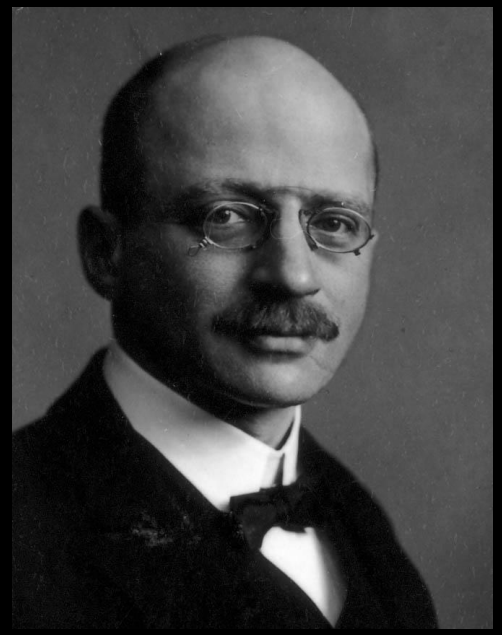

"Climate Change and the role of chemistry in creating a more sustainable future".
Solvay Prize Awards Ceremony
29 March 2022

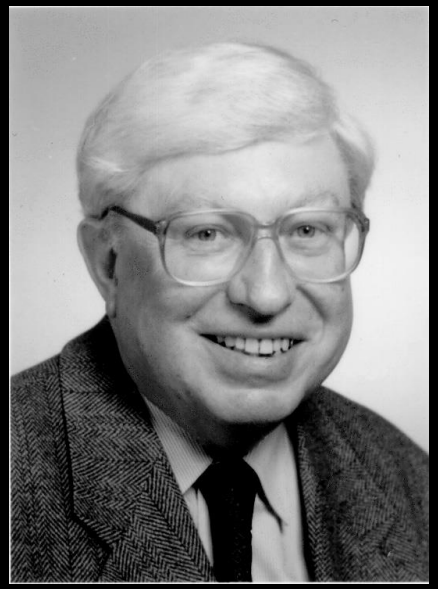
Significant advances in chemistry in the past 100 years

- Fertilizers, pesticides
- Birth Control
- Synthetic fibers –e.g. nylon and Kevlar
- The quantum chemistry that led to a molecular understanding of life
- Medicines, antibiotics, anesthetics, …
- … and mRNA vaccines



Fritz Haber: 1918

Carl Bosch: 1931



Gerhard Ertl: 2007

At the beginning of the industrial revolution (~1750) there were 700 M people. The Haber-Bosch process enabled us to feed a world that doubled in population.

Norman Borlaug 1970 Nobel Peace Prize

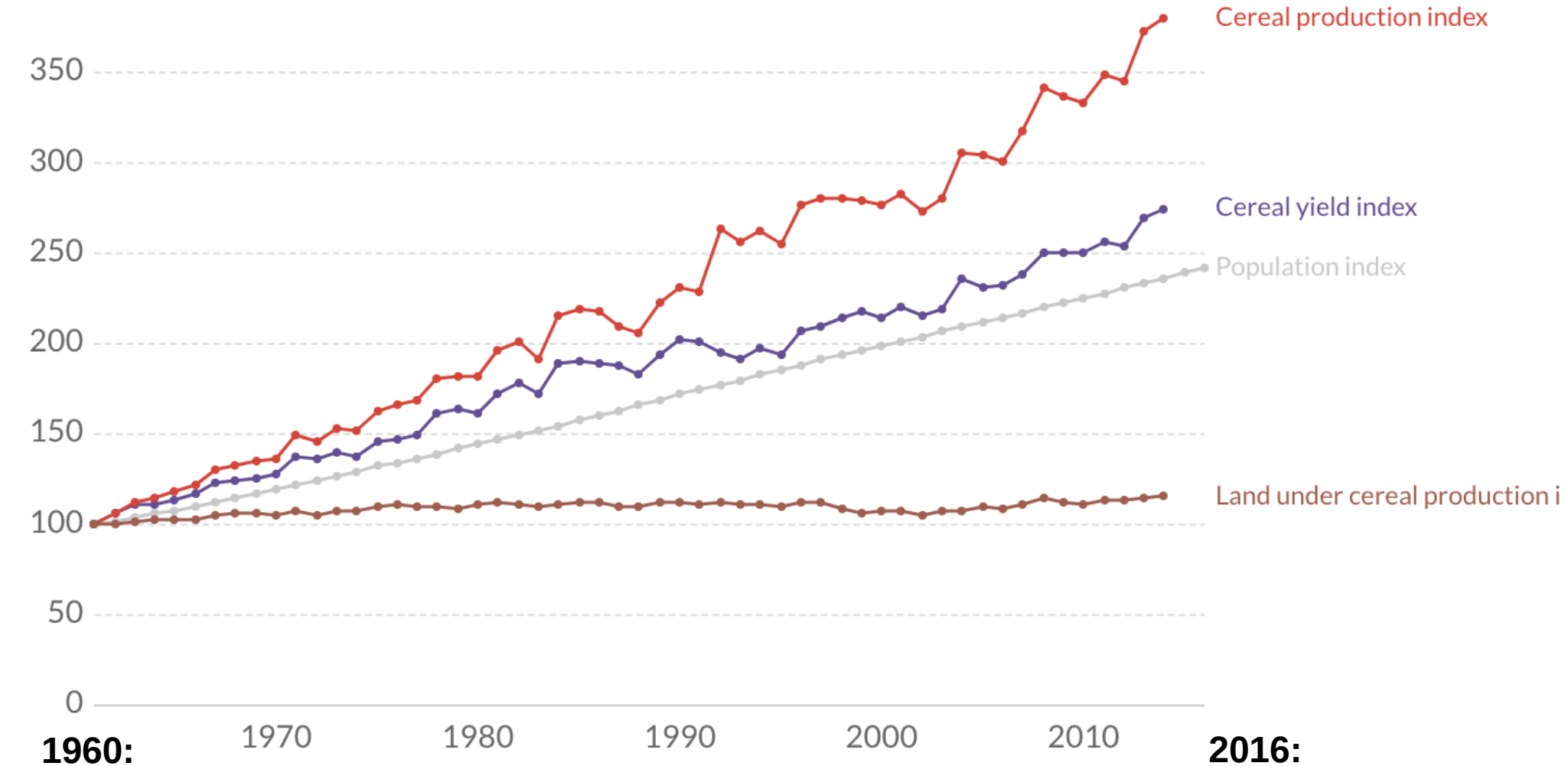
Borlaug bred disease-resistant and dwarf strains of wheat with thick stems that could support heavier kernels.

His plants didn't collapse after rapid growth spurts due to nitrogen fertilizer used in the poor soils.

"The green revolution has an entirely different meaning to most people in the affluent nations of the privileged world than to those in the developing nations of the forgotten world."

"…the first essential component of social justice is adequate food for all mankind."

World Production of Grain (1961 – 2004)

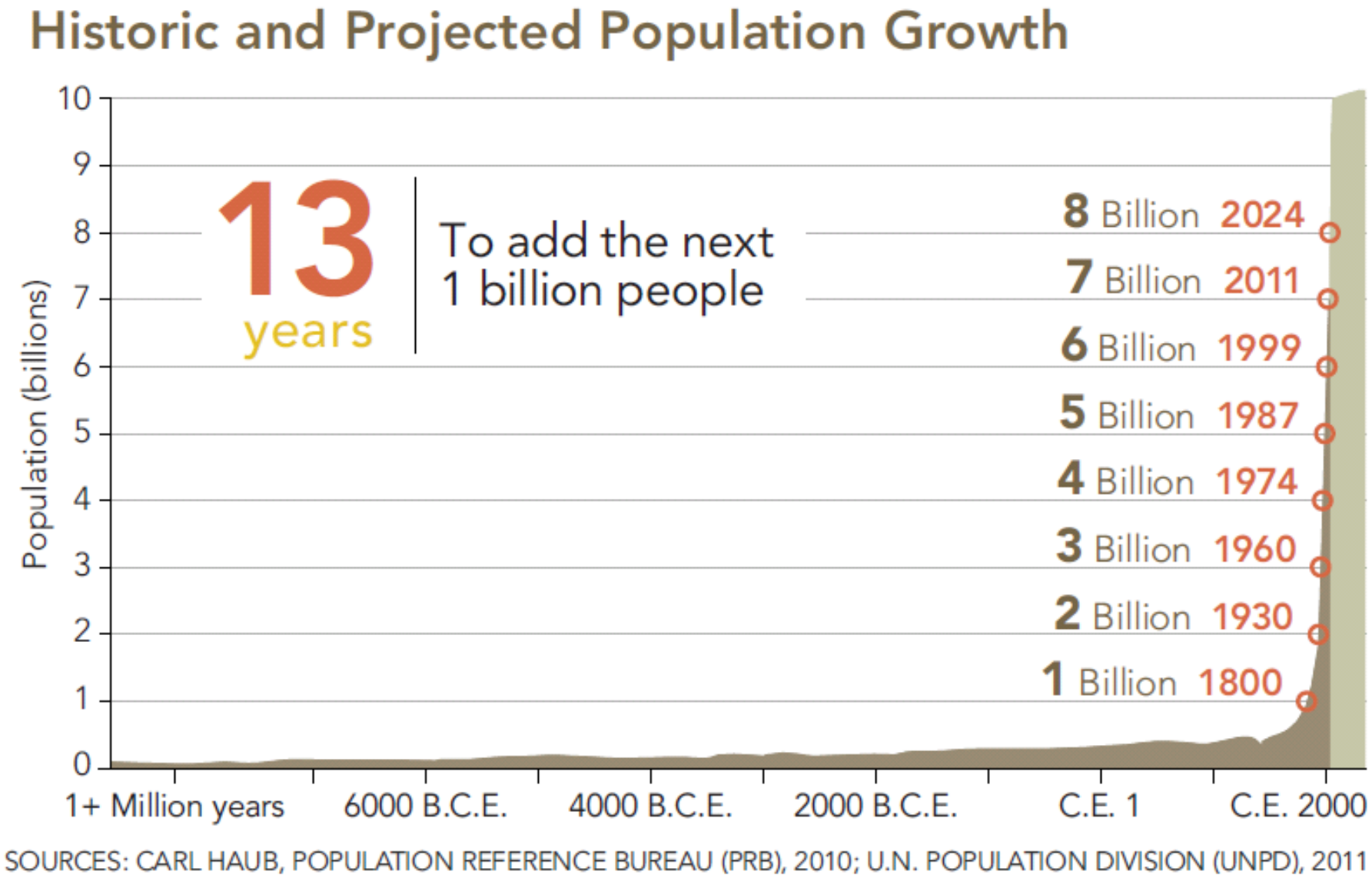


1960:
Pop = 3 B

2016:
Pop = 7.4 B

Source: Food and Agriculture Organization (FAO), United Nations

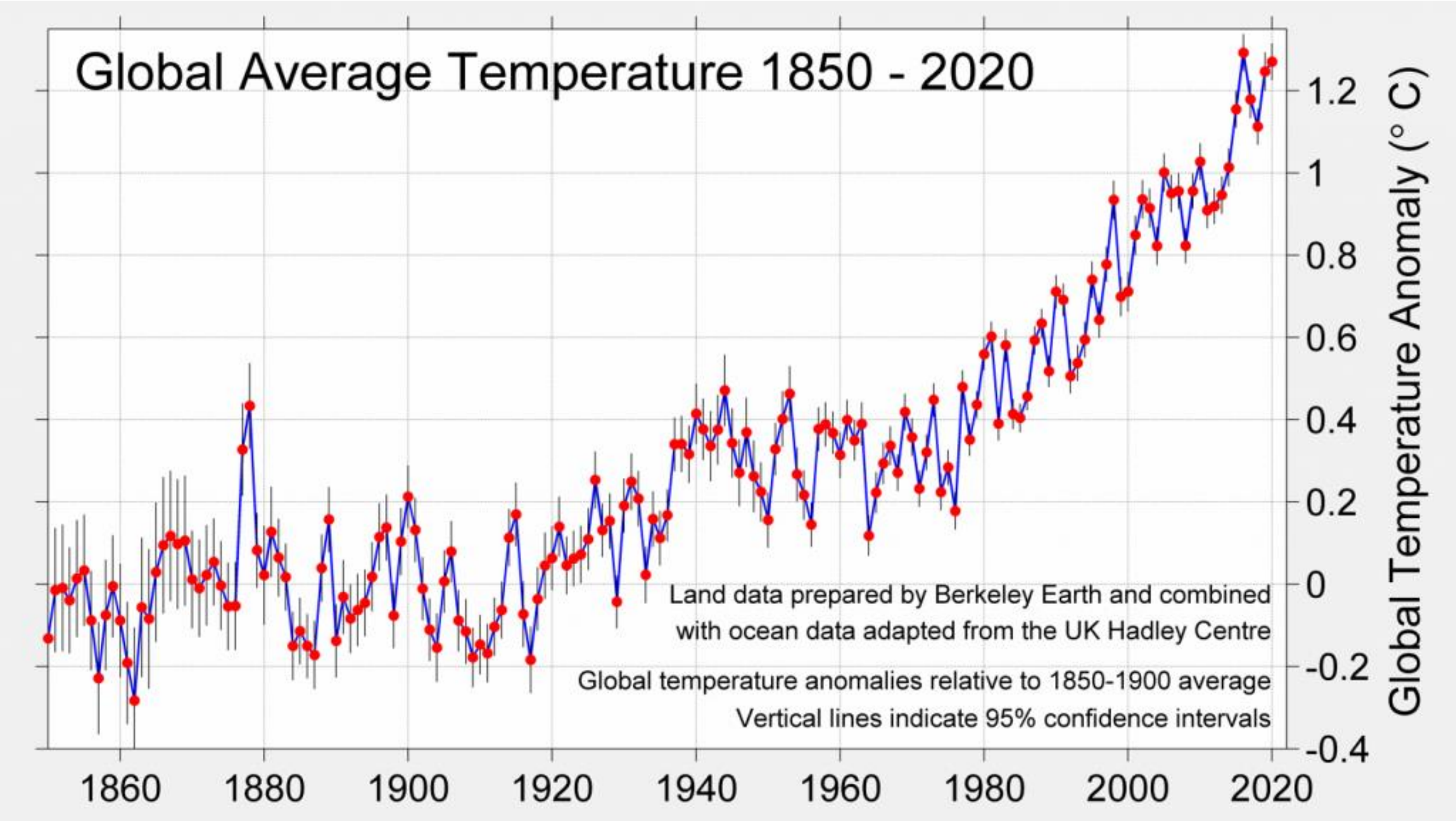
How long can we postpone an inevitable population crisis?



Source: Science **333,** 489-660 (2011)

There were unintended consequences to the multiple energy (industrial) and agricultural revolutions.

- Greenhouse gas emissions are changing our climate.
- Insecticides and pesticides found unintended victims.
- Chemicals and other new “miracle” materials created new pollution

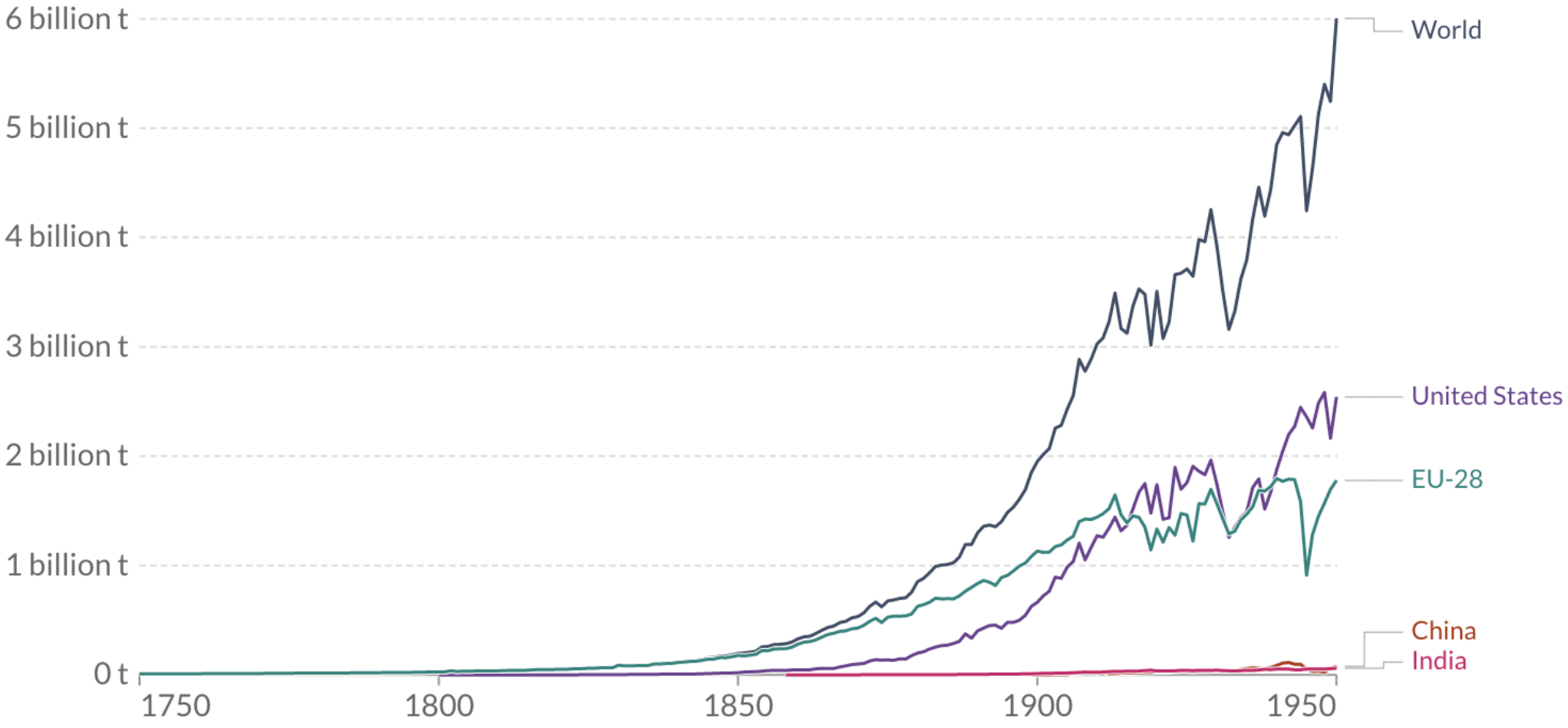

Global Average Temperature 1850 - 2020
Land data prepared by Berkeley Earth and combined
with ocean data adapted from the UK Hadley Centre
Global temperature anomalies relative to 1850-1900 average
Vertical lines indicate 95% confidence intervals
Global Temperature Anomaly (° C)
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
1860
1880
1900
1920
1940
1960
1980
2000
2020

Annual CO_2 emissions

Carbon dioxide (CO_2) emissions from the burning of fossil fuels for energy and cement production. Land use change is not included.

Our World in Data

LINEAR | LOG Add country Relative change



Source: Global Carbon Project

OurWorldInData.org/co2-and-other-greenhouse-gas-emissions/ • CC BY

1750 — 2020

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Carbon dioxide (CO_2) emissions from the burning of fossil fuels for energy and cement production. Land use change is not included.

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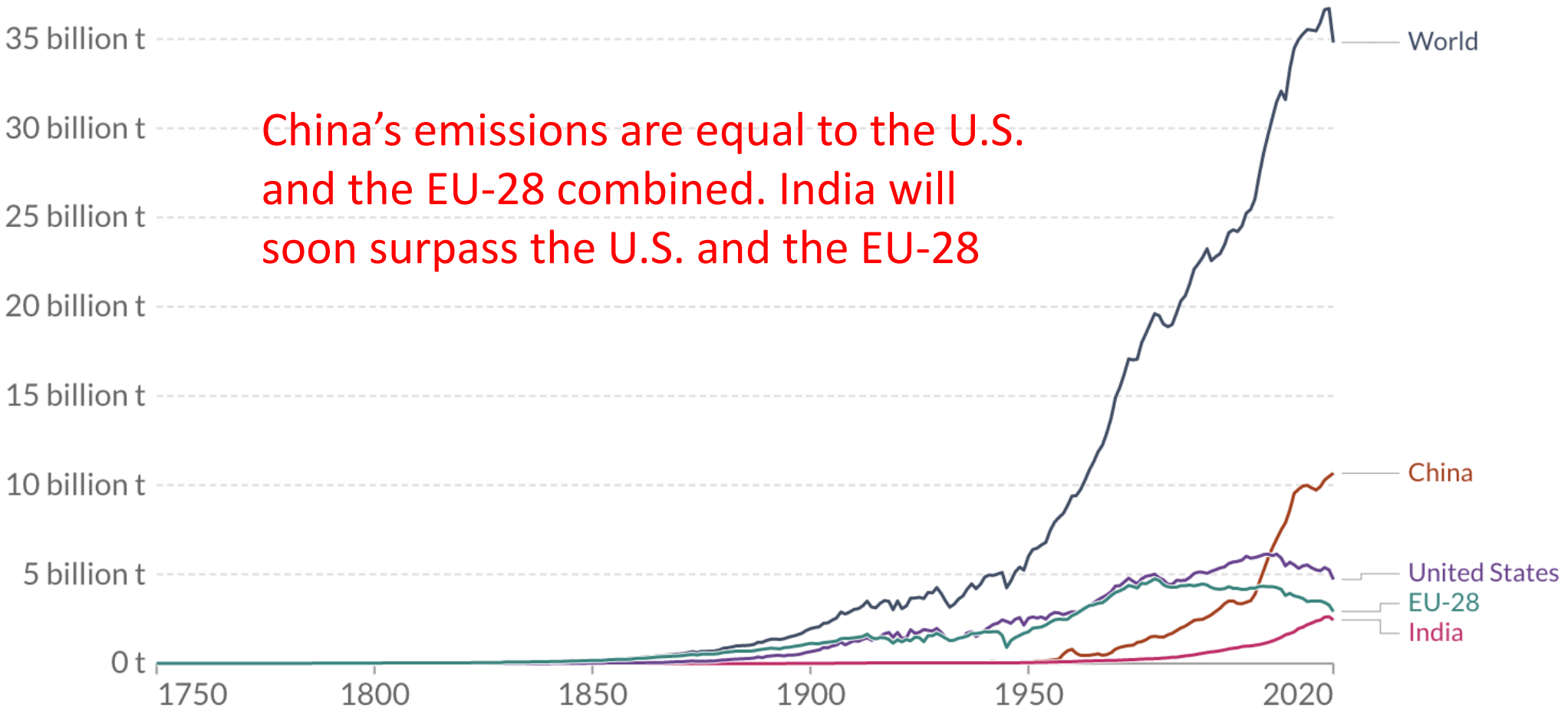


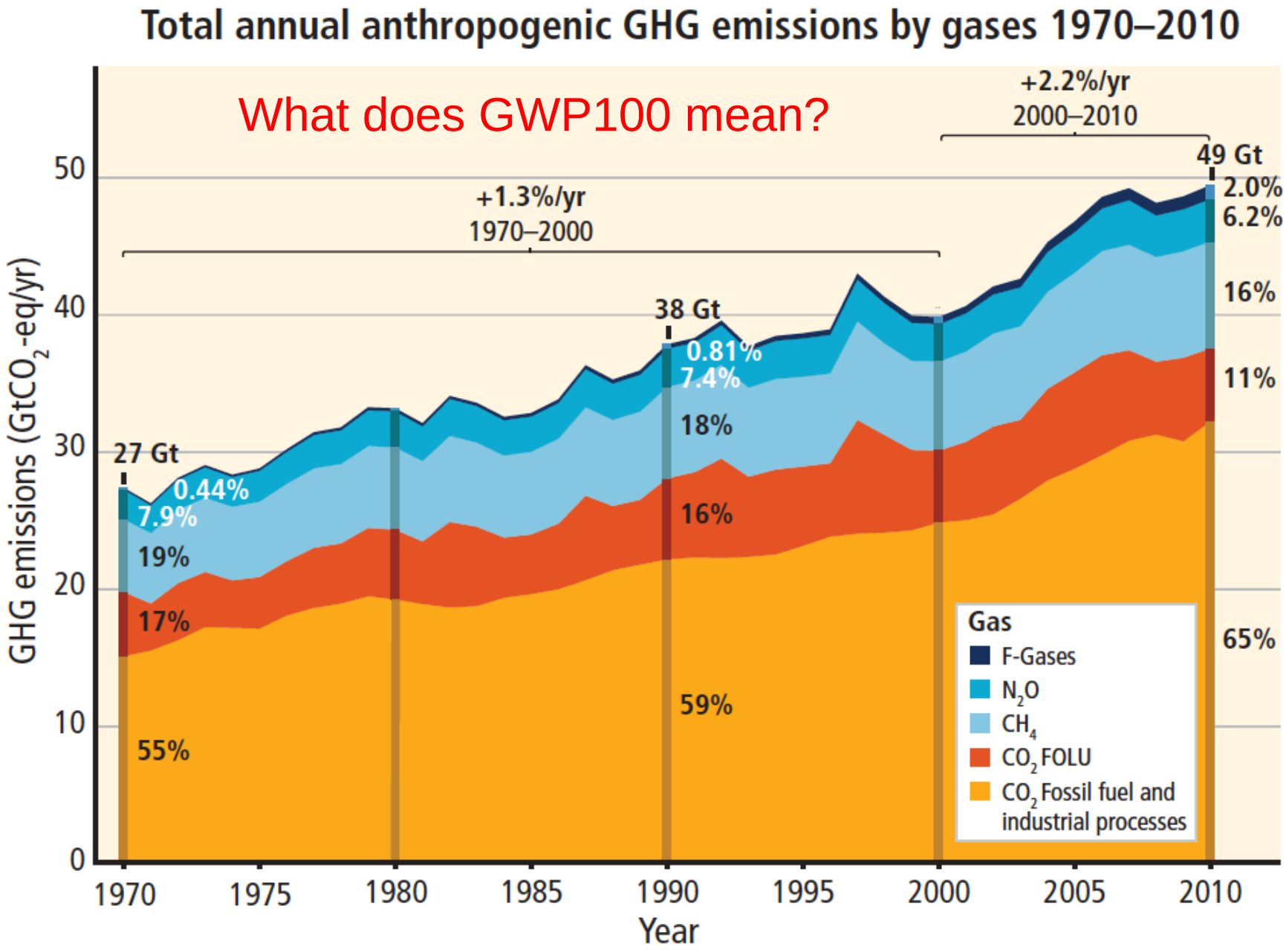
China's emissions are equal to the U.S. and the EU-28 combined. India will soon surpass the U.S. and the EU-28

Source: Global Carbon Project

OurWorldInData.org/co2-and-other-greenhouse-gas-emissions/ • CC BY

1750 — 2020

How might the chemist “come to the rescue”



Source: IPCC Summary for Policy Makers 2014

Calculated based on 100-year Global Warming Potential (GWP100)

CO_2 from fossil fuel combustion and industrial processes

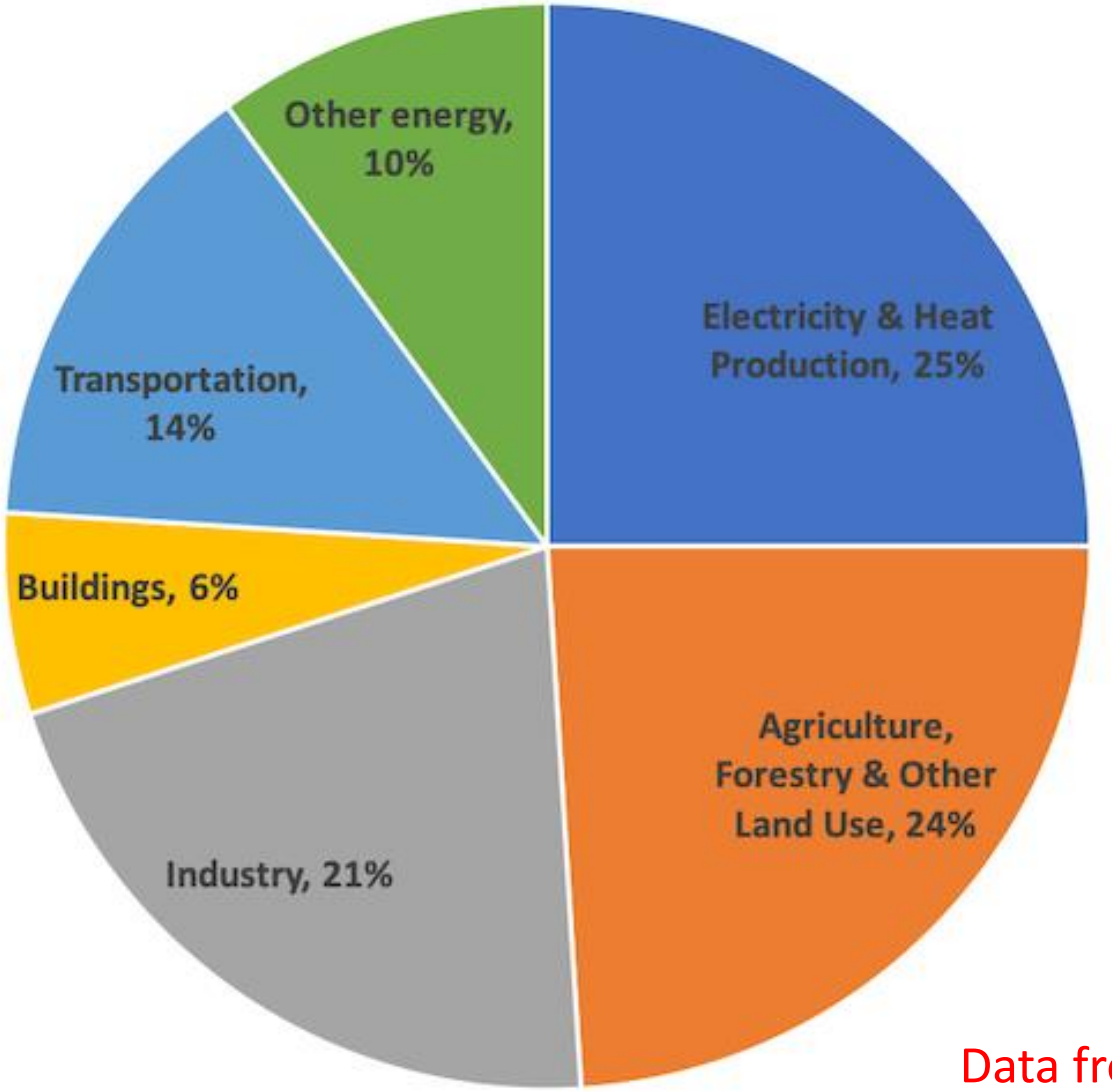
FOLU: CO_2 from Forestry and Other Land Use

CH_4: Methane

N_2O: Nitrous oxide

F-gases: Fluorinated gases covered under the Kyoto Protocol

Global Greenhouse Gas Emissions by Economic Sector



Data from the IPCC 2014 Report

In Europe and Africa, there is suspicion of genetically modified plants.

We have been genetically modifying plants and animals for over 4,000 years.

The breeding of teosinte into modern corn

Beef Cattle
(18 – 24 months)

Pigs
(22 – 26 weeks)

Average market weight of a pig: 280 lbs.

Broiler chicken
(40 days)

Turkey
(14 – 16 weeks)

Livestock have been bred to optimize early growth in a small fraction of their natural life-cycle.

Domestic turkeys (~ 3.5 months before slaughter)

Farm-bred turkeys are so breast heavy they cannot mate

Wild Turkeys

Of unknown ages

Wild Turkey (101)

Aged 8 years

Annual CO_2 emissions

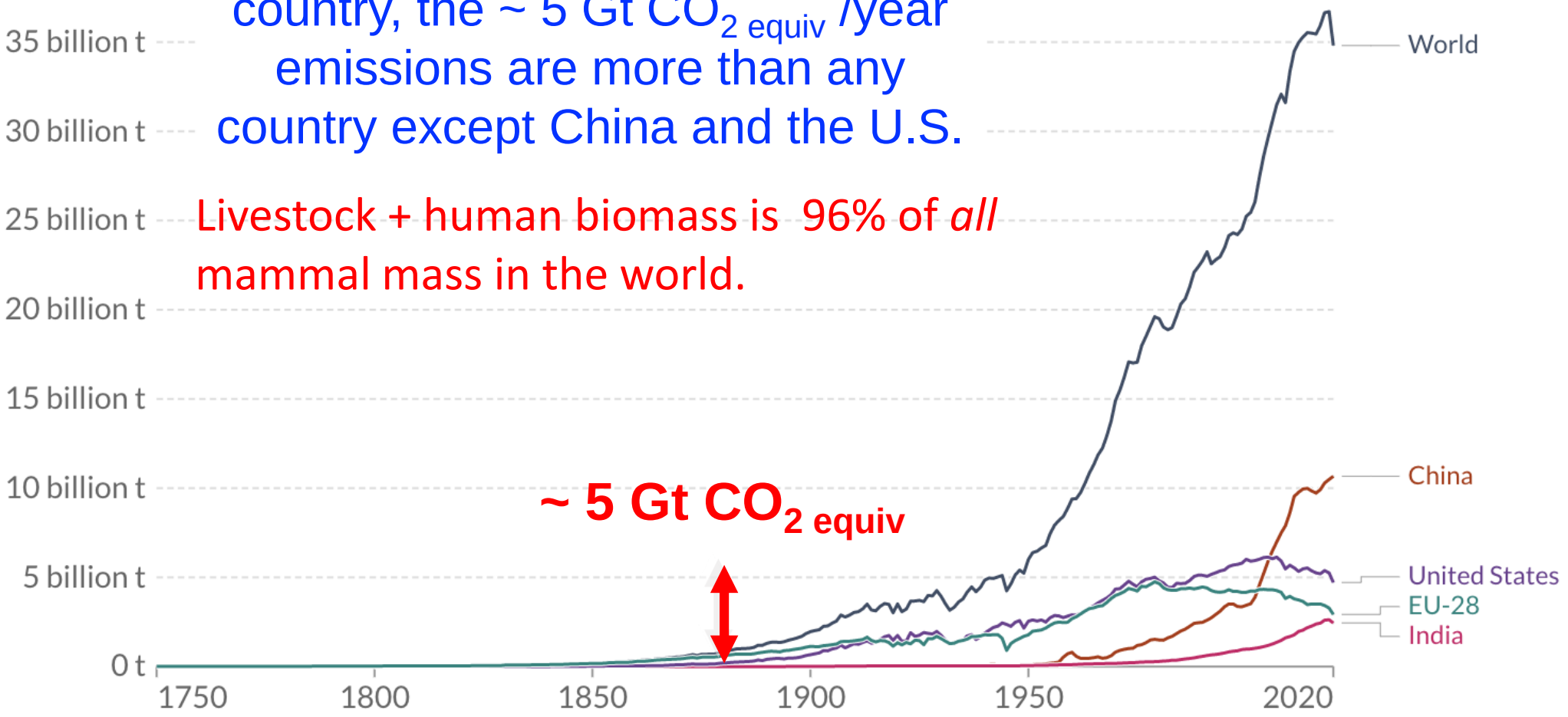
Carbon dioxide (CO_2) emissions from the burning of fossil fuels for energy and cement production. Land use change is not included.

Our World in Data

LINEAR LOG

If Beef and Dairy Cattle were a country, the ~ 5 Gt $CO_{2\ equiv}$ /year emissions are more than any country except China and the U.S.

Livestock + human biomass is 96% of *all* mammal mass in the world.



Source: Global Carbon Project

OurWorldInData.org/co2-and-other-greenhouse-gas-emissions/ • CC BY

1750 2020

Feeding cattle seaweed (*Asparagopsis taxiformis*) reduces their greenhouse

vaccines

Review

Are Vaccines the Solution for Methane Emissions from Ruminants? A Systematic Review

Vaccines are being considered as a possible solution to methane emissions from cattle and dairy cows.

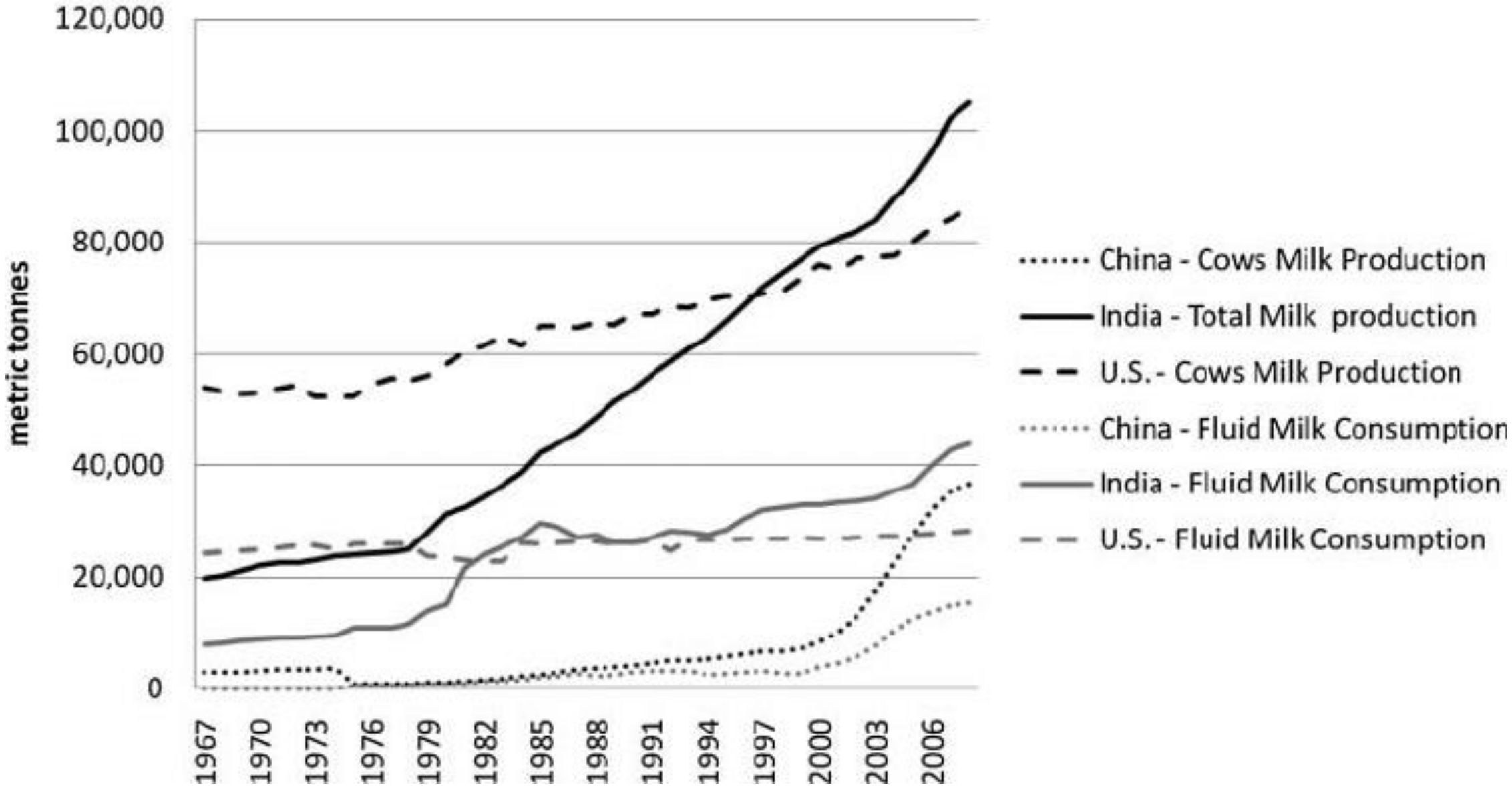
Vaccines 2020,8, 460; doi:10.3390/vaccines8030460 www.mdpi.com/journal/vaccine

Impossible Food Burger

Beyond Meat Burger

Blood taste from **hemoglobin-like molecules** derived from plants. Juices released from **myosin** molecules.

Milk consumption adds ~ 2 Billion tonnes of $CO_{2\ equiv}$ / year.
Milk is a primary source of protein in India



Plant-based substitutes from soy, oats, almonds, coconuts, …

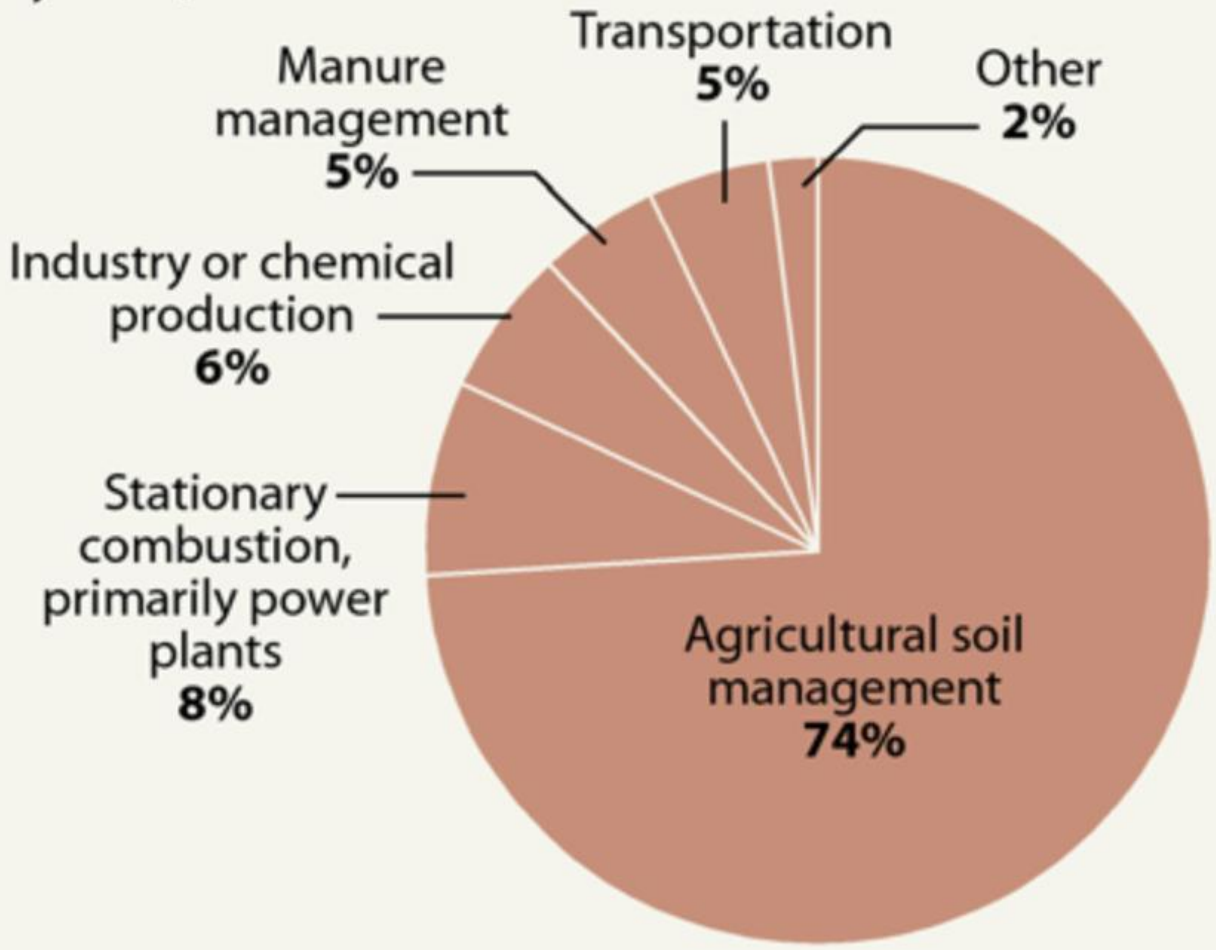
Full disclosure: I am on the Board of Directors of Oatly. We want to develop improved enzymes to increase the oat protein in milk by 50% and add more fiber

Where Does N_2O Come From?

Agriculture, particularly fertilized soil and animal waste, accounts for about three quarters of U.S. nitrous oxide emissions.

U.S. NITROUS OXIDE EMISSIONS

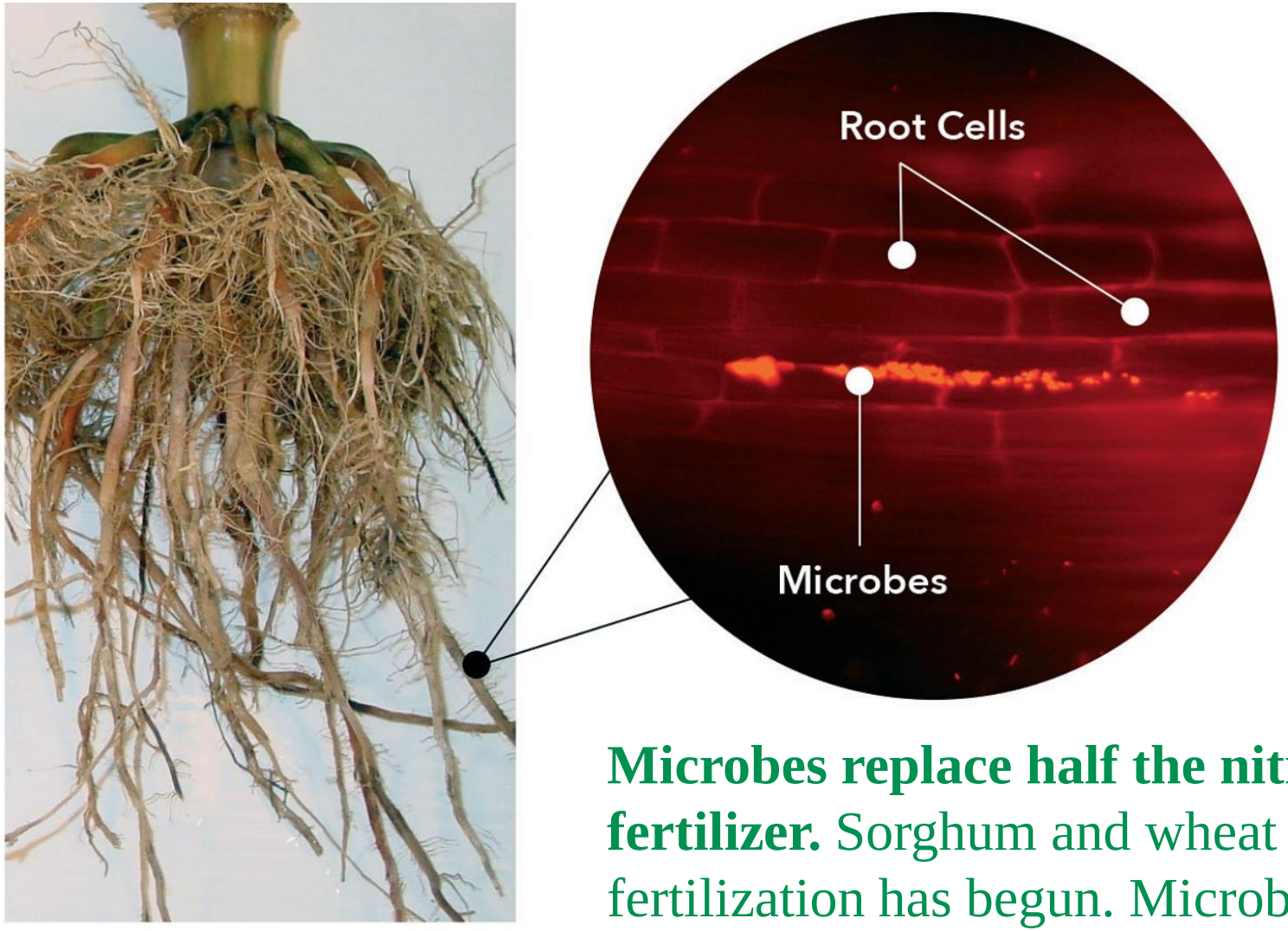
By source, 2017



SOURCE: EPA

PAUL HORN / InsideClimate News

PIVOT BIO



Microbes replace half the nitrogen-based fertilizer. Sorghum and wheat with microbial fertilization has begun. Microbial Phosphorus and potash production are the next targets.

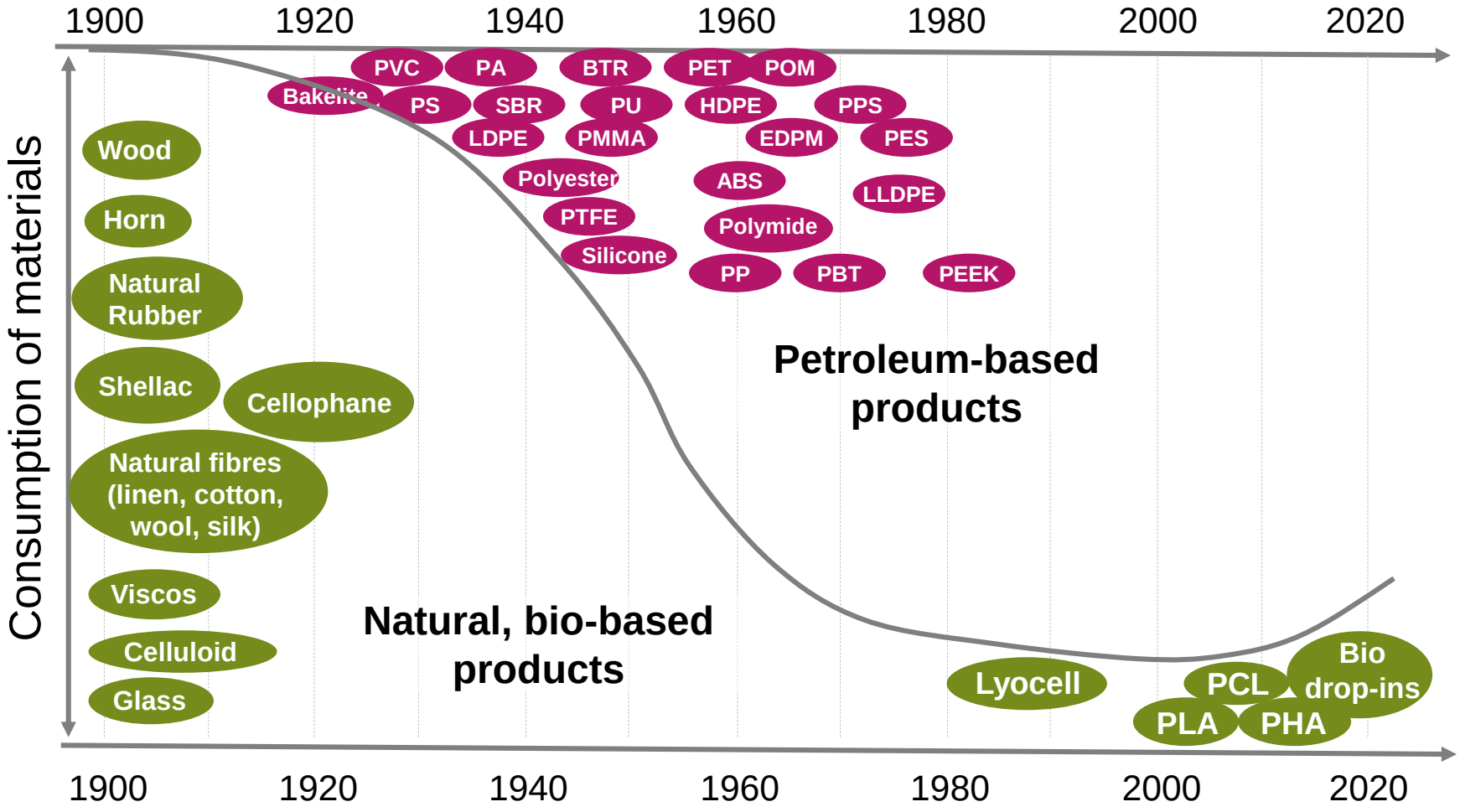
Synthetic Biology

How to Design New Life

After the discovery of oil, petroleum-based relaced many nature made materials

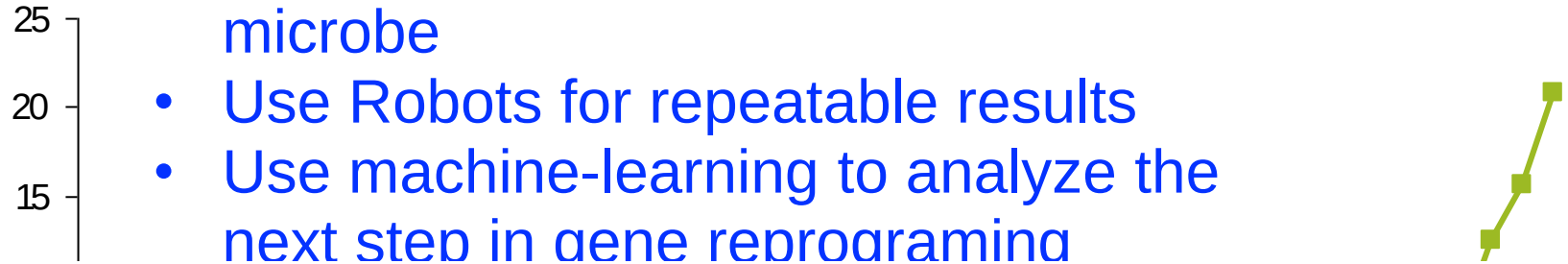
There has been a return to natural products.

Bioengineering is emerging and hybrid solutions may be possible.

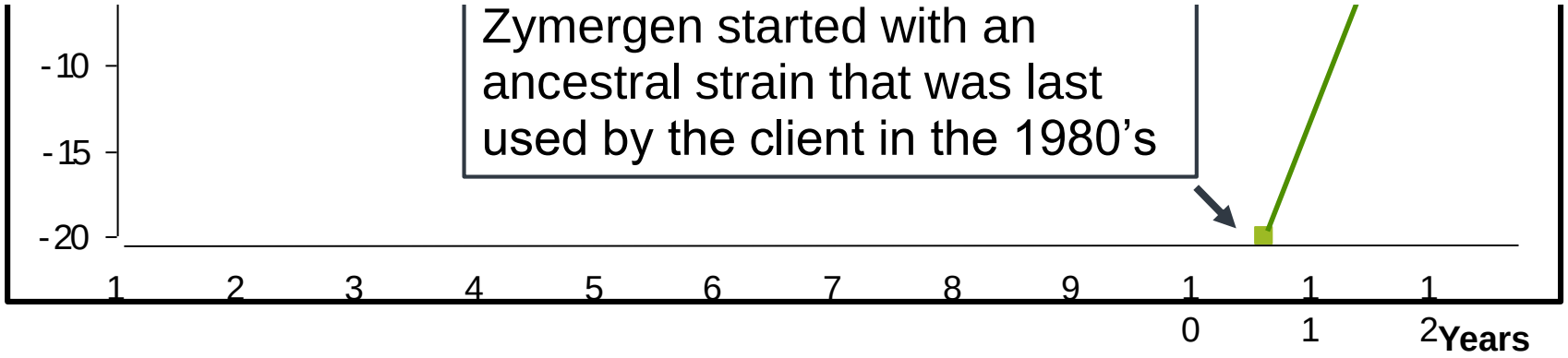


zymergen®

- Investigate ***all*** the genes of the microbe
- Use Robots for repeatable results
- Use machine-learning to analyze the next step in gene reprograming



Currently technology allow the insertion of only one gene at a time. If dozens of genes can be inserted, the optimization would increase exponentially. My lab is developing methods to insert 10s genes into cells with very high cell survival.




Bio-degradeable plastics is not the solution.
Wooden buildings can last for hundreds of years.

Renewable energy costs (L.C.O.E.) at the best sites around the world is now below

2 ¢/kWh at the best sites.

Costs will continue to decline to

< 1.5 ¢/kWh by 2030

In order to replace 50 – 80% of electrical power with wind or solar power, very inexpensive energy storage is crucial

Progress in Batteries and other forms of energy storage

Pump water when the wind blows or the sun shines

China has installed 30 GW of pumped storage by 2020.

China is planning 62 GW by 2025 and 120 GW by the end of the decade.

The Nobel Prize in Chemistry 2019

© Nobel Media. Photo: A. Mahmoud

John B. Goodenough

Prize share: 1/3

© Nobel Media. Photo: A. Mahmoud

M. Stanley Whittingham

Prize share: 1/3

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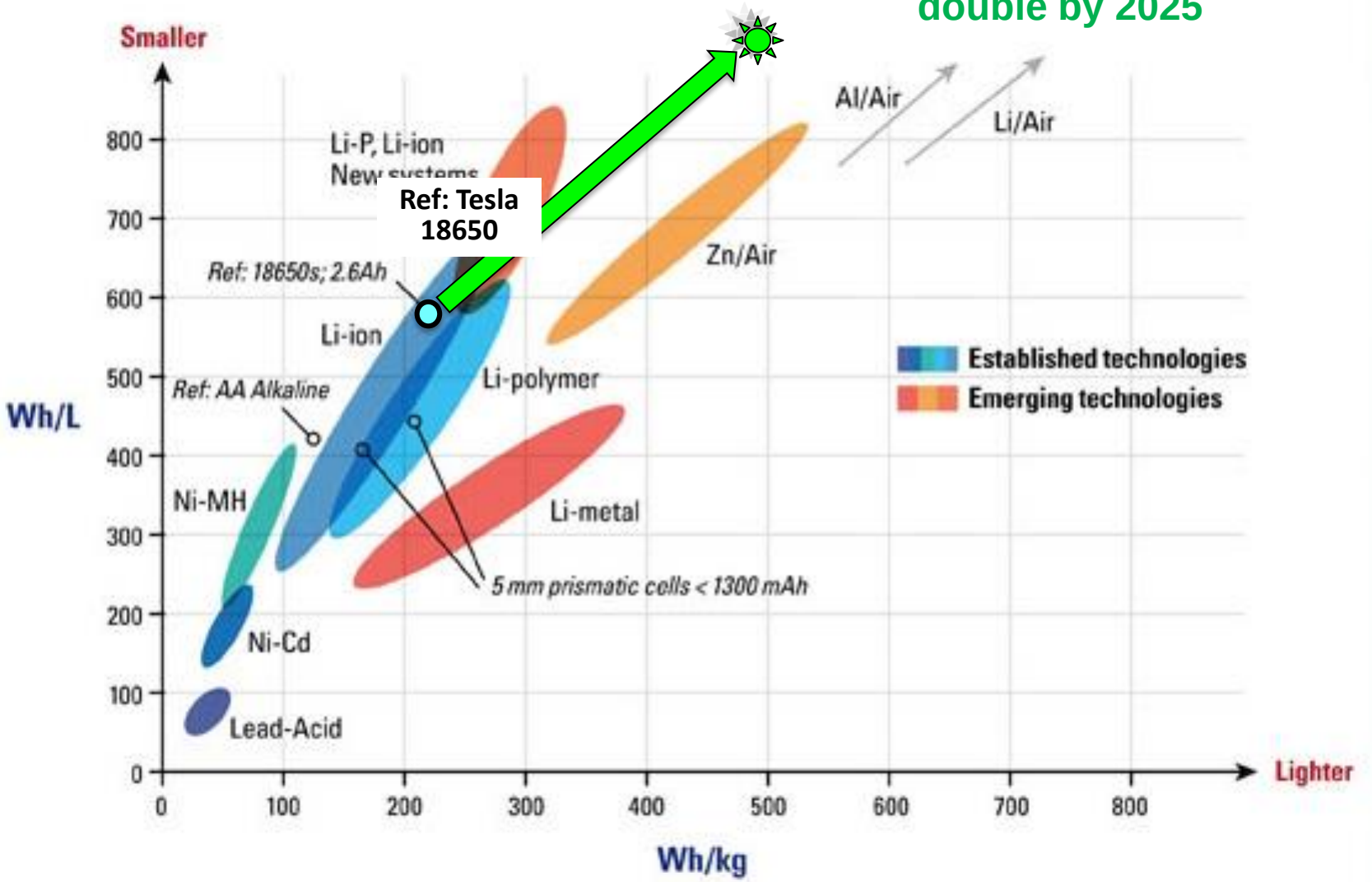
Akira Yoshino

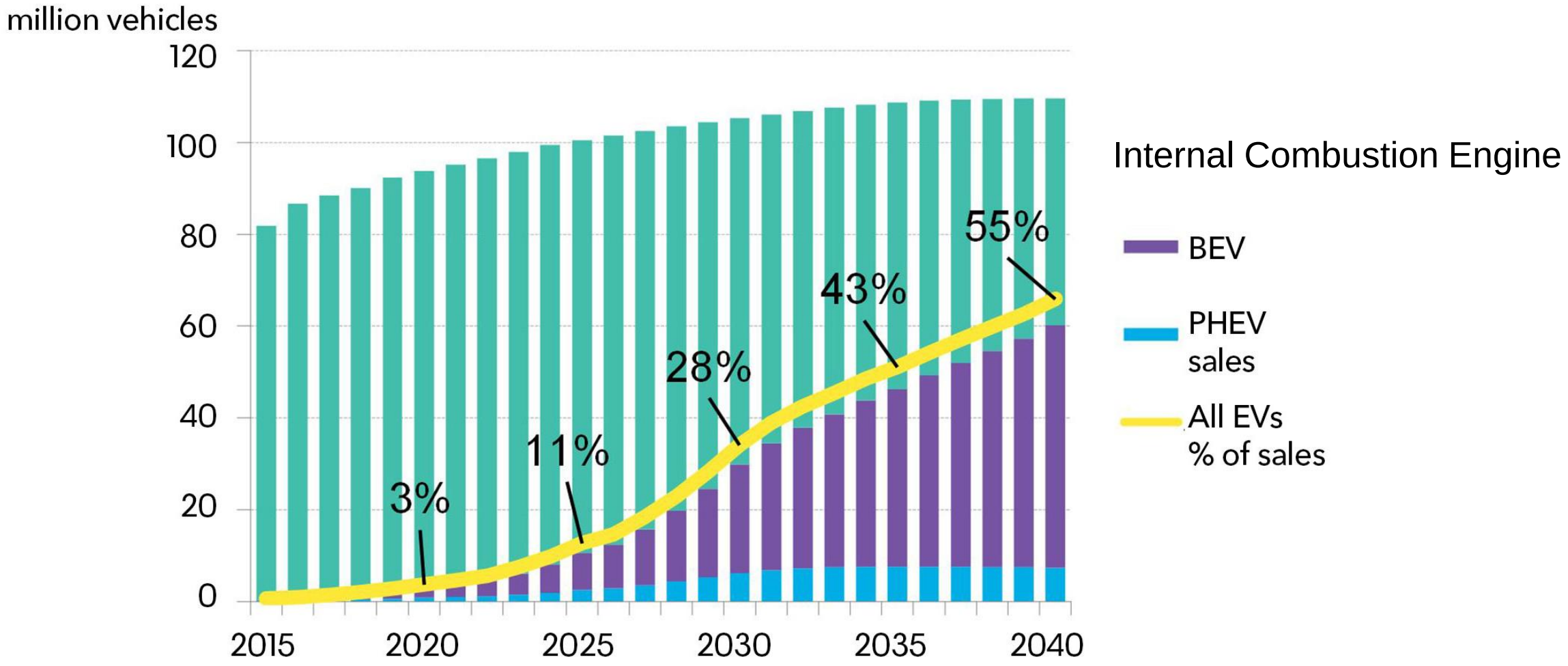
Prize share: 1/3

The cost of EV batteries declined 10-fold in 2010 ➞ 2020

The energy density may double by 2025



Will there be enough lithium, cobalt, and nickel to meet the expected demand?

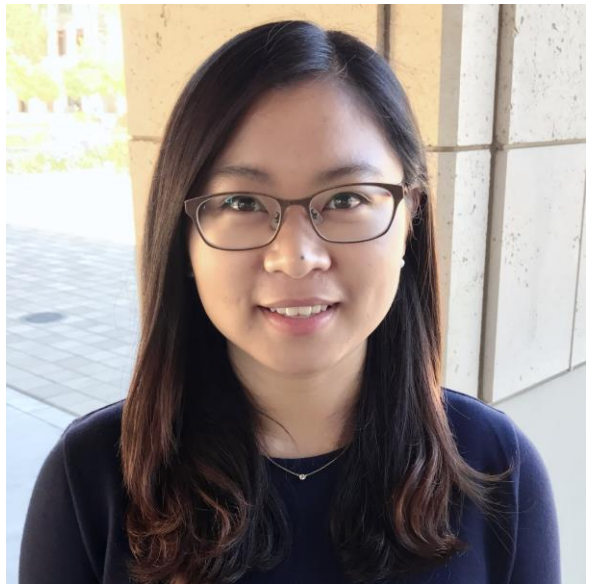


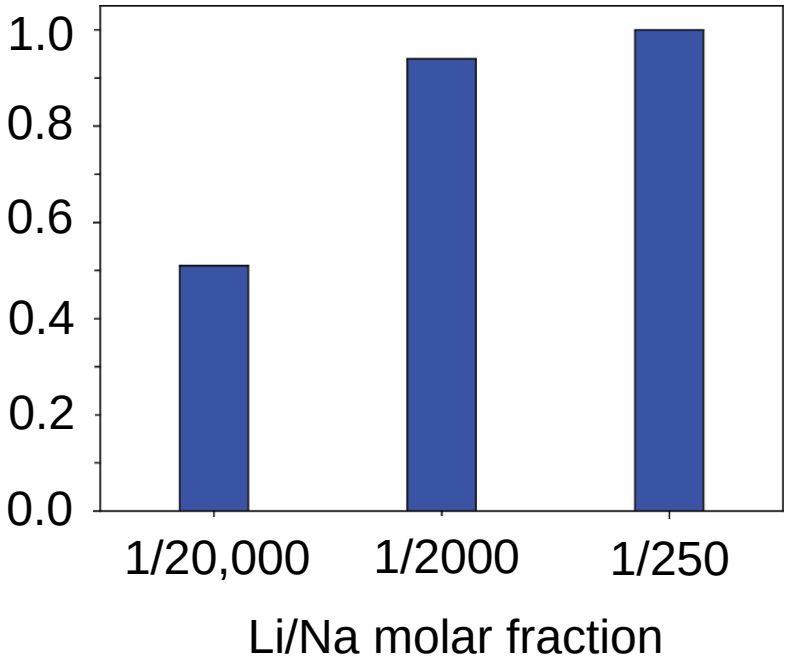
Source: Bloomberg New Energy Finance

Li Extraction from salt water could increase lithium resources ~ 10,000x

(Chong Liu, … ,Yi Cui, Steven Chu, *Joule* 4, 1 – 11, July 15, 2020)

Location	Conc.	Li/Na molar
Brine (salt lakes)	0.017-0.15%	1/2000 - 1/200
“Produced water” from oil	~ 4.7×10^{-5}	1/2000 – 1/500
Sea Water	~1.7×10^{-5}	1/20,000

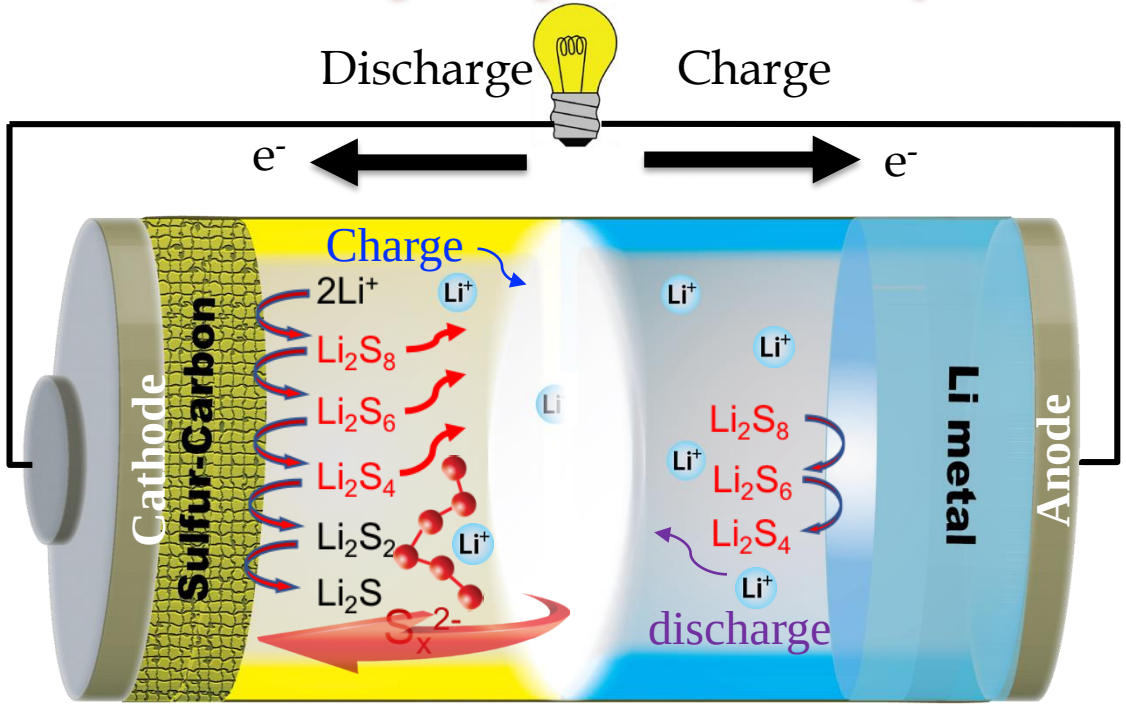




An important target: Lithium metal – sulfur battery or lithium metal –iron phosphate battery

Problem: Lithium metal forms dendrites when recharging.

Also, sulfur reacts with the electrolyte and can migrate to the anode-side of the battery



All well-known separators allow sulfur to reach the anode

A new separator allows lithium **metal**-sulfur battery operate until the chemical reactions with electrolyte is depleted.

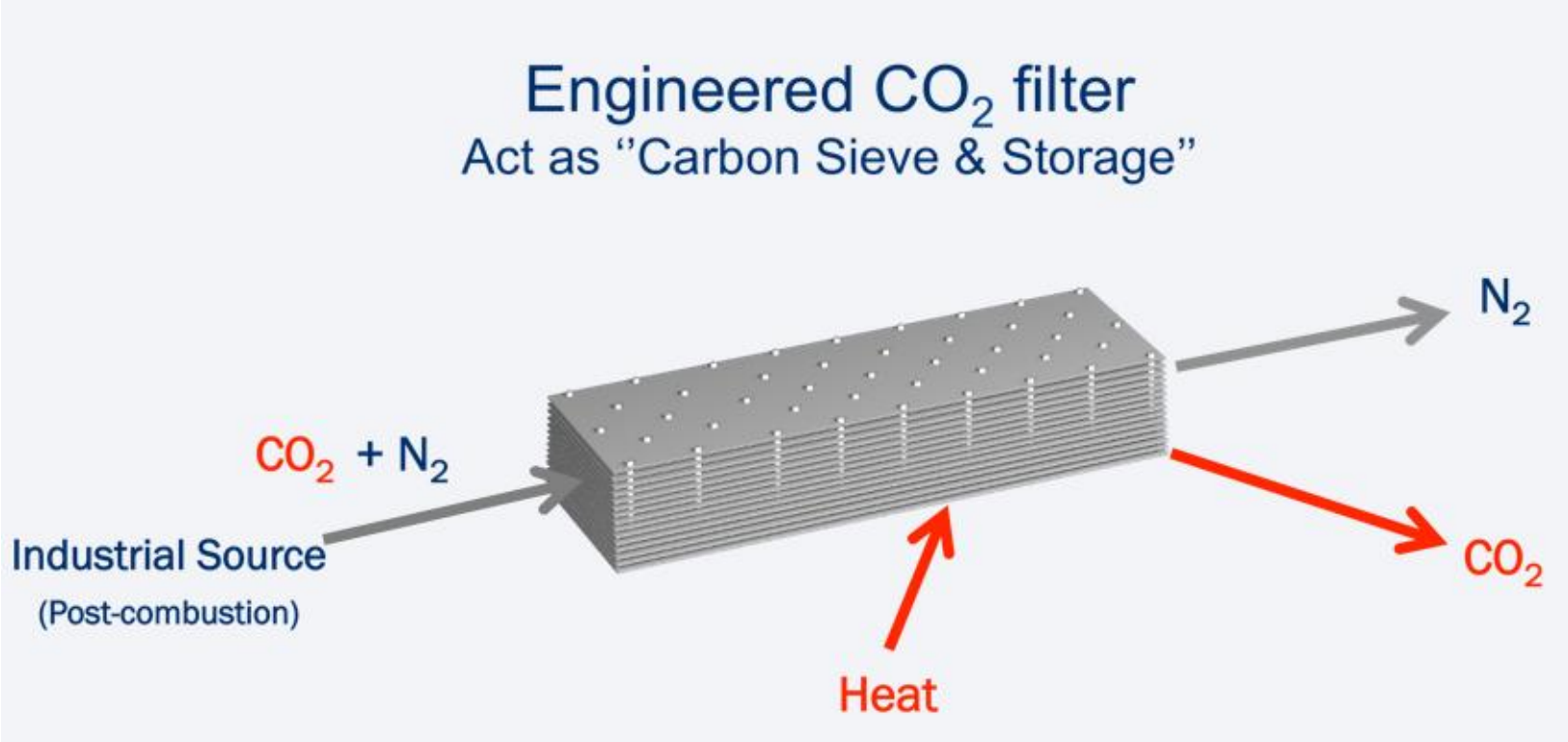
Life-cycle testing is now underway for a $Li_3Fe_2(PO_4)_3$ battery at 3x faster charging rate.

In order to reach zero net carbon, we will need to capture CO_2 from chemical, steel, and cement production.

We will also have to capture ~20 billion tonnes of CO_2 from the atmosphere

Svante

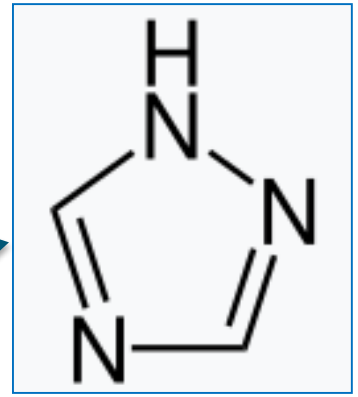
Carbon capture at half the cost of today's technology?

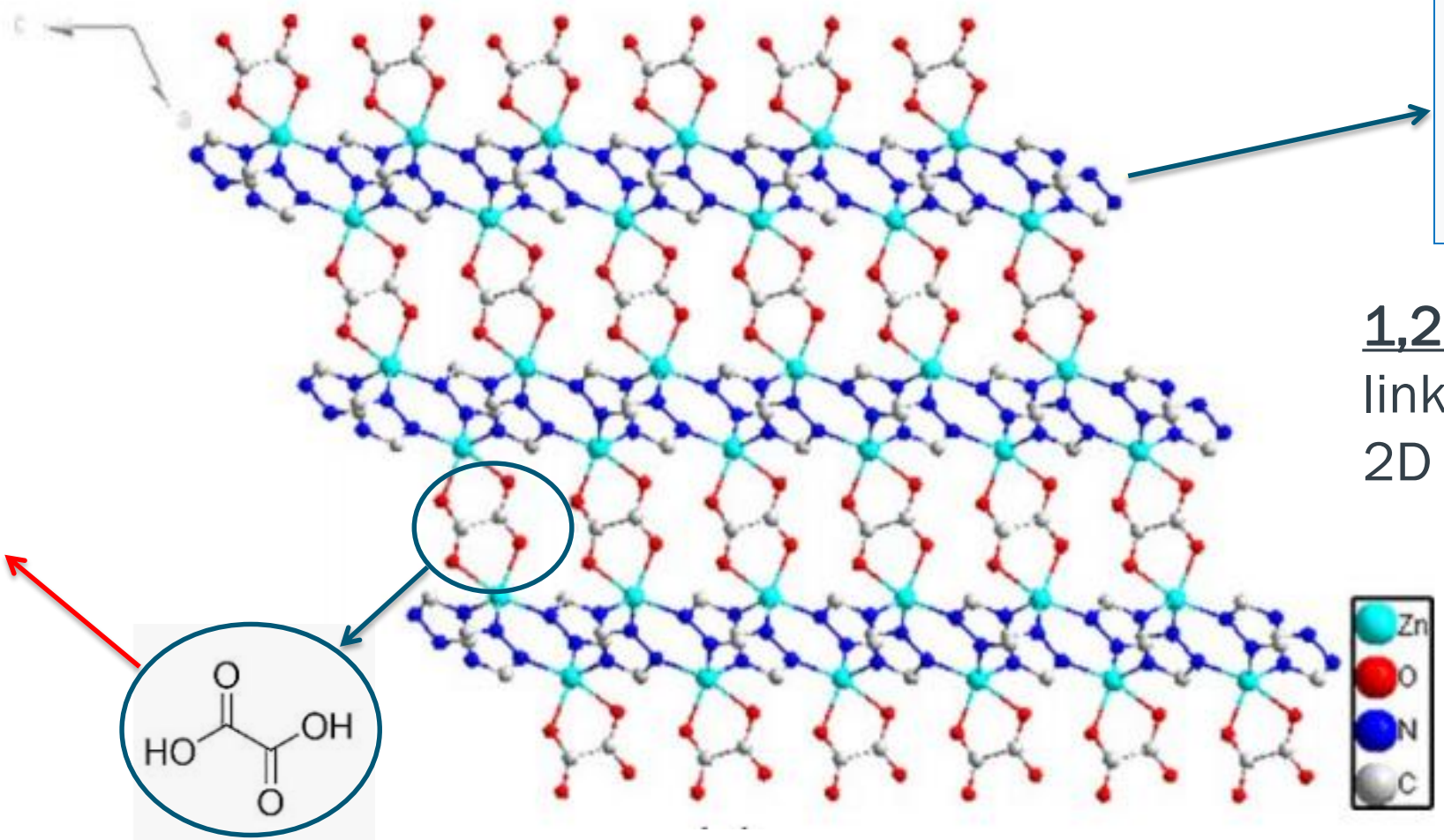


Svante Metal Organic Framework (MOF)

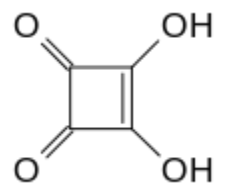
Svante

CALF-20 (Zinc 1,2,4 – Trisolate Oxalate)





1,2,4-Triazole links Zn^{2+} as 2D layers



Squaric acid

Oxalic acid as pillar

After carbon capture, the CO_2 needs to be either sequestered (e.g. geological storage underground) or converted into useful materials

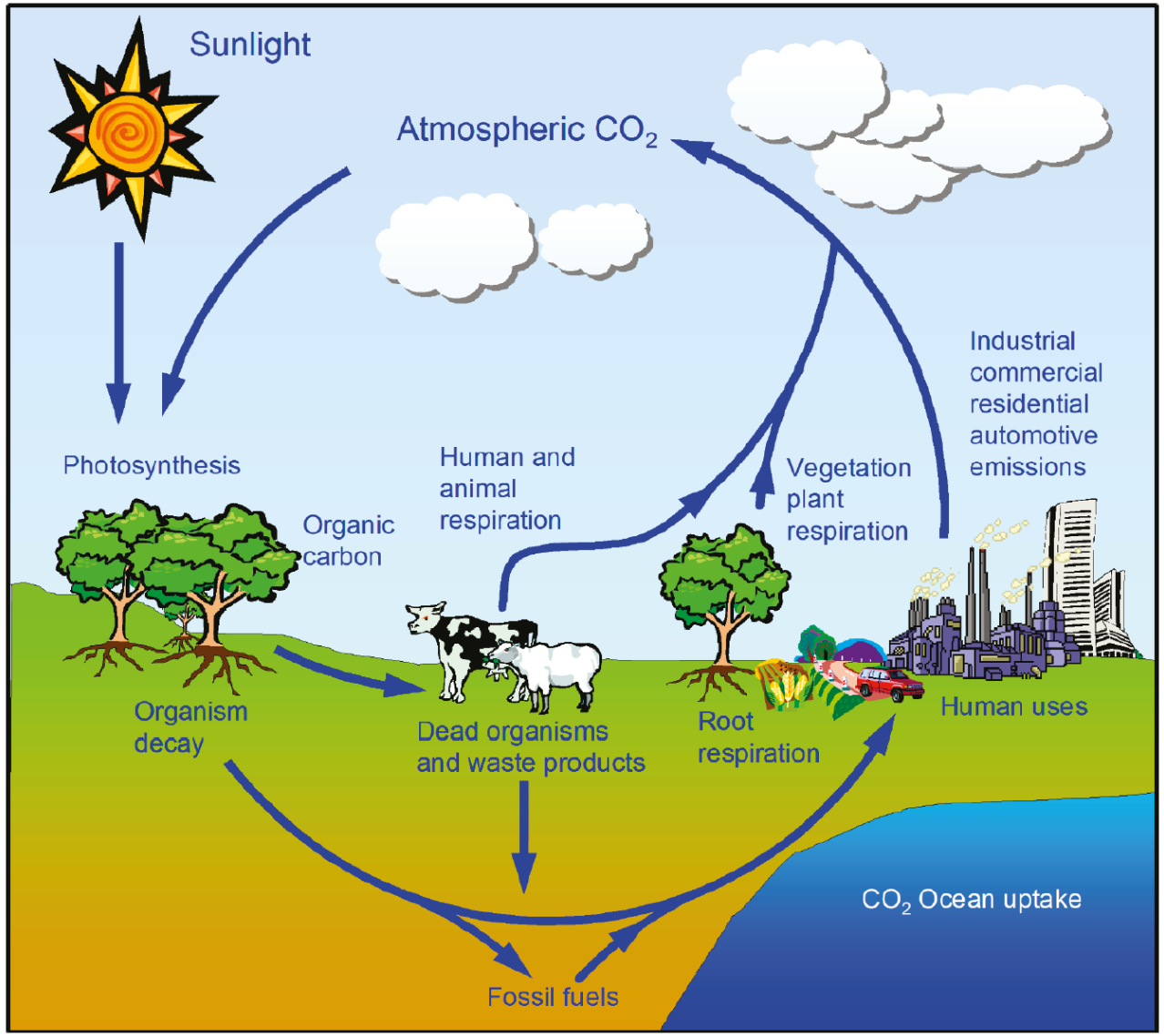
The carbonate–silicate geochemical cycle
transformations silicate rocks to carbonate rocks
by weathering and sedimentation.

Marine organisms create calcium carbonate shells from $H_2CO_3^-$ that deposit on the ocean floor and are buried.

Researchers are working accelerate the conversion of silicates into carbonates for carbon fixation.

Crops capture 30 $GtCO_2$ /year. Pasture: 48 $GtCO_2$

Total Global human emissions ~ 40 $GtCO_2$



The burial of compacted, residual biomass from food crops and plants grown capture carbon ~ 5x more biomass per hectare) is may provide a partial solution.

Increased economic prosperity and global competitiveness of virtually all countries is based on producing/recruiting more young workers to support a smaller aging population.

Pyr·a·mid scheme

A form of investment in which each paying participant recruits two further participants, with returns being given to early participants using money contributed by later ones.

Pon·zi scheme

/ˈpänzē ˌskēm/

noun

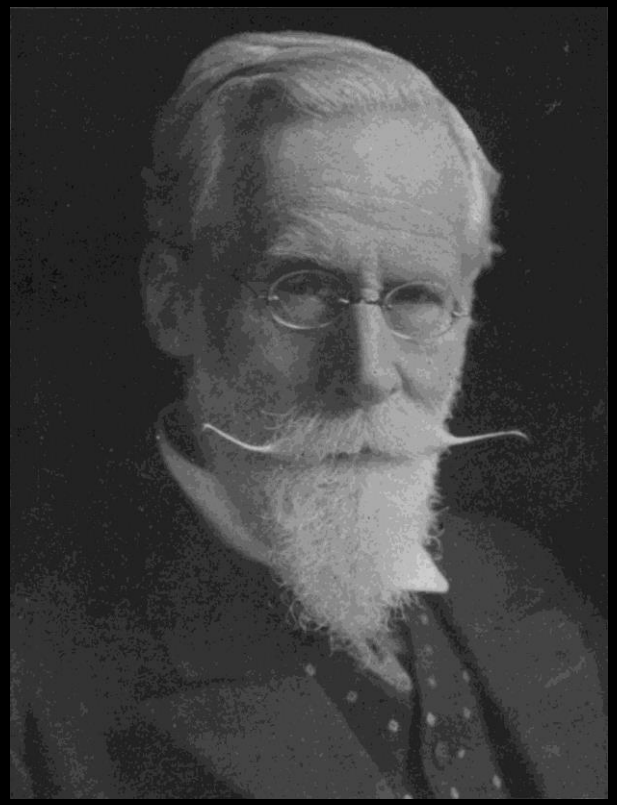
We need a different measure of “wealth”.

The world needs a new model of how to generate a rising standard of living that is not dependent on population growth, and increased production and consumption of “stuff”

The Human Development Index (the logarithm of GDP/person, longevity and level of education) is a step in the right direction.

“Wealth and quality of life” should include **longevity + quality of health in old age, security, continuing education, living comfort.**

end



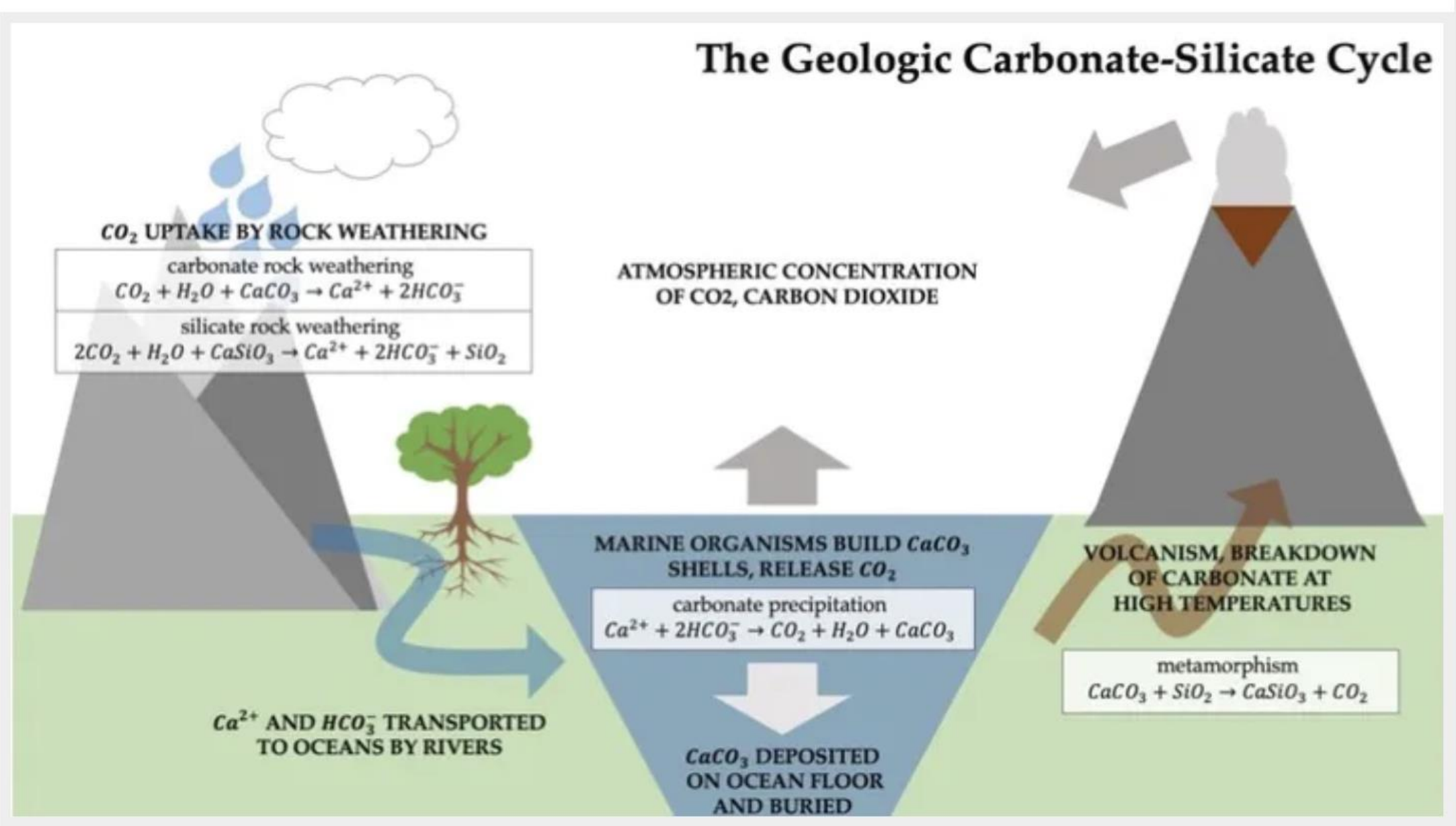
In 1898, Sir William Crookes delivers his inaugural lecture as President of the British Association for the Advancement of Science.

"England and all civilized countries are in deadly peril"

Europe was running out of saltpeter ($NaNO_3$) fertilizer from South America Unless a substitute was found, millions would starve.

"It is the chemist who must come to the rescue…before we are in the actual grip of actual dearth, the chemist will step in and postpone the day of famine to so distant a period that we and our sons and grandsons may legitimately live without undue solicitude for the future."

The natural carbon sequestration via the conversion of silicates to carbonates?



Accelerating Carbonate Mineralization with for High Speed, Low-cost and Scalable Carbon Removal (Yi Cui, Steven Chu, Arun Majumdar, …)

Net reaction: $CaSiO_3\,(s) + CO_2(g) = CaCO_3(s) + SiO_2(s)$

The relevant reactions could involve the following:

$CaSiO_3\,(s) + H_2O\,(l) \rightarrow Ca^{2+}\,(aq) + HSiO_3^{-}\,(aq) + OH^{-}\,(aq)$

$CO_2\,(g) \rightarrow CO_2\,(aq)$

$CO_2\,(aq) + OH^{-}\,(aq) \rightarrow HCO_3^{-}\,(aq)$

$HCO_3^{-}\,(aq) + OH^{-}\,(aq) \leftrightarrow H_2O\,(l) + CO_3^{2-}\,(aq)$

$Ca^{2+}\,(aq) + CO_3^{2-}(aq) \rightarrow CaCO_3\,(s)$

$HSiO_3^{-}\,(aq) \rightarrow SiO_2\,(s) + OH^{-}\,(aq)$

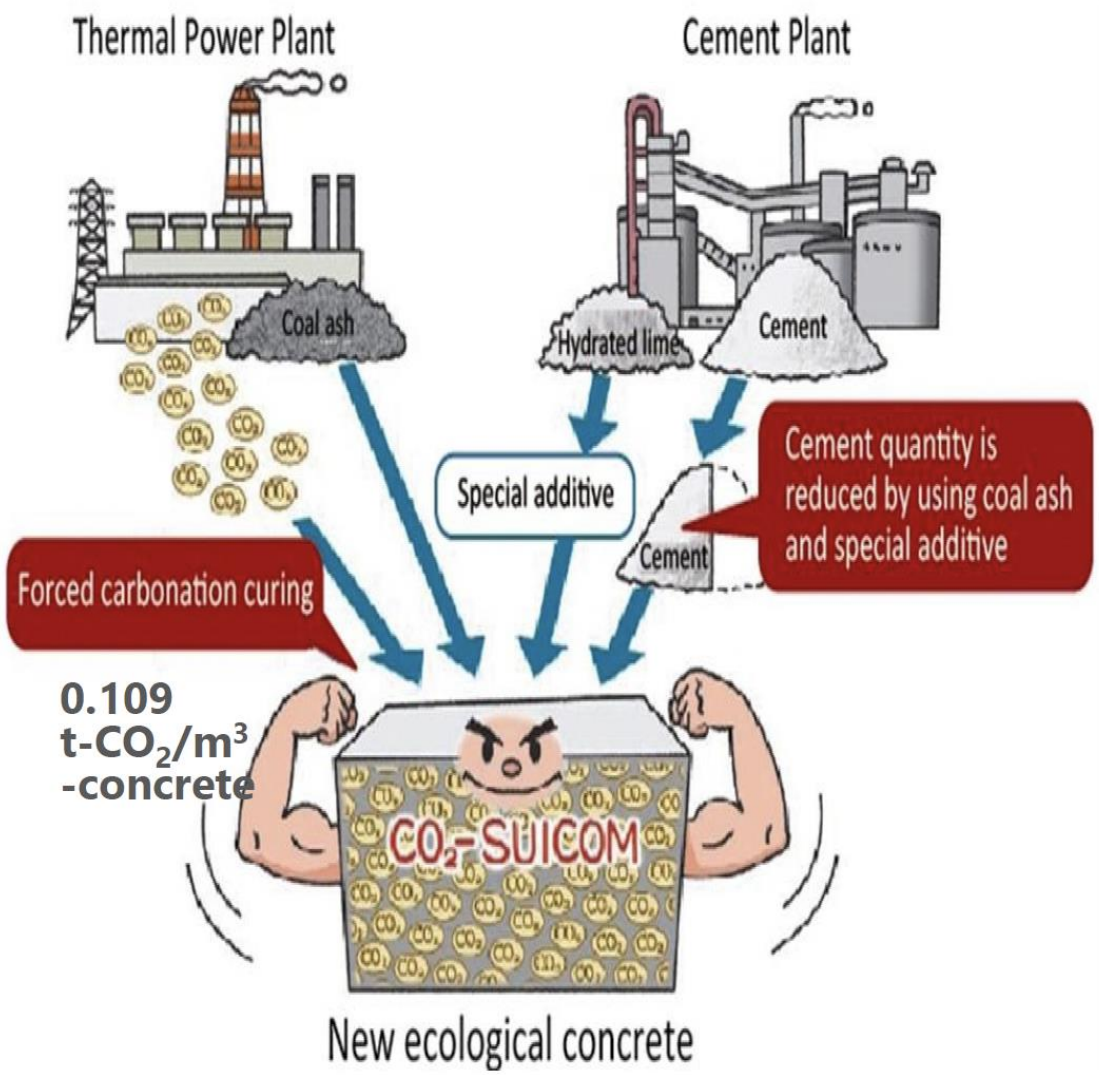
Viridos (formerly Synthetic Genomics), founded by Craig Venter and Hamilton Smith in 2005, increased the algae production of biofuel (jet fuel) with *Nannochloropsis gaditana* algae by 5-6x while maintaining the reproductive rate.

Global investment in biofuel production dropped from £22.9 billion in 2007 to $500 million in 2019.

Viridos and ExxonMobil's target is to produce 10,000 barrels of algal biofuels a day by 2025

CO_2 absorption through concrete curing

- **CO_2-SUICOM** is an abbreviation of **CO_2-Storage Under Infrastructure by COncrete Materials**
- **CO_2-SUICOM** is the world's first concrete product that makes CO_2 emission from the production of cement below zero by utilizing coal ash and special additive as substitute of cement and absorbing CO_2 from power plant



Source: Chugoku Electric Power Co., Inc. press release

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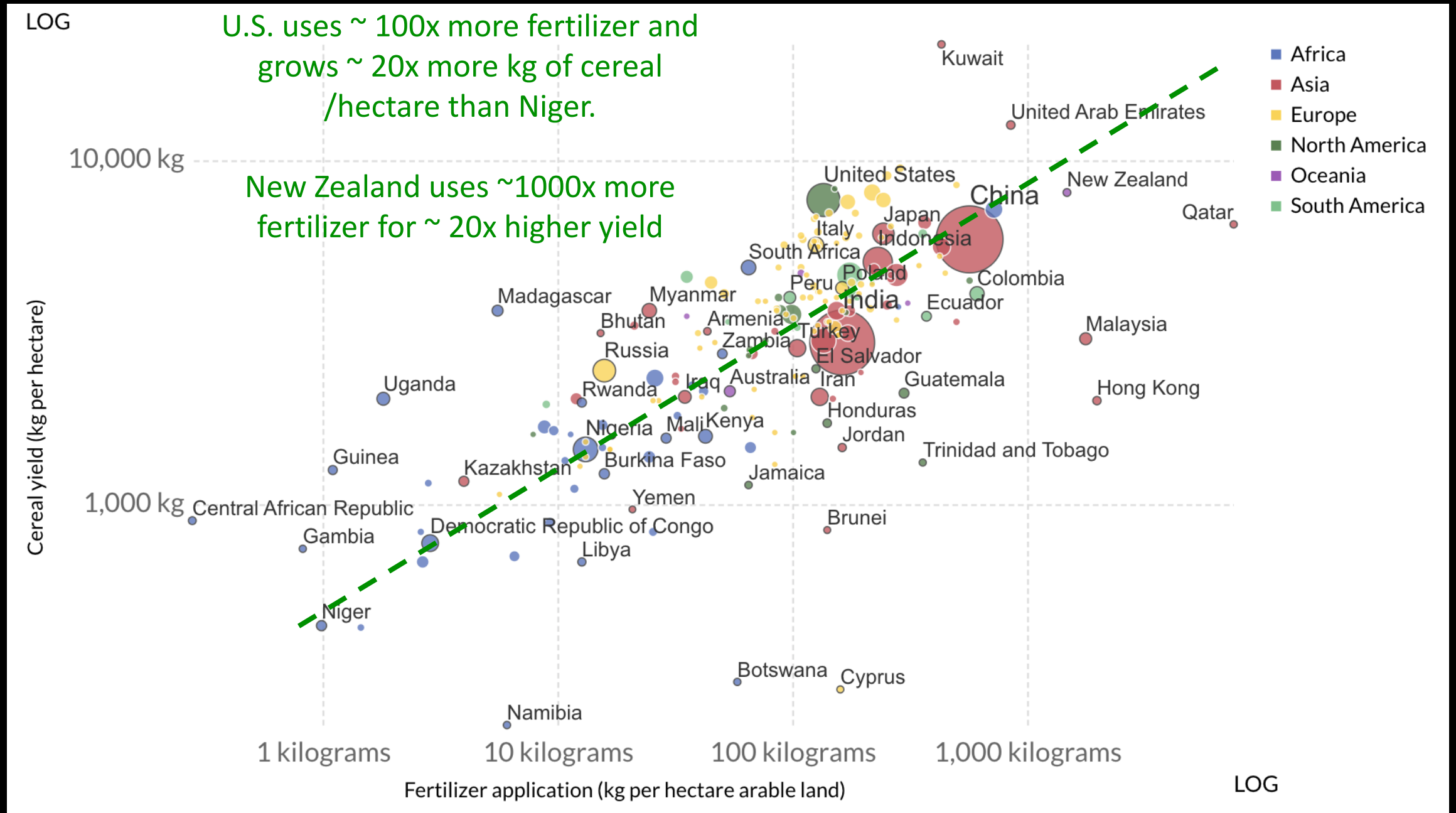
“Wealth and quality of life” should include

How much per gallon of gasoline does it cost to ship and store crude oil?

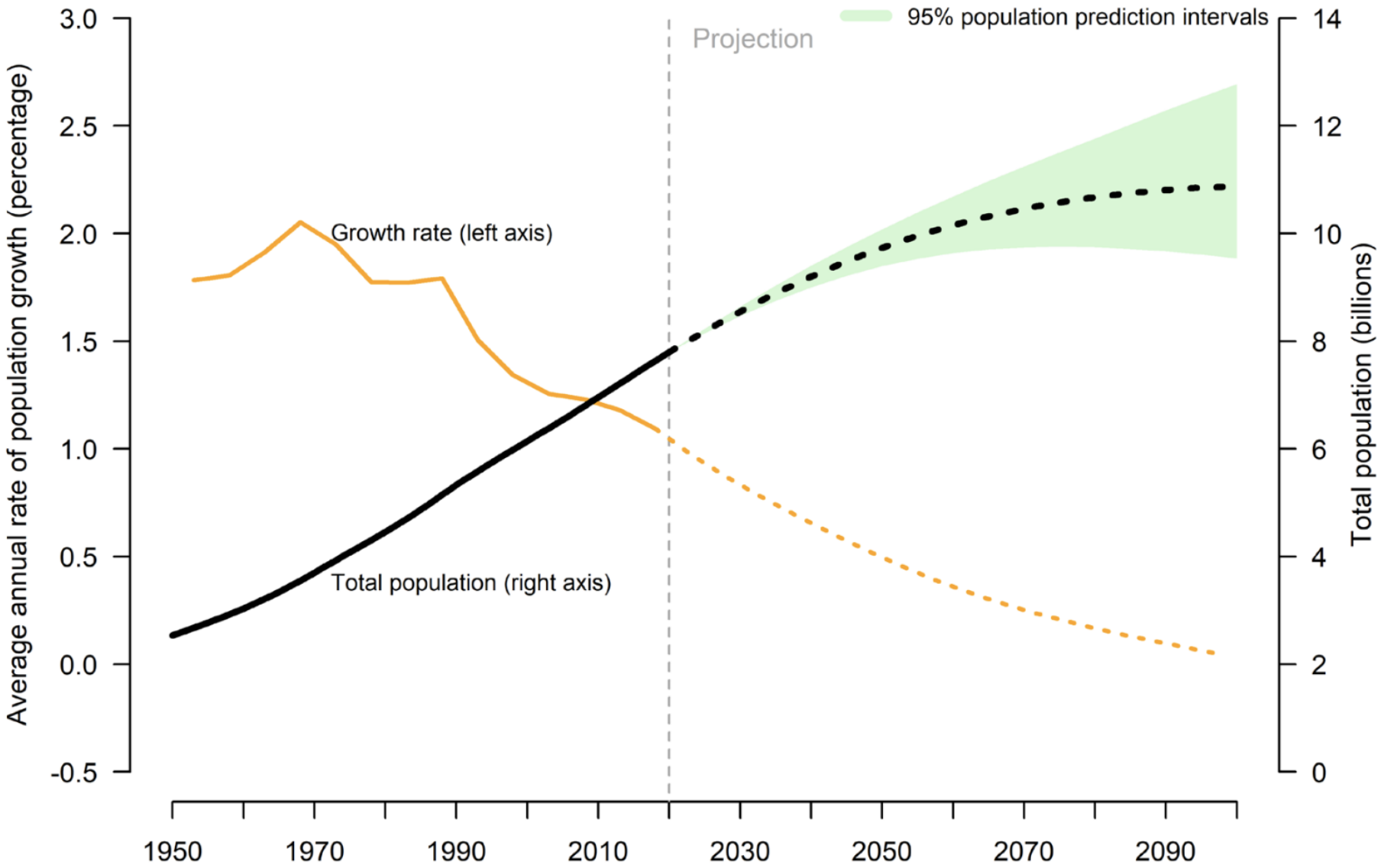
2 ¢ /gallon of gasoline.

Oil tankers are intercontinental energy "transmission lines"

Cereal crop yield vs. fertilizer application (2014)



The world population (currently 7.8 B) may peak at 11 B at 2100



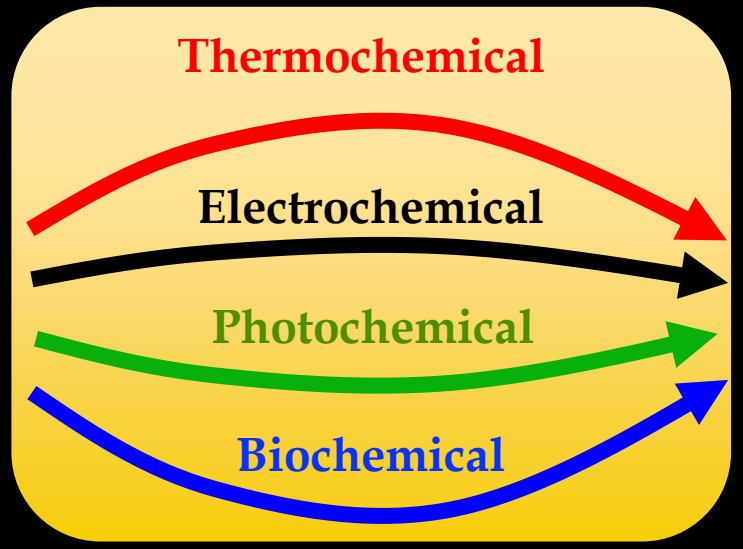
Source: U.N. Dept. of Economic and Social Affairs Population Division, World Population

A challenge for the 21st Century

100% renewable energy will require
recycling combustion products

CO_2

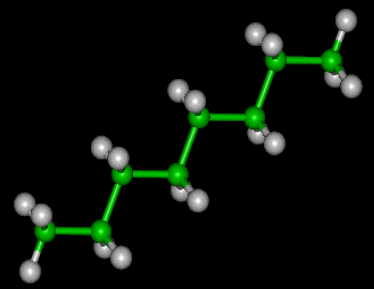
H_2O



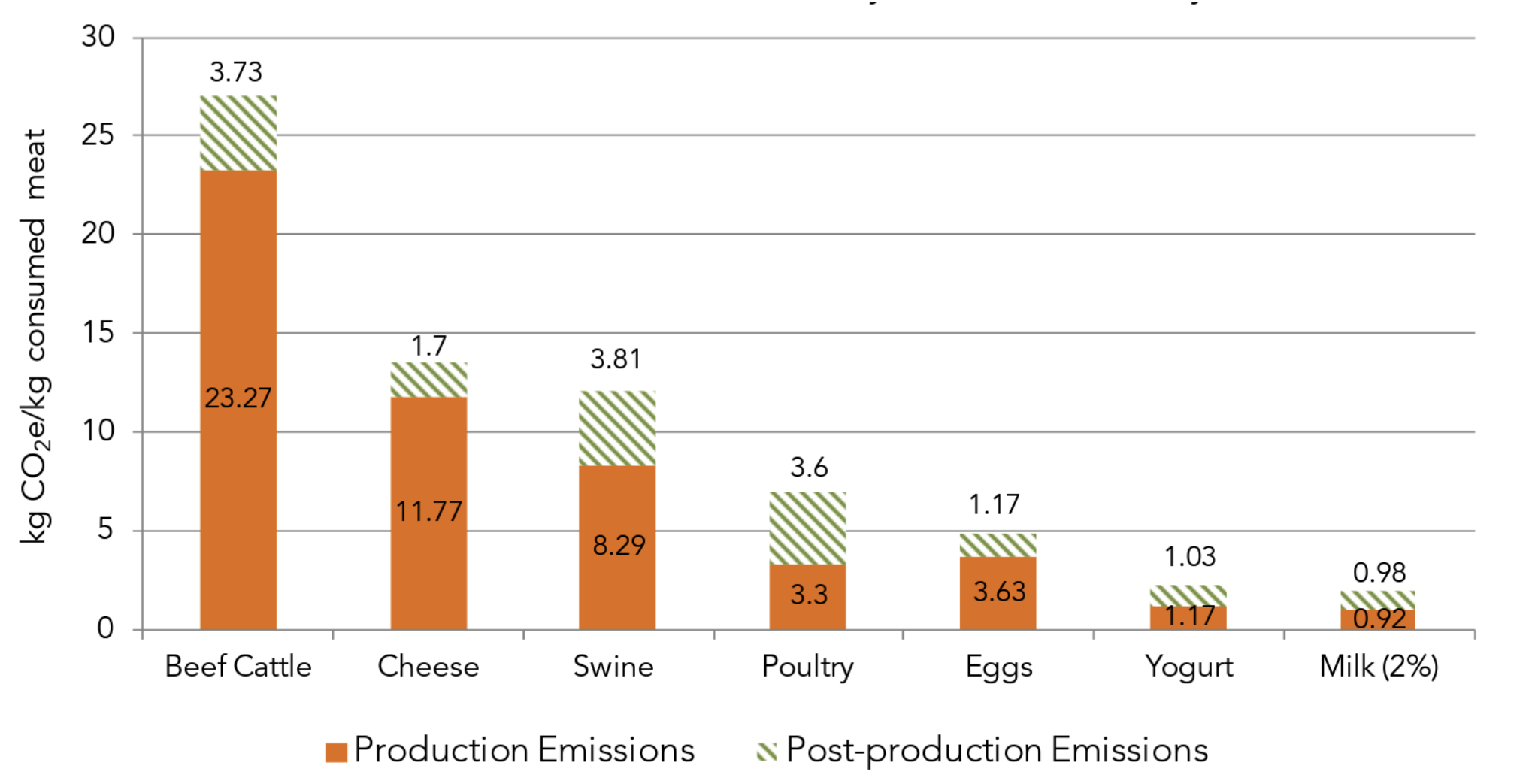
H_2, CO

H_2 , O_2

Liquid hydro-carbon

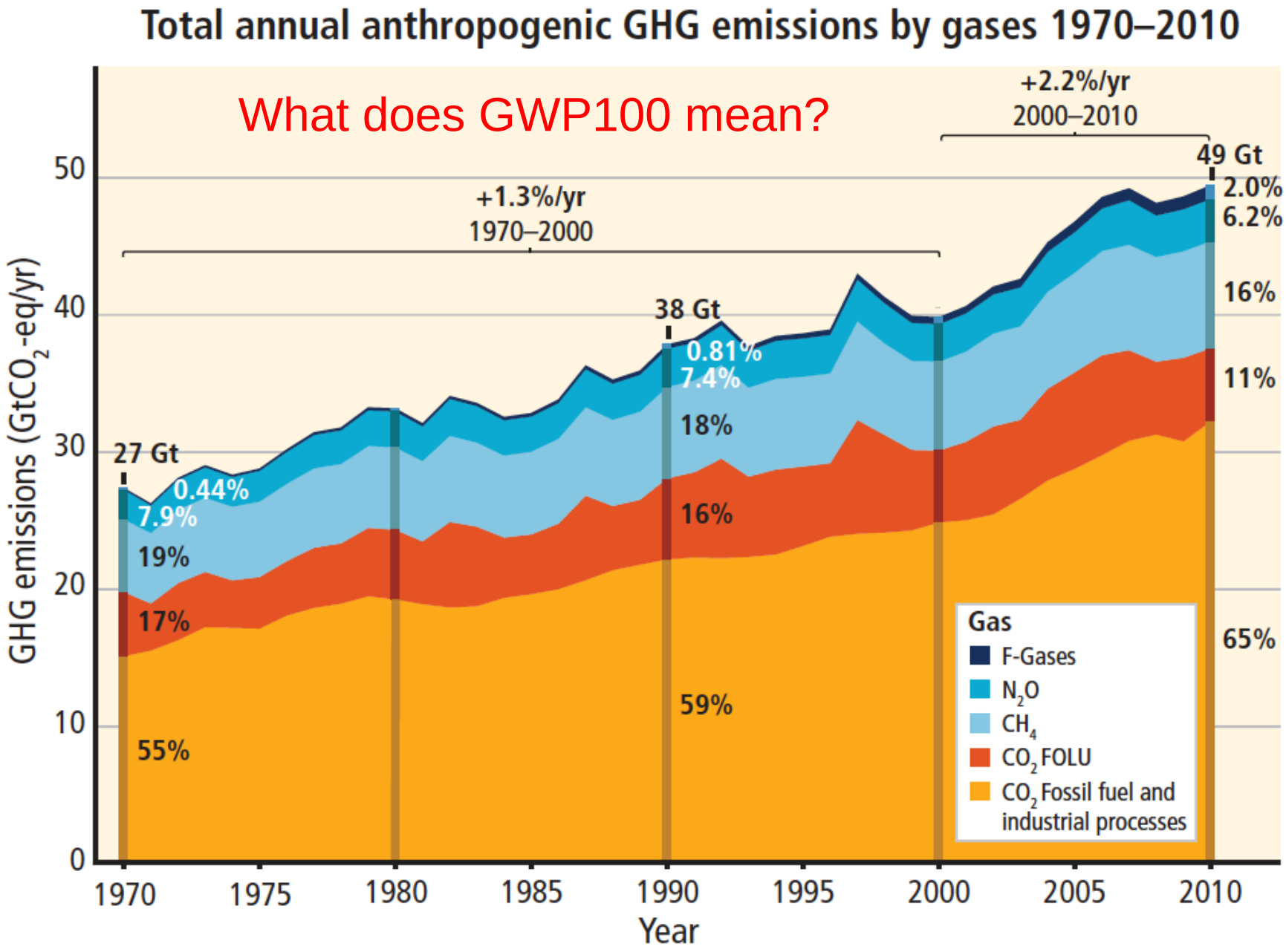


Life Cycle Assessment emissions for beef cattle, dairy, swine and poultry



Greenhouse Gas Emissions from Livestock and Poultry, C. S. Dunkley, K. D. Dunkley, Agric. Food Anal. Bacteriol. 3: 17-29, 2013

We will need a 4th agricultural revolution



Source: IPCC Summary for Policy Makers 2014

Calculated based on 100-year Global Warming Potential (GWP100)

CO_2 from fossil fuel combustion and industrial processes

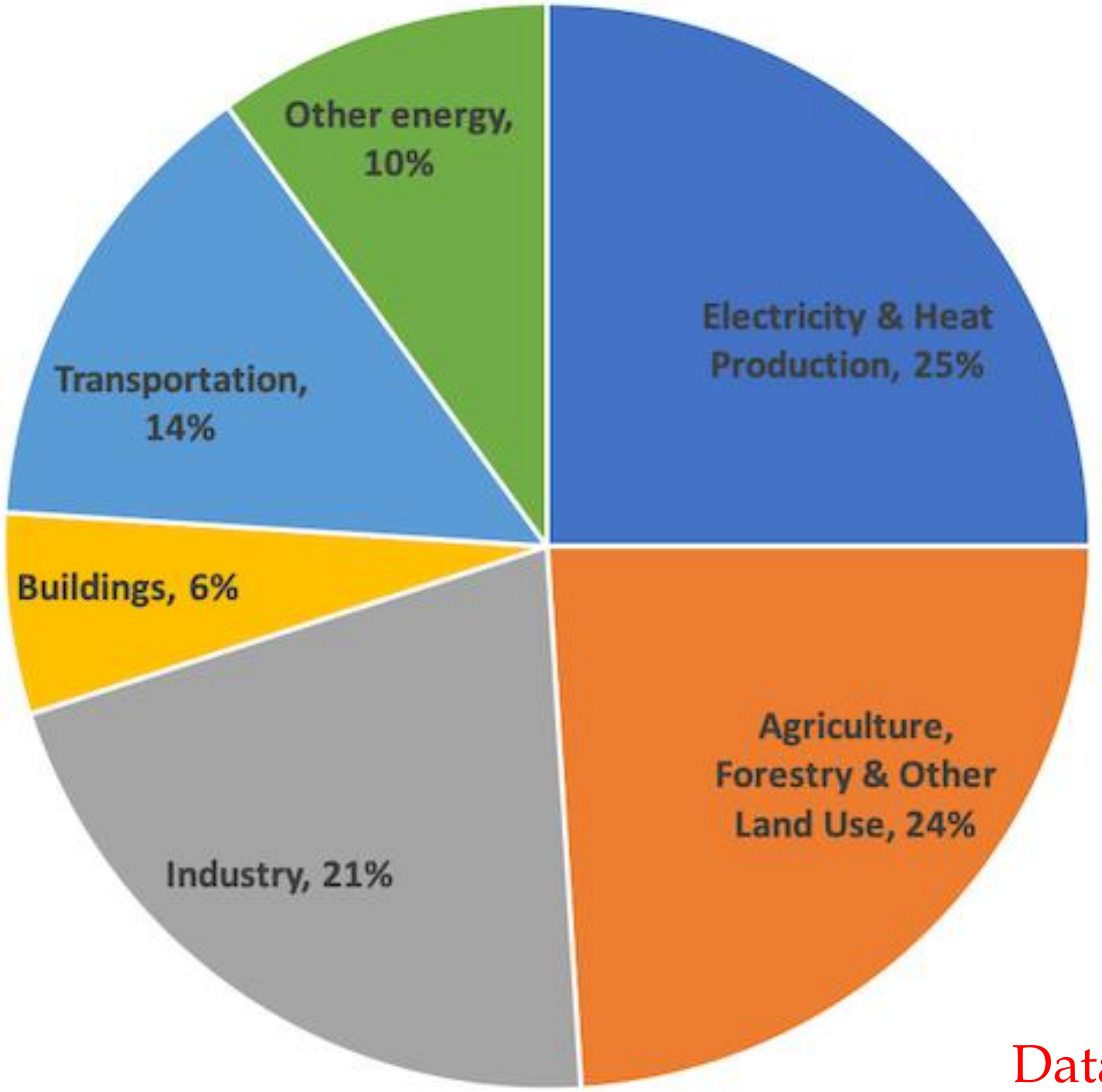
FOLU: CO_2 from Forestry and Other Land Use

CH_4: Methane

N_2O: Nitrous oxide

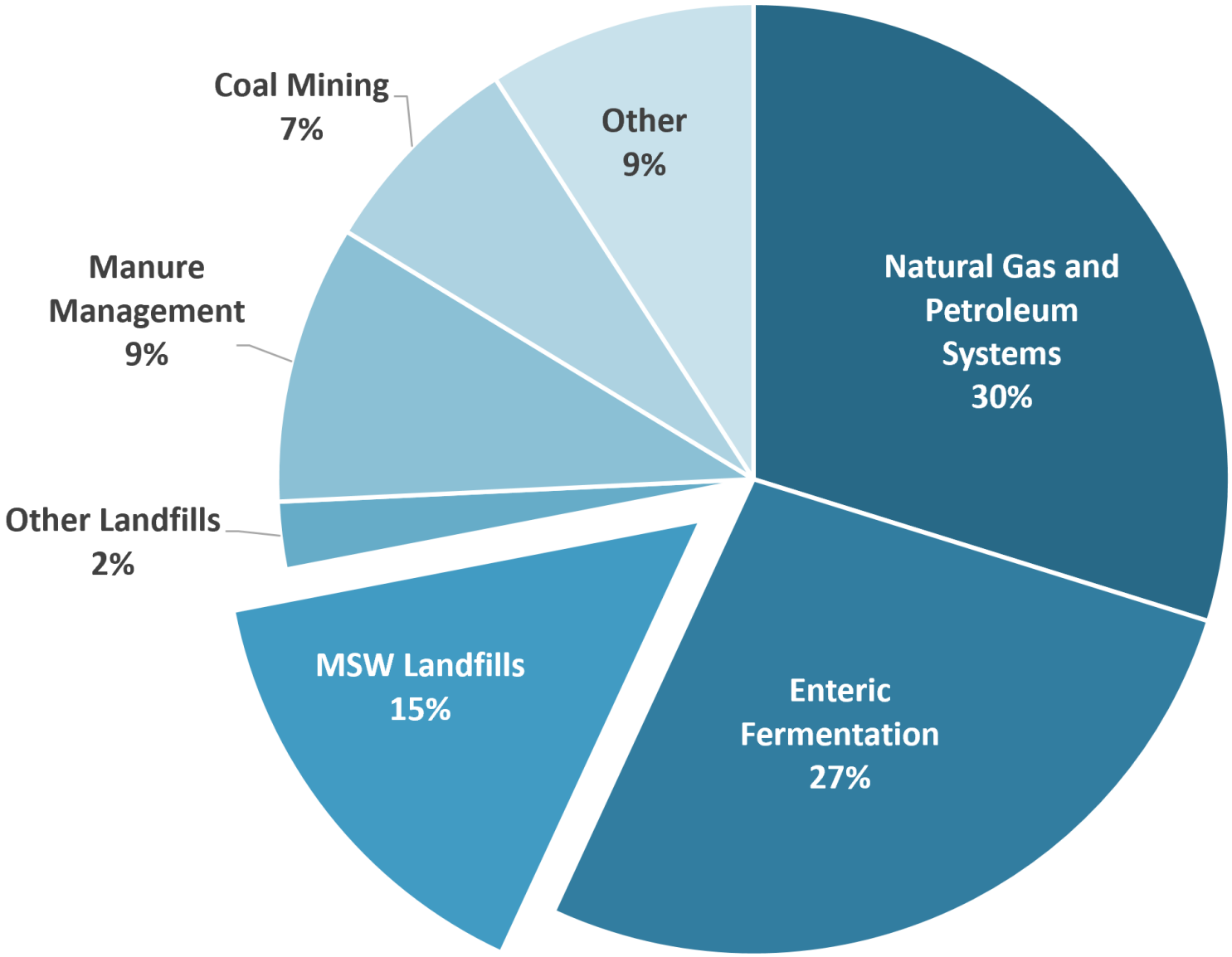
F-gases: Fluorinated gases covered under the Kyoto Protocol

Global Greenhouse Gas Emissions by Economic Sector



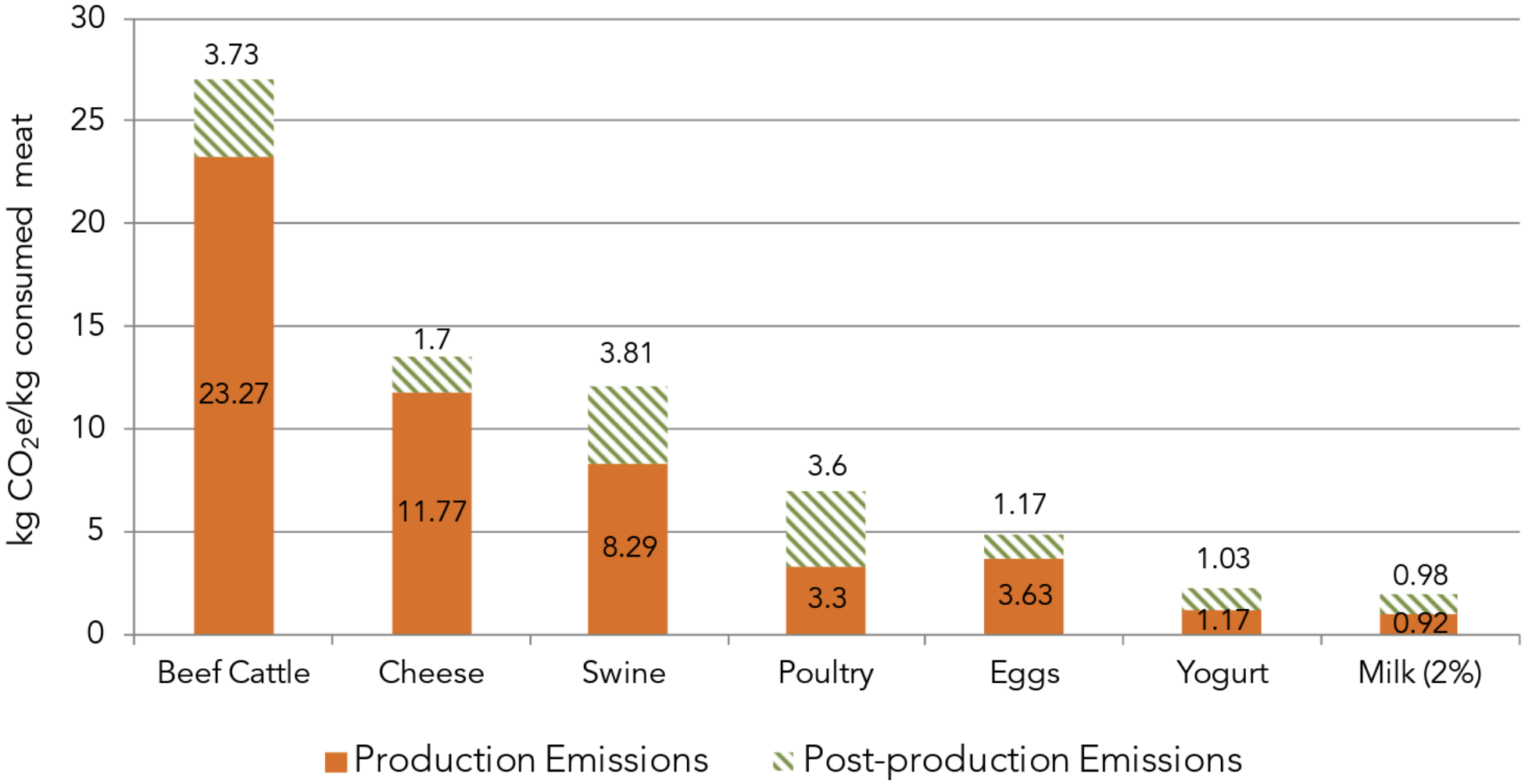
Data from the IPCC 2014 Report

2019 U.S. Methane Emissions, By Source



Note: All emission estimates from the *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2019*. U.S. EPA. 2021.

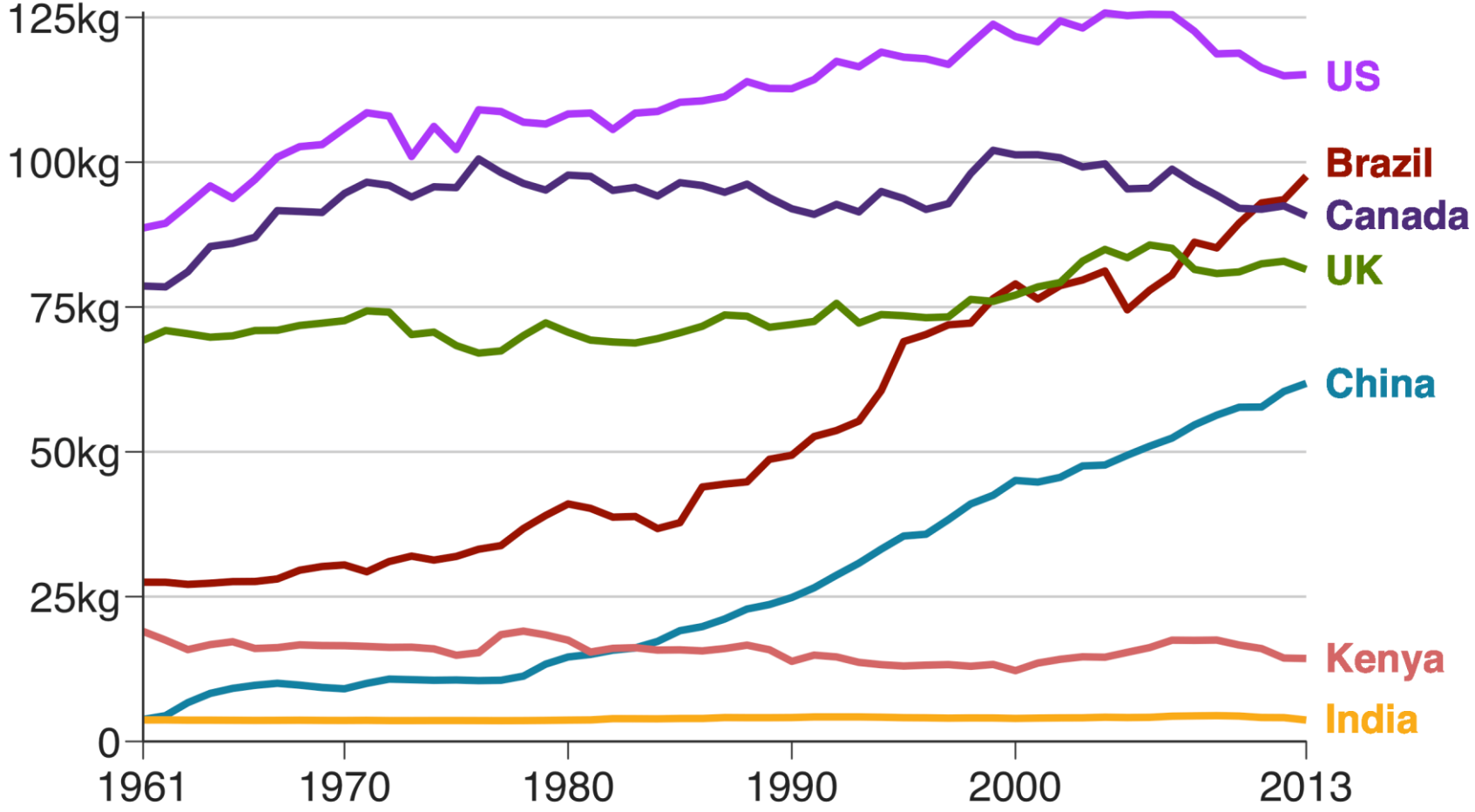
Life Cycle Assessment emissions for beef cattle, dairy, swine and poultry



Greenhouse Gas Emissions from Livestock and Poultry, C. S. Dunkley, K. D. Dunkley, Agric. Food Anal. Bacteriol. 3: 17-29, 2013

Meat consumption by selected country

Average annual consumption per person



Source: UN Food and Agriculture Organization / Our World in Data

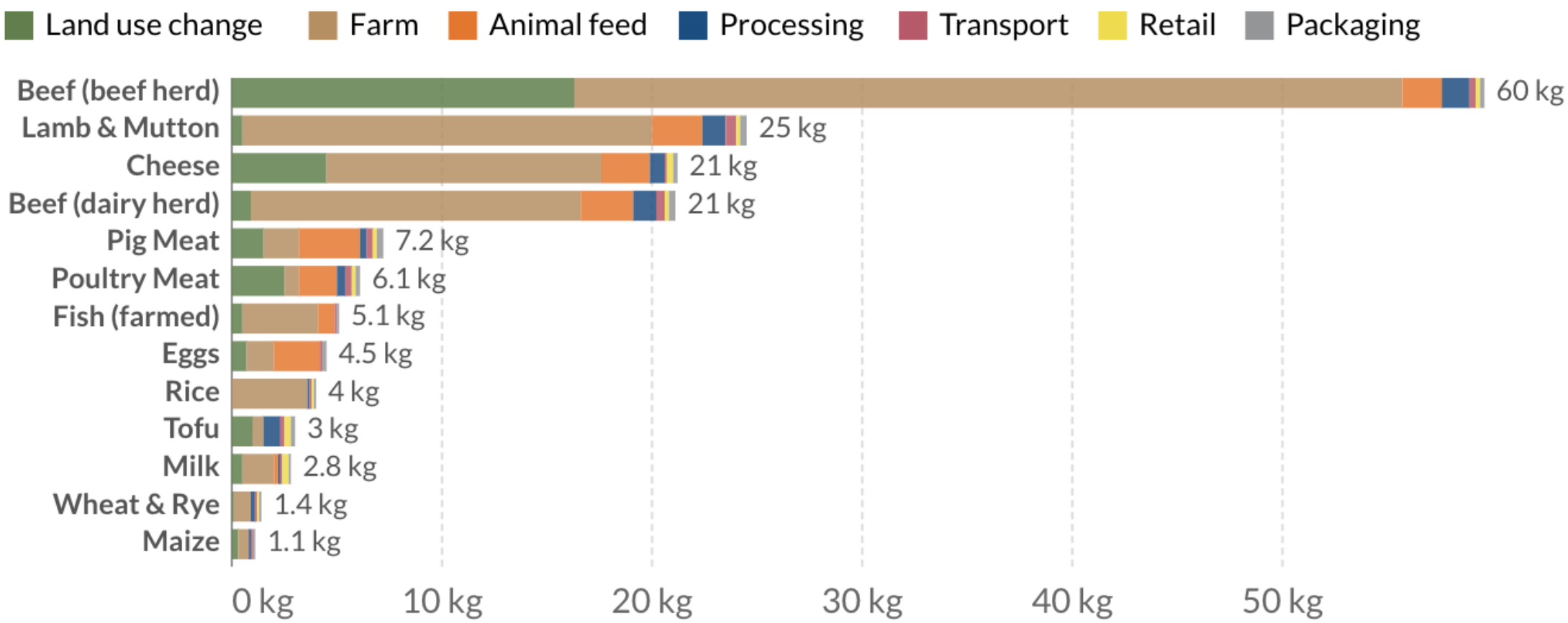
BBC

Food: greenhouse gas emissions across the supply chain

Our World in Data

Greenhouse gas emissions are measured in kilograms of carbon dioxide equivalents ($kgCO_2eq$) per kilogram of food. This means non-CO_2 greenhouse gases are included and weighted by their relative warming impact.

Add food Relative



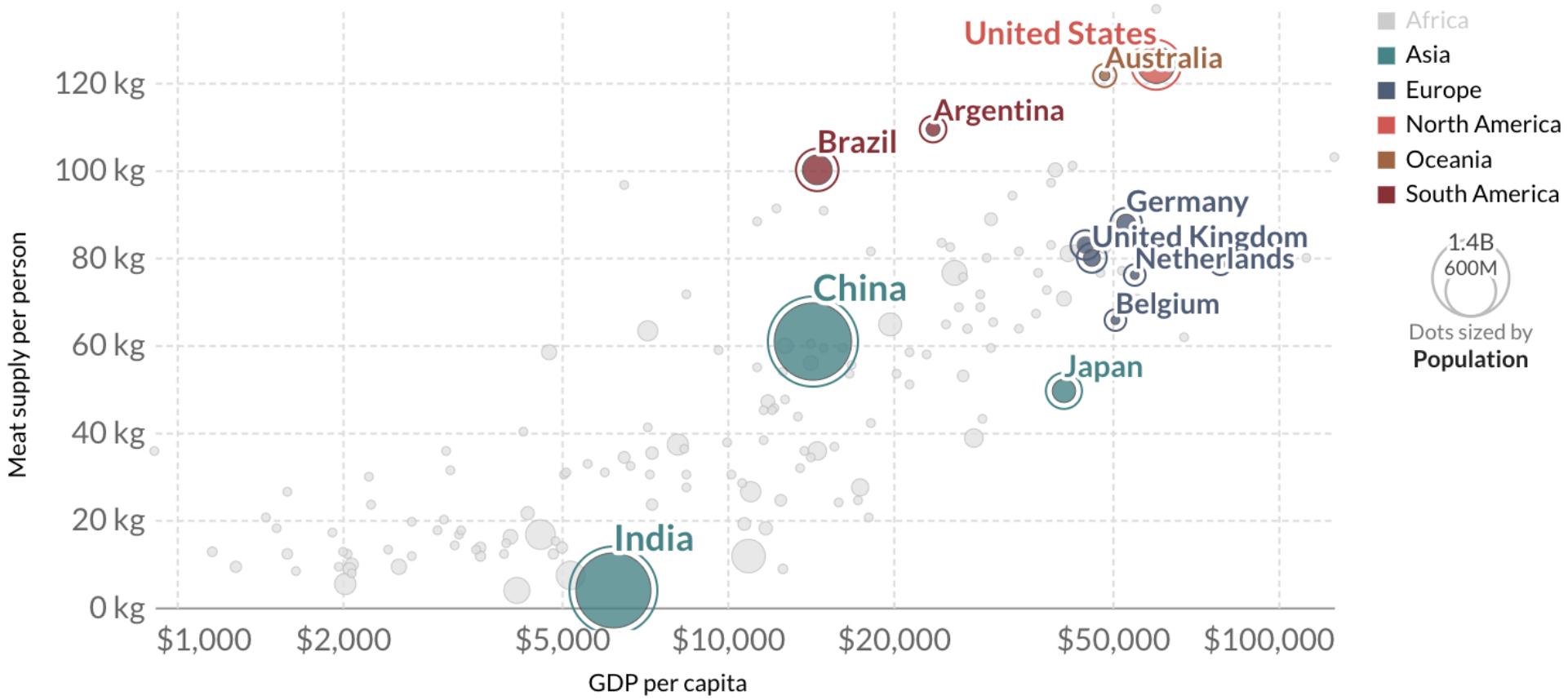
Source: Poore, J., & Nemecek, T. (2018). Reducing food's environmental impacts through producers and consumers. Science.
OurWorldInData.org/environmental-impacts-of-food • CC BY

Meat consumption vs. GDP per capita, 2017

Our World in Data

Average meat consumption per capita, measured in kilograms per year versus gross domestic product (GDP) per capita measured in constant international-$. International-$ corrects for price differences across countries. Figures do not include fish or seafood.

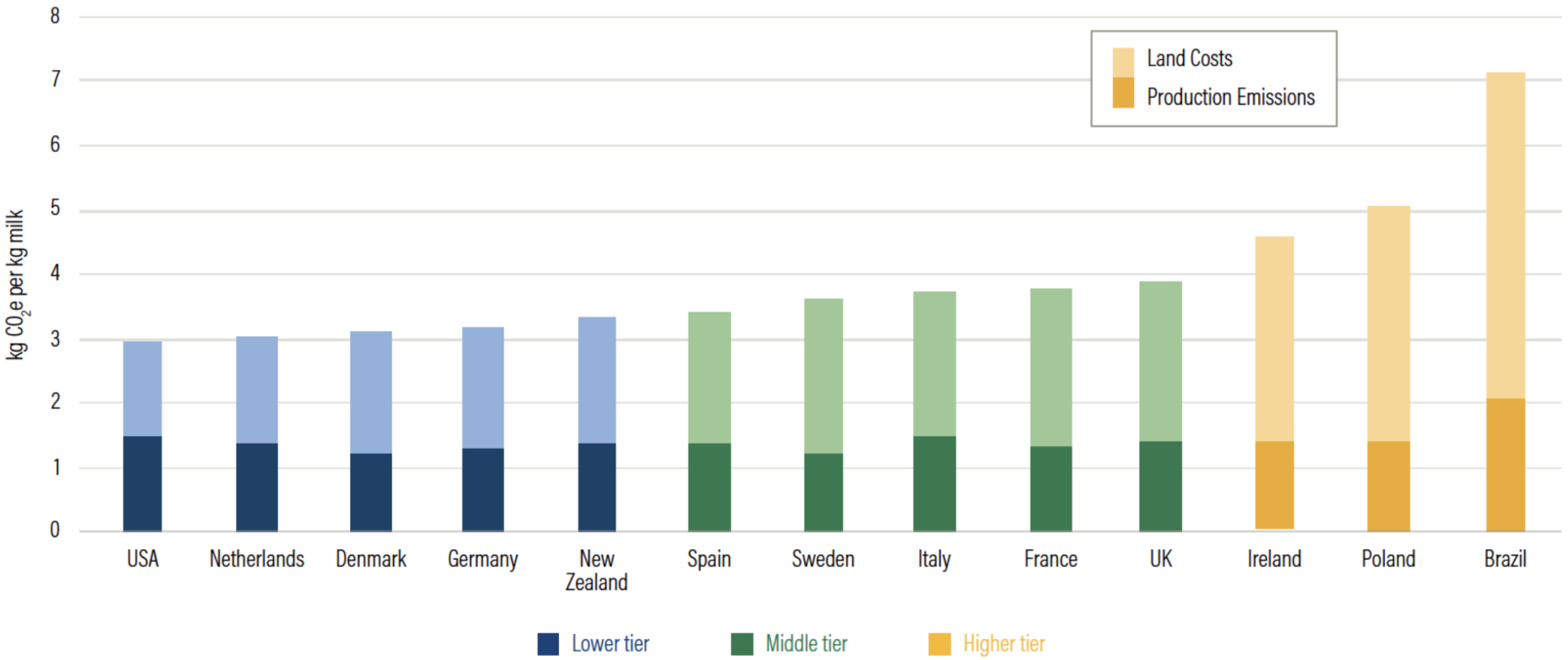
Y: LINEAR | Y: LOG | X: LINEAR | X: LOG | Select countries | Zoom to selection | Average annual change | More



Source: Food and Agriculture Organization of the United Nations, Data compiled from multiple sources by World Bank
OurWorldInData.org/meat-production • CC BY

1990 2017

Figure 1 | Production and Dairy Emissions by Country



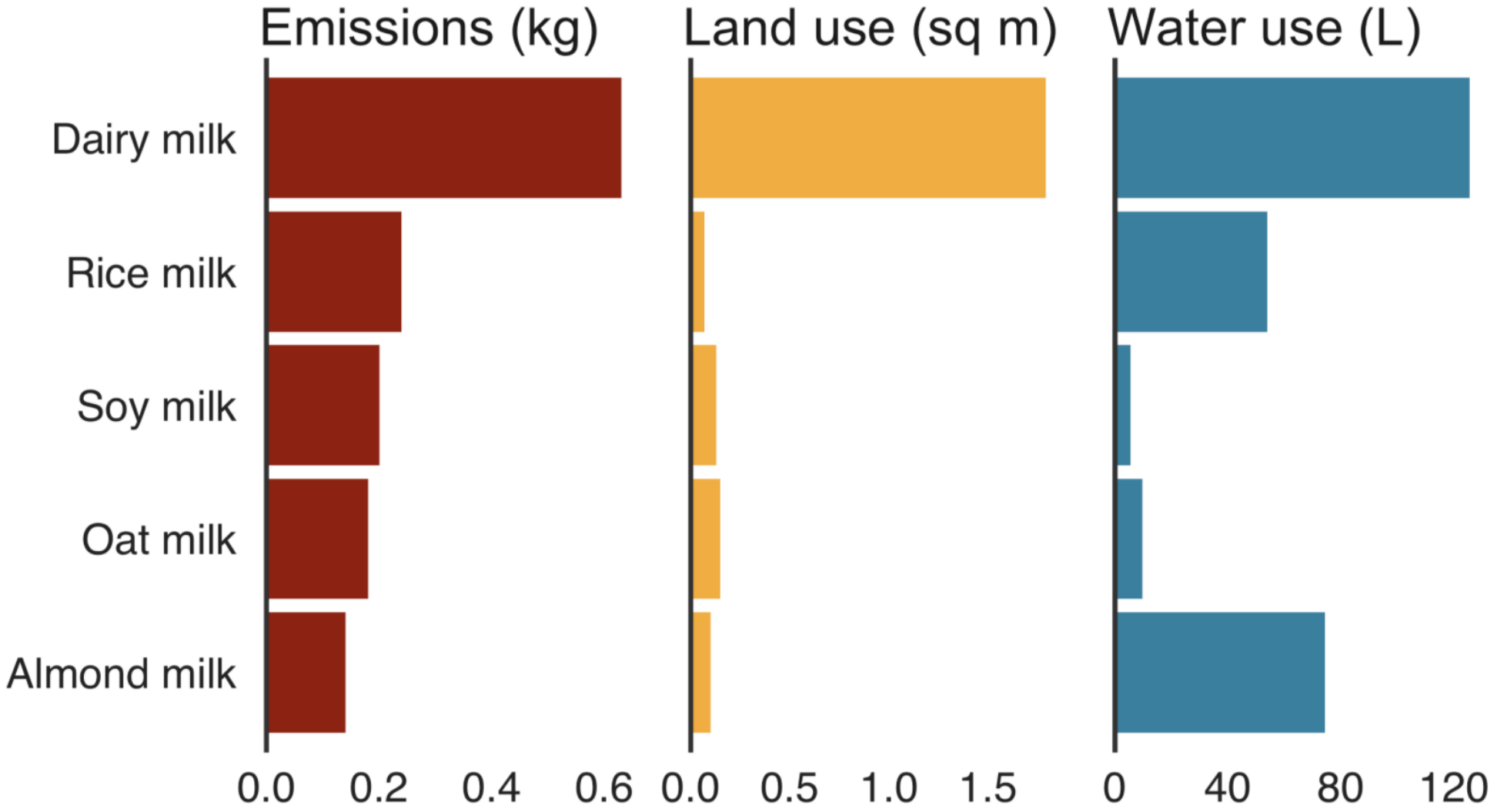
Notes: CO_2 = carbon dioxide.
Source: Authors' calculations.

Figure 2 | **Pork Efficiencies by Country**

Notes: CO_2 = carbon dioxide.
Source: Authors' calculations.

Which milk should I choose?

Environmental impact of one glass (200ml) of different milks

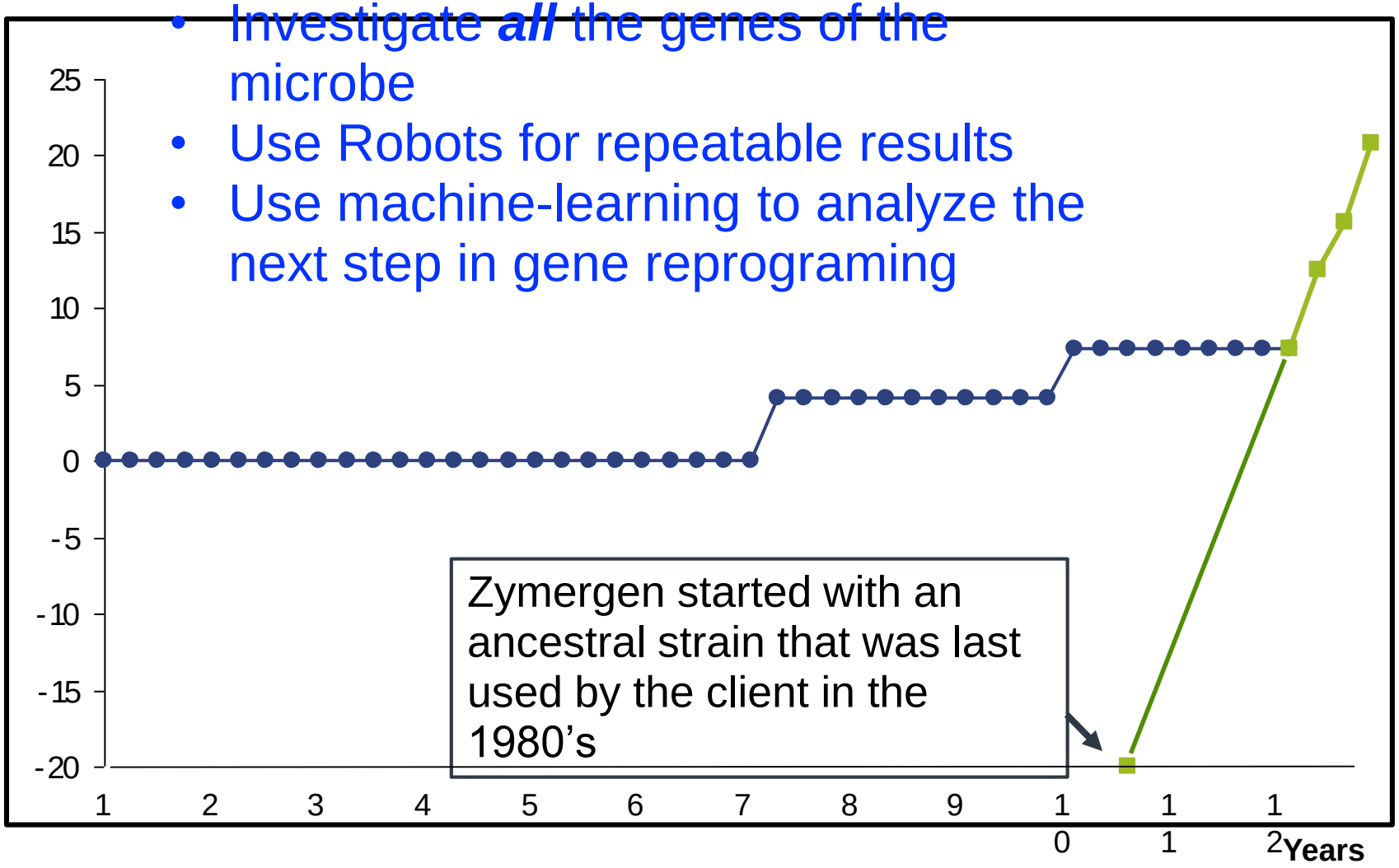


Source: Poore & Nemecek (2018), Science. Additional calculations, J. Poore

BBC

zymergen

- Investigate ***all*** the genes of the microbe
- Use Robots for repeatable results
- Use machine-learning to analyze the next step in gene reprograming



Direct Air Capture of10 – 20 Giga tonnes of CO_2 will be needed to achieve negative emissions

Accelerating Carbonate Mineralization with for High Speed, Low-cost and Scalable Carbon Removal (Yi Cui, Steven Chu, Arun Majumdar, …)

Net reaction: $CaSiO_3\,(s) + CO_2(g) = CaCO_3(s) + SiO_2(s)$

The relevant reactions could involve the following:

$CaSiO_3\,(s) + H_2O\,(l) \rightarrow Ca^{2+}\,(aq) + HSiO_3^{-}\,(aq) + OH^{-}\,(aq)$

$CO_2\,(g) \rightarrow CO_2\,(aq)$

$CO_2\,(aq) + OH^{-}\,(aq) \rightarrow HCO_3^{-}\,(aq)$

$HCO_3^{-}\,(aq) + OH^{-}\,(aq) \leftrightarrow H_2O\,(l) + CO_3^{2-}\,(aq)$

$Ca^{2+}\,(aq) + CO_3^{2-}(aq) \rightarrow CaCO_3\,(s)$

$HSiO_3^{-}\,(aq) \rightarrow SiO_2\,(s) + OH^{-}\,(aq)$

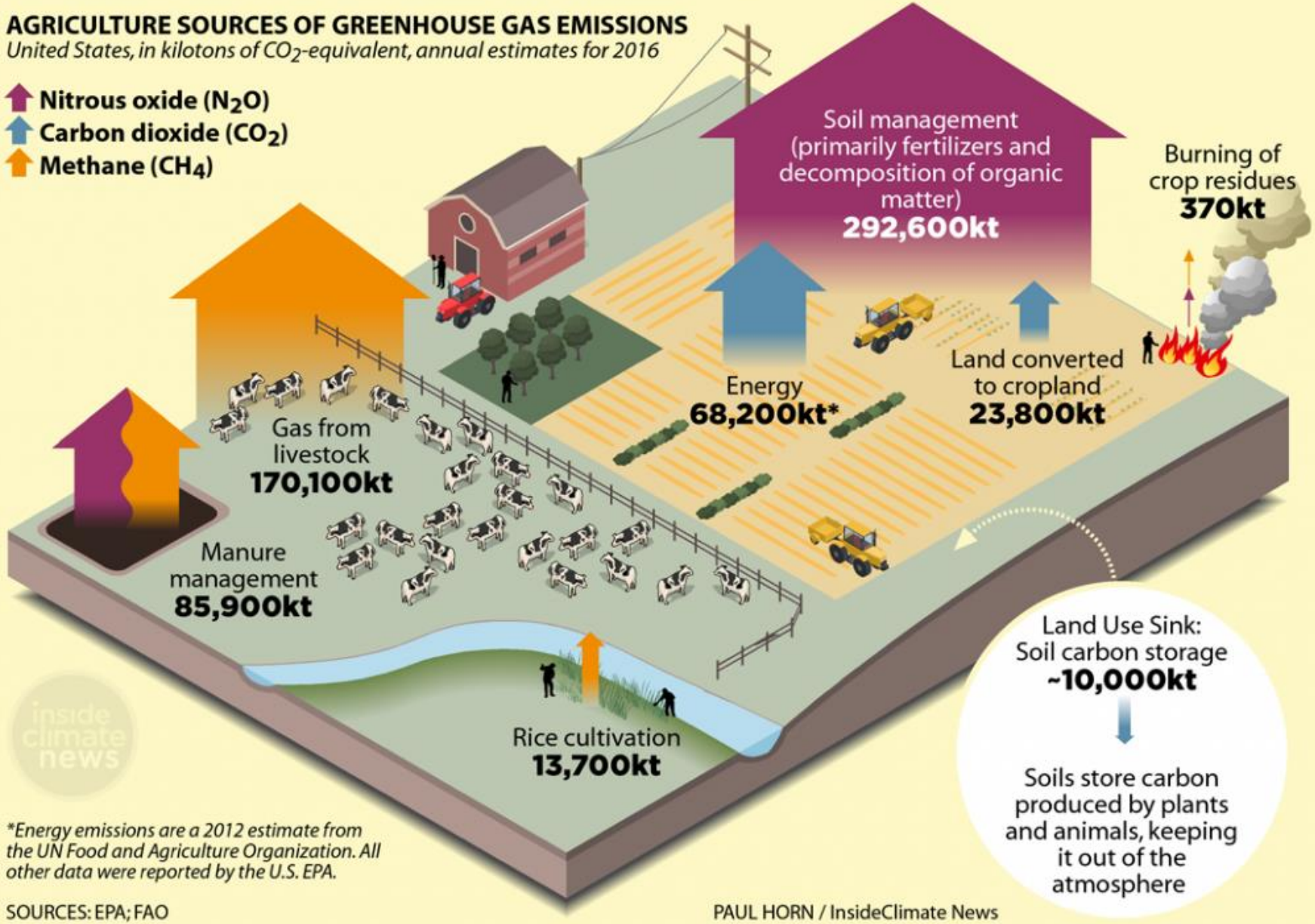
end

How Farms Contribute to Climate Change

Agriculture today is responsible for nearly a quarter of the world's greenhouse gas emissions. It's also threatened by climate change and uniquely positioned to fight it.

AGRICULTURE SOURCES OF GREENHOUSE GAS EMISSIONS

United States, in kilotons of CO_2-equivalent, annual estimates for 2016

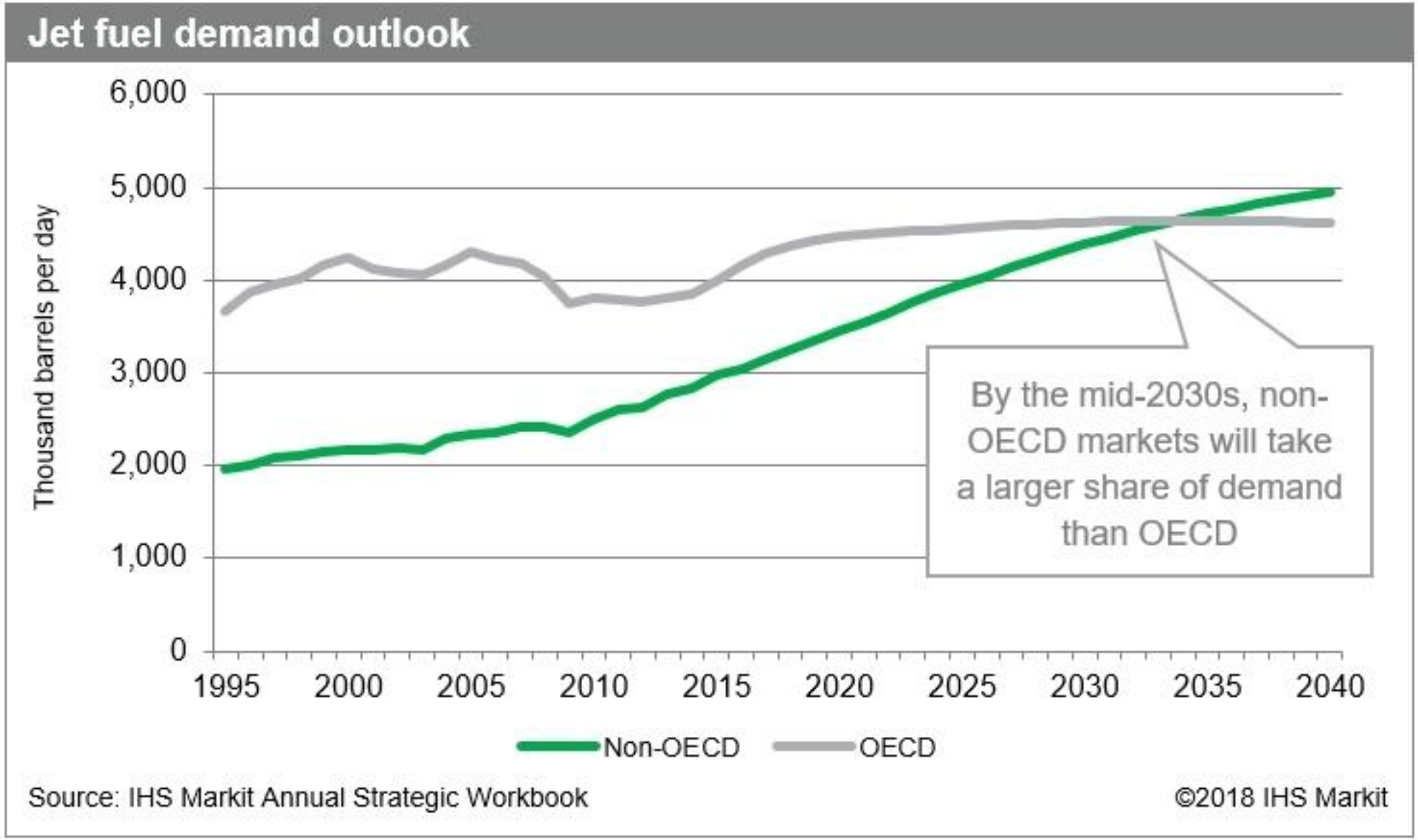


**Energy emissions are a 2012 estimate from the UN Food and Agriculture Organization. All other data were reported by the U.S. EPA.*

SOURCES: EPA; FAO

PAUL HORN / InsideClimate News

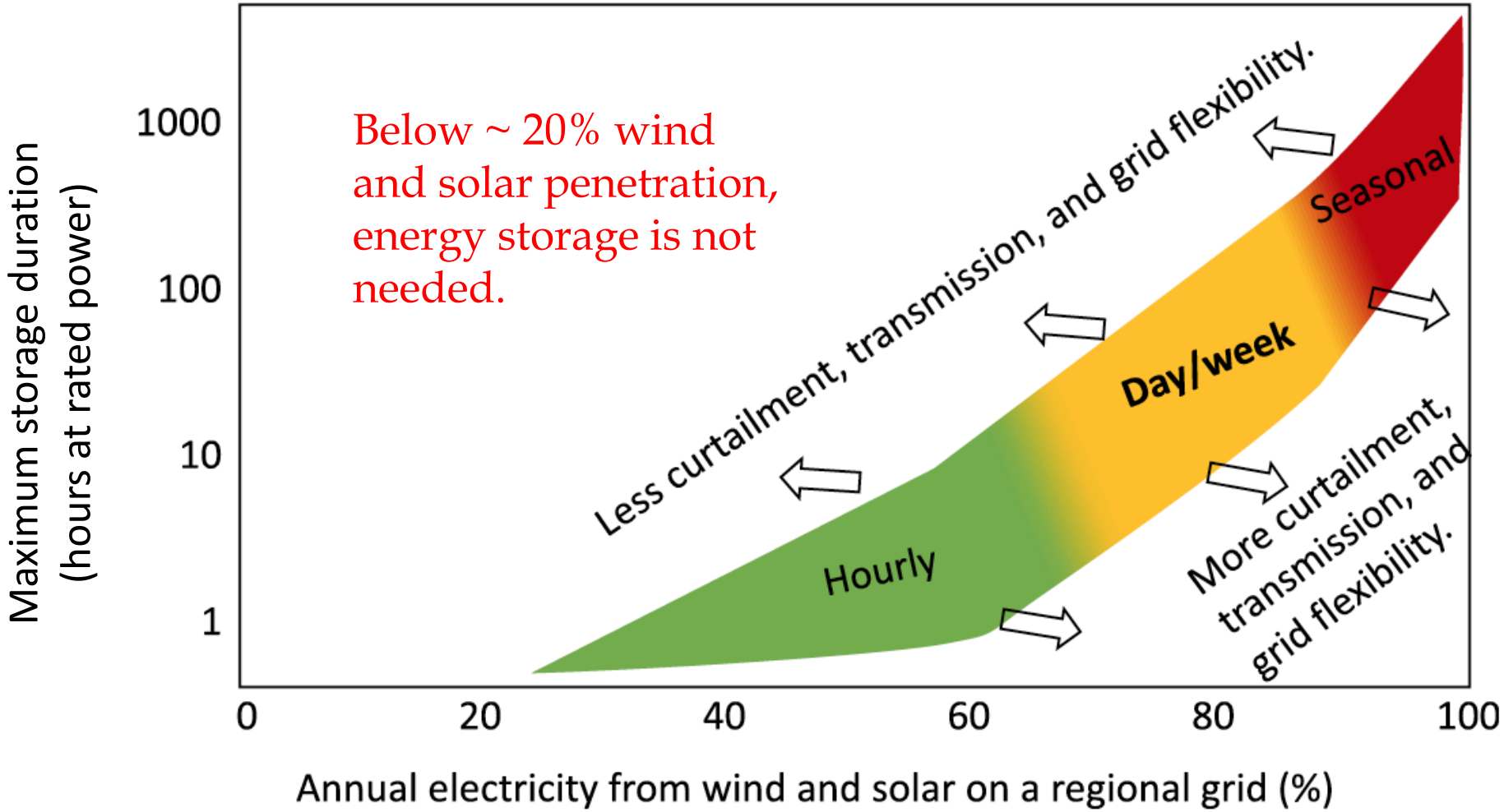
Current jet fuel consumption is ~ 8 million barrels per day (Viridos/Exxon-Mobil output will be 1.2 x 10^{-3} of jet fuel use)



Clean electricity at 1.5¢/kWh may become a reality in 10-20 years at the best sites.
This opens up exciting opportunities in electrochemistry.

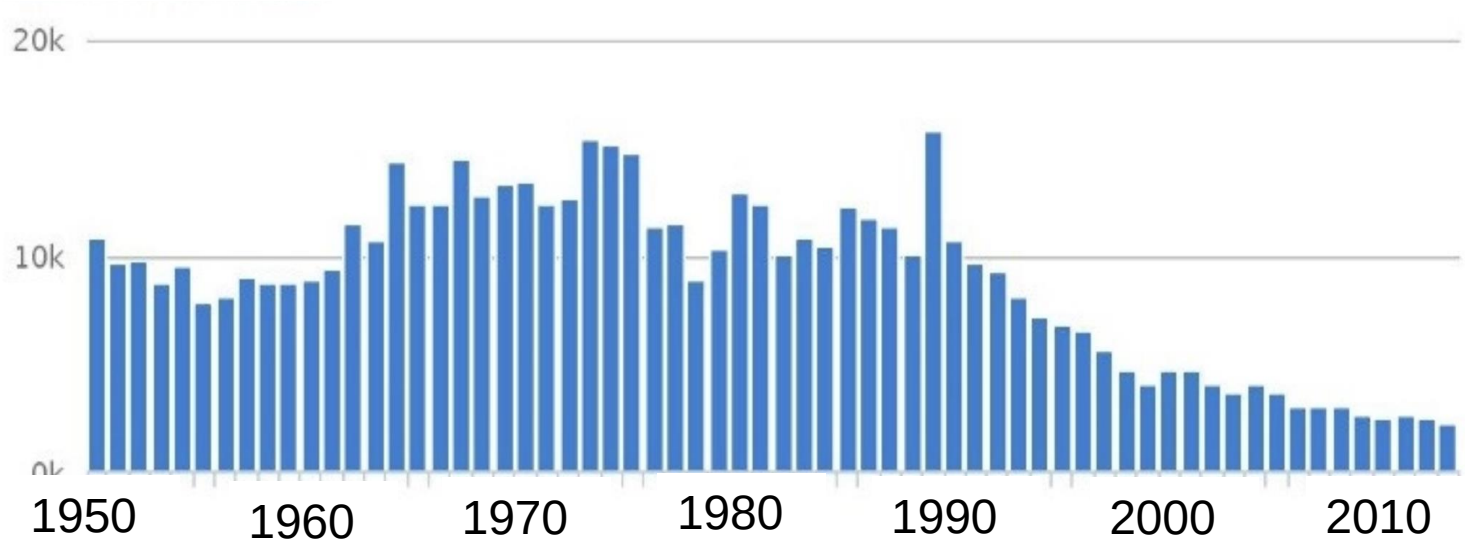
At 1.5 ¢/kWh, the cost of electricity to make hydrogen is ½ of the current price of hydrogen.

"Long-Duration Electricity Storage Applications, Economics, and Technologies,"
Paul Albertus, Joseph Manser, Scott Litzelman, Joule **4**, 21 - 32 (2020)



20 – 100 hours of energy to supply the US grid. In 2019, ~ 4.13 trillion kWh of utility-scale electricity was generated. There (365 d/yr)(24h/d) = 8.76 x 10^3 hr/yr. 100 hours of storage = 47.15 x 10^9 kWh = 4715 GWh storage. For summer peak months 2x – 3x will be needed.

Global Wild salmon catch (tonnes)



The salmon contains a growth hormone gene from the fast growing Pacific Chinook salmon and a promoter sequence from the ocean pout. The gene and promoter sequence enable the salmon to grow all year.

Approval process by the FDA took 20 years