1 in 8, or 6.8 million, deaths each year , which makes actions that reduce fossil fuel use likely to improve health and save lives.

Electricity and Emissions

Globally, fossil fuels, including coal and natural gas, dominate electricity production, accounting for more than 60% of electricity production.

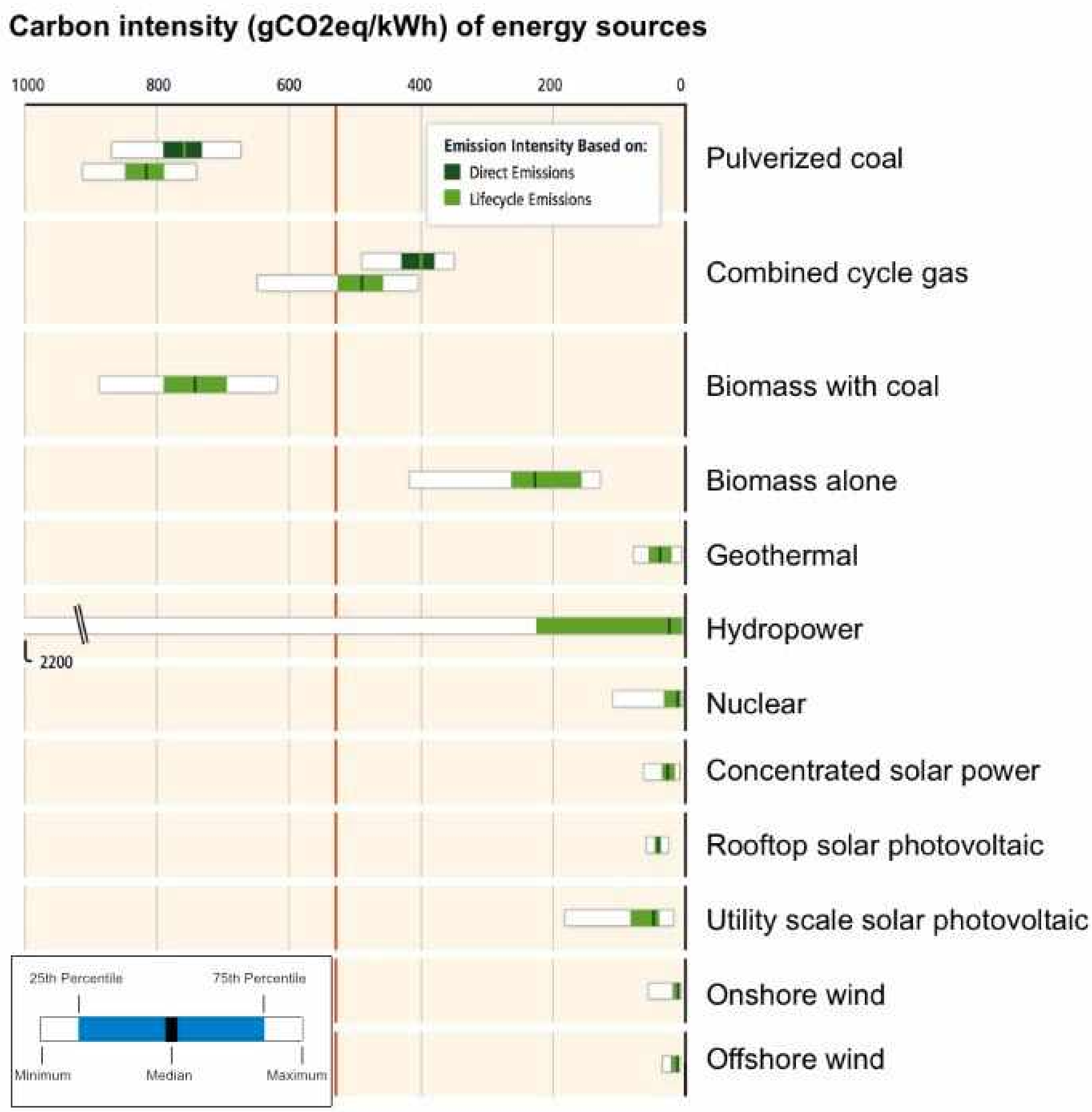


Click image to enlarge.

Data source: International Energy Agency (IEA) Graphic created by A. Bernstein

Natural gas, coal and oil all release greenhouse gases when used. Hydropower can also result in substantial emissions of greenhouse gases as flooded areas can emit methane, nitrous oxide and carbon dioxide. To better understand which energy sources produce the most energy

with the least greenhouse gas emissions, researchers have looked at their relative carbon intensity - or the amount of greenhouse gas produced per the amount of energy generated.



Click image to enlarge.

Adapted from figure 7.7, Intergovernmental Panel on Climate Change (IPCC) AR5 Chapter 7, Bruckner T., et al, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

This graph shows the direct and full lifecycle greenhouse gas emissions that are needed to use a variety of energy sources to produce electricity (Visit the US Energy Information Administration's site for an overview of the different types of energy sources) Direct emissions come about from the generation of energy itself. Lifecycle emissions include everything that goes into the making of electricity for the specified source, including, for example, constructing new power plants, wind turbines, or dams, the transportation of fuels, or other emissions sources (the range of emissions intensities for hydropower is large because of the variability in emissions that can come from flooding land).

Based on this, what energy sources would be the best to decarbonize electrical supplies?

Electricity and Health

Another important consideration with decarbonizing electricity (as well as heat) comes from the known health effects. Burning fossil fuels releases many pollutants that cause immense harms for people everywhere in the world. The table below outlines some of the pollutants and their associated health effects that come from using fossil fuels.

Pollutant Source	Health effects

Particluate matter (Coal, diesel, gasoline, natural gas)	**Heart attack** **Stroke** **Hypertension** **Lung Cancer** **Asthma** **Premature birth** **Type 2 diabetes** **Depression** **Pneumonia** **Miscarriage**
Mercury (Coal)	**Learning problems** **ADHD** **Kidney disease** **Heart disease**
Lead (Coal)	**ADHD** **Learning problems** **Lower IQ** **Violent behavior** **Kidney disease** **Hypertension**
Ozone (Coal, diesel, gasoline, natural gas)	**Asthma** **Breathing difficulty**
Polyaromatic hydrocarbons (PAHs)	**Asthma** **Lung** **cancer** **ADHD**

Of these pollutants, particulate matter results in the greatest harm worldwide, and many of you are living in places where burning fossil fuels has made air quality unhealthy. Nearly 7 million people die each year— nearly 1 in 10— from particulate matter put in the air from burning fossil fuels. Another personal experience with the pollution generated from relying on fossil fuels, and coal in particular, can come when we eat fish. Many fish at the top of the food chain have high concentrations of mercury. This mercury got into the food chain primarily because of burning coal.

A key take home message from knowing the pollution associated with fossil fuels: reduced reliance on fossil fuels for electricity can result in lighter disease burdens.

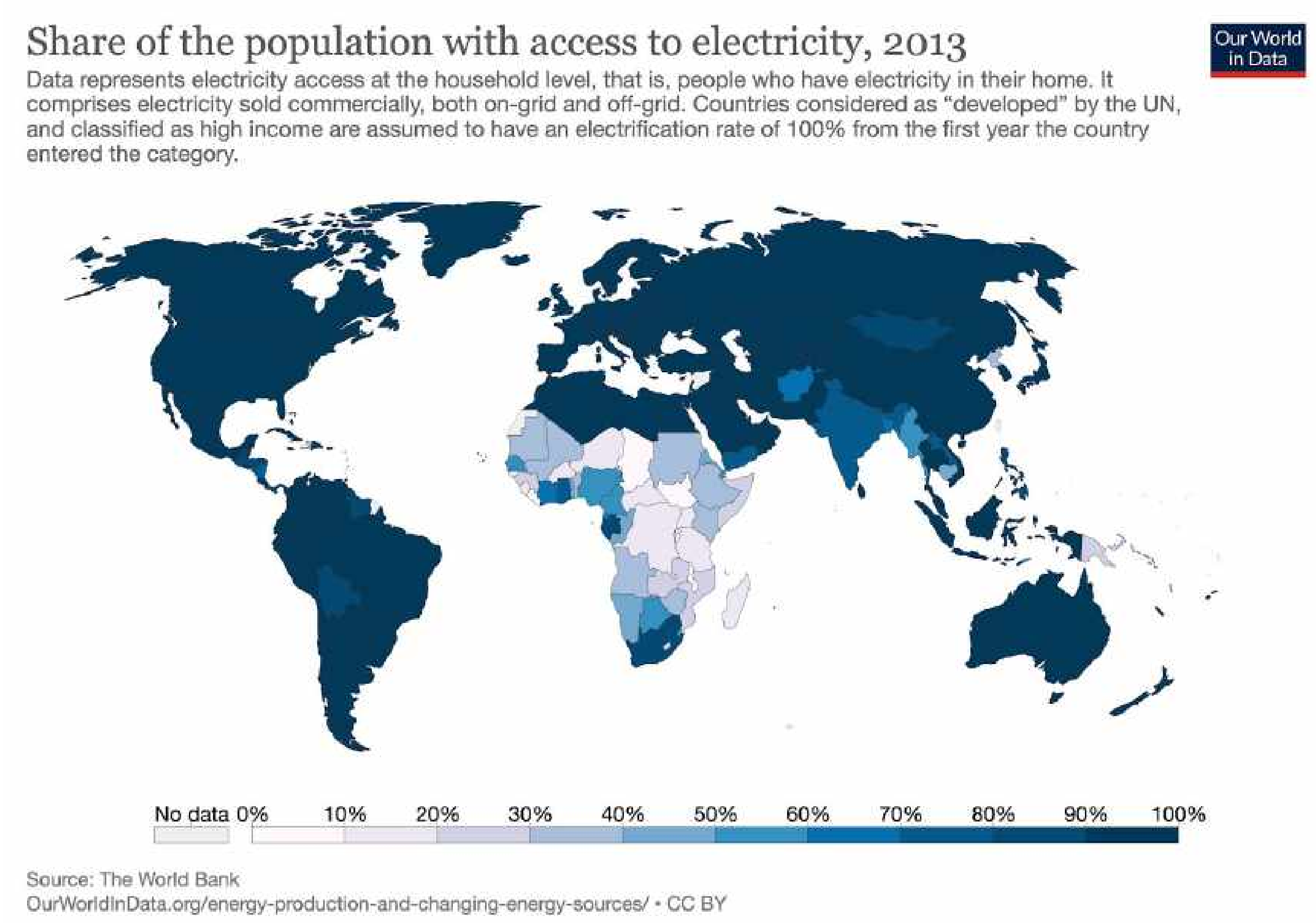
The adverse health effects that come from burning fossil fuels matters especially for the roughly 1 billion people in the world, mostly in sub-Saharan Africa, who currently lack access to electricity. Many more have highly irregular electricity supplies.

Interactive: World Electricity Access, 1990-2016

The interactive map below shows the share of the population with access to electricity from 1990 to 2016. If you are unable to use the interactive map, an image follows that displays the data for 2013. Below this image the data for 1990 to 2016 is represented in table form.

Development goals seek to provide stable electricity access to everyone who lacks it today. Finding a way to do this, while protecting health, economic growth, and the environment is a major challenge for this century.

Source: Our World in Data **Image: Population with Access to Electricity, 2013**



Renewables

The image below shows that renewables are currently used to produce a fairly small percentage of our planet's electricity.

Estimate share of final energy consumption, 2016

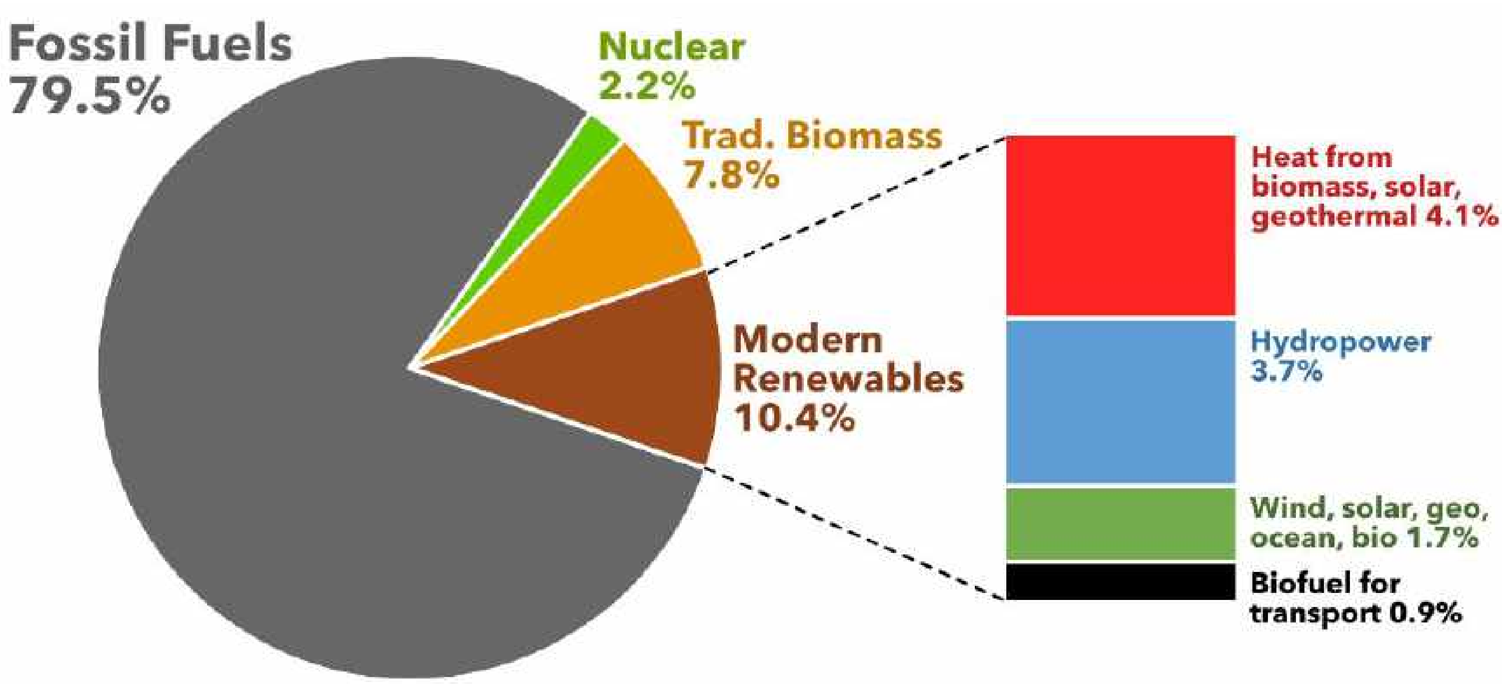


Image courtesy of Harvard. Adapted from Ren21

Amount	Source	Renewable?
79.5%	Fossil Fuels	No
7.8%	Traditional biomass (e.g. burning wood for heat)	Yes
4.1%	Heat engines using biomass, solar, or geothermal energy	Yes
3.7%	Hydropower (from dams)	Yes

2.2%	Nuclear Energy	No
1.7%	Wind, solar, biomass, geothermal, and ocean power (combined)	Yes
0.9	Biofuels for transport (i.e. ethanol)	Yes

There's plenty of room to grow, as most of the world's energy comes from fossil fuels. Modern renewables, such as wind and solar, provide less than 2% of global energy consumption. The move from fossil fuels to renewables is happening. Unfortunately, it is not happening at a pace commensurate with the goal set out in the Paris Agreement (which recommended limiting warming to 2°C). Aside from the challenge of transitioning energy systems toward lower carbon and healthier fuels, about 1 billion people lack access to electricity. More than 80% of the people without electricity live in rural areas, predominantly in sub-Saharan Africa and South Asia. Some of the nations in these areas also are among the poorest in the world. Moving from no electricity to renewable energy could be a leapfrog opportunity in these locations. But for many nations, fossil fuels may be a more accessible and affordable energy source than renewables. This reality pits economic development against health and climate goals.

Co-benefits of Renewables

Health benefits from decarbonization can be substantial . This is especially true when it comes to air quality improvements, if coal becomes a much smaller portion of the fuel used to generate electricity around the world.

Renewable electricity as a percentage of total output among low-income countries

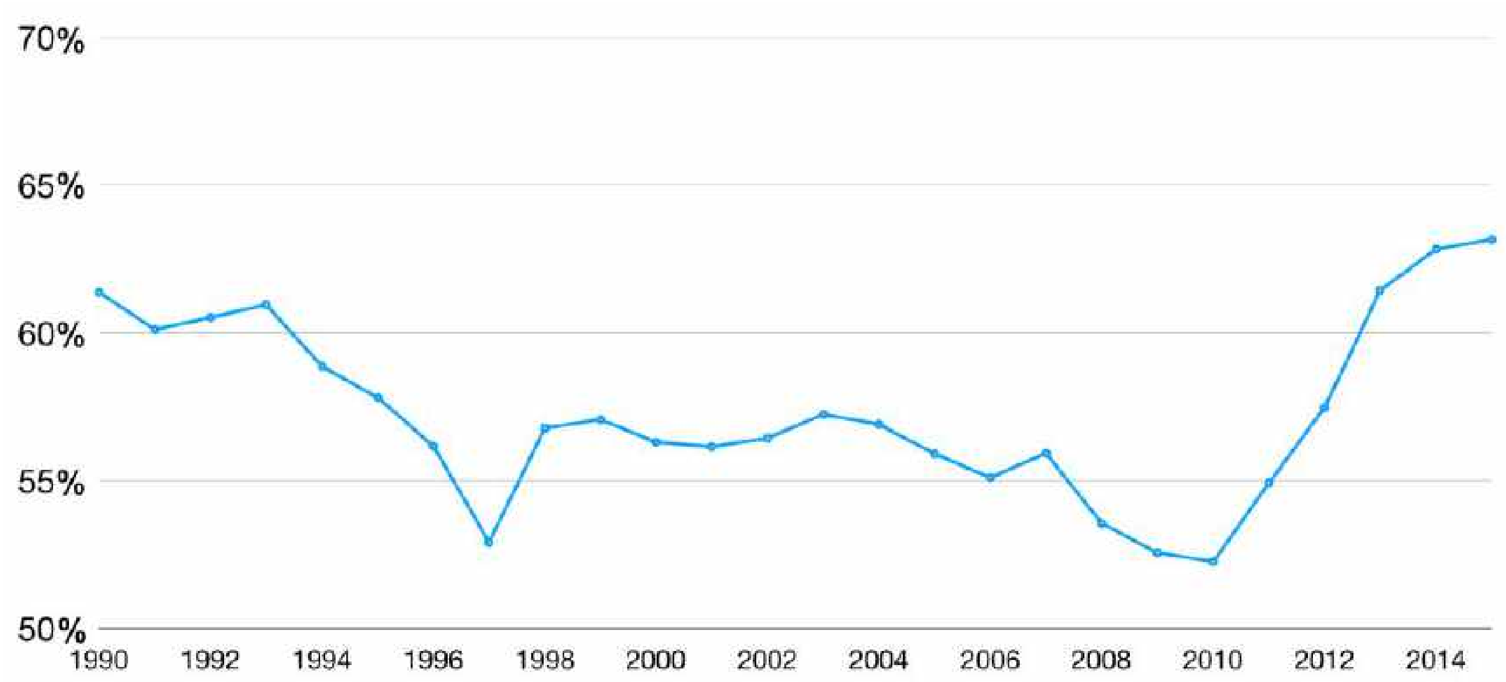


Image courtesy of Harvard. Data from the International Energy Agency - © IEA Statistics OECD/IEA 2018.

How to provide greater access to electricity while minimizing exposure to pollution and carbon emissions is a key objective of sustainable development. Many low income countries have substantially increased the percent of electricity generated from renewables.

Health Benefits

Another draw of renewable energy is its health profile in comparison to fossil fuels. Burning coal for electricity and gasoline/petrol and diesel for cars, trucks and trains contribute to hundreds of thousands of deaths in China and India alone each year While wind, solar, hydro and geothermal all have adverse health effects, including potential for water pollution and reliance on rare earth elements (and their mining), their operation results in comparatively little harm to humans and other species as the burning of fossil fuels.

Plans for 100% Renewable Energy

Plans have been laid out to provide 100% of the world's energy needs through renewable energy sources alone (see, as examples, Renewables100 and The Solutions Project). But renewable energy resources may not always be located near where people live. The windiest or sunniest places may be far afield from cities and this requires building new transmission infrastructure. Another barrier to greater adoption of renewables is their intermittency

(i.e., when the sun doesn't shine or the wind doesn't blow, there's no electricity). To address this requires storage - either in batteries, fuel cells or some other way. We'll dive more into battery technologies a bit later in the course.

Nuclear energy Nuclear energy via atomic fission, while not a renewable energy source, has been proposed as a viable fossil fuel alternatives. It is a more steady source of energy than wind and solar, and can be used on existing electricity gids. It is relatively low-carbon

and produces little in the way of air pollution. A nuclear power plant can also produce as much or more electricity as a traditional coal fired power plant.

The primary barrier to great uptake of nuclear energy has been the concern around the safety of nuclear plants, radioactive waste and its disposal, and their cost. Most of the nuclear plants in operation around the world make use of systems that carry these problems. Newer types of nuclear plants may avert these problems, but their technology has largely not been proven and debates remain active about their affordability , and the availability of materials and skilled people needed to build and operate them

Transition to Renewables: Barriers and Opportunity

Given the extent of harm from fossil fuel use to health, one reasonable question to ask is: why hasn't a transition to renewables happened more quickly? The cost of producing electricity with renewables is increasingly not the reason.

As the graph below illustrates, the price of renewable energy has been falling sharply, particularly for solar energy. Renewable costs are now in line with the costs for electricity from fossil fuels in most countries. Note that these costs do not include health impacts of energy. If the health impacts of energy production were included, the costs of fossil fuels would be substantially higher.

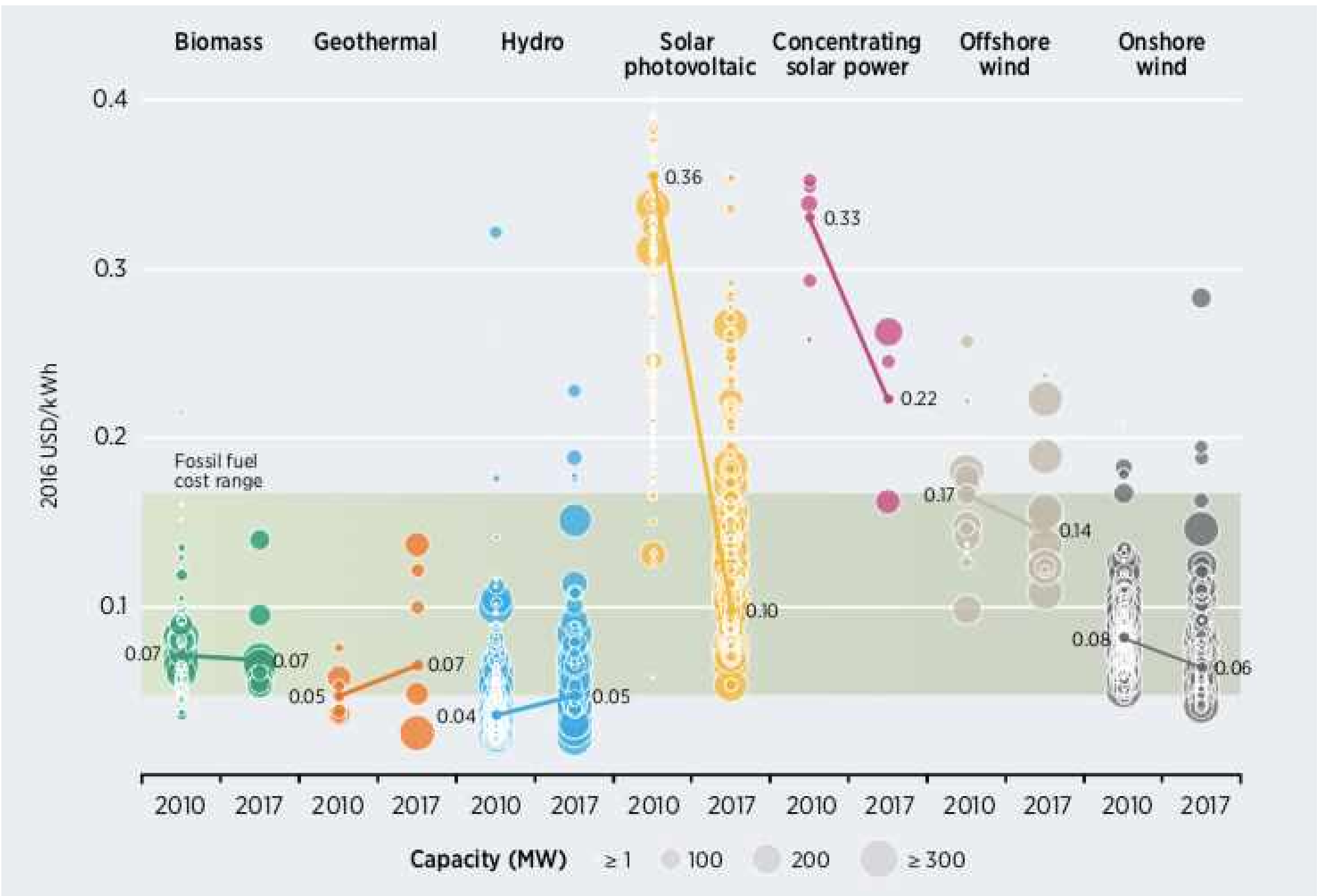


Image from Renewable Power Generation Costs in 2017 © IRENA 2017. Appears under terms of use. The diameter of each circle represents the energy produced, and its height represents the cost per kilowatt-hour. The lines for each segment show the change in cost between 2010 and 2017. The band near the bottom shows the range of fossil fuel generation costs.

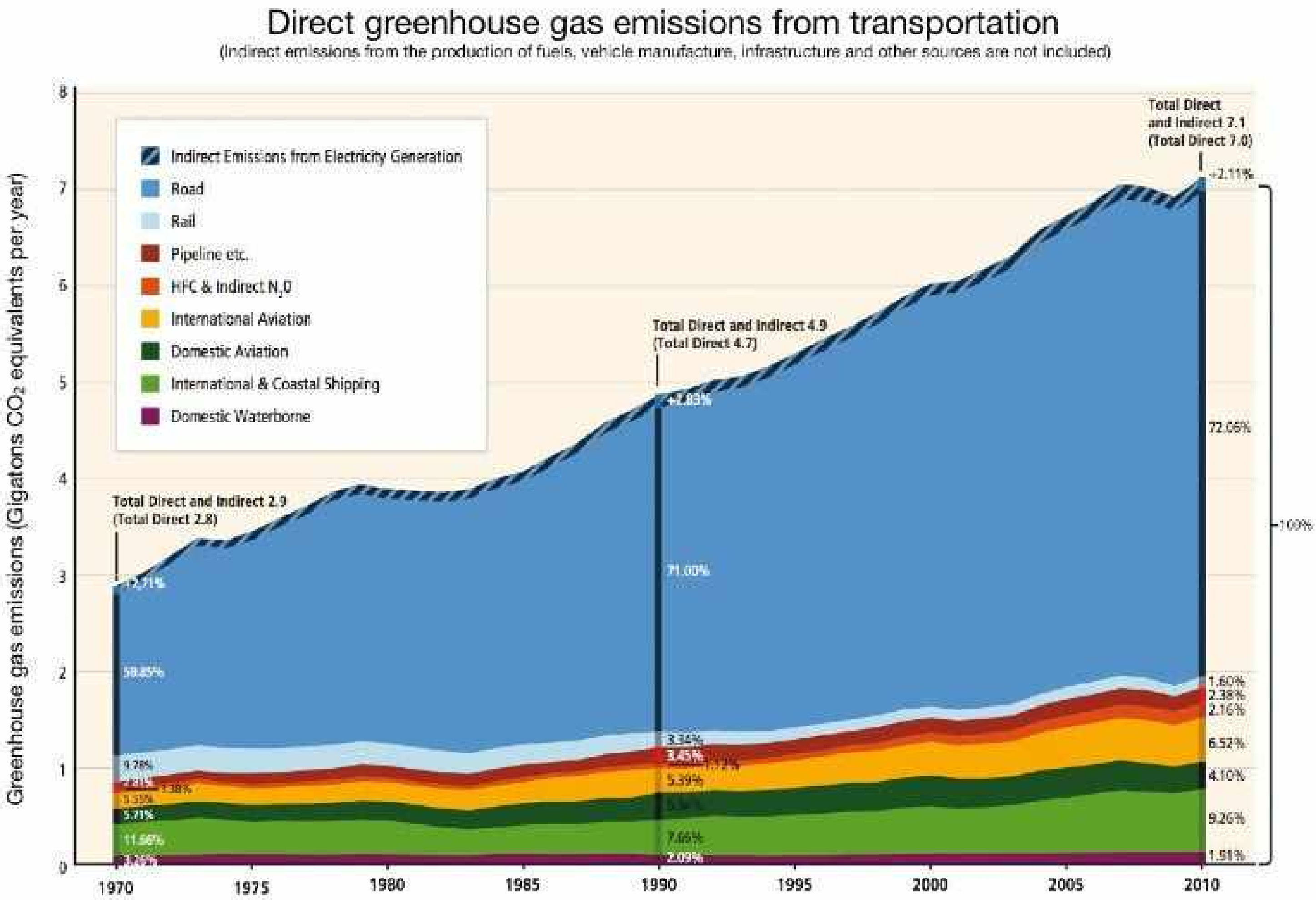
One of the obstacles to using more wind and solar power to produce electricity results from the intermittent availability of wind and sun. To overcome this requires battery storage. Current technology isn't quite ready to meet the needs of a world powered on intermittent renewables, but it's getting closer.

Michael Aziz: Aqueous Flow Batteries

In the next four videos, Harvard University Professor of Materials and Energy Technologies Michael Aziz discusses a promising new technology his group is working on: Aqueous Flow Batteries. Learn more about how this technology works, its benefits, and the ways Professor Aziz and his team are working to meet the challenges of cost and scale.

Progress in Transportation

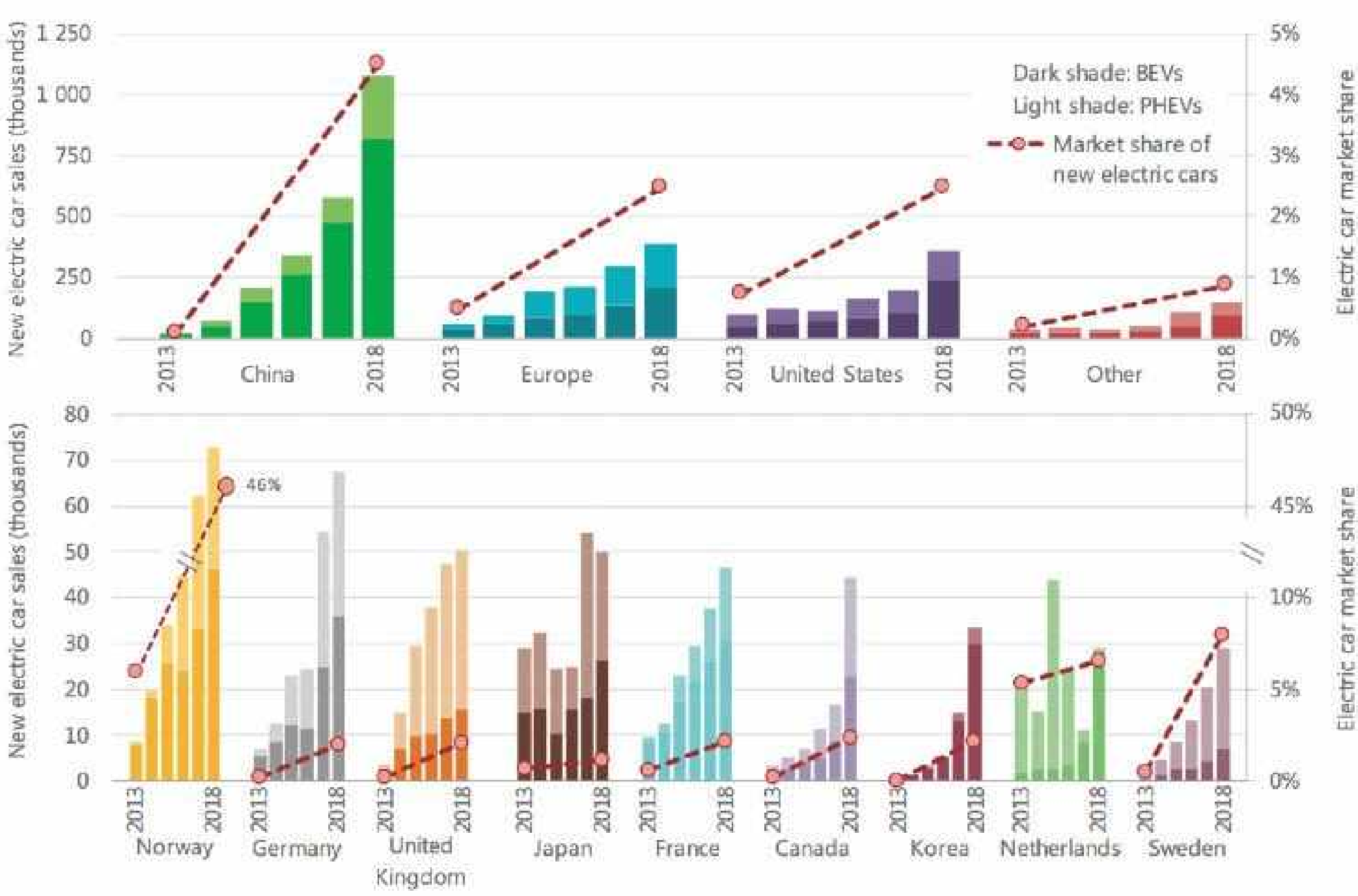
In 2010, the transportation sector accounted for 7 gigatons gigatons of carbon emissions.



Adapted from Sims R., R. Schaeffer, F. Creutzig, X. Cruz-Núñez, M. D'Agosto, D. Dimitriu, M.J. Figueroa Meza, L. Fulton, S. Kobayashi, O. Lah, A. McKinnon, P. Newman, M. Ouyang, J.J. Schauer, D. Sperling, and G. Tiwari, 2014: Transport. In: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Since then, we have made some progress. In recent years, electric cars, trucks and buses have become more available and every indication is that they will supplant vehicles which burn fossil fuels around the world.

Global electric car sales and market share, 2013-18



BEVs - battery electric vehicles; PHEVs - plug-in hybrid electric vehicles

Source: Global EV Outlook 2019, International Energy Agency

Source: Global EV Outlook 2019, International Energy Agency

Of course, a transition to electric vehicles will only reduce greenhouse gases and air pollution if the electricity used to power them comes from non-fossil sources. Providing enough electricity to power all these cars and trucks will require many batteries in the vehicles as well as utility scale batteries to store electricity as well. Today, lithium ion batteries are the leading technology for use in cars and other vehicles. Advancing this, and other battery technologies, as well as addressing concerns about battery waste through improved battery recycling will be essential to sustainable electric car deployment.

The growth in car and truck use around the world has led to more people spending more time sitting in vehicles and less time walking and bicycling. Studies in countries around the world, including the United Kingdom and Japan have suggested that how adults and children get to and from work and school can affect their risk of obesity. Use of active forms of transportation (e.g., walking or biking) or public transportation appears to prevent weight gain, whereas commuting by car promotes it.

Overweight and obesity, as you will recall from an earlier section of the course, affect about 1 in 5 children and 2 in 5 adults worldwide and exact heavy burdens on health. Better access to active and public transportation will likely help curb this growing threat to global health while at the same time reducing global greenhouse gas emissions.

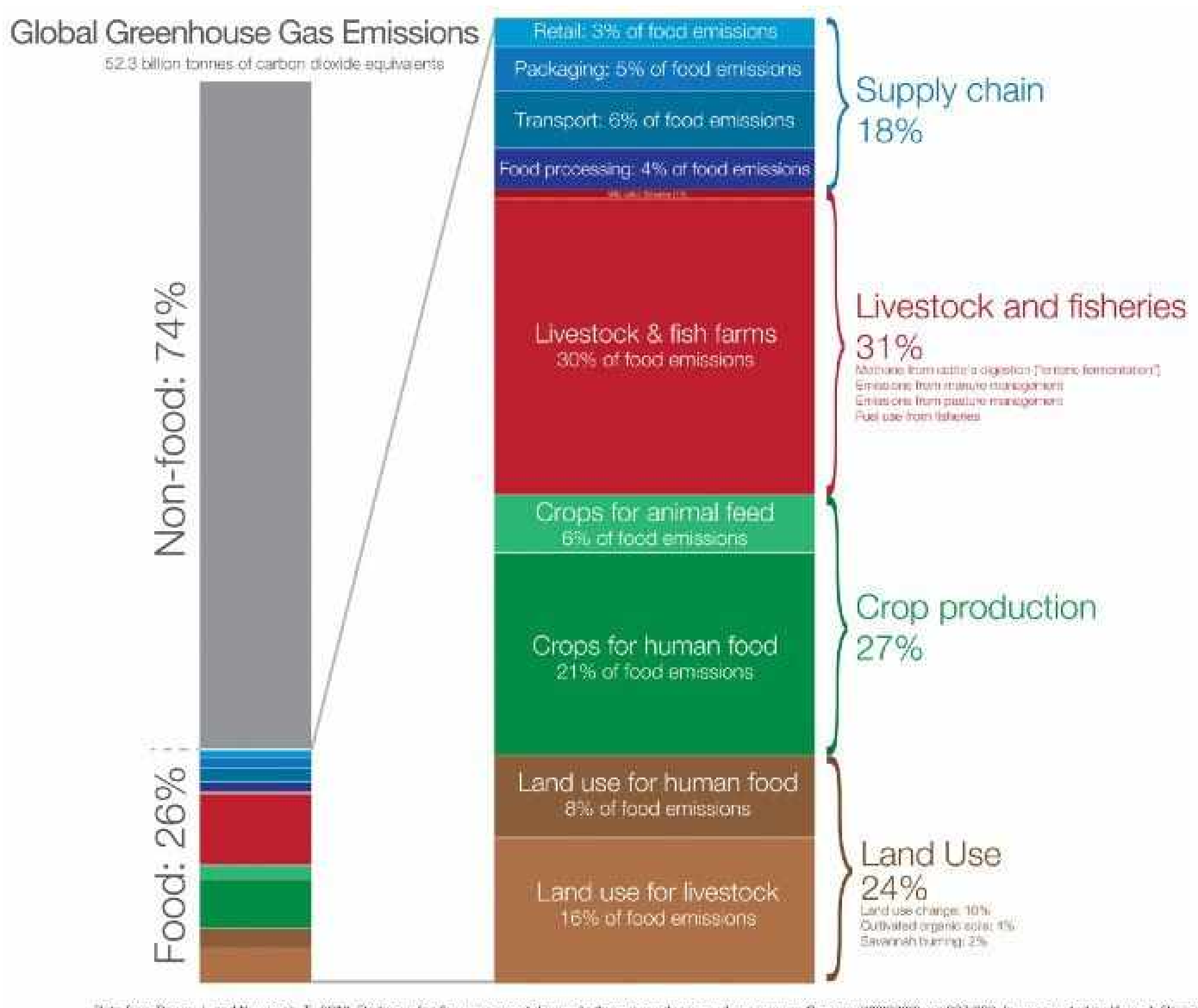
Airplane Travel and Cargo Ships

Aside from ground transportation vehicles, international air travel and maritime shipping represent the next two largest sources of greenhouse gases from transportation, both of which are anticipated to grow substantially in coming years. Solutions to aviation emissions will require using a carbon neutral or low carbon liquid fuel to replace current aviation fuel. No alternative fuel source meets the needs for cost, availability and performance needed by the aviation industry as yet.

Cargo ships have been fueled by waste oil, which is essentially what is left over after all other parts of crude oil are used and is some of the dirtiest fuel available. As of January 1, 2020, cargo ships are now required to switch to low-sulfur fuels, which will reduce their contributions to air pollution but may not curtail greenhouse gas emissions.

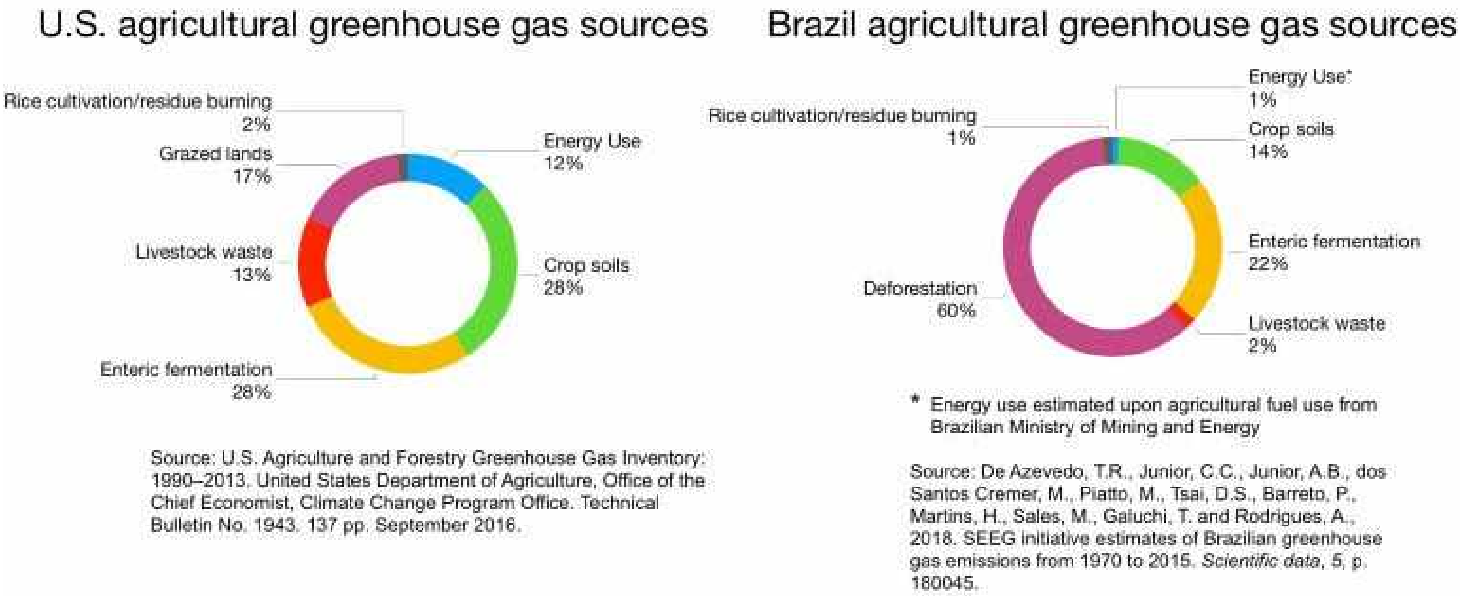
Emissions from Food Production

Worldwide, food production (which includes food production, processing, storage and distribution) accounts for about 20-30% of greenhouse gas emissions.



Data from Poore, J. and Nemecek, T., 2018 Reducing food's environmental impacts through producers and consumers. Science. 360(6392, pp 987-992. Image created by Hannah Ritchie.

The sources of these emissions vary substantially by country.



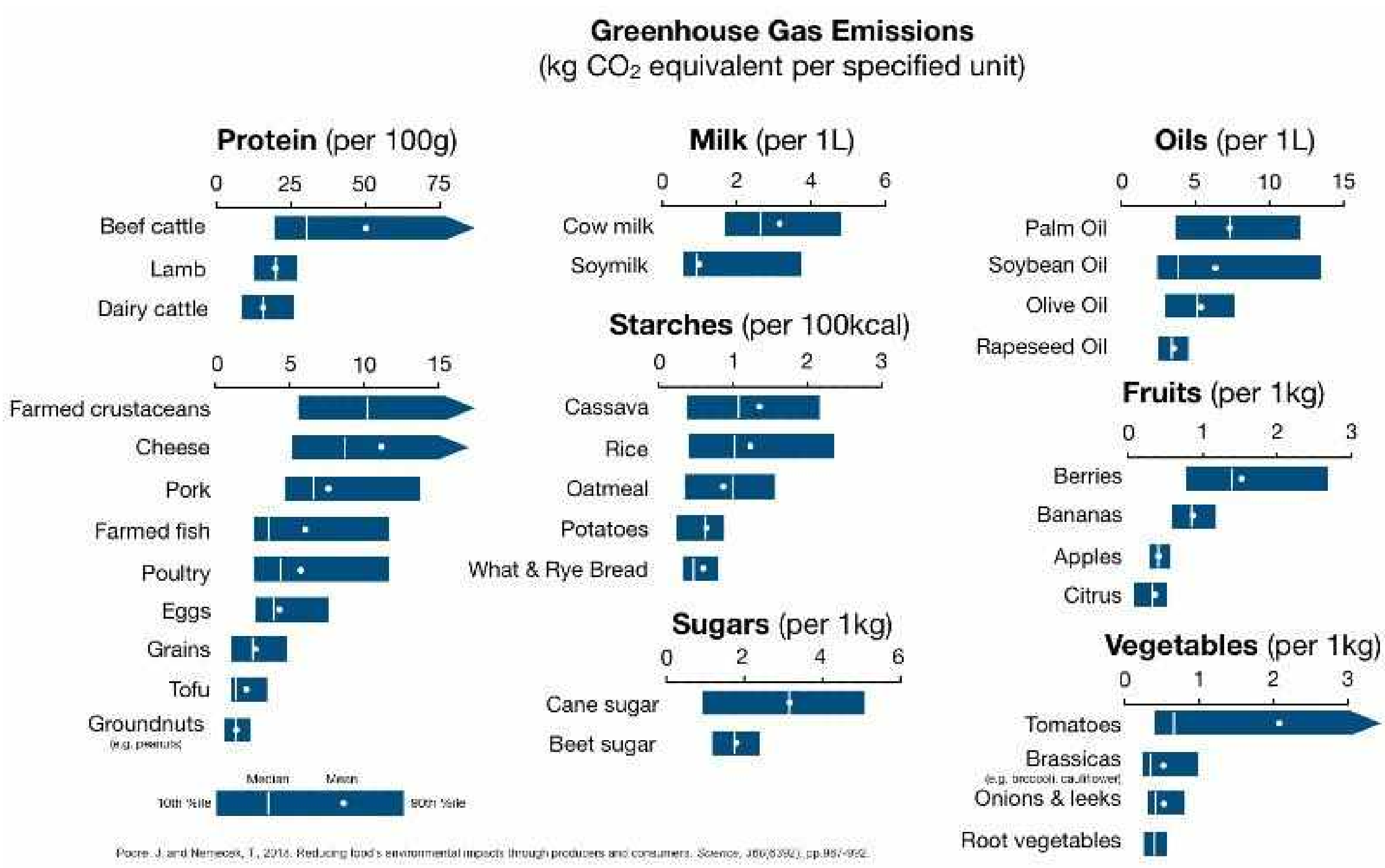
Source, Chart 1: U.S. Agriculture and Forestry Greenhouse Gas Inventory: 1990-2013. United States Department of Agriculture, Office of the Chief Economist, Climate Change Program Office. Technical Bulletin No. 1943.137 pp. September 2016. Source, Chart 2: De Azevedo, T.R., Junior, C.C., Junior, A.B., dos Santos Cremer, M., Piatto, M., Tsai, D.S., Barreto, P., Martins, H., Sales, M., Galuchi, T. and Rodrigues, A., 2018. SEEG initiative estimates of Brazilian greenhouse gas emissions from 1970 to 2015. Scientific data, 5, p. 180045.

In the United States, livestock produce the most greenhouse gas emissions. In many tropical countries, such as Brazil, deforestation accounts for the greatest share. What these figures don't include are the contributions of refrigeration and transportation, among other sources, to greenhouse gas emissions, which vary based upon the need to refrigerate goods and the distance from point of production to market and means of transportation, which is most often cargo ships and trucks.

Fossil fuels get used widely for the production of food. Natural gas is used to make fertilizer for most of the staple crops. Both liquid petroleum products and natural gas are used in herbicide and pesticide production. And farm equipment, including tractors, combine harvesters, and planters primarily run on liquid petroleum.

Decarbonizing Agriculture

Decarbonizing agriculture can come from a variety of strategies. Reducing demand for livestock (livestock grazing is a major driver of tropical deforestation) and beef in particular can make a difference.



Poore, J. and Nemecek, T., 2018. Reducing food, environmental impacts through producers and consumers. Science, 360(6392), pp. 7-992.

A look at the carbon intensity of a wide variety of foods shows that red meat production generates more carbon per unit protein produced than any other food source. Reducing red meat consumption can also reduce risk for a variety of diseases, including heart disease and cancer, as well as premature death from any cause.

Changing soil management practices to favor low or no-tillage and conservation agriculture practices also help as they allow carbon to be sequestered in the ground. Organic food production generally avoids the use of synthetic fertilizers, herbicides and pesticides, all of which use fossil fuels to manufacture. Addressing food waste, which we shall turn to next, provides a major opportunity to reduce carbon emissions and improve health.

Carbon Effects of Wasted Food

Enough food is grown on earth to feed 10 billion people. That's roughly 1.5 times as much as we need to feed all 7 billion people on earth. Globally, nearly 1/4 of all food calories produced never get eaten. Existing undernutrition and the addition of 2 billion people to the global population by mid-century would be reasons enough to drastically reduce wasted food.

Wasted food, however, also embodies a startling amount of greenhouse gas emissions.

If Food Loss were its Own Country (Billions of tons of CO2 emissions)

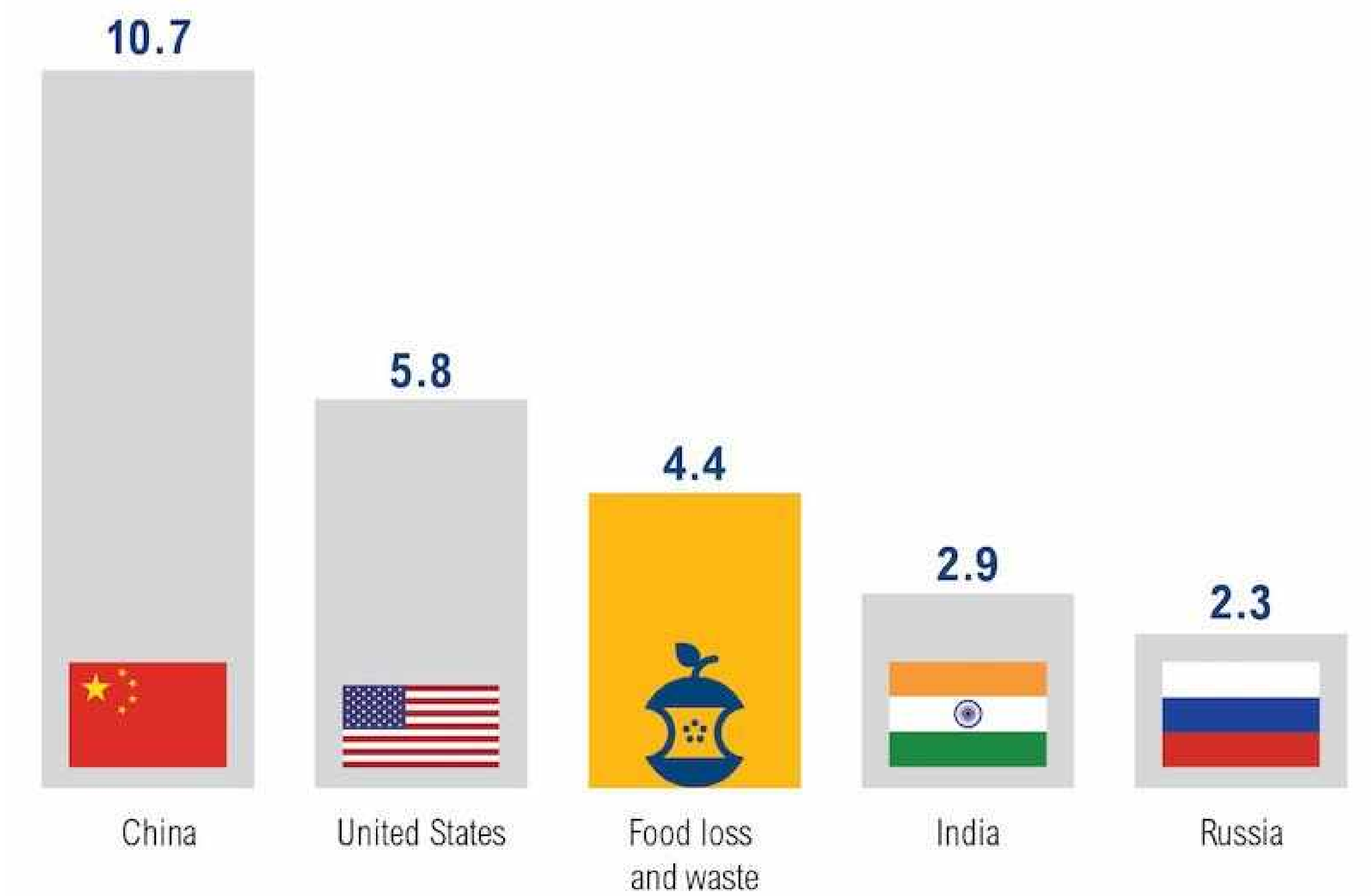


Figure from Can We Really Cut Food Waste in Half?, blog post at the World Resources Institute. Figures reflect all six anthropogenic greenhouse gas emissions, including land use, land-use change, and forestry. Country data is for 2012; food loss and waste data is for 2011. To avoid double-counting, the food loss and waste emissions figure should not be added to the country figures.

Water Effects of Wasted Food

Wasted food uses 45 trillion gallons of water, which is nearly 25% of all the water used for agriculture globally each year. The graph below identifies how much water is productively used for growing food and how much is wasted across the food supply chain. The figures are given in cubic meters of water per person per year.

Sources of Food Waste

The food supply chain can be broken down into food production, processing, distribution and market, handling and storage and consumption.

Food Waste Quantity and Sources

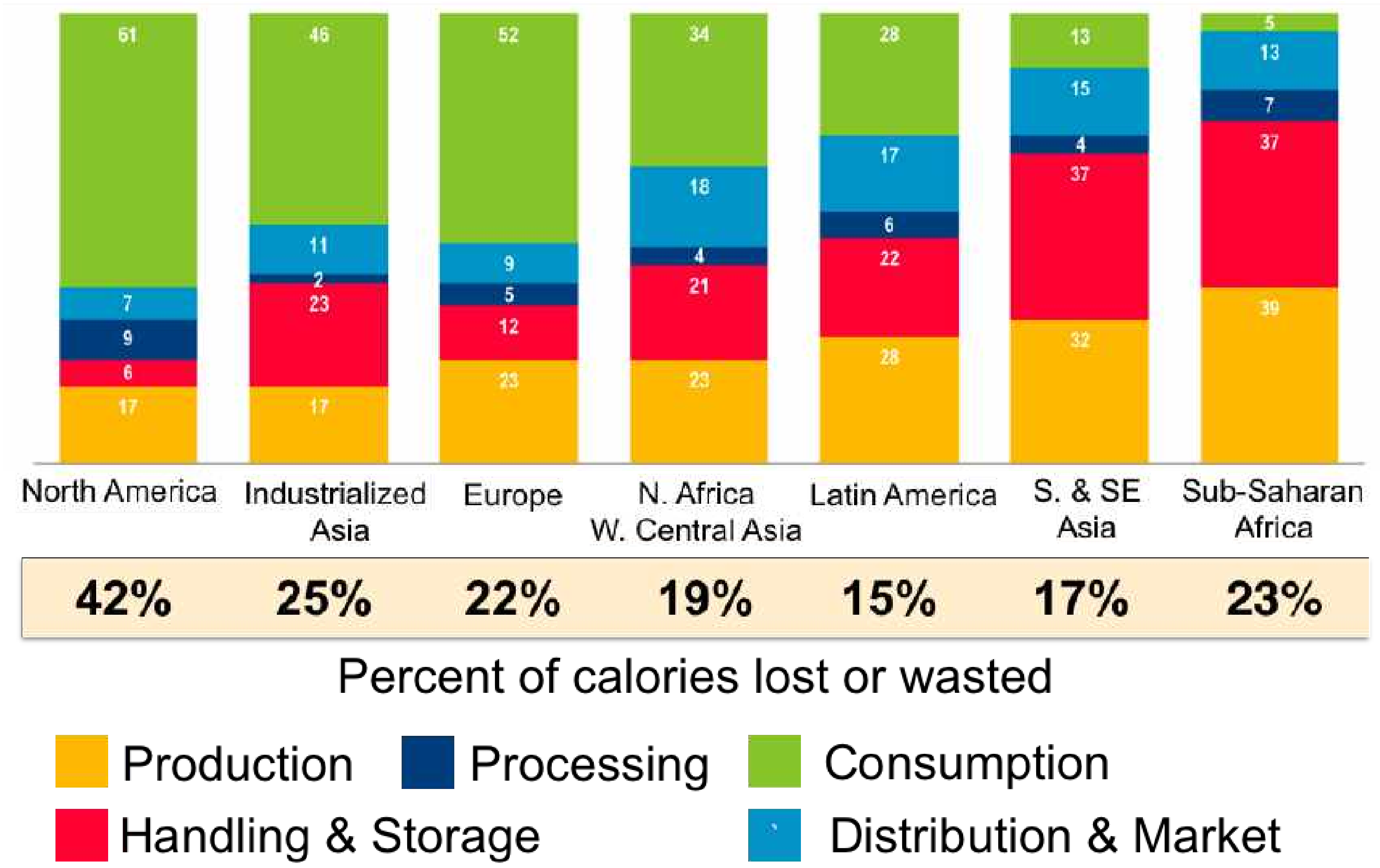


Figure adapted from Lipinski, B. et al. 2013. Reducing Food Loss and Waste , Working Paper, Installment 2 of Creating a Sustainable Food Future. Washington, DC: World Resources Institute. Available online at http://www.worldresourcesreport.org

The above figure demonstrates that wealthier nations tend to waste more food after harvest - in homes and restaurants, for example - whereas less developed nations lose more food on the farm and in storage and distribution before food ever reaches a consumer.

Prevention, recycling, and redistribution.

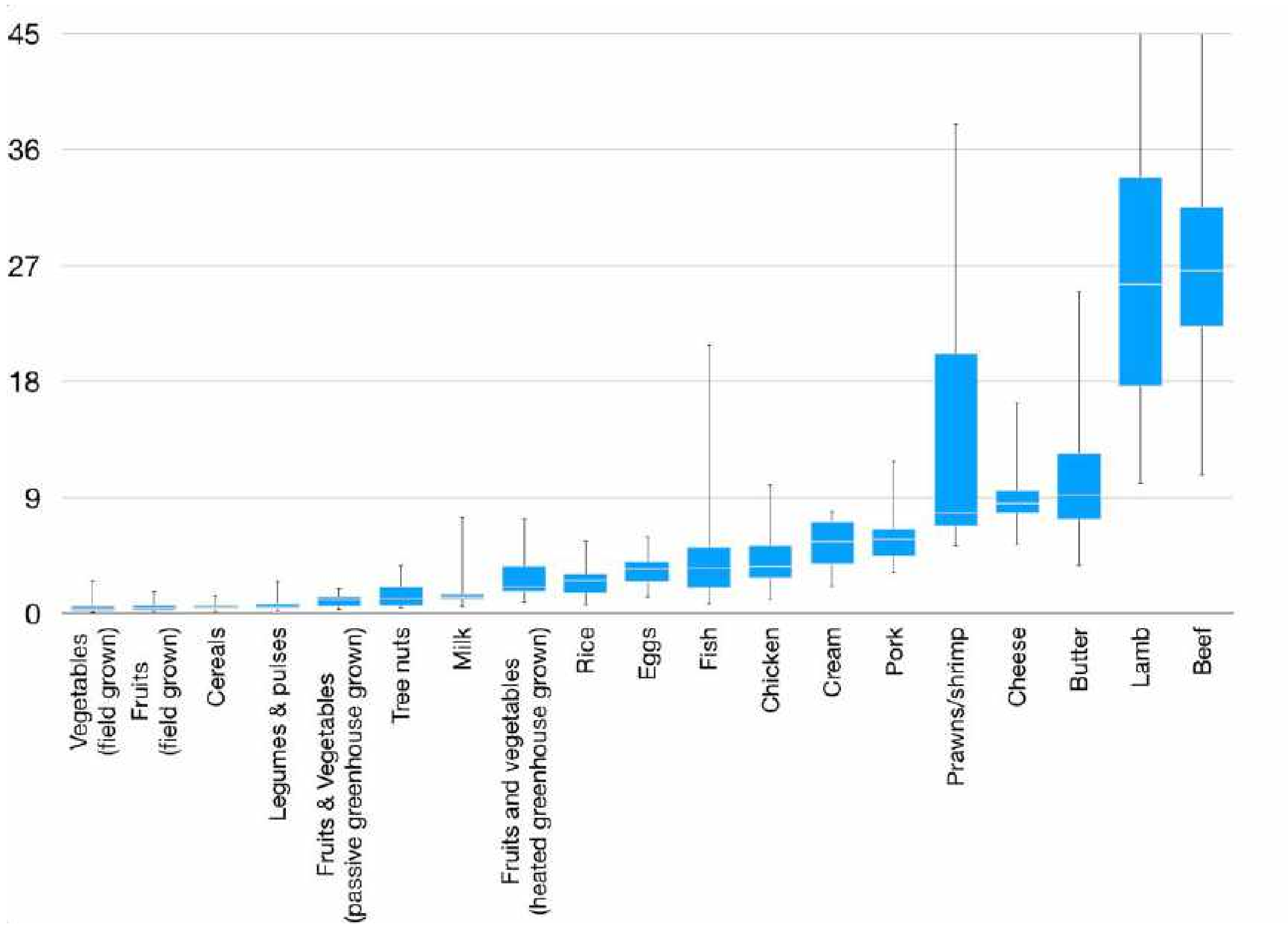
Reducing food waste can be achieved through prevention, redistribution, or recycling. Preventing food waste provides for the greatest overall financial, nutritional, water and other benefits but redistributing food and recycling food are also valuable and certainly better than food going to a landfill. Several organizations have established strategies to address food waste, including from ReFED , which focuses on food waste in the United States, and http://www.reducefoodwaste.eu/ , an official site of the European Union.

Diet and Agriculture

A look back at the diagram showing the sources of greenhouse gas emissions shows that forestry and agriculture account for about 20% of global greenhouse gas emissions.

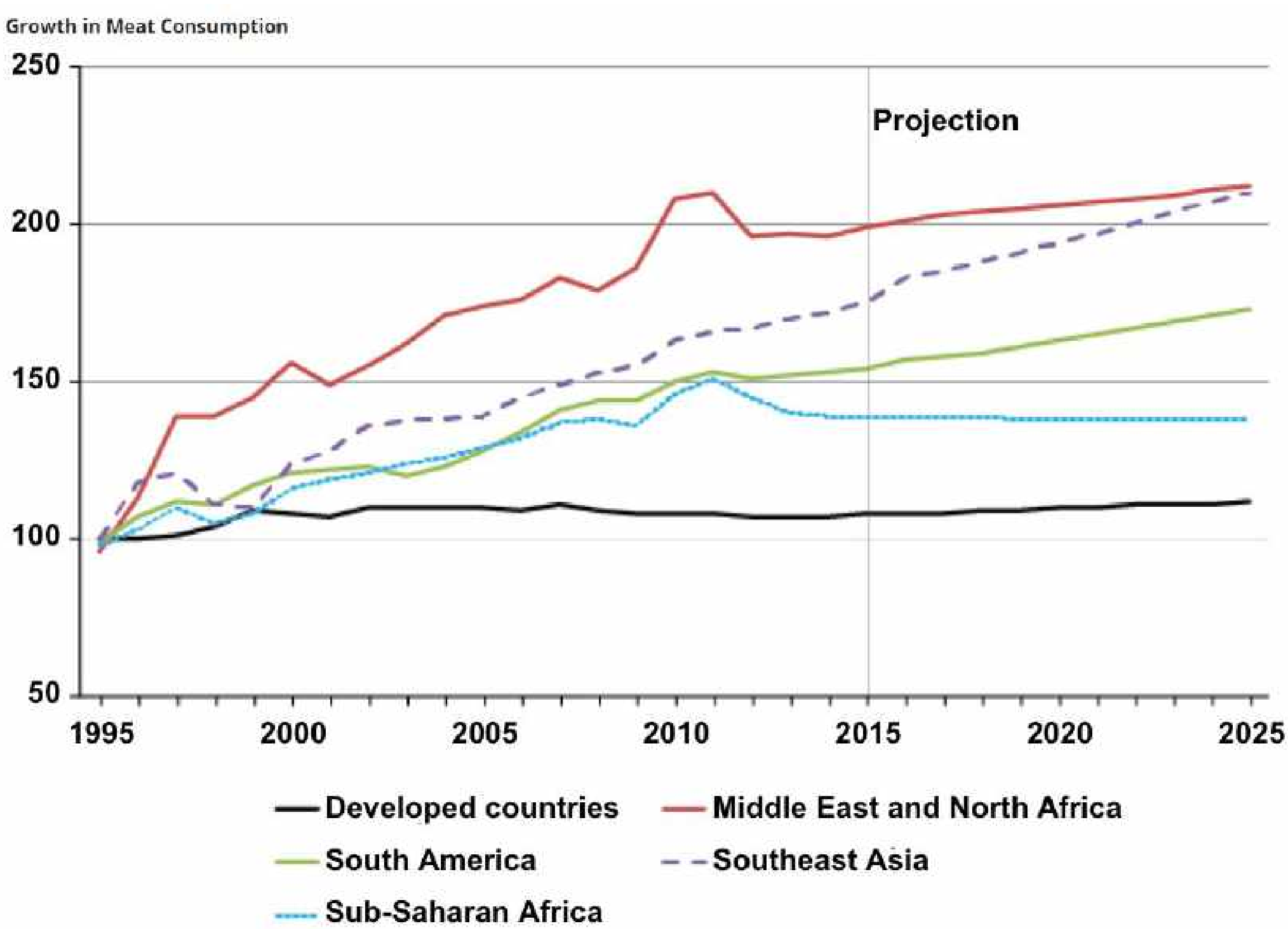
The share of greenhouse gas emissions associated with agriculture may grow considerably if people around the world start to consume more animal protein, and especially red meat, which carries the highest greenhouse gas emissions by weight.

Kilograms of CO2 eqiv. per kg of food produced



Graph by Harvard. Data from Systematic review of greenhouse gas emissions for different fresh food categories , Clune, Crossin, and Verghese. Journal of Cleaner Production Volume 140, Part 2, 1 January 2017, Pages 766-783. https://doi.org/10.1016/j.jclepro.2016.04.082 . Blue bars show the upper and lower quartiles; whiskers indicate the upper and lower values.

Projections indicated that as economies develop, particularly in east and southeast Asia, more meat consumption will come with it. Growth in Meat Consumption



Graph by Harvard. Data from USDA Economic Research Service: USDA Agricultural Projections to 2024 . Meat consumption in 1995 is normalized to 100.

More meat consumption poses problems for the climate, water resources, and pollution, but also directly for health. Eating meat, and especially red meat, has been associated with adverse health outcomes. Several studies have shown that those who eat red meat are more likely to die from a variety of conditions including cancer, heart disease, and stroke . Evidence indicates that processed meat, especially when meats are treated with nitrates, can be particularly harmful. The good news is that by reducing red meat consumption, and replacing that food with healthier choices such as fish, nuts, or legumes, can markedly reduce an individual's chance of premature death

Water Loss Across the Food Supply Chain

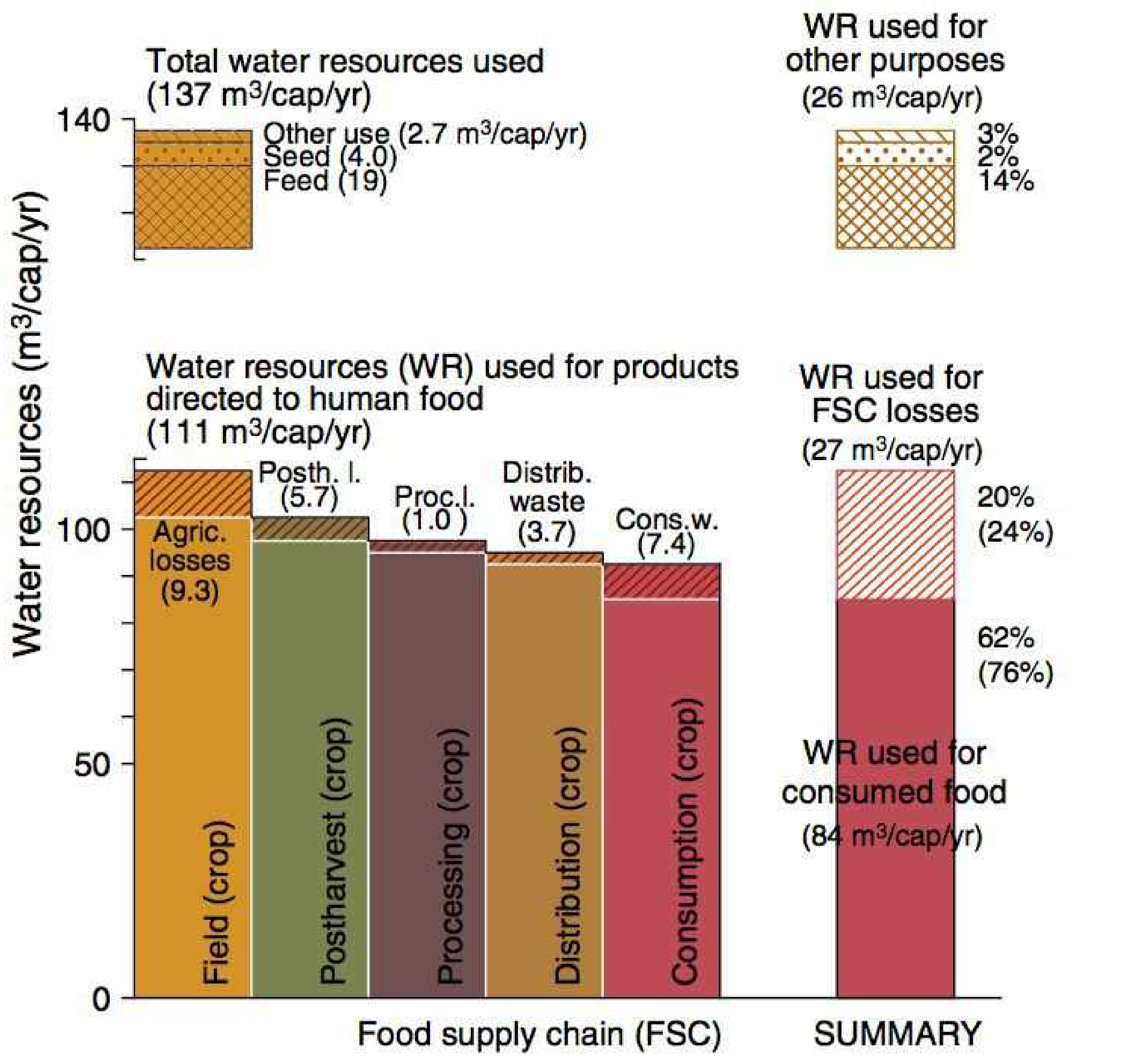
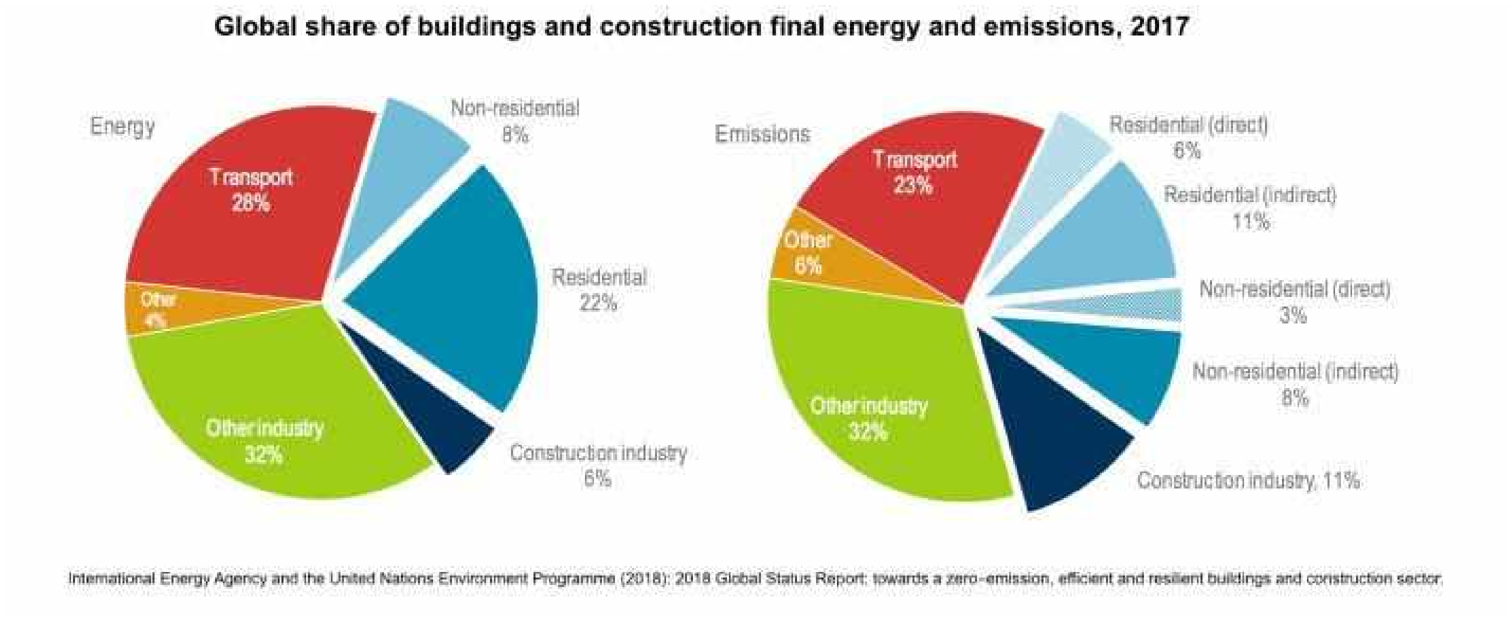


Figure from Lost food, wasted resources: Global food supply chain losses and their impacts on freshwater, cropland, and fertiliser use, M. Kummu et al, Science of The Total Environment Volume 438, 1 November 2012, Pages 477-489 https://doi.org/10.1016/j.scitotenv.2012.08.092

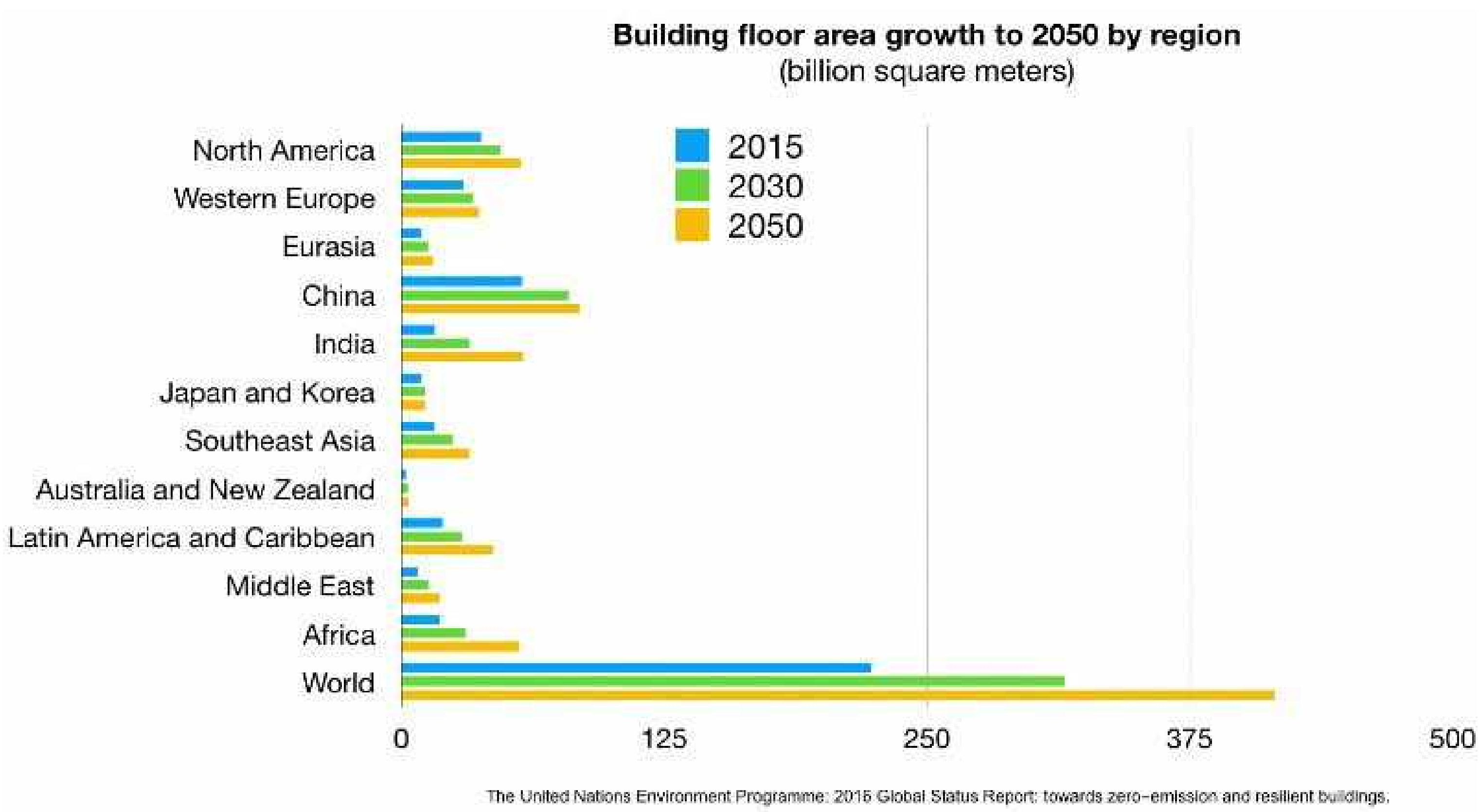
Emissions from Building and Construction

Buildings provide another lens to examine global carbon emissions.



International Energy Agency and the United Nations Environment Programme (2018): 2018 Global Status Report: towards a zero-emission, efficient and resilient buildings and construction sector.

All told, the construction and operation of buildings accounts for about one-third of global energy use and slightly more than one-third of global greenhouse gas emissions.



The United Nations Environment Programme: 2016 Global Status Report towards zero-emission and resilient buildings.

Over the next few decades, more than 350 billion square meters of new buildings are expected to be erected, roughly doubling the amount of building space on earth over 2010 .

Why Buildings?

Worldwide, buildings account for about 40% of all energy related carbon dioxide emissions . And, in the next 40 years an additional 230 billion square meters of buildings are expected to be built - that's the equivalent of building all of Paris every week! Given this, strategies to mitigate greenhouse gas emissions must include greater energy efficiency in new and existing buildings.

Green building standards

Given how much energy and electricity buildings consume, achieving carbon mitigation targets to prevent the worst of climate impacts on health has to address the building sector. Many programs have been established to incentivize better energy (and other resource) efficiency in buildings, such as LEED and BREEAM . These rating systems have been adopted in countries around the world, in many cases as a result of policies that require buildings to meet efficiency standards. When building construction is more efficient and building operation is more energy efficient, less fossil fuel is burned and this can yield health dividends from better air quality.

Health Benefits of Green Buildings

It's important to make the construction of green buildings enticing to developers. By articulating the health benefits—above and beyond the savings in water and electricity bills—we stand to make a difference in the pace of green building globally.

Bending the Curve

Our choices today have a dramatic impact on our health, both now and well into the future. No conversation about the solutions to climate change should ignore this. For example, air pollution, as you have learned, causes 1 in 9 deaths around the world each year, along with a host of other harms. Much of this pollution comes from burning fossil fuels for energy and wood on cookstoves, which means that lesser reliance on fossil fuels and greater use of cleaner cookstoves can prevent immense harm and also the release of greenhouse gas emissions.

Limiting further emissions of greenhouse gases can dramatically shift how much warming will occur over this century.

The graph below illustrates scenarios of the future under different greenhouse gas emission trajectories. These are called Representative Concentration Pathways, or RCPs, and each comes with a number (e.g., 2.6, 4.5, etc.) that describes the additional amount of energy that will be trapped in the atmosphere. The higher the number, the greater the amount of heat trapped. On the graph, the scenarios for the best case are shown in blue, with warming stopping at a particular date. Yellow, orange, and red show increasingly worse conditions for our globe, some of which continue to worsen even after 2100.

Representative Concentration Pathways (RCPs)

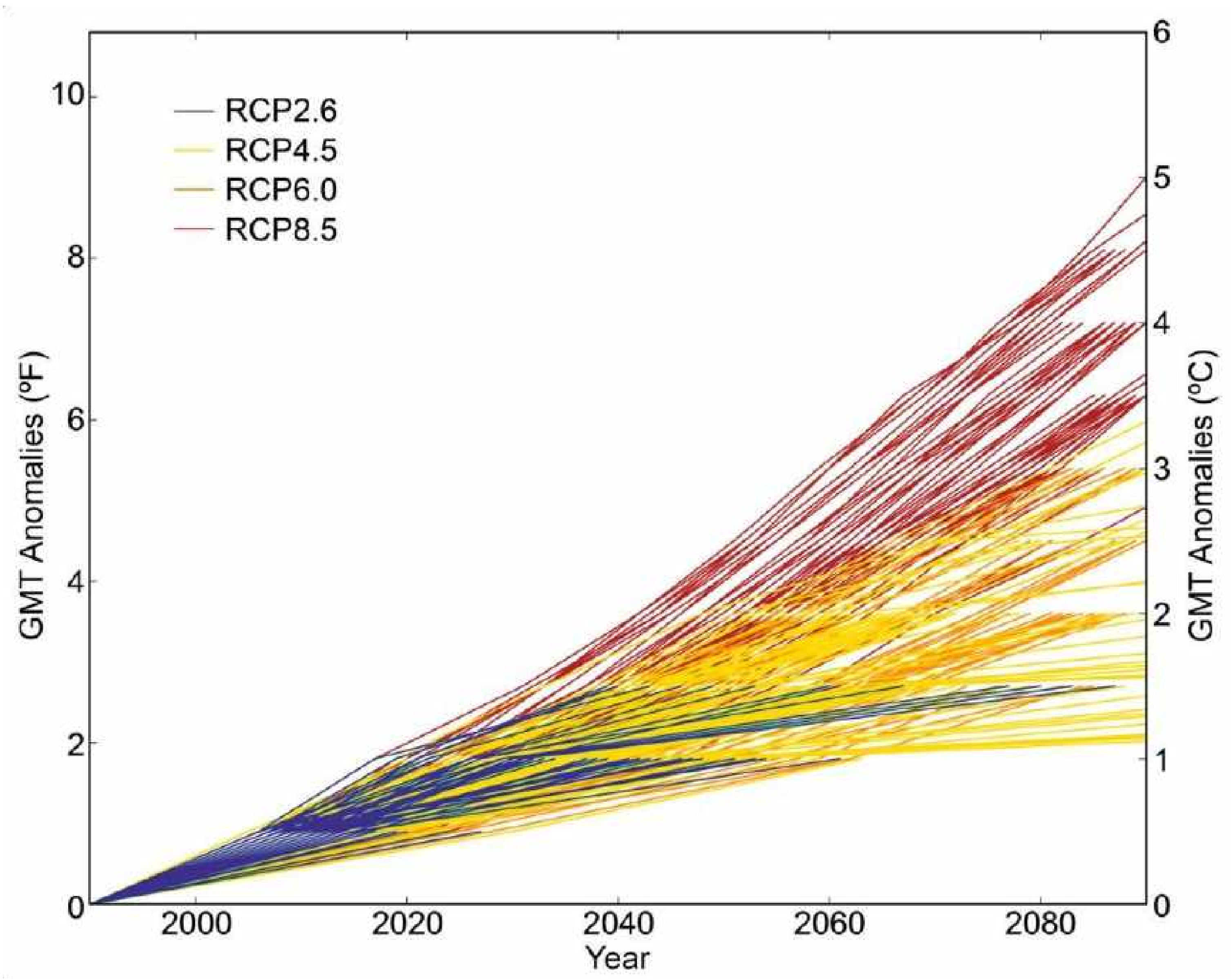


Image courtesy of US EPA. Colors shifted from the original to improve accessibility.

You can see that there is some uncertainty in each scenario - but not so much that we can't see where things are headed.

The pathways labeled RCP 2.6 lead to warming of around 1° C by 2100. However, RCP 8.5 scenarios come with warming of more than 4° C at the end of the century. The trajectory we follow depends on the actions we take today to reduce greenhouse gas emissions - our actions can bend the warming curve down.

No one is immune from the effects of climate change, and that means everyone has a stake in addressing it. In this section of the course we'll hear from people working in different sectors of society who are working to address the causes and consequences of climate change. You'll learn about how each sector has unique opportunities to find solutions and how those solutions are taking shape. You'll also learn how actions that prevent greenhouse gas emissions may provide perhaps unprecedented health gains.

Overview

In this final chapter, we examine the responses to climate change. In particular, we'll talk about the roles of various institutions, including adademic teaching and research, investment banks, and cities.

The Role of Academic Institutions

As primary sources of education, schools for people of all ages clearly matter to having an educated population capable of understanding the problem of climate change and what's needed to address it. But the important lessons about climate change differ based upon the age of the learner.

Schools also have the opportunity to research and demonstrate to students the actions needed to combat climate change.

Learning

Knowing the facts about climate change is important when it comes to fixing it, and schools can provide this knowledge to students. Learning about climate change traditionally has meant learning about climate science and evidence that points to specific impacts on economies, environments and health, to name a few, as well as potential solutions such as alternative energy sources and strategies to combat deforestation.

However, effectively combatting climate change requires more than just knowledge of facts from these disciplines. With all that's known about the causes and consequences of climate change, as well as viable solutions to reduce greenhouse gas emissions, much more might have been done to prevent further greenhouse gas emissions. Reasons for inaction are many but include biases in how we think as well as cultural norms . And this means that learning about climate change and how to fix it ought to include learning about psychology, sociology, and anthropology.

Research

Higher education institutions also conduct research that can illuminate aspects of climate change. What is the most accurate climate sensitivity ? How much will carbon policies influence health ? Can carbon capture and storage technologies contribute to decarbonization? And if all else fails, can we engineer our climate to protect life on earth? Answers to these questions are vital for us to make the best choices we can. Funding to pursue climate research by the U.S. Government was just over $2 billion in the mid 1990's. It's roughly the same today. Of that amount, almost none supports research on climate change and health outcomes. The National Institutes of Health spends roughly 0.05% of its total budget of $37.3 billion on climate-change-related health research.

Partnerships

By finding new ways to partner with public and private sector organizations, academic institutions can accelerate the movement of knowledge generated within themselves to the rest of society.

Schools as Living Laboratories

Schools can not only teach their students about climate change, and do research about climate change, they can be test beds for how to decarbonize.

Mitigation Plans

When it comes to reducing greenhouse gas emissions, academic institutions have the opportunity to research and educate about the potential of mitigation to improve health outcomes. They also have an opportunity to demonstrate how to reduce emissions through their own actions, which can provide a powerful example of what is possible.

In this clip, Heather Henriksen describes Harvard University's plans to decarbonize its campus. A more complete description of the University's Climate Action Plan is available here

Private Sector Decarbonization

The private sector has increasingly embraced its role in decarbonization through operational greenhouse gas reductions. Sometimes this comes through improved energy efficiency; sometimes it is reflected in their products. John Mandyck of United Technologies joins us to discuss his company's work in this area.

Corporate Partnerships

Large groups of corporations have come together to commit to transitioning their business operations to 100% renewable energy. Their actions continue to drive investments in renewable energy sources. In 2017, these companies sourced enough renewable energy to supply the entire nation of Chile's energy needs.

Environmental Regulation and Market Trends

The private sector responds to laws - or even the *prospect* of laws - that will affect business. However, as you'll see in this clip, moving towards lower-carbon products has become a market signal that can't easily be ignored.

Why Cities?

Cities are where governments are in closest touch with residents. This makes them potentially more accountable to their citizens' needs. As Austin Blackmon will make clear, cities are also the epicenters of climate change impacts and solutions. Most people live in cities already and even more people will live in cities in coming decades . The effects of floods and heat are felt particularly strongly in cities both because of their population sizes and because urban environments promote heat exposure (as you've learned) and are prone to floods because so much of urban landscapes is impervious to water and stormwater sewer systems have limited capacities.

Boston as a Case Study

Boston is a good case study to understand the vulnerabilities of coastal cities to the effects of climate change. In the next video, Austin discusses these vulnerabilities and the ways in which Boston has begun to work towards greater resilience to extreme weather, especially events driven by climate change.

Coalitions of Cities

Cities have recognized their shared lot. Several collaborative organizations have emerged, such as C40 , Climate Mayors , and Urban Sustainability Directors Network, to enable cities to learn from each other about the best ways to mitigate emissions and prepare for climate change.

Reducing Global Emissions

Cities account for about 2/3 of global energy consumption and 70% of greenhouse gas emissions. As such, their actions to address climate change can go a long way to reduce global emissions.

Healthcare and Communication

Austin Blackmon provides some thoughts on what the healthcare sector and health researchers can do to advance climate progress in cities.

Development Banks

Preparing for climate change takes a lot of money. Estimates about the amount of financial resources required to assist climate change adaptation vary widely, from $30 to $300 billion annually by 2050. Where will all that money come from?

Developed countries have given money to so-called development banks for the purposes of providing financial support for projects that will aid their economic development. Increasingly, these banks have been concerned with climate change. The World Bank, as an example, has taken steps to address the risks that climate change poses because it may unravel the progress in development they have invested in.

Choices for how to invest funds for development that can also bolster resilience to climate change can be difficult. But as Paul Farmer describes in the video below, focusing on investments that improve education and opportunity are critical to advancing other development goals.

Targeting Resources

The resources that development banks deploy are substantial and are particularly important for low and middle income countries where climate impacts may be greatest. Below, Timothy Bouley presents an overview of how health considerations drive investments.

Making sound investments requires knowledge about their potential to do good and the risks that come with them. In the video below, Timothy Bouley discusses the role that new research can have in helping to shape future investments.

Madagascar and the World Bank

As an example of how development banks can work with a low income country to better equip it for climate impacts, let's hear about the partnership between Madagascar and the World Bank that Dr. Bouley describes.

Green Bonds

At the same time as development banks directly invest in national infrastructure to spur development, they also innovate ways to incentivize more sustainable investments. Among these innovations, green bonds have emerged as a major force in global finance.

Climate Finance Links

Several funds have been specifically established to provide money to support climate mitigation and adaptation. They include the Green Climate Fund , which has the goal of raising $100 billion each year, though contributions to it have fallen far short of this goal. Climate finance, which describes funds earmarked for climate change related investments, has totalled around $400 billion dollars in recent years.

Non-Governmental Organizations (NGOs)

Preparing for climate change requires more than just money. It requires people and organizations to deliver aid when and where it's needed. Particularly in low and middle income nations, where governmental resources to deal with disasters may be limited, NGOs have been critical to preventing harm.

Migrants in Conflict Areas

You will recall from the section of the course on population migration that the final common pathway of climate change effects on humanity is to force people to move from their homes, as a result of sea level rise, droughts, floods, food insecurity or other forces. It can be difficult to provide aid to distressed migrants. Even more challenging, as Maarten van Aalst details, can be reaching distressed migrants in conflict zones. In this clip, he also makes clear that governments for the most vulnerable may be least able to access aid funds.

Acting Before Disasters

International aid organizations have traditionally been known for providing assistance after disasters. More recently, however, the benefits of acting before disaster strikes have motivated innovative strategies to prepare for extreme weather events.

Forecast-based Financing

Forecast based financing , in which financial resources are disbursed in advance of a possible disaster, has become an attractive prospect to limit damages from extreme weather. As you have heard, to do this well requires accurate and timely forecasts as well as a coordinated partnership between forecasters, aid agencies and governments.

Forecasting Epidemics

The prospects for forecast-based financing extend beyond natural disasters to infectious epidemics as Maarten van Aaslt describes here.

Knowledge and Skills

To improve the ability of organizations like the Red Cross to meet the growing demands of climate change-related disasters will require more resources - both financial and people - as well as knowledge. In the following clip, listen to the kinds of knowledge and skills that Maarten van Aalst describes as valuable to the Red Cross' work on climate preparedness.

Our Shared Planet and Future

This course has hopefully made clear what is at stake for our health with climate change. Based upon what you've learned, you can now trace pathways from greenhouse gas emissions to specific health outcomes and populations at risk. We encourage you to return to the Climate Impact Explorer to refresh your knowledge or explore the connections between course topics.

You've also seen that much more needs to be learned about how climate affects health: not just about what health risks may grow, and how we can predict them, but also about how we may benefit when we act to curtail greenhouse gas emissions.

The near term and local (if not personal) health benefits of actions to decarbonize energy systems, transportation systems, buildings, and diets make climate change mitigation an unprecedented opportunity. We have the chance to improve health for everyone, and in particular, for vulnerable populations in developed and developing nations alike. We hope that in this course you've seen opportunities both for yourself and others, and that you've started to recognize health as the human face of climate change.