FIELD FACTS

The Greenhouse Effect and Greenhouse Gases

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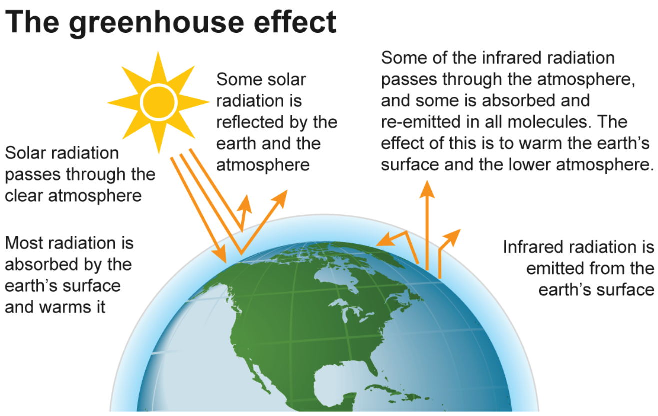
Key Points

- Human activities have increased the concentration of several greenhouse gases in the atmosphere, which has amplified Earth's greenhouse effect and elevated global mean temperature by around 1.8 °F.
- Carbon dioxide is the most important anthropogenic greenhouse gas – it comprises the largest proportion of emissions from human activity and is the largest contributor to global warming.
- Methane and nitrous oxide are more powerful greenhouse gases but are emitted in smaller quantities than carbon dioxide.
- Carbon dioxide, methane, and nitrous oxide all cycle in and out of the atmosphere through natural processes but human emissions have altered the balance of these cycles, leading to buildup in the atmosphere.
- Transportation and electricity generation are the largest sources of greenhouse gases, accounting for over half of total emissions, with agriculture accounting for around 10%.

What are Greenhouse Gases?

A greenhouse gas is a gas with a molecular structure that causes it to absorb and emit infrared radiation. When incoming radiant energy from the sun is absorbed by the Earth's surface and re-emitted as infrared energy, greenhouse gases in the atmosphere prevent some of this heat from escaping into space, instead reflecting the energy back to further warm the surface creating an insulating effect from the cold of space (Figure 1).



This heat-trapping phenomenon is known as the greenhouse effect and is essential for life on Earth. Without any greenhouse effect at all, Earth would be uninhabitable – global mean surface temperature would be around 5 °F (-15 °C) rather than the current average of 59 °F (15 °C). The strength of the greenhouse effect is determined by the concentration of greenhouse gases in the atmosphere. Consequently, any process that significantly changes the concentration of these gases – be it natural or human-caused – will alter the energy balance between incoming solar radiation and the heat released back into space, resulting in a change to Earth's temperature.

Paleoclimatology records show that, over the vast timescales of Earth's history, greenhouse gas concentrations have varied considerably and, along with several other important factors, have caused dramatic changes in Earth's temperature and climate. However, the beginning of the industrial era marked the first time in human history in which population growth and technological innovation made it possible for humans to significantly alter the composition of the atmosphere. Industrial activities carried out on a global scale have increased, and continue to increase, the concentration of several greenhouse gases in the atmosphere; the result of which has been an amplification of the greenhouse effect that has raised global mean temperature by around 1.8 °F since the late 19th Century.

Greenhouse Gases Differ in Strength

Greenhouse gases produced through human activities include carbon dioxide, methane, nitrous oxide and fluorinated gases. Carbon dioxide, methane, and nitrous oxide all have natural sources as well, while fluorinated gases come exclusively from human activity. The overall contribution of each of these gases to climate forcing depends on their inherent heat-trapping efficiency (referred to as *global warming potential*), abundance, and residence time in the atmosphere (Table 1).

Global warming potential of greenhouse gases is expressed as an index relative to CO_2. For example, the global warming potential of methane is 25, meaning it has 25 times the heat trapping efficiency as CO_2. Nitrous oxide is an even more power greenhouse gas with a global warming potential of 298 and fluorinated gases are extremely powerful. When discussing emissions of greenhouse gases other than CO_2, quantities are often expressed in terms of their equivalency to CO_2 (CO_2e).

Table 1. Greenhouse gas emissions from human activity: global warming potential and percent of total (U.S. EPA, 2019).

Greenhouse Gas	Global Warming Potential*	Percent of U.S. GHG Emissions
Carbon dioxide (CO_2)	1	81%
Methane (CH_4)	25	10%
Nitrous Oxide (N_2O)	298	6%
Fluorinated gases	7,390-22,800	3%

[1] A measure of how much energy the emissions of 1 ton of a gas will absorb over 100 years, relative to the emissions of 1 ton of carbon dioxide (CO_2).

Much of the concern around greenhouse gas emissions has focused on CO_2. It has a relatively low global warming potential relative to other greenhouse gases but comprises by far the largest proportion of emissions from human activity and is the largest contributor to overall climate forcing (Figure 1). In contrast, the fluorinated gases are far more powerful greenhouse gases but comprise a relatively small proportion of emissions and consequently have a smaller contributing effect to climate forcing (Figure 2).

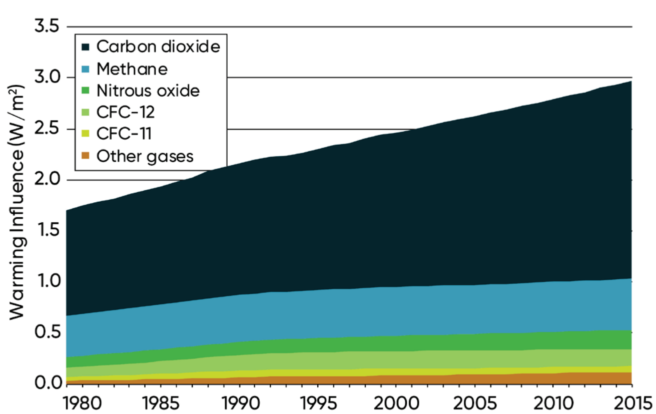


Figure 2. Radiative forcing caused by major long-lived greenhouse gases produced by human activity, 1979-2015 (NOAA, 2021).

Carbon Dioxide Emissions

Human CO_2 emissions are primarily a product of the burning of fossil fuels for electricity generation, transportation, and industry but are also produced by deforestation and land use change. Carbon dioxide is naturally present in the atmosphere as a part of the Earth's carbon cycle and is essential for plant life. In fact, carbon flux from human activity is relatively small compared to the carbon flux associated with natural processes such as photosynthesis and respiration (Figure 3). However, carbon dioxide emissions constitute a persistent shift in the balance of the Earth's carbon cycle, pulling billions of tons of carbon stored in the Earth's crust and putting it into the atmosphere on an ongoing basis and causing atmospheric CO_2 concentrations to rise.

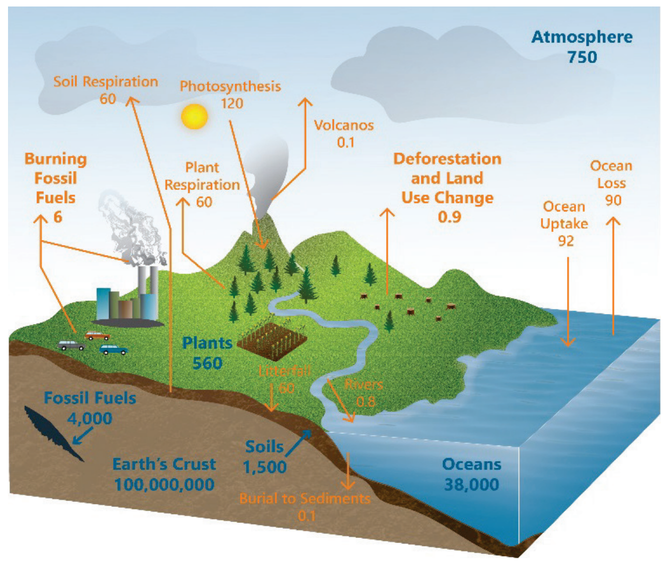


Figure 3. Global carbon cycle diagram showing carbon pools (blue text) and annual carbon fluxes (orange text) measured in petagrams. (Source Univ. of New Hampshire GLOBE Carbon Cycle, http://globecarboncycle.unh.edu)

Global carbon dioxide emissions currently exceed 35 billion metric tons per year and are primarily the result of fossil fuel burning (coal, oil, and natural gas), cement production, and gas flaring (Figure 4).

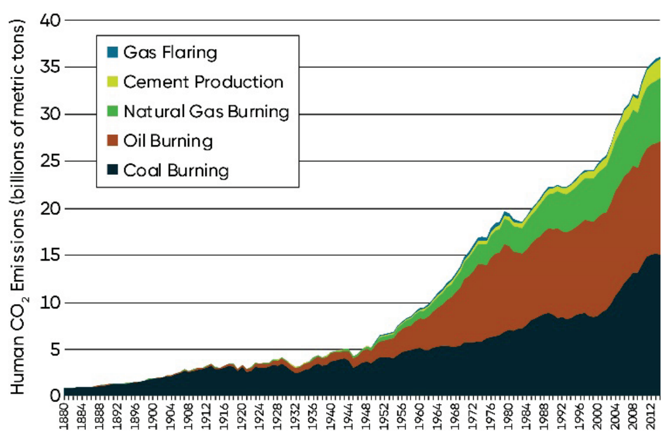


Figure 4. Global CO_2 emissions from fossil fuel burning, cement production and gas flaring, 1880-2014. (Source: Carbon Dioxide Information Analysis Center)

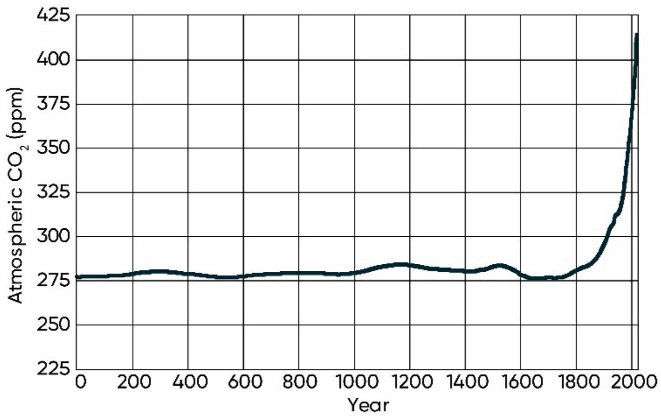


Figure 5. Atmospheric CO_2 concentration over the past 2000 years based on ice core data (before 1958), and direct measurements taken at Mauna Loa and the South Pole (1958-present) (Keeling et al., 2001; MacFarling Meure et al., 2006).

The concentration of carbon dioxide in the atmosphere naturally cycles over extremely long time scales as the Earth cycles between ice ages and interglacial periods; however, emissions from fossil fuel burning over the past 150 years or so have dramatically increased the amount of CO_2 in the atmosphere in an extremely short period of time relative to changes driven by natural factors (Figure 5).

A combination of direct measurements and ice core data allow us to track the concentration of CO_2 in the atmosphere over a long period of time. For most of the past 2000 years, CO_2 levels were relatively stable, fluctuating in a range between 275 and 285 ppm until the mid-1800s when emissions from human activity began driving atmospheric CO_2 upward. Atmospheric CO_2 reached 300 ppm in 1912, 350 ppm in 1988, and 400 ppm in 2015. In fact, over the course of the past 800,000 years for which we have a reliable ice core record, atmospheric CO_2 never exceeded 300 ppm until the 20th Century, making our current state unprecedented in human history (Lüthi et al., 2008).

Methane Emissions

Methane (CH_4) is a considerably more powerful greenhouse gas than CO_2, with a 25x greater heat-trapping capacity. Like CO_2, methane is a naturally occurring gas and cycles in to and out of the atmosphere via a number of different natural processes. The largest natural source of methane is wetlands, where certain types of microorganisms produce methane as a byproduct of metabolic reactions carried out in anaerobic environments.

As with CO_2, human activity has altered the balance of the global methane cycle, with total inputs of methane into the atmosphere exceeding removal by approximately 18.2 Tg per year (Figure 6). This has resulted in an increase in atmospheric methane levels. The concentration of methane in the atmosphere has more than doubled from a pre-industrial level of 722 ppb to 1892 ppb in 2020 (Dlugokencky, 2021).

The largest anthropogenic source of methane emissions is livestock production, with methane emitted via enteric

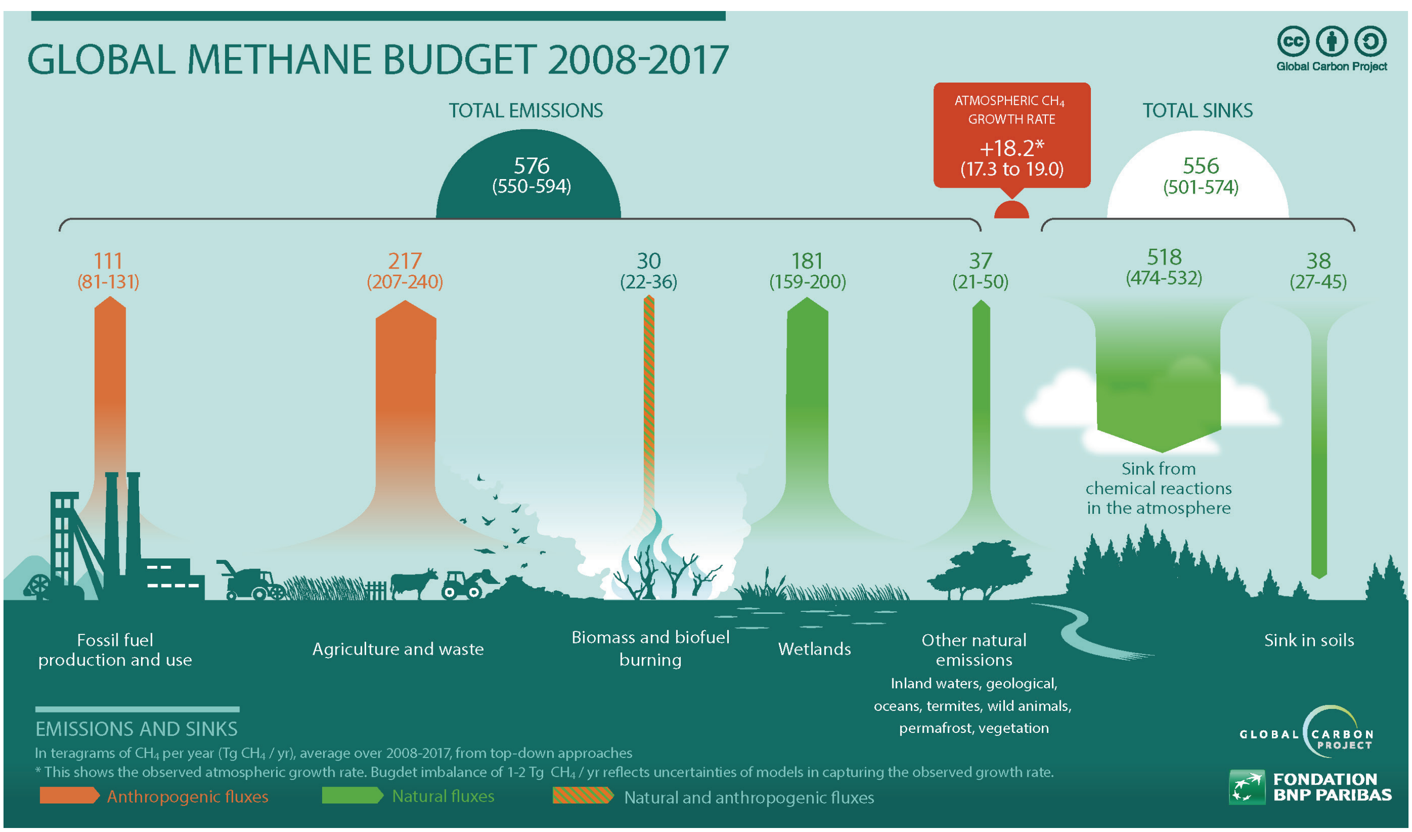


Figure 6. Diagram of the global methane budget showing anthropogenic and natural fluxes of methane into and out of the atmosphere. Source: Global Carbon Project.

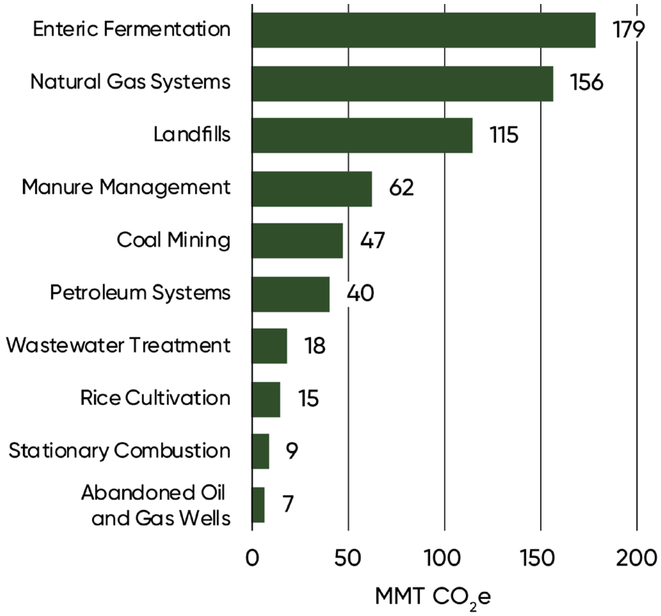


Figure 7. Major sources of methane emissions in the U.S., 2019. (Source: Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2019, Figure ES-9).

fermentation (primarily from cattle) and manure comprising two of the top four sources overall (Figure 7). Other major sources include natural gas systems, landfills, coal mining, and petroleum systems.

Nitrous Oxide Emissions

Nitrous oxide is a much more powerful greenhouse gas than either CO_2 or methane, with a heat-trapping capacity 298 times that of CO_2. Like the other two major greenhouse gases, nitrous oxide is naturally occurring and cycles into and out of the atmosphere through natural process. Nitrous oxide is produced by biological processes that occur in soil and water (Figure 8).

By far, the largest anthropogenic source of nitrous oxide emissions is nitrogen losses from agriculturally managed soils, accounting for over 75% of total nitrous oxide emissions and around 5% of greenhouse gas emissions overall. Wastewater treatment, fossil fuel combustion, livestock manure, and various industrial processes are also major sources (Figure 9). Atmospheric nitrous oxide levels have increased by around 20% during the industrial era, from 270 ppb in 1850 to 335 ppb today (MacFarling Meure et al., 2006; Elkins et al., 2021).

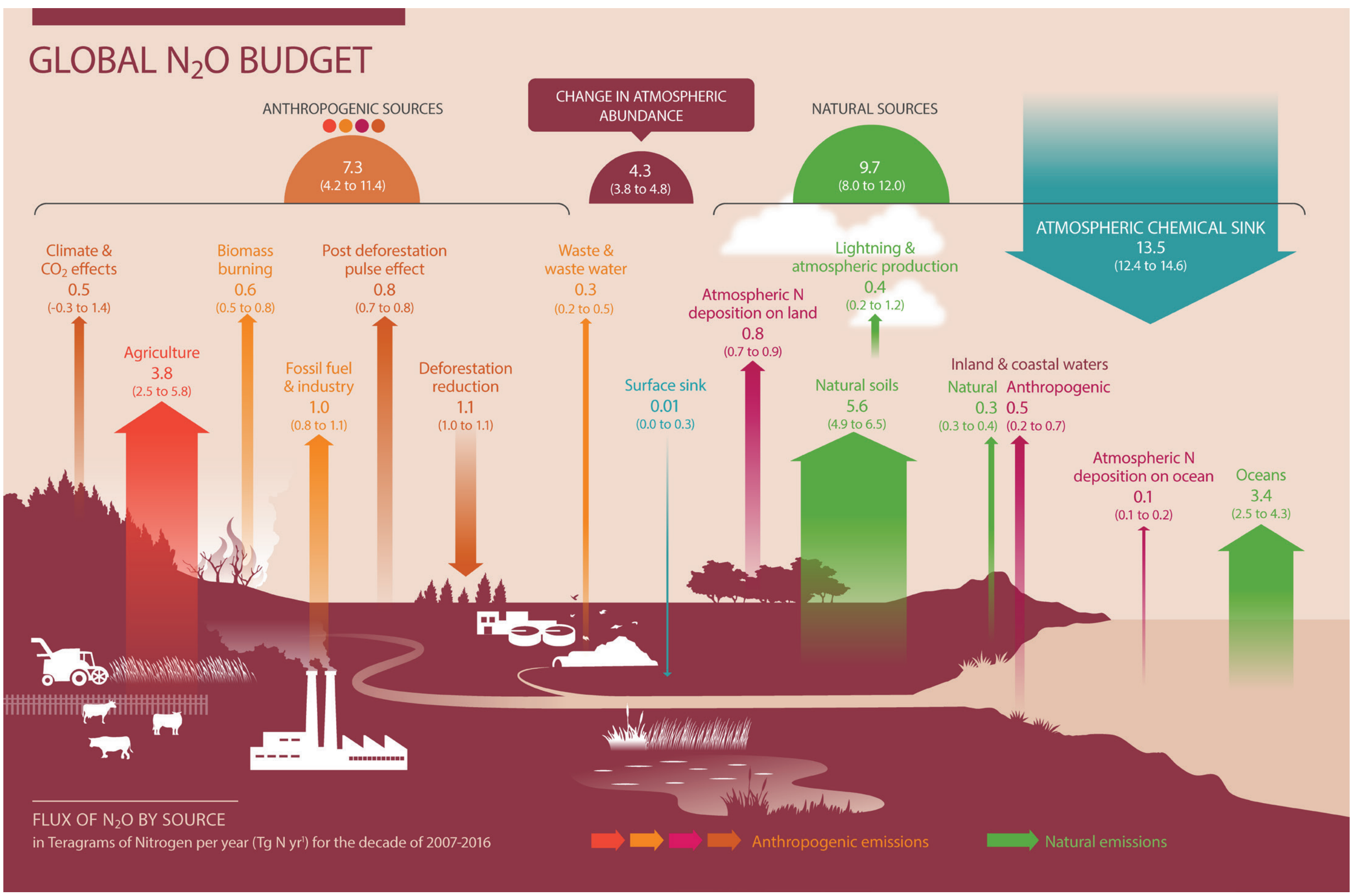


Figure 8. Diagram of the global nitrous oxide budget showing anthropogenic and natural fluxes of methane into and out of the atmosphere. Source: Global Carbon Project.

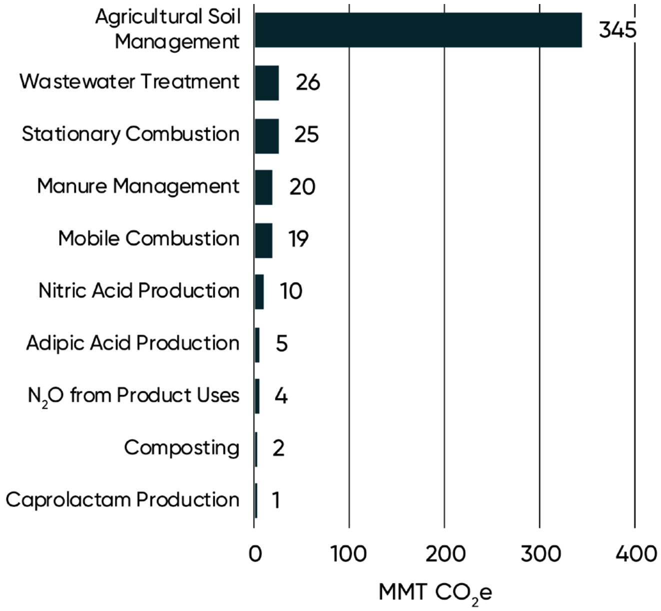


Figure 9. Major sources of nitrous oxide emissions in the U.S., 2019. (Source: Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2019, Figure ES-10).

What About Water Vapor?

The gas that contributes the most to Earth's greenhouse effect is water vapor, accounting for about 60% of the total warming effect – so why is it never mentioned when discussing global warming? It's because water vapor in the atmosphere is not a driver of higher temperatures but rather it reacts to higher temperatures.

The temperature of the atmosphere dictates the maximum amount of water vapor the atmosphere can contain. If air contains its maximum amount of water vapor and the temperature decreases, some of the water vapor will condense to form liquid water and precipitate out of the atmosphere.

As temperatures rise due to the increasing concentrations of other greenhouse gases, the amount of water vapor can increase as well, creating a positive feedback effect and further amplifying the greenhouse effect.

Greenhouse Gases in Agriculture

The economic sectors responsible for the majority of greenhouse gases are transportation, electricity generation, and industry, accounting for a combined total of 77% of emissions in the U.S. (Figure 10). Agriculture accounts for around 10% of greenhouse gas emissions, making it a significant contributor, but not nearly as large as the top three sectors. The percent of greenhouse gas emissions attributable to agriculture is somewhat lower in the U.S. than it is globally due to the greater efficiency of agriculture in the U.S. compared to much of the world.

Greenhouse gas estimates for agriculture typically do not include emissions associated with production of agricultural inputs or the transportation, processing, and packaging of agricultural products, so estimates of greenhouse gas emissions attributable to the global food system as a whole often run much higher – as much as 34% (Crippa et al. 2021).

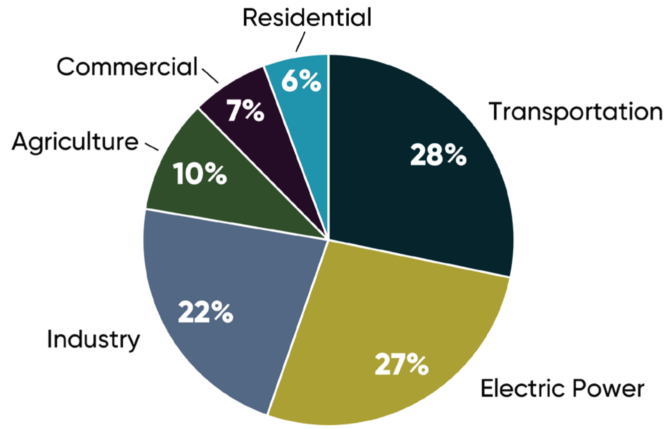


Figure 10. U.S. greenhouse gas emissions by economic sector, 2018. (Source: Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2019, Table ES-6).

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