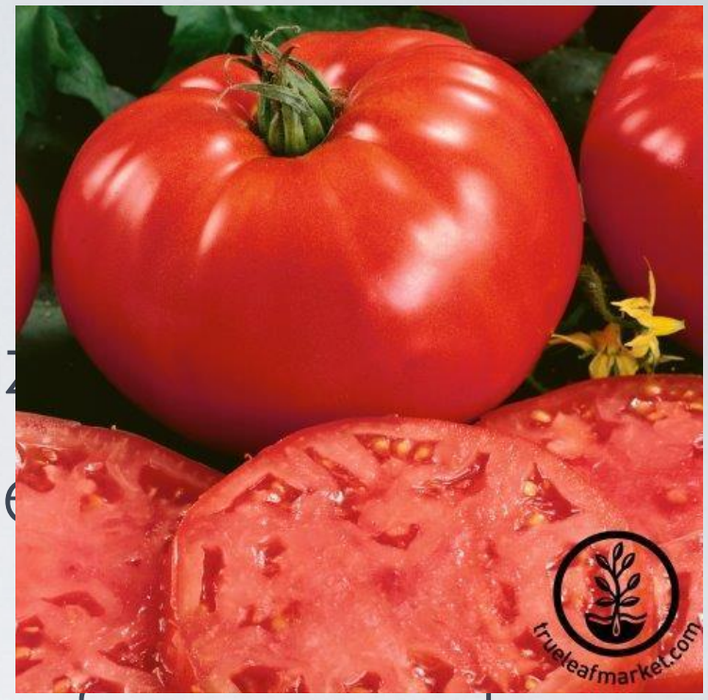
SUSTAINABILITY FROM THE VIEW OF A CHEMICAL ENGINEER

Mark J McCready
Professor of Chemical and Biomolecular Engineering
University of Notre Dame

OUTLINE



- Nature conservancy is an outstanding organiz
  serious threats from changes in the atmosphe

- Sustainability is associated with a wide range of issues and appears to have many different meanings.
  - We will examine this topic.

- What tradeoffs exist for future development of the energy to sustain our society and allow various parts of the world to develop?

OPENING REMARKS

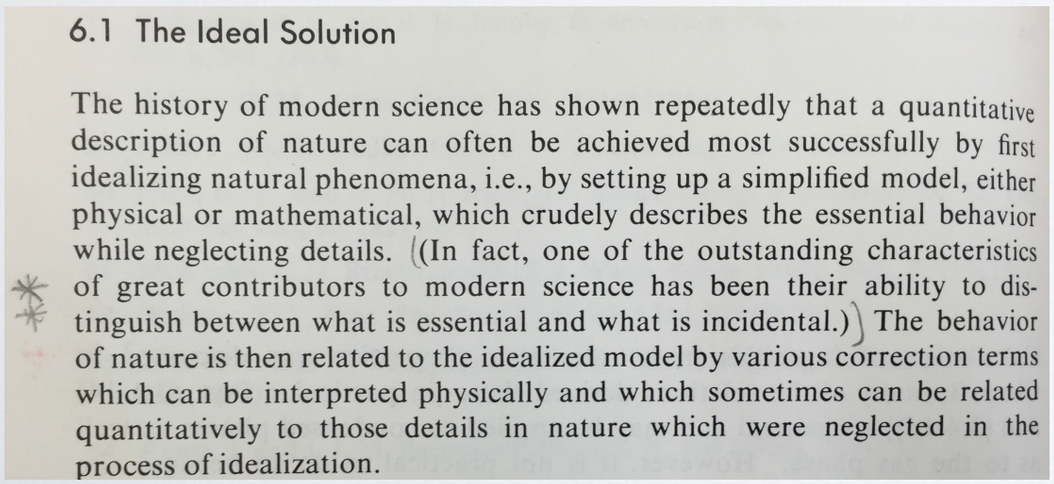
- For any complex system, there is considerable uncertainty in our quantitative and perhaps qualitative understanding
  - Scientists and engineers should always be clear about this.
- My background leads me to specific ways of considering such issues as energy technologies and sustainability.
- Regardless of our understanding, Science" does not provide a definite path forward for society
  - Policies that affect how we live our lives are political decisions — there are always tradeoffs.

HOW CAN WE THINK ABOUT HARD PROBLEMS?

- **… In fact, one of the outstanding characteristics of great contributors to modern science has been their ability to distinguish between what is essential from what is incidental) …"**

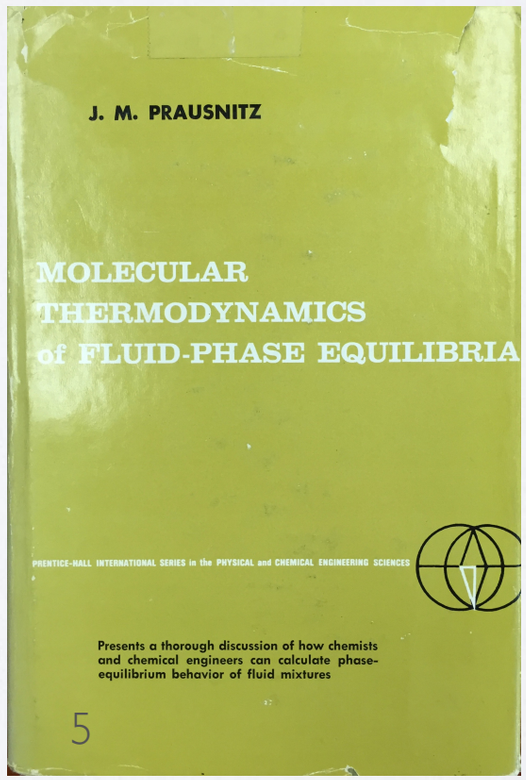
- John M. Prausnitz
- Professor of Chemical Engineering UC Berkeley
- An "academic uncle of mjm"

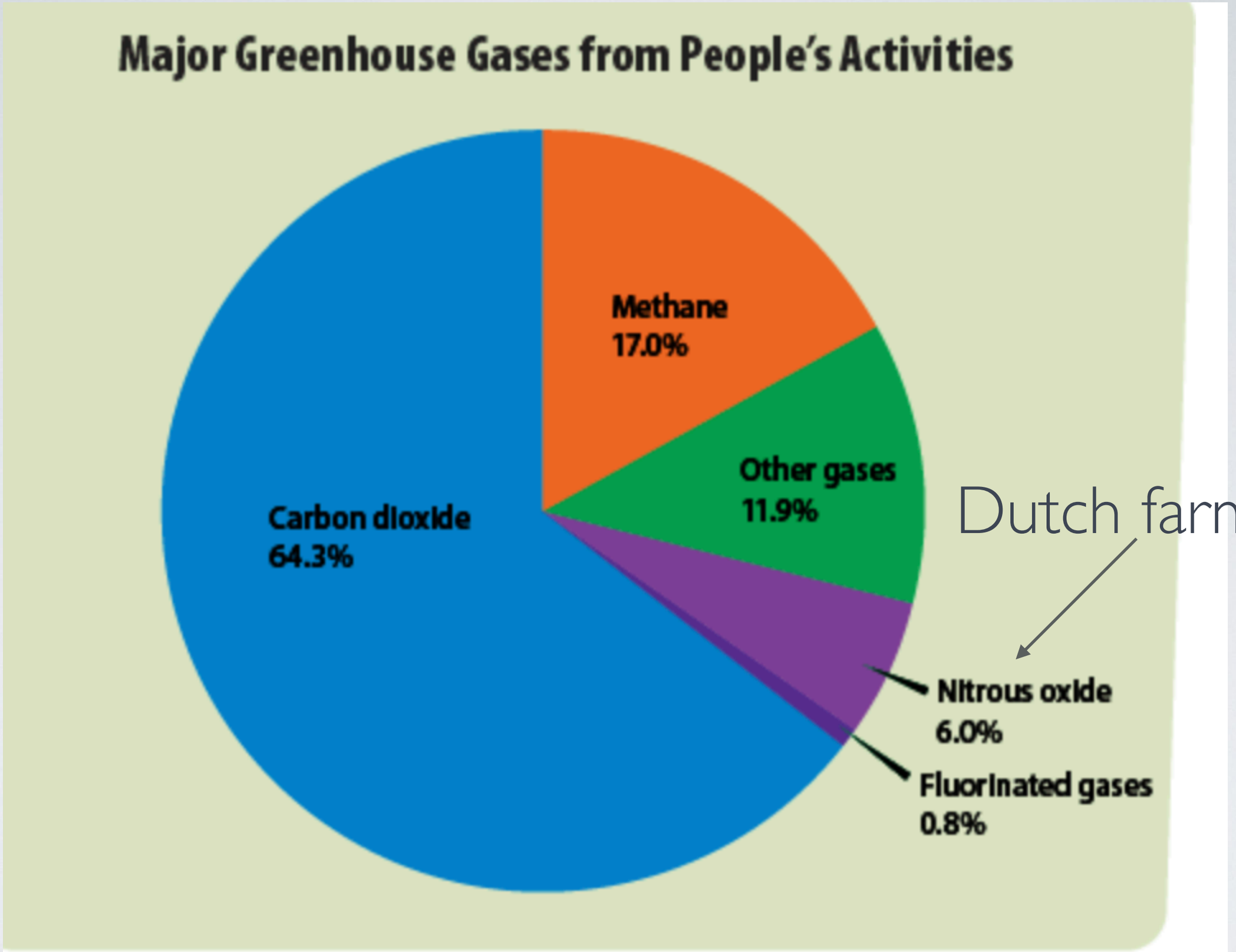
- From: Molecular Thermodynamics of Fluid Phase Equilibria



6.1 The Ideal Solution

The history of modern science has shown repeatedly that a quantitative description of nature can often be achieved most successfully by first idealizing natural phenomena, i.e., by setting up a simplified model, either physical or mathematical, which crudely describes the essential behavior while neglecting details. (In fact, one of the outstanding characteristics of great contributors to modern science has been their ability to distinguish between what is essential and what is incidental.) The behavior of nature is then related to the idealized model by various correction terms which can be interpreted physically and which sometimes can be related quantitatively to those details in nature which were neglected in the process of idealization.



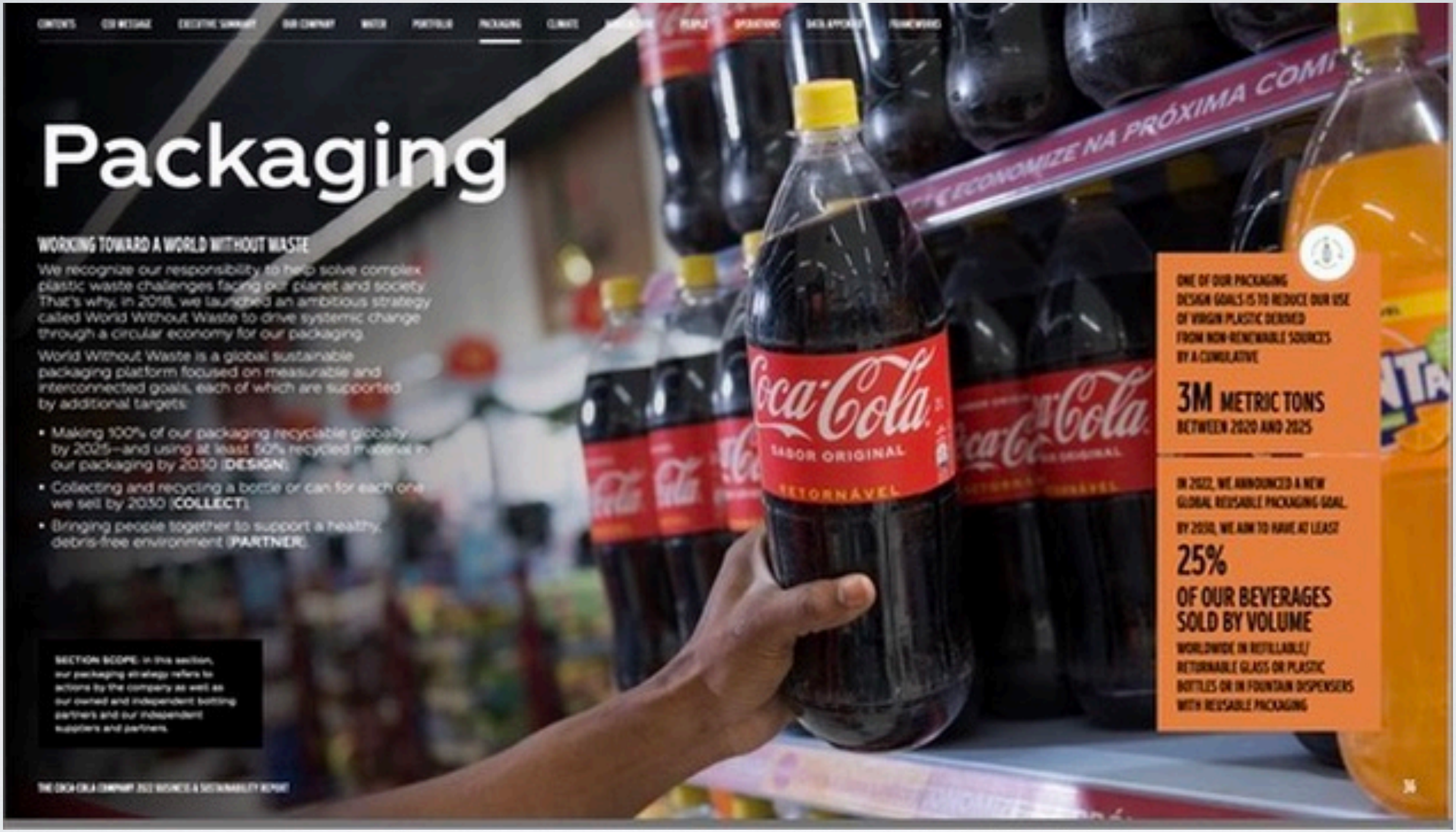


Dutch farmers!

The size of each piece of the pie represents the amount of warming that each gas is currently causing in the atmosphere as a result of emissions from people's activities.
Source: Intergovernmental Panel on Climate Change, Fifth Assessment Report (2014).

ONE "WIN"

- Coca cola
  - Recycling of drink containers
  - Specifically producing new PET bottles from recycled material
    - Converted to use of more "clear" containers (e.g., Sprite)
- Business advantage
- Apparently not a significant "cost" that causes loss of competitiveness

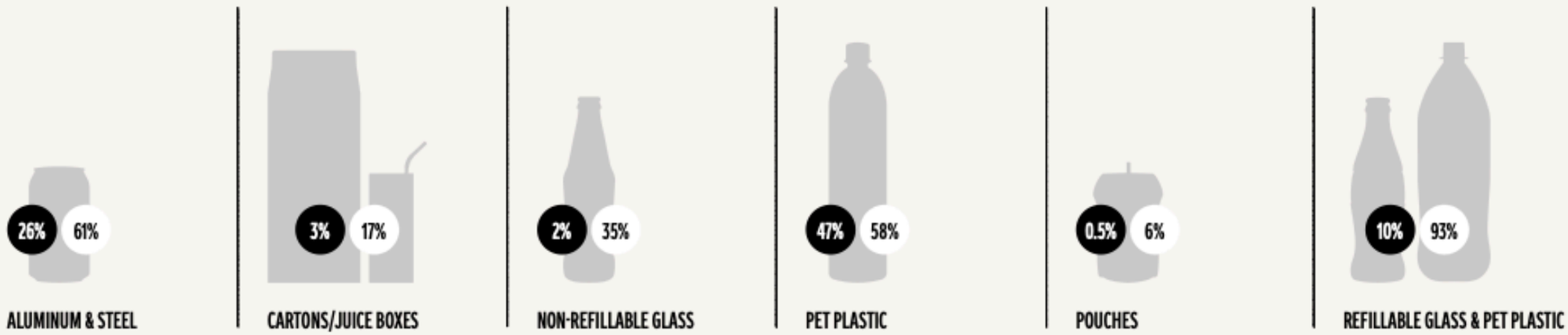

Packaging
WORKING TOWARD A WORLD WITHOUT WASTE
We recognize our responsibility to help solve complex plastic waste challenges facing our planet and society. That's why, in 2018, we launched an ambitious strategy called World Without Waste to drive systemic change through a circular economy for our packaging.
World Without Waste is a global sustainable packaging platform focused on measurable and interconnected goals, each of which are supported by additional targets:
• Making 100% of our packaging recyclable globally by 2025—and using at least 50% recycled material in our packaging by 2030 (DESIGN).
• Collecting and recycling a bottle or can for each one we sell by 2030 (COLLECT).
• Bringing people together to support a healthy, debris-free environment (PARTNER).
SECTION SCOPE: In this section, our packaging strategy refers to actions by the company as well as our owned and independent bottling partners and our independent suppliers and partners.
ONE OF OUR PACKAGING DESIGN GOALS IS TO REDUCE OUR USE OF VIRGIN PLASTIC DERIVED FROM NON-RENEWABLE SOURCES BY A CUMULATIVE
3M METRIC TONS
BETWEEN 2020 AND 2025
IN 2022, WE ANNOUNCED A NEW GLOBAL REUSABLE PACKAGING GOAL.
BY 2030, WE AIM TO HAVE AT LEAST
25%
OF OUR BEVERAGES SOLD BY VOLUME
WORLDWIDE IN REFILLABLE/RETURNABLE GLASS OR PLASTIC BOTTLES OR IN FOUNTAIN DISPENSERS WITH REUSABLE PACKAGING
SABOR ORIGINAL
RETORNÁVEL

COCA COLA PACKAGING

Our Packaging Types

61%

of the equivalent bottles and cans we introduced into the market in 2022 were collected and refilled or collected for recycling.[1]



● Material Mix ○ Collection Rates by Packaging Type[1]

GOAL	2022 STATUS	
Collect and recycle a bottle or can for each one we sell by 2030	61%[1]	61%

1 The collection rate represents a weighted average of national collection rates, collected for recycling rates or refillable rates by packaging type to TCCS's sales in units to express the percent of equivalent bottles and cans introduced into the market that were collected and refilled or collected for recycling for the year.

We work with partners across business, government and civil society to create or support closed-loop systems that ensure our packages are collected and recycled or reused. Delivering a circular economy will require significant and urgent improvement in waste management and recycling systems around the world. Preserving the inherent economic value of our packaging—and ensuring circularity—requires robust collection and recycling systems across packaging types.

Collection challenges vary, as every country has unique governments, regulatory environments and consumer behaviors. Though some countries have high recycling rates across packaging types, in many regions the recycling rate for PET bottles lags that of some other materials. While we continue to focus on national collection rates, in 2022, with input from key external stakeholders, we updated our collection tracking guidance to account for material collected through system-led efforts. Company and bottler teams in markets with limited recycling infrastructures (including parts of Latin America, Africa and Asia) are financing system-led collection initiatives to supplement national systems and are launching our own tracking systems. In 2023, we will start incorporating Coca-Cola system-led collection data into our aggregate numbers.

In emerging markets, we advocate for government regulations permitting the use of rPET in food and beverage packaging, and we seek ways to empower the informal waste collection sector in the circular economy. In developed markets, we are working with industry peers to build collection infrastructures—including our more than 40 years of experience operating 40+ local Deposit Return Systems (DRS). Countries with a well-designed DRS scheme, like Germany, can achieve high levels of collection (approximately 97% collection for non-refillable packages in Germany).

PET Plastic bottle recycling to recycled fabric

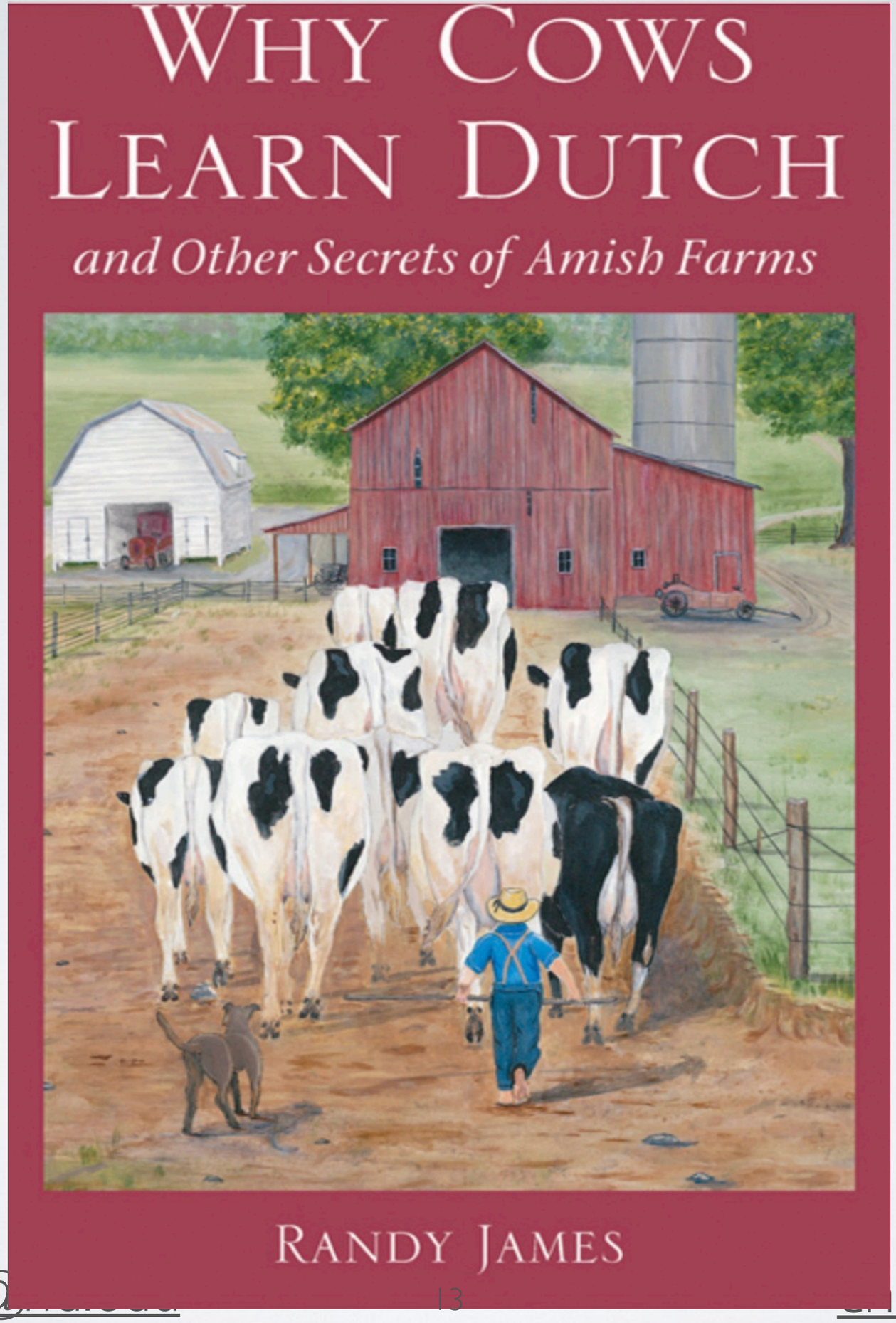
- A number of steps are needed, but PET can be recycled

Switch to clear bottles increases recyclability

mjm@nd.edu

How valuable is biodegradable plastic ?

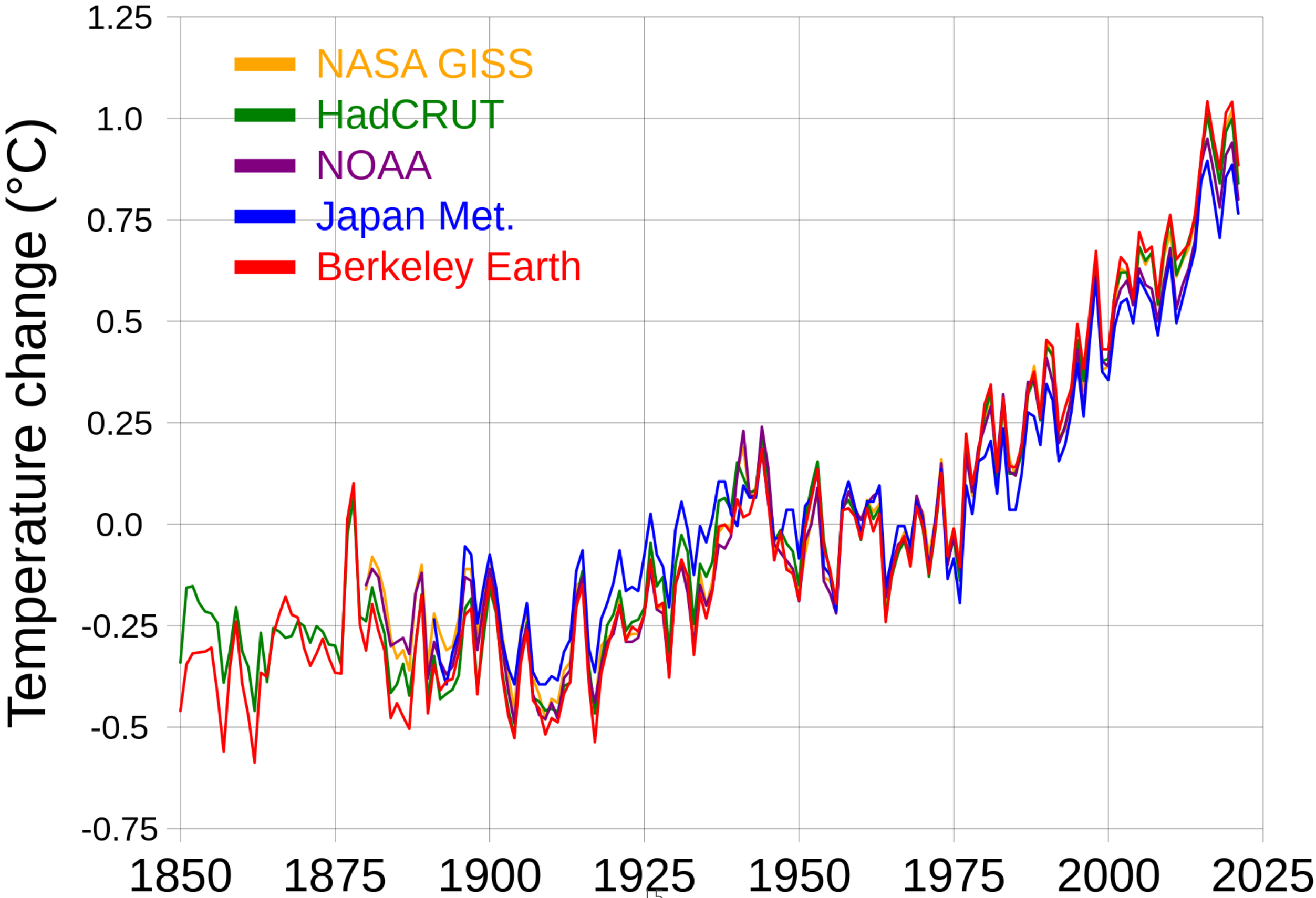
You have many beautiful lands and properties, can we judge the threat from climate change?


WHY COWS
LEARN DUTCH
and Other Secrets of Amish Farms
RANDY JAMES

AMISH FARMS

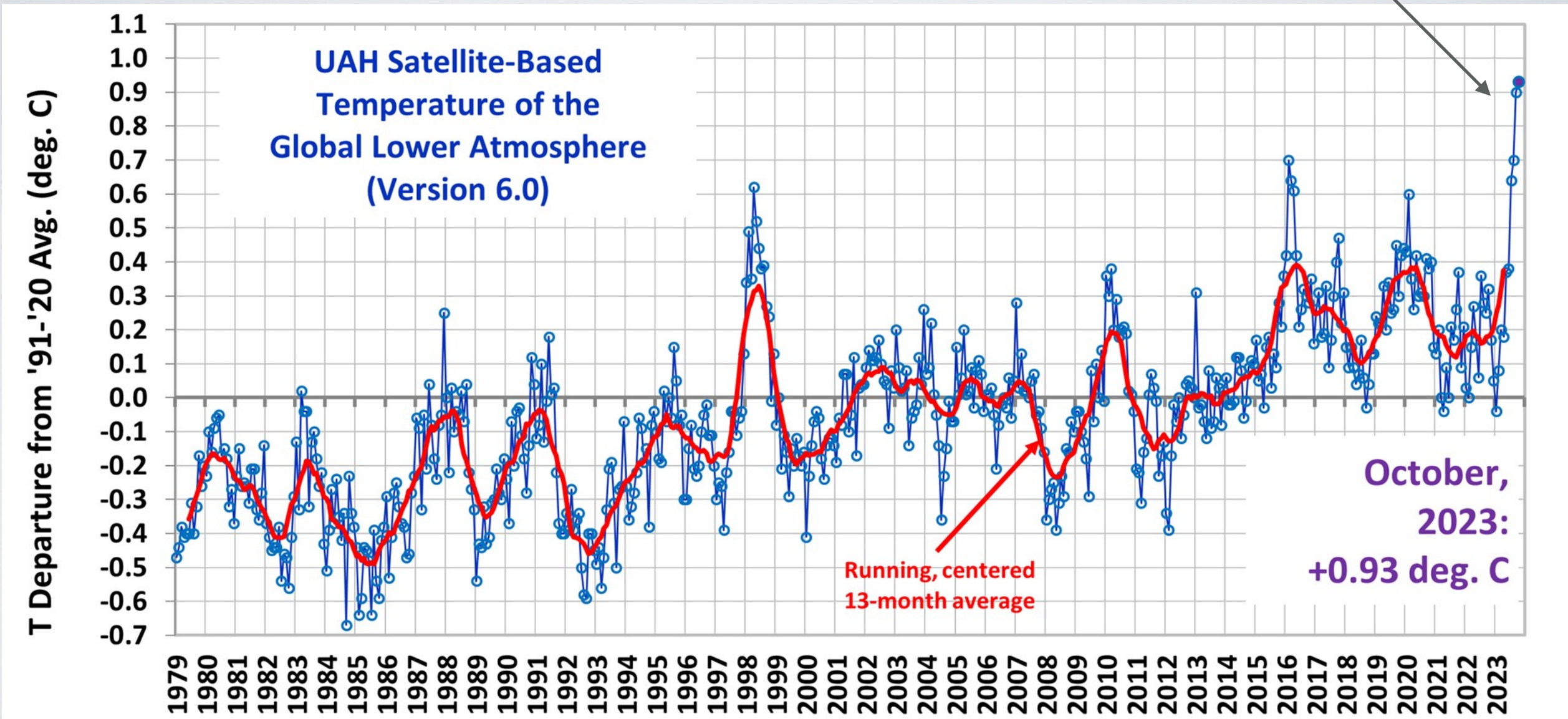
- At least in the region in Maryland that covered in this book, the Amish use much more labor intensive processes
    - And an "interesting" mix of animal and combustion powered machines
- But they do use some chemical fertilizer to get yields similar to the "modern" farmers in the region ~100 bushels/acre for corn.
- Various "natural" remedies for weed and insect control are used.

Global average temperature change

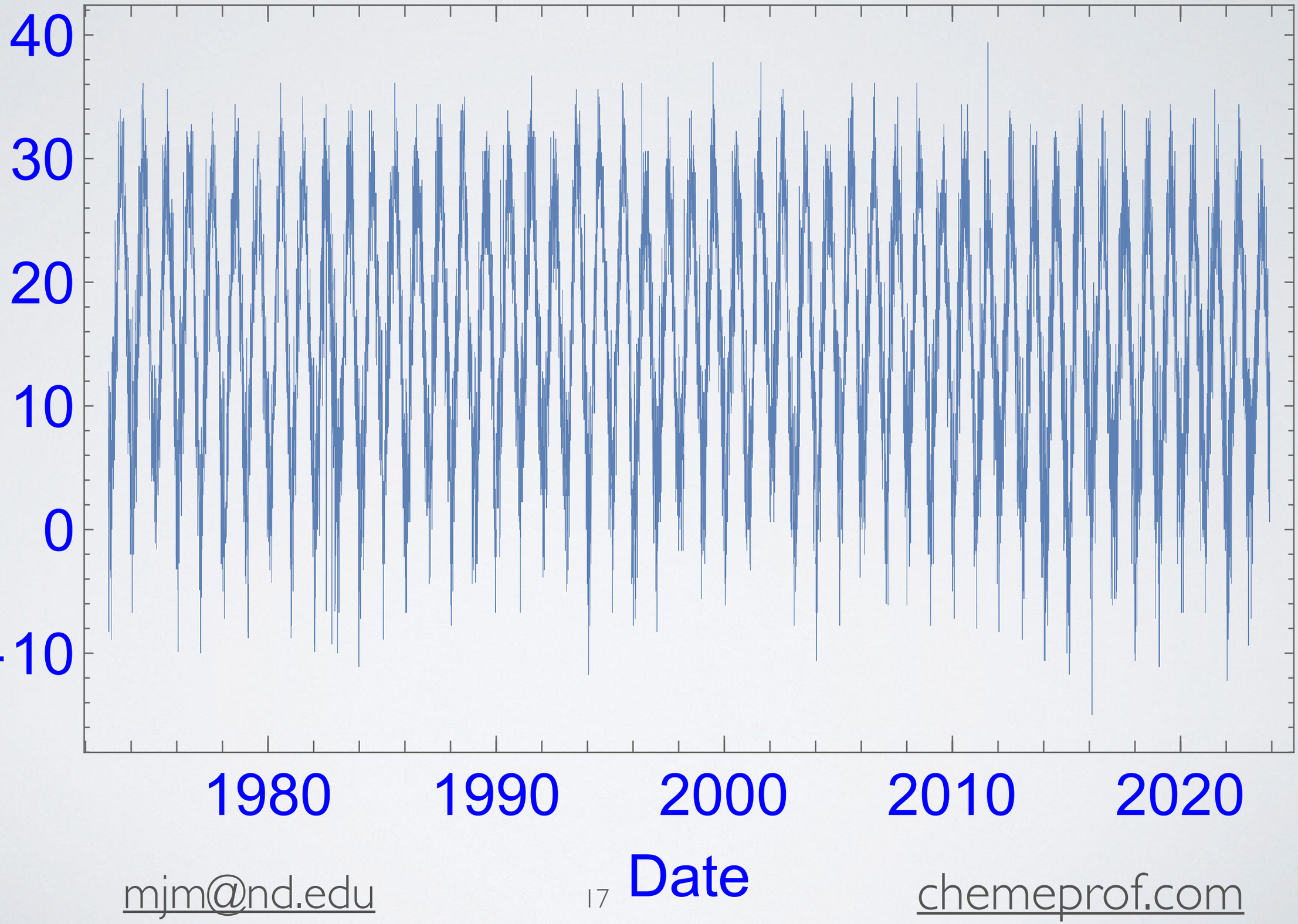


TEMPERATURE TIME SERIES

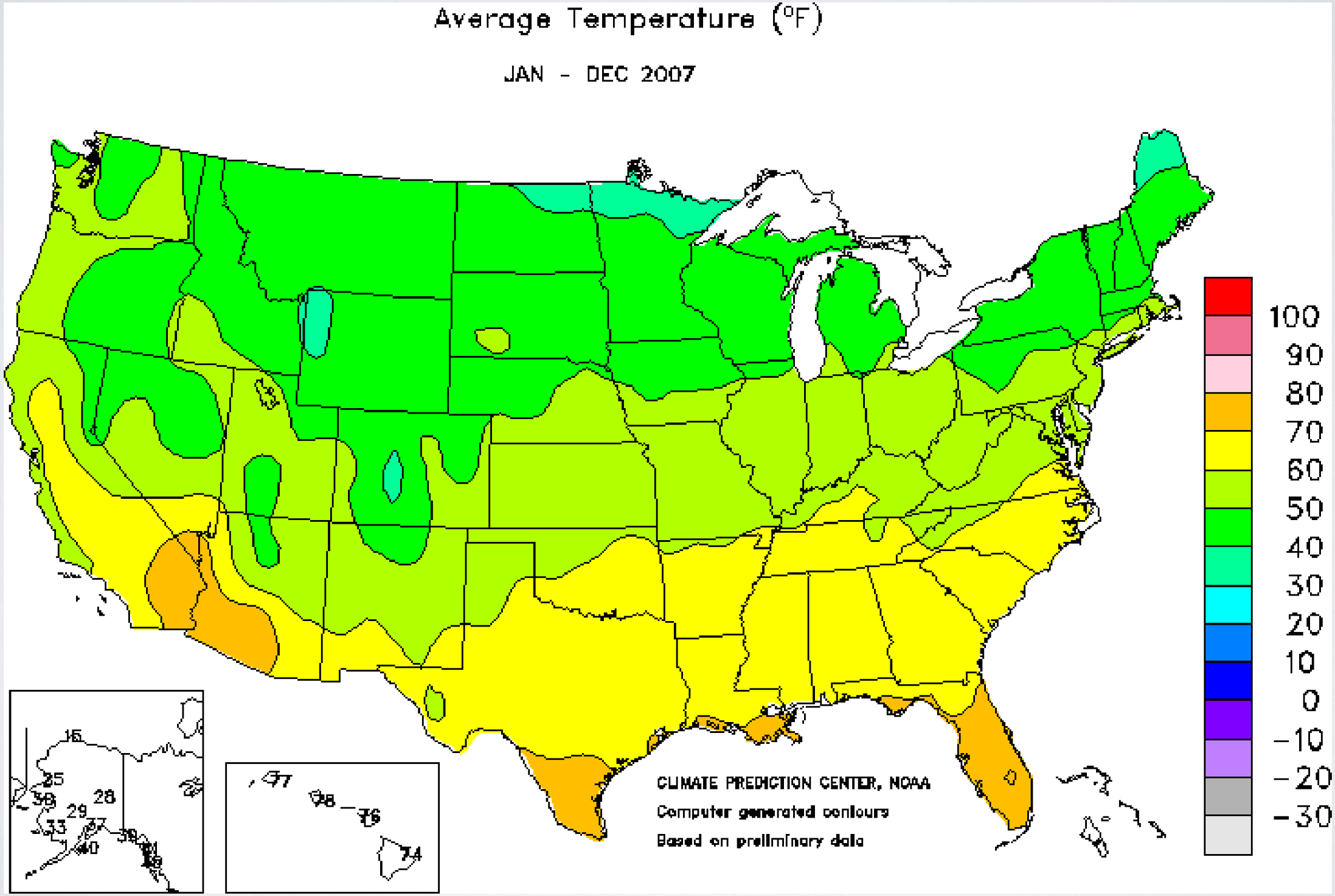
Tonga volcano?



Maximum daily temperature in Bridgeport



US AVERAGE TEMPS



Effect of Temperature on Growing season

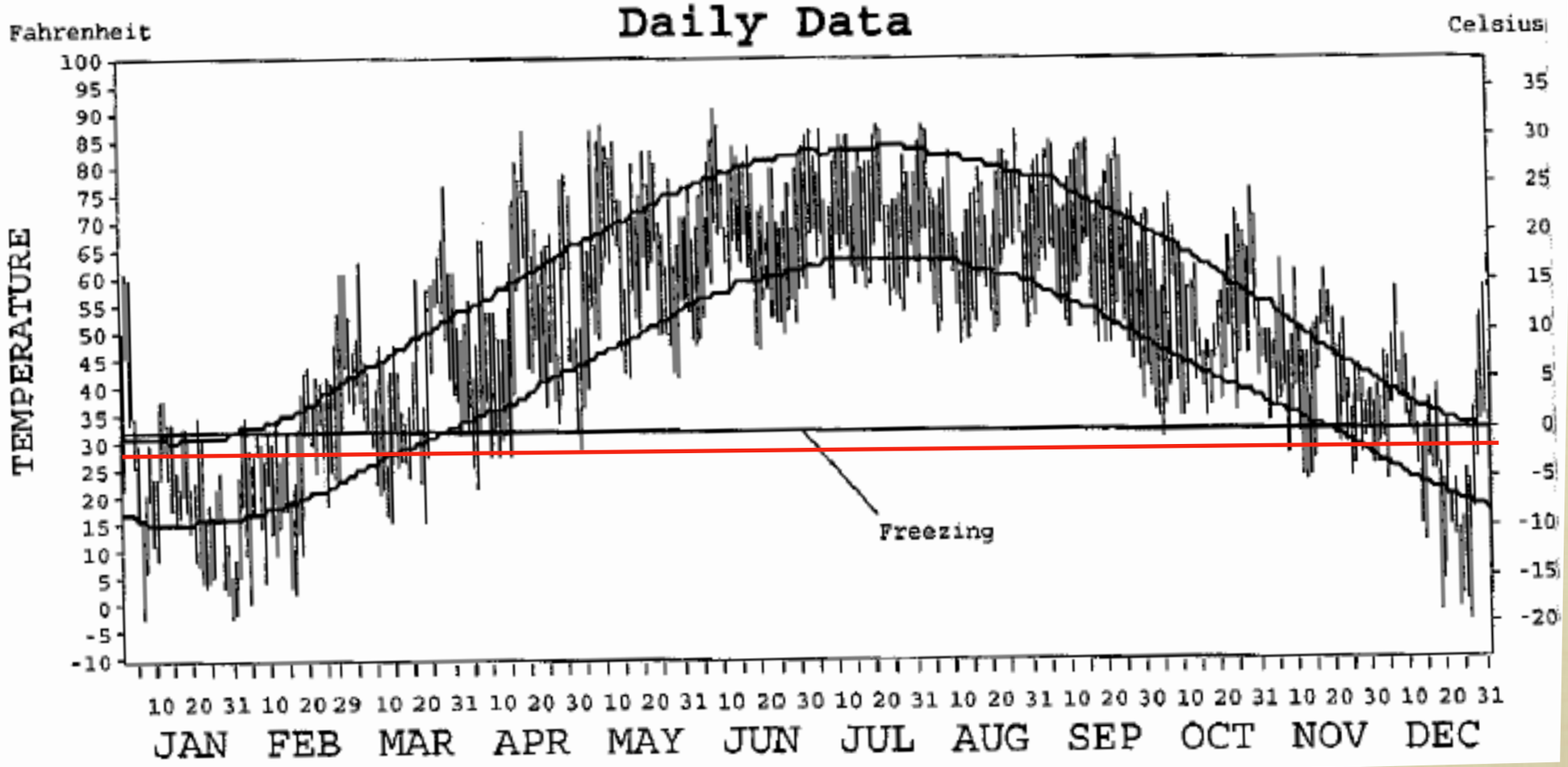
2004

LOCAL CLIMATOLOGICAL DATA
ANNUAL SUMMARY WITH COMPARATIVE DATA

SOUTH BEND,
INDIANA (SBN)

ISSN 0198-201X

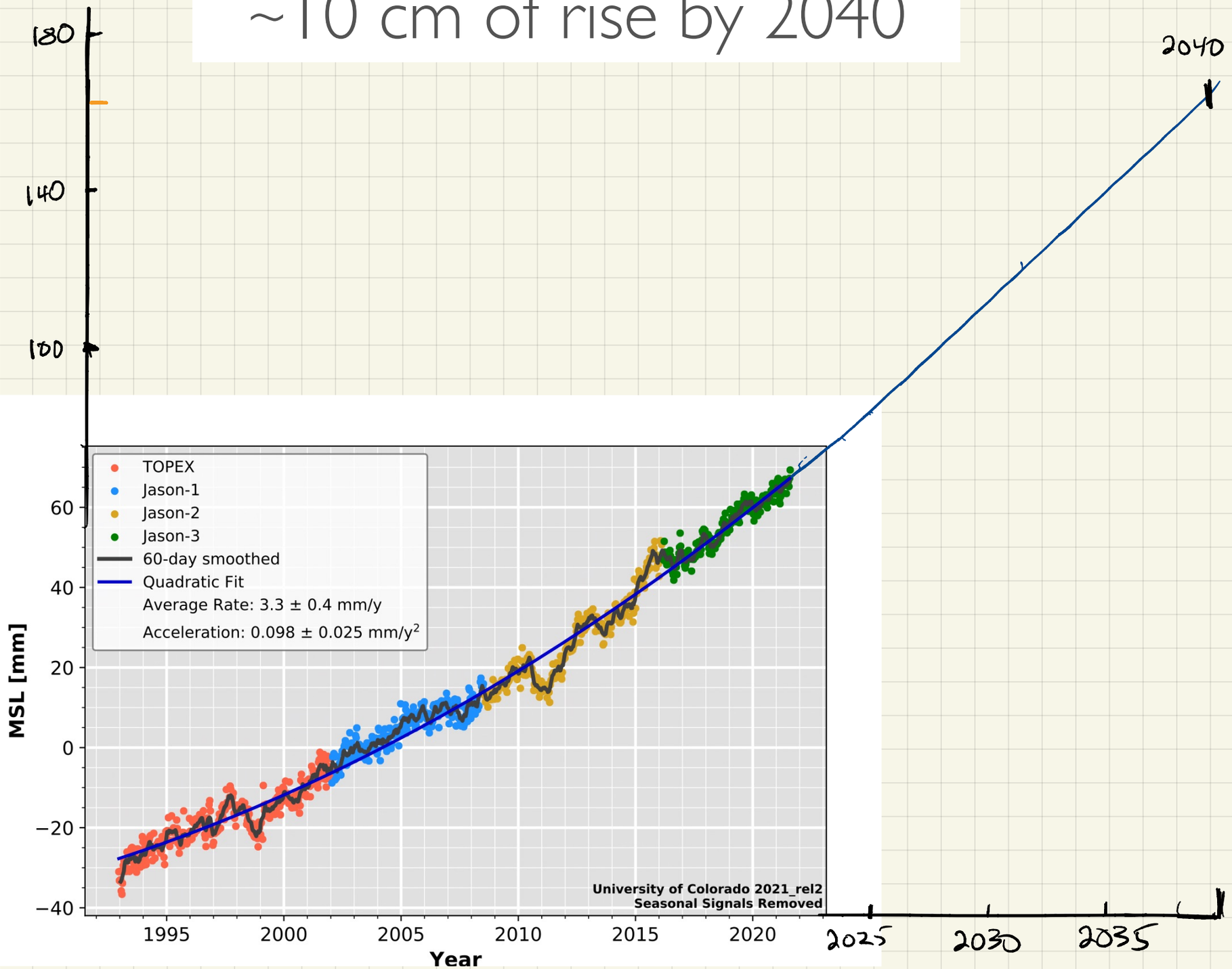
Daily Data

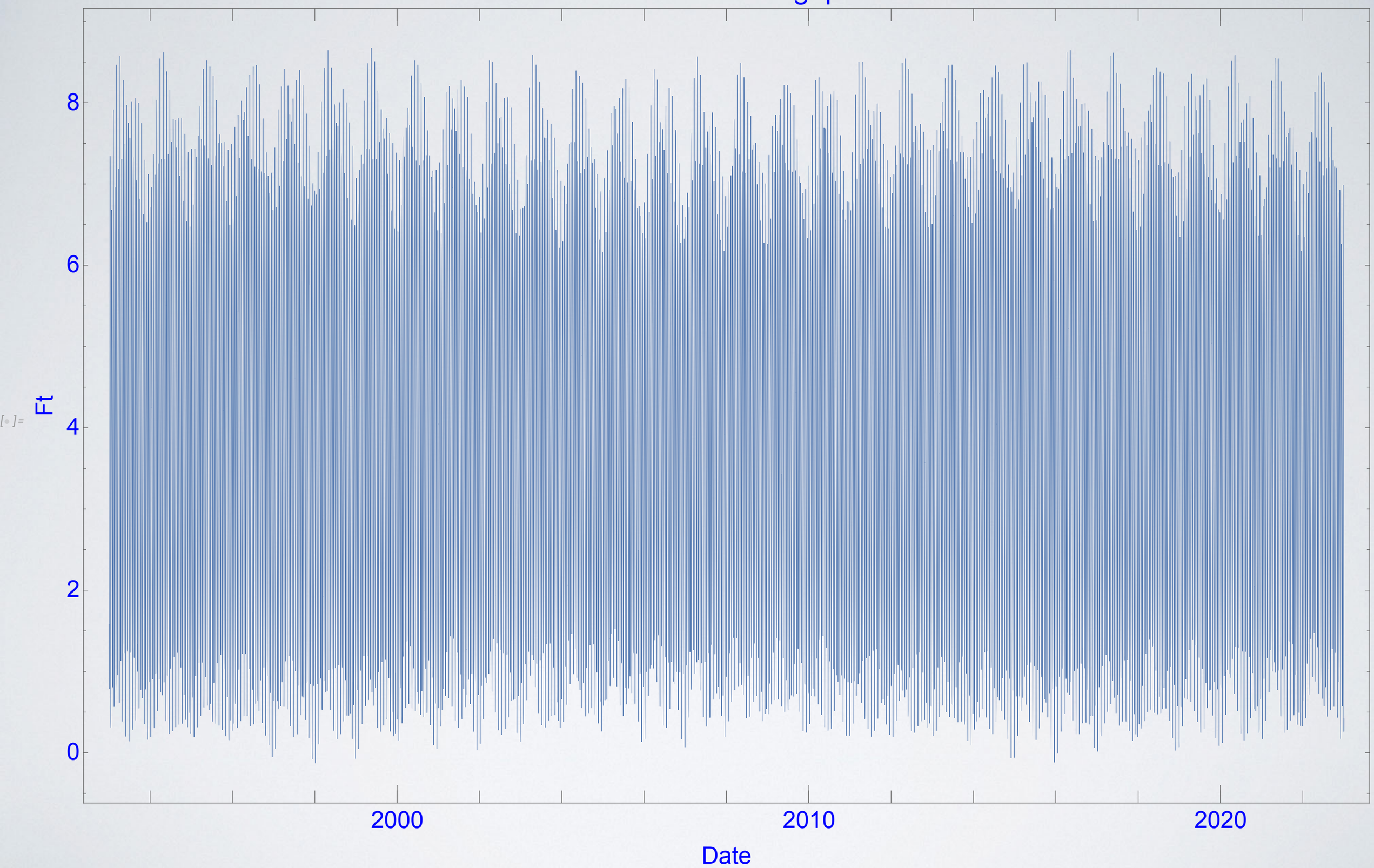


AN ESTIMATE OF SEA LEVEL RISE

USING GLOBAL #'S

~10 cm of rise by 2040




Tidal data in Bridgeport
Ft
8
6
4
2
0
2000
2010
2020
Date

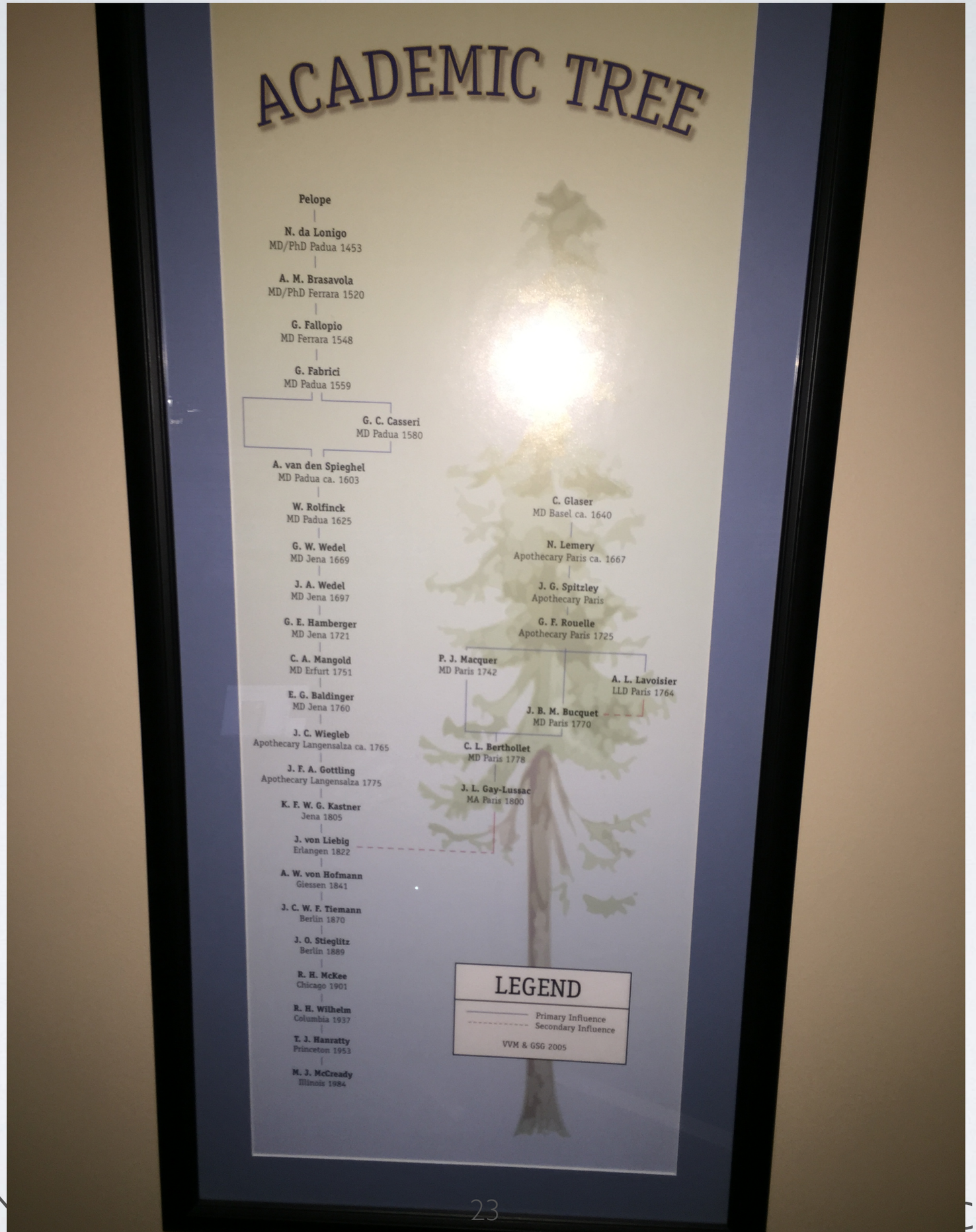
WALL STREET JOURNAL BESTSELLER

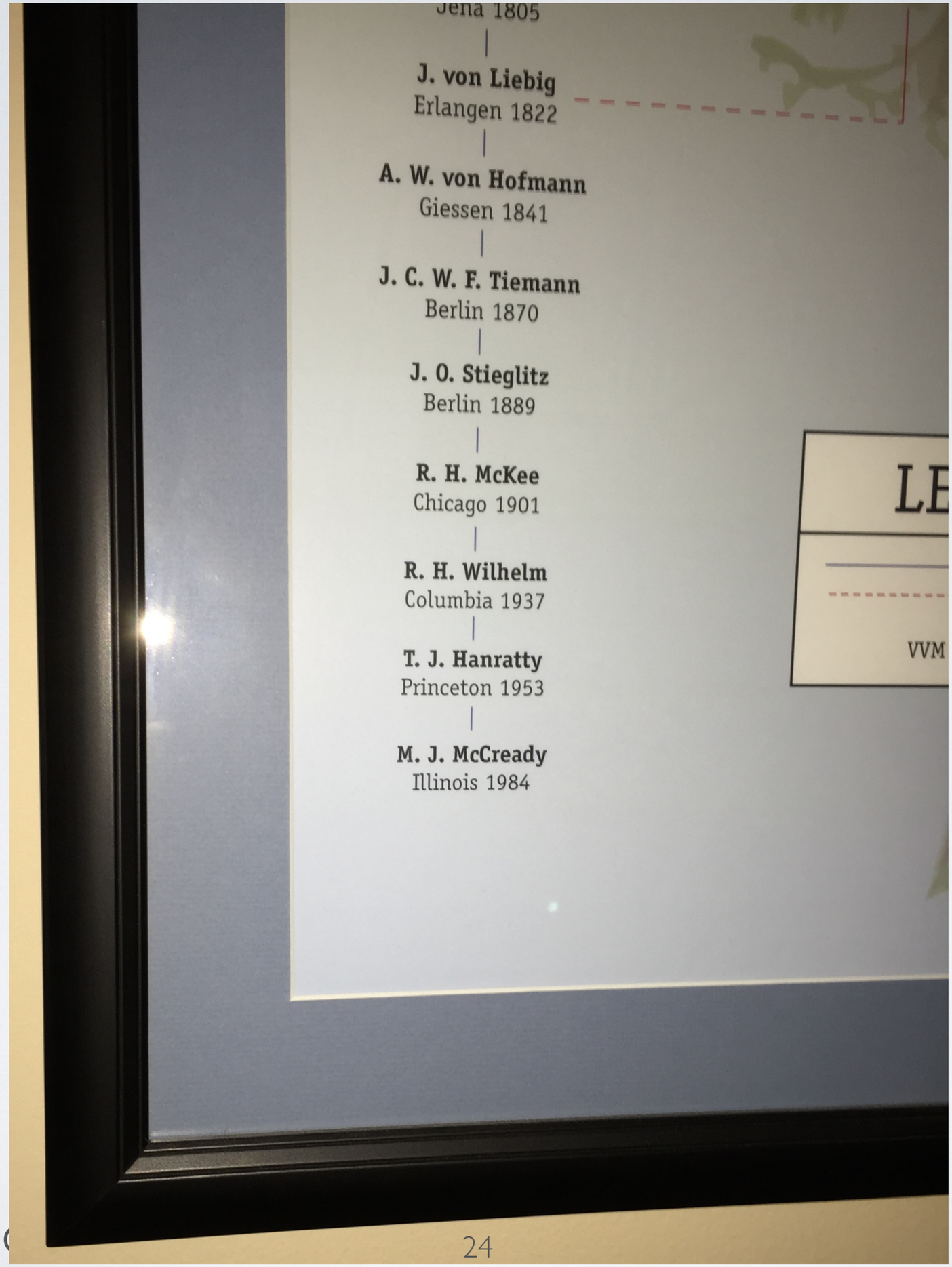
Unsettled

WHAT CLIMATE SCIENCE
TELLS US, WHAT IT DOESN'T,
AND WHY IT MATTERS

Steven E. Koonin

FORMER UNDERSECRETARY FOR SCIENCE,
U.S. DEPARTMENT OF ENERGY
UNDER THE OBAMA ADMINISTRATION


ACADEMIC TREE
Pelope
N. da Lonigo
MD/PhD Padua 1453
A. M. Brasavola
MD/PhD Ferrara 1520
G. Fallopio
MD Ferrara 1548
G. Fabrici
MD Padua 1559
G. C. Casseri
MD Padua 1580
A. van den Spieghel
MD Padua ca. 1603
W. Rolfinck
MD Padua 1625
G. W. Wedel
MD Jena 1669
J. A. Wedel
MD Jena 1697
G. E. Hamberger
MD Jena 1721
C. A. Mangold
MD Erfurt 1751
E. G. Baldinger
MD Jena 1760
J. C. Wiegleb
Apothecary Langensalza ca. 1765
J. F. A. Gottling
Apothecary Langensalza 1775
K. F. W. G. Kastner
Jena 1805
J. von Liebig
Erlangen 1822
A. W. von Hofmann
Giessen 1841
J. C. W. F. Tiemann
Berlin 1870
J. O. Stieglitz
Berlin 1889
R. H. McKee
Chicago 1901
R. H. Wilhelm
Columbia 1937
T. J. Hanratty
Princeton 1953
M. J. McCready
Illinois 1984
C. Glaser
MD Basel ca. 1640
N. Lemery
Apothecary Paris ca. 1667
J. G. Spitzley
Apothecary Paris
G. F. Rouelle
Apothecary Paris 1725
P. J. Macquer
MD Paris 1742
A. L. Lavoisier
LLD Paris 1764
J. B. M. Bucquet
MD Paris 1770
C. L. Berthollet
MD Paris 1778
J. L. Gay-Lussac
MA Paris 1800
LEGEND
Primary Influence
Secondary Influence
VVM & GSG 2005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J. von Liebig
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Giessen 1841
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T. J. Hanratty
Princeton 1953
M. J. McCready
Illinois 1984
LE
VVM

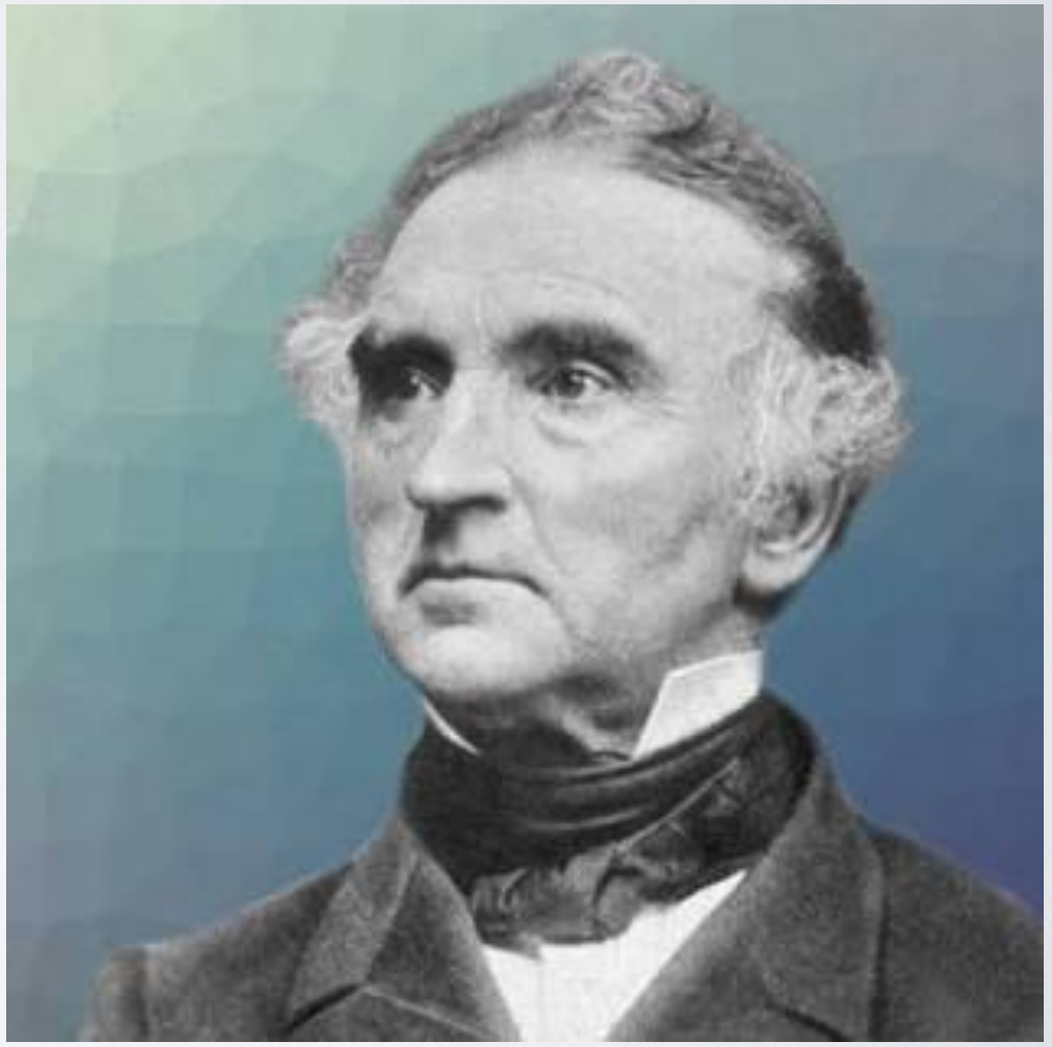
JUSTUS VON LIEBIG (1803-1873)

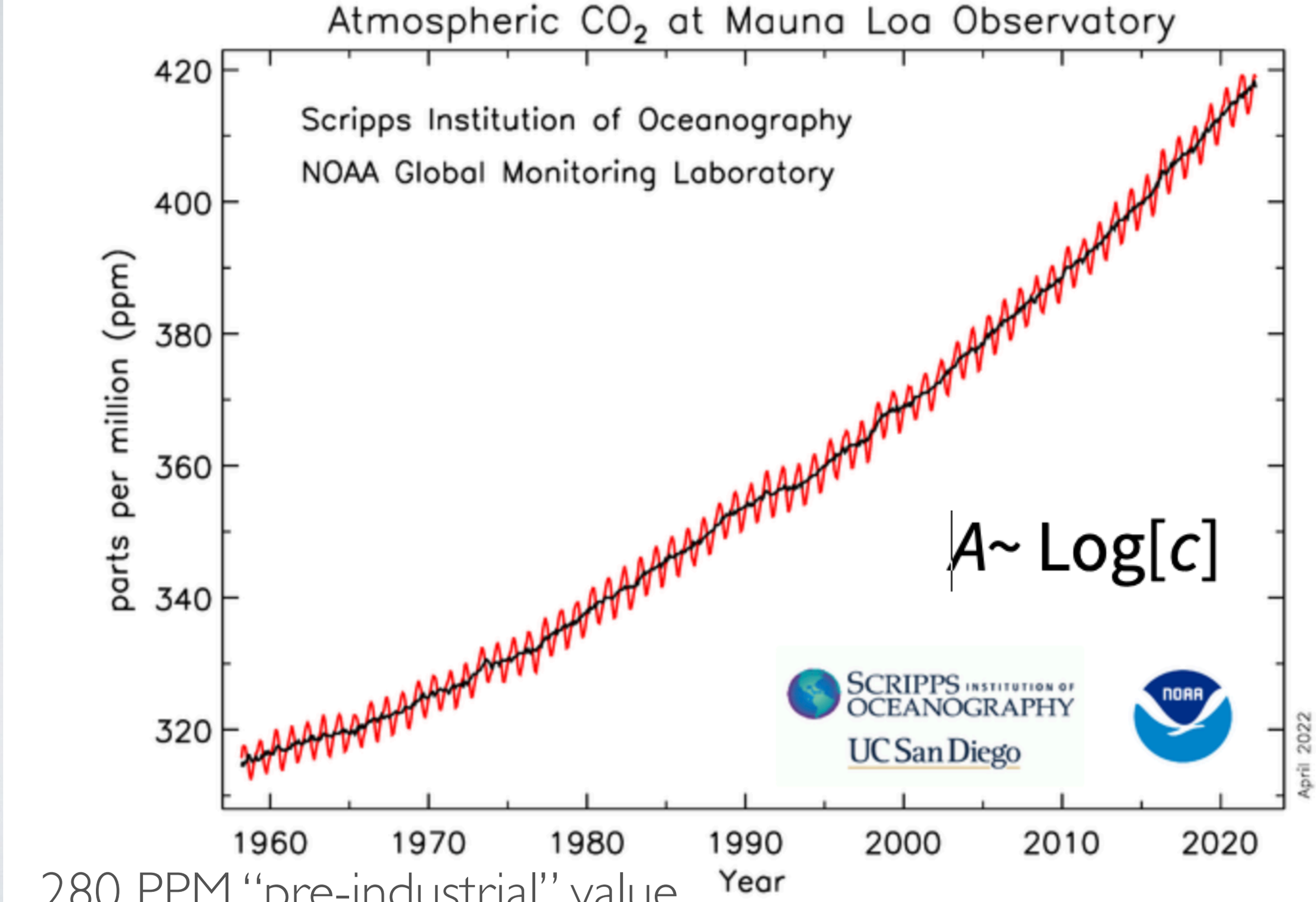
- "Organic" Chemist, established "Agricultural" Chemistry

- First studies on the chemistry of plant growth

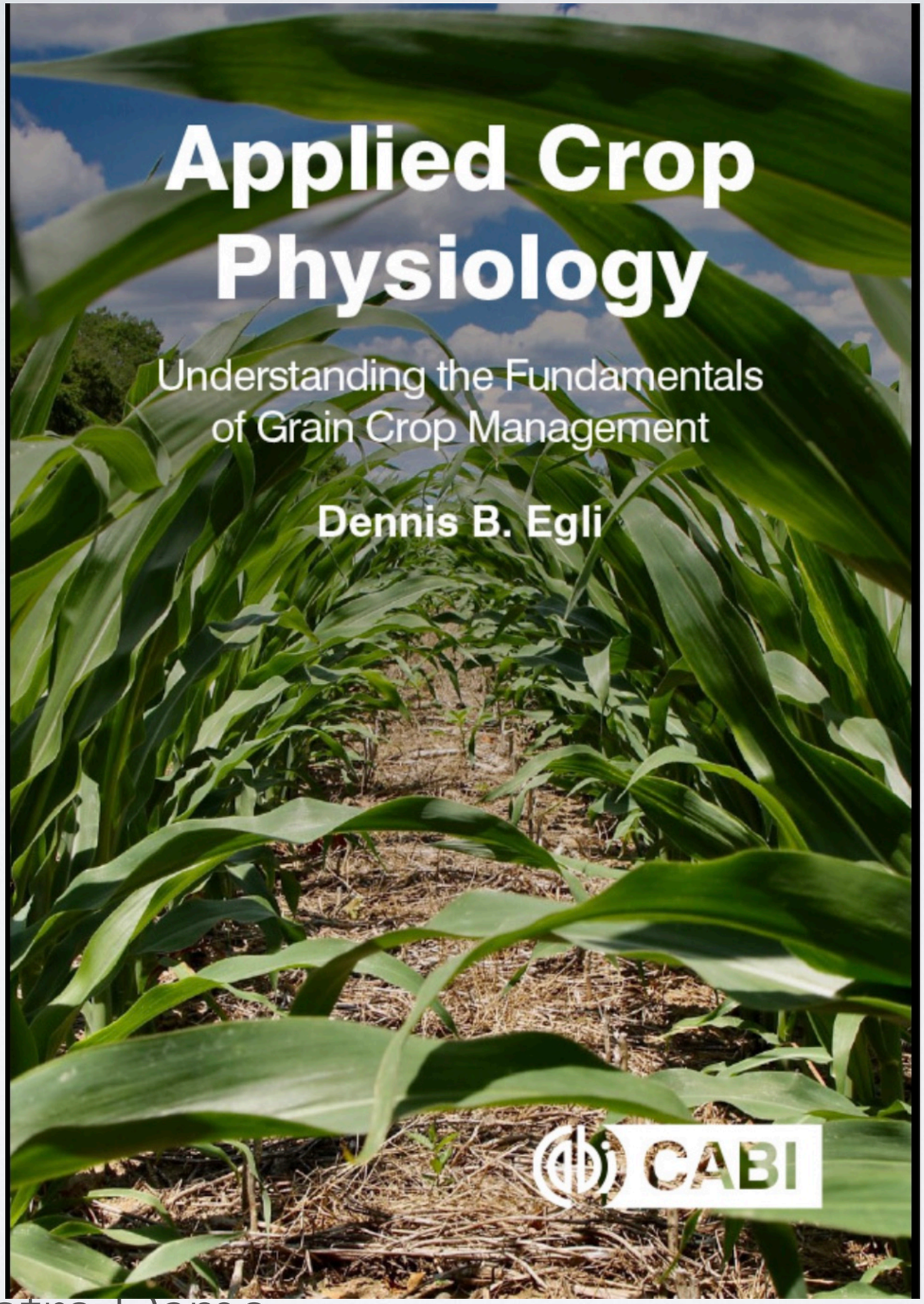
- Affirmed the importance of nitrogen compounds as fertilizer

- Explained the concept of a "limiting" nutrient.





280 PPM "pre-industrial" value


Applied Crop Physiology
Understanding the Fundamentals of Grain Crop Management
Dennis B. Egli
CABI

HOW DOES ELEVATED CO2 AFFECT PLANT GROWTH?

- Greenhouses often have a carbon dioxide concentration 2-3 times higher than the outside atmosphere.

- The basic photosynthesis reaction is:

$$6CO_2 + 6H_2O \xrightarrow{\text{Solar radiation}} C_6H_{12}O_6 + 6O_2$$

- Carbon dioxide enters leafs through stomata (pores). Water is lost through the stomata.

- Higher atmospheric CO2 allows plants to produce fewer stomata or for these to be open for a lower fraction of time which has the effect of allowing less water to escape.

EFFECT OF CO2 ON SOYBEAN GROWTH

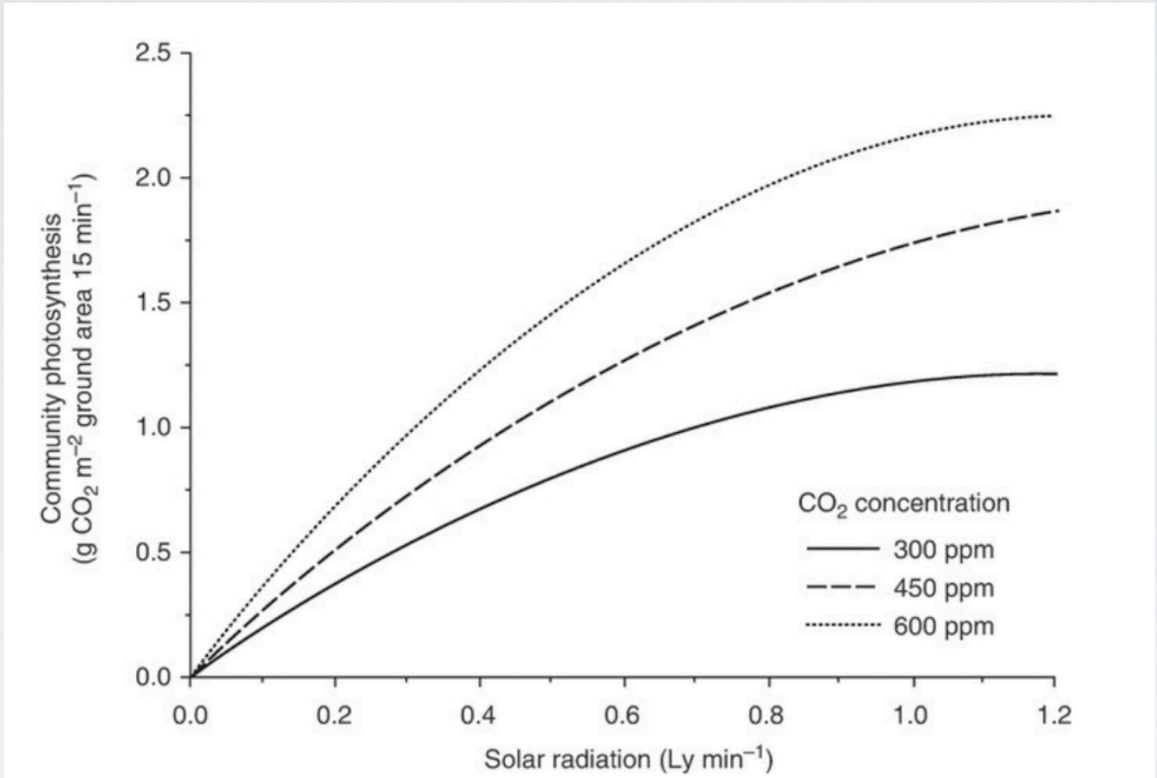
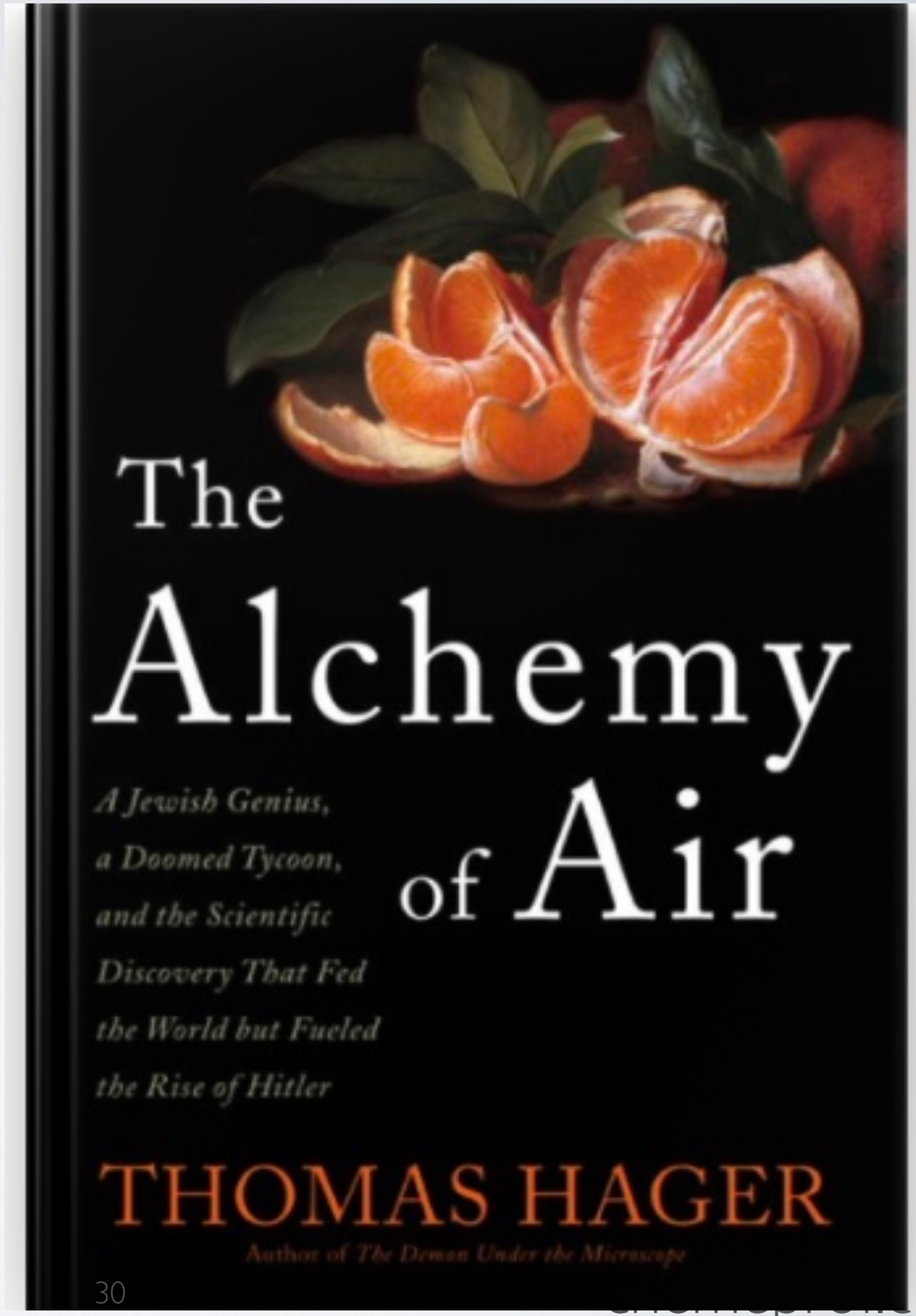


Fig. 2.2. Photosynthesis of a soybean (a C_3 species) community (variety 'Harasoy') in the field as a function of the CO_2 concentration and solar radiation levels. Current atmospheric CO_2 concentration is approximately 414 ppm. Maximum solar radiation levels in mid-summer on a clear day would be approximately 1.2 Ly min^{-1}. Ly, Langley. (Redrawn from Egli *et al.*, 1970.)

- Largest benefit is to C3 plants (wheat, rice soybeans…) not so much for C4 plants (e.g. maize).
- Increases in yield of food crops are partially the result of CO2 increases as is the expansion of "wild" vegetation.

- More than 1/2 of the food supply of the world is made possible by synthetic fertilizer.



University of Notre Dame

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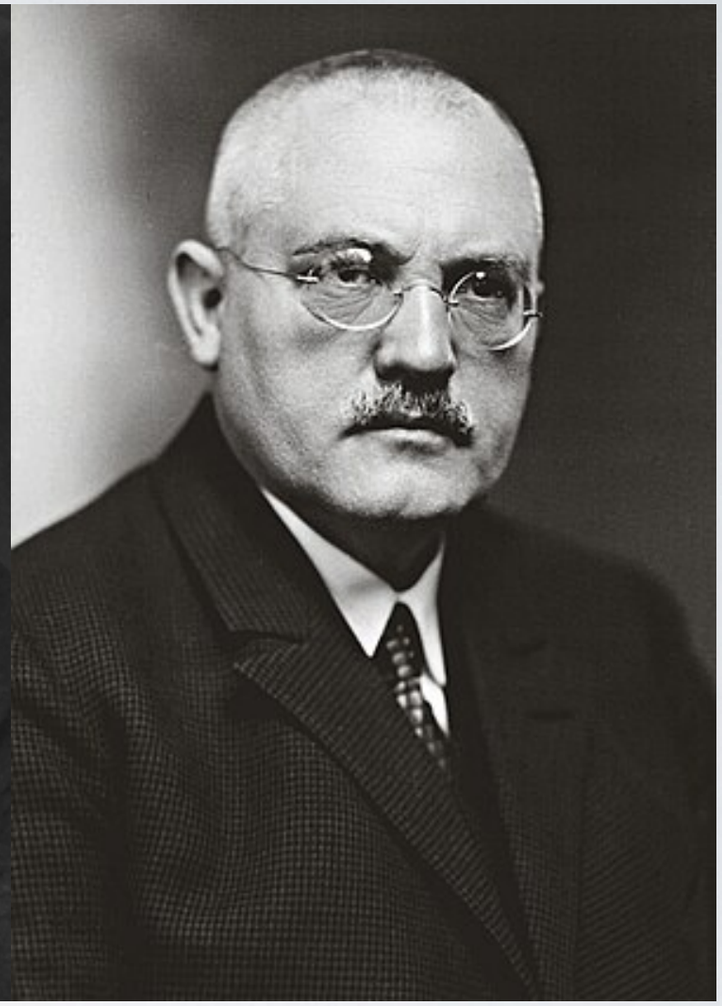
HABER-BOSCH PROCESS (~1913)

- Still used today to produce ammonia which is a precursor to nitrogen fertilizer as well as explosives and many industrial chemicals

Fritz Haber

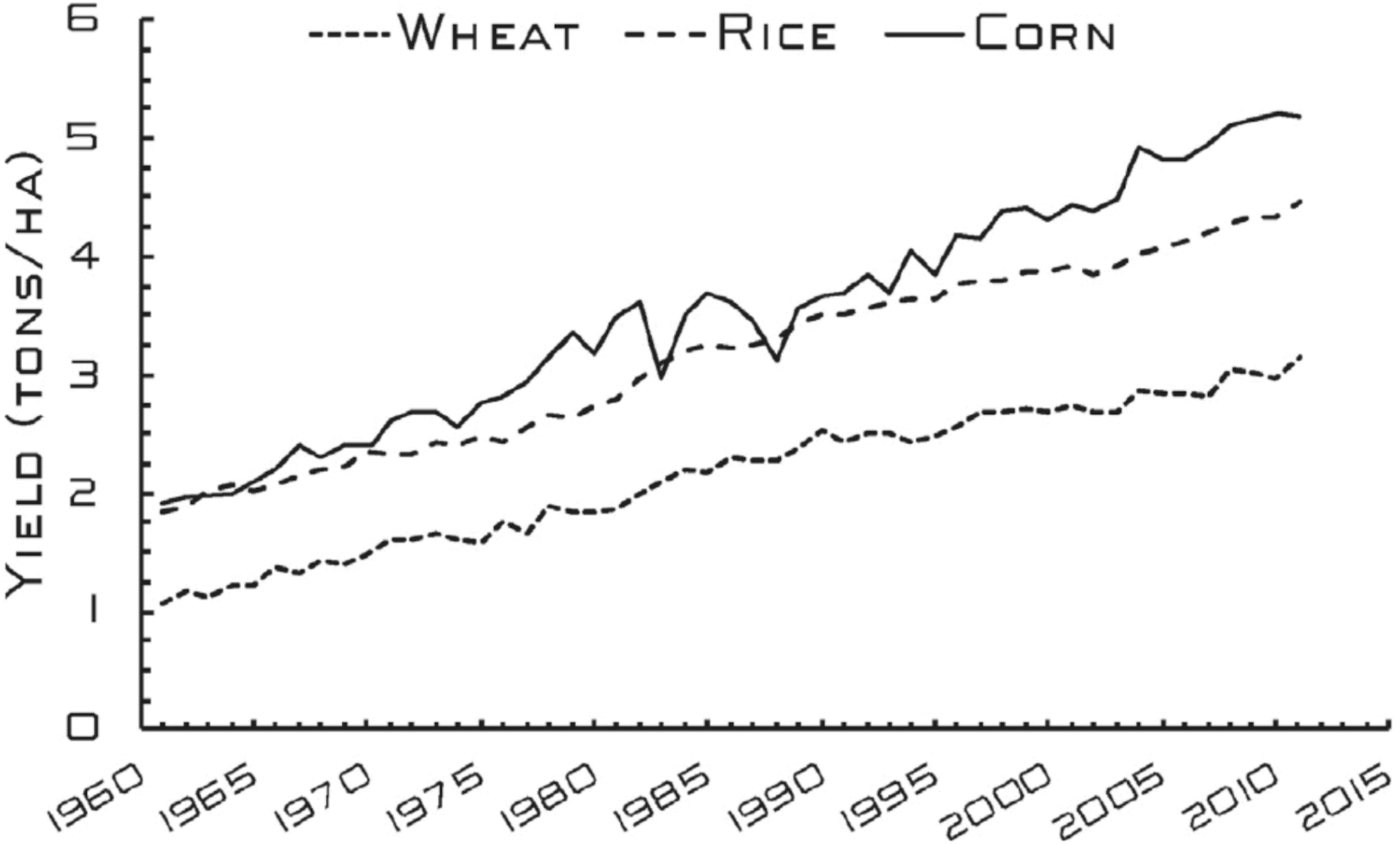


Carl Bosch

$$\mathbf{N_2 + 3\,H_2 \longrightarrow 2\,NH_3} \quad \Delta H^\circ = -91.8\ \mathbf{kJ/mol}$$

GLOBAL CROP YIELDS (1961–2011)

Sustainable?



ROUNDUP-READY SOYBEANS

Sustainable? Probably, but not what we mean in the topic of *Sustainability*

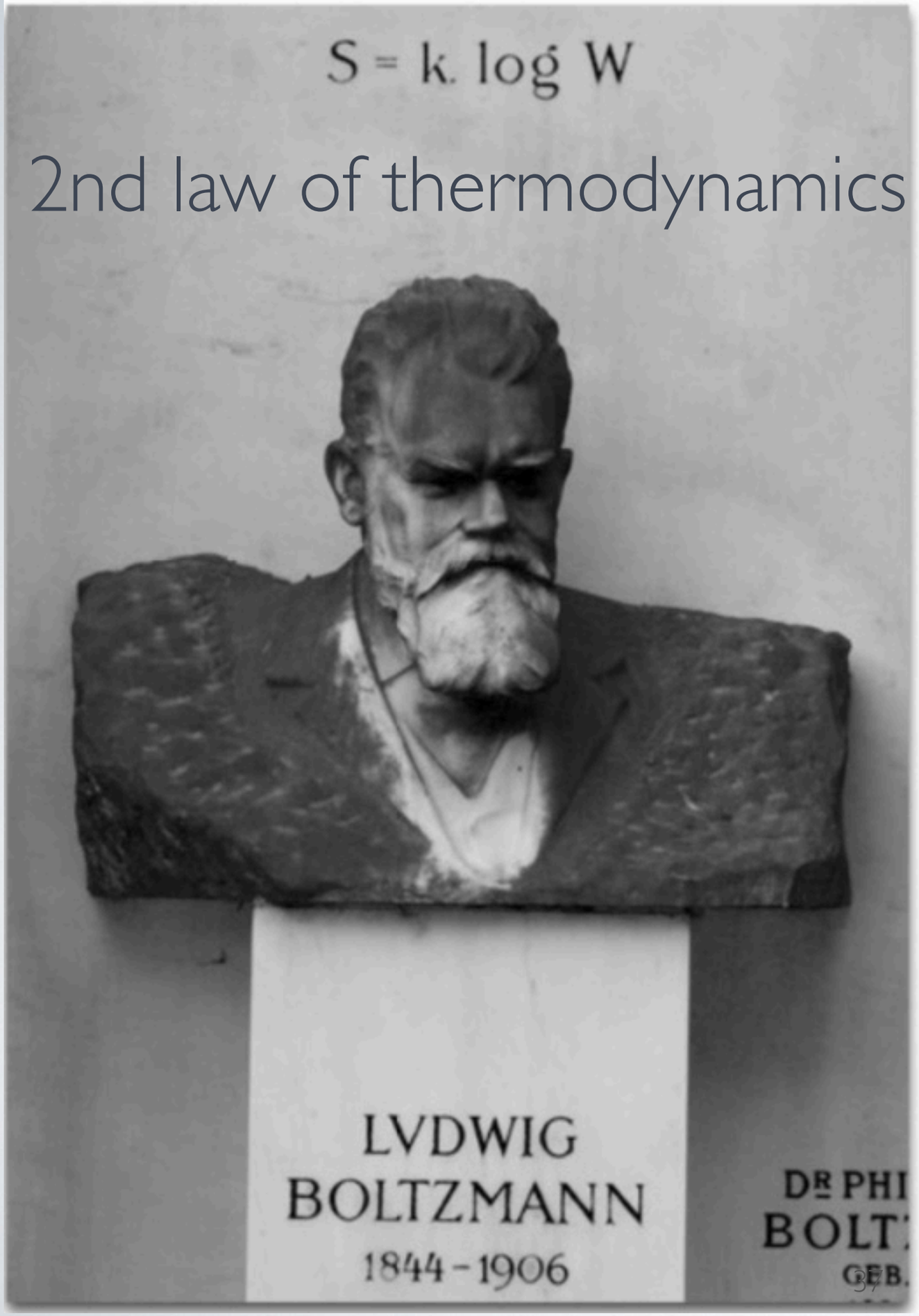
https://wnax.com/news/180081-monsanto-roundup-ready-2-xtend-soybeans-get-china-nod/

EVERYTHING THAT WE **KNOW** IS NOT CORRECT!

- Some things we thought we knew:
    - Margarine was considered a health food (oops… 1990's)
    - Left-handed people die sooner because of the hazards of the right-handed world. (Obviously wrong from the beginning — debunked after a decade or so)
    - Stomach Ulcers are caused by stress. (H. Pylori, 1982)
    - Plants absorb CO2 and emit O2 (Yes, but…)
    - The adult brain has no capacity to regenerate itself (~2003)
    - Komodo Dragons bit their prey and waited for them to succumb to bacterial infections. (Venom! —- May 2009)
    - We used to think that there were no other "Goldilocks" planets that could support life as we know it. (Exoplanet —1992, *Kepler 186g* — 2014)

PATH FORWARD WITH ENERGY WILL BE HARD!

Sorry, I don't have Rockne's grave…



2nd law of thermodynamics

$$p_i = \frac{1}{Q}\exp\left(-\frac{\varepsilon_i}{kT}\right) = \frac{\exp\left(-\frac{\varepsilon_i}{kT}\right)}{\sum_{j=1}^{M}\exp\left(-\frac{\varepsilon_j}{kT}\right)}$$

Plants grow faster, crickets chirp faster, chemical reactions are faster as temperature is increased!

chemeprof.com

CONSEQUENCES OF THE 2ND LAW OF THERMODYNAMICS

- The chemical energy stored in hydrocarbon fuels can be converted to electricity at less than 50% efficiency

- Any means of energy storage we have (e.g., "pumped hydro", batteries) will give us less than ~80% of the stored energy back

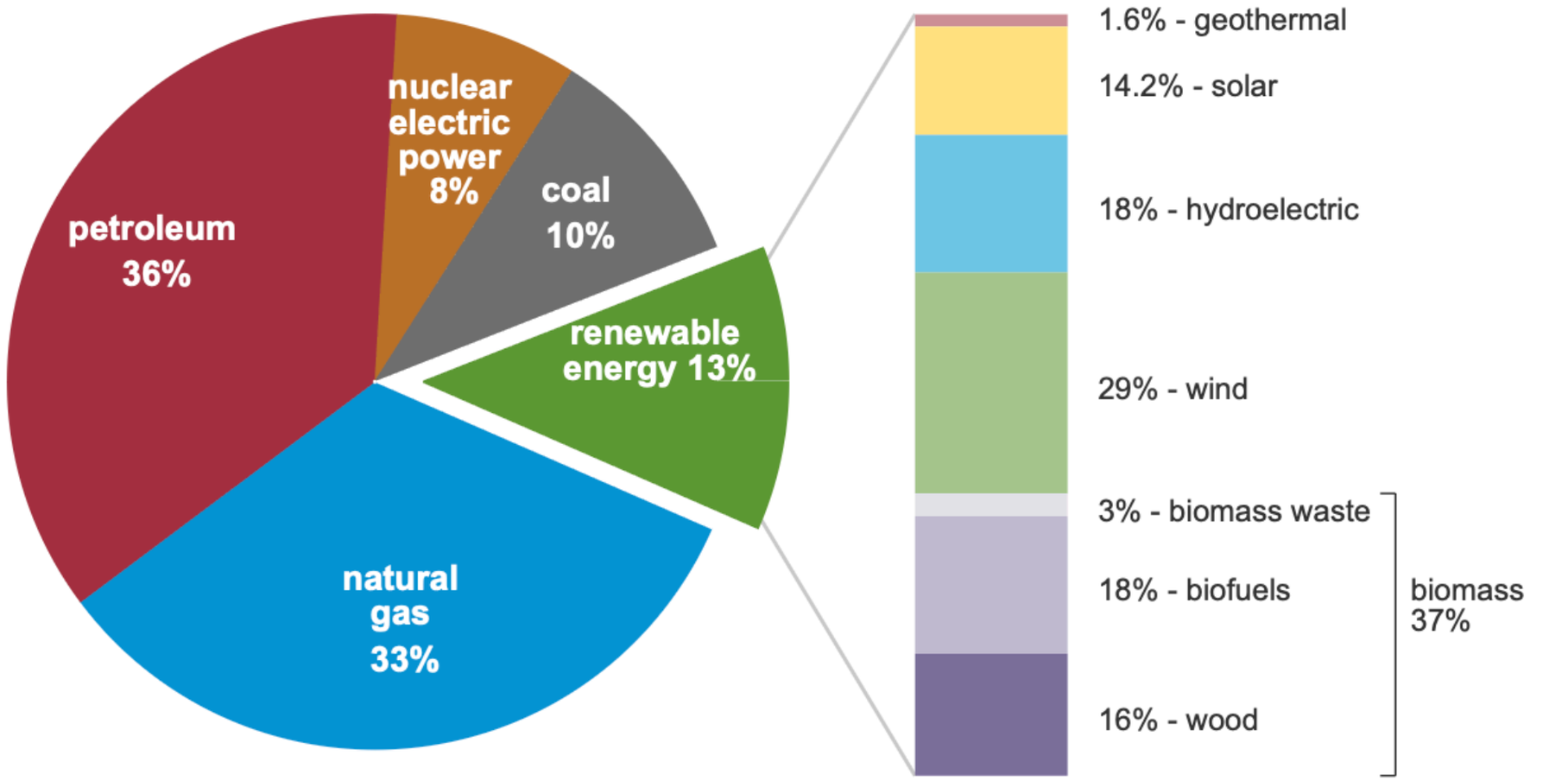
- "Waste" heat is of limited usefulness.

ENERGY FOR SOCIETY

U.S. primary energy consumption by energy source, 2022

total = 100.41 quadrillion British thermal units (Btu)

total = 13.18 quadrillion Btu



Data source: U.S. Energy Information Administration, *Monthly Energy Review*, Table 1.3 and 10.1, April 2023, preliminary data
Note: Sum of components may not equal 100% because of independent rounding.

Notre Dame geothermal

Ground source heat pump

NOTRE DAME

- At a local level, with sufficient resources, substantial gains can be made. (In some sense this is the easy part!)

- As an *academic initiative* Notre Dame seeks an

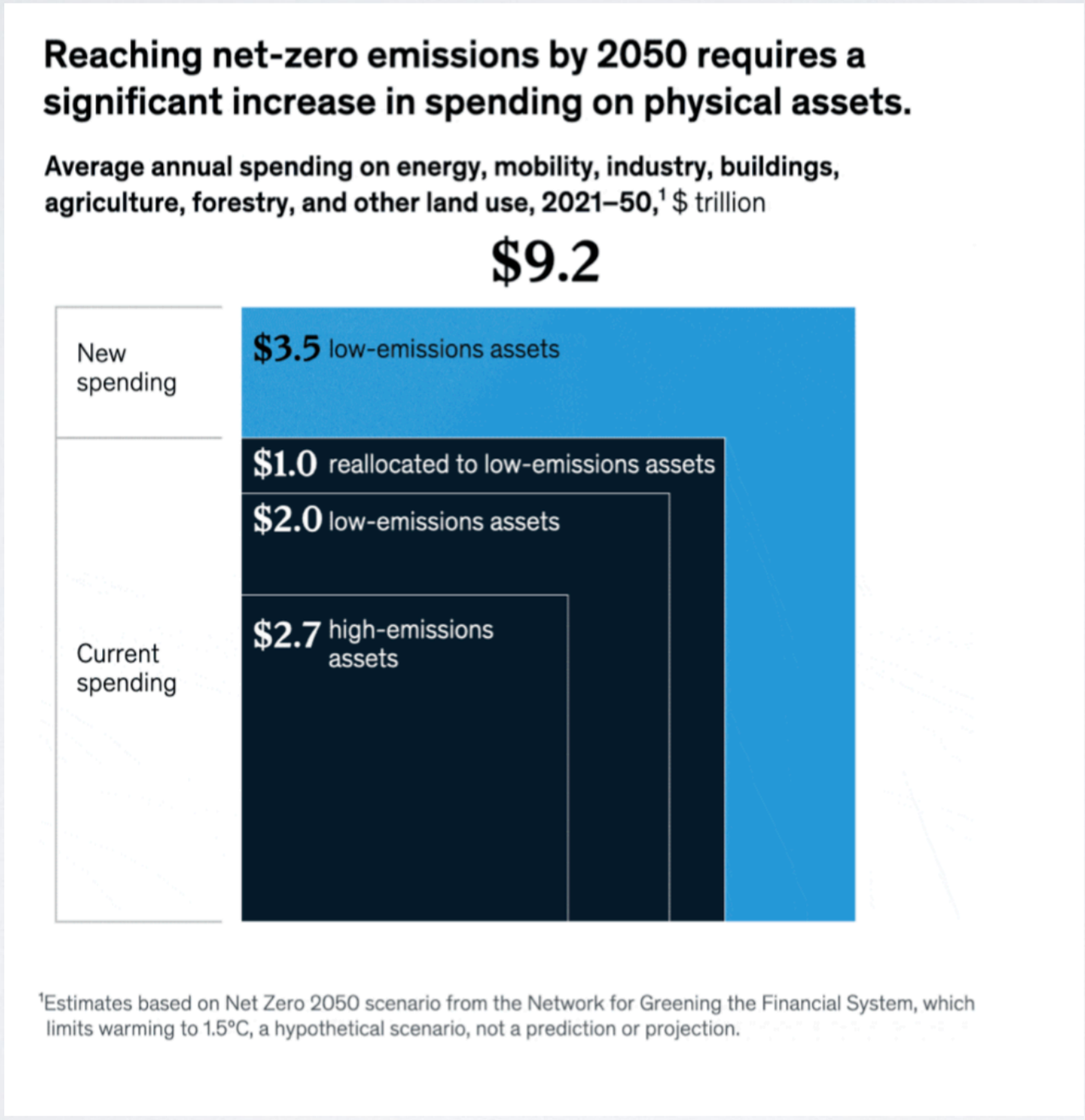
- "Equitable" energy transition

- Path forward must allow continued economic gains by 3rd world.

- What technologies could allow such countries to not use fossil fuels?

HOW MUCH WILL NET-ZERO COST?

- McKinsey: An extra $3.5 Tril/year from now until 2050.



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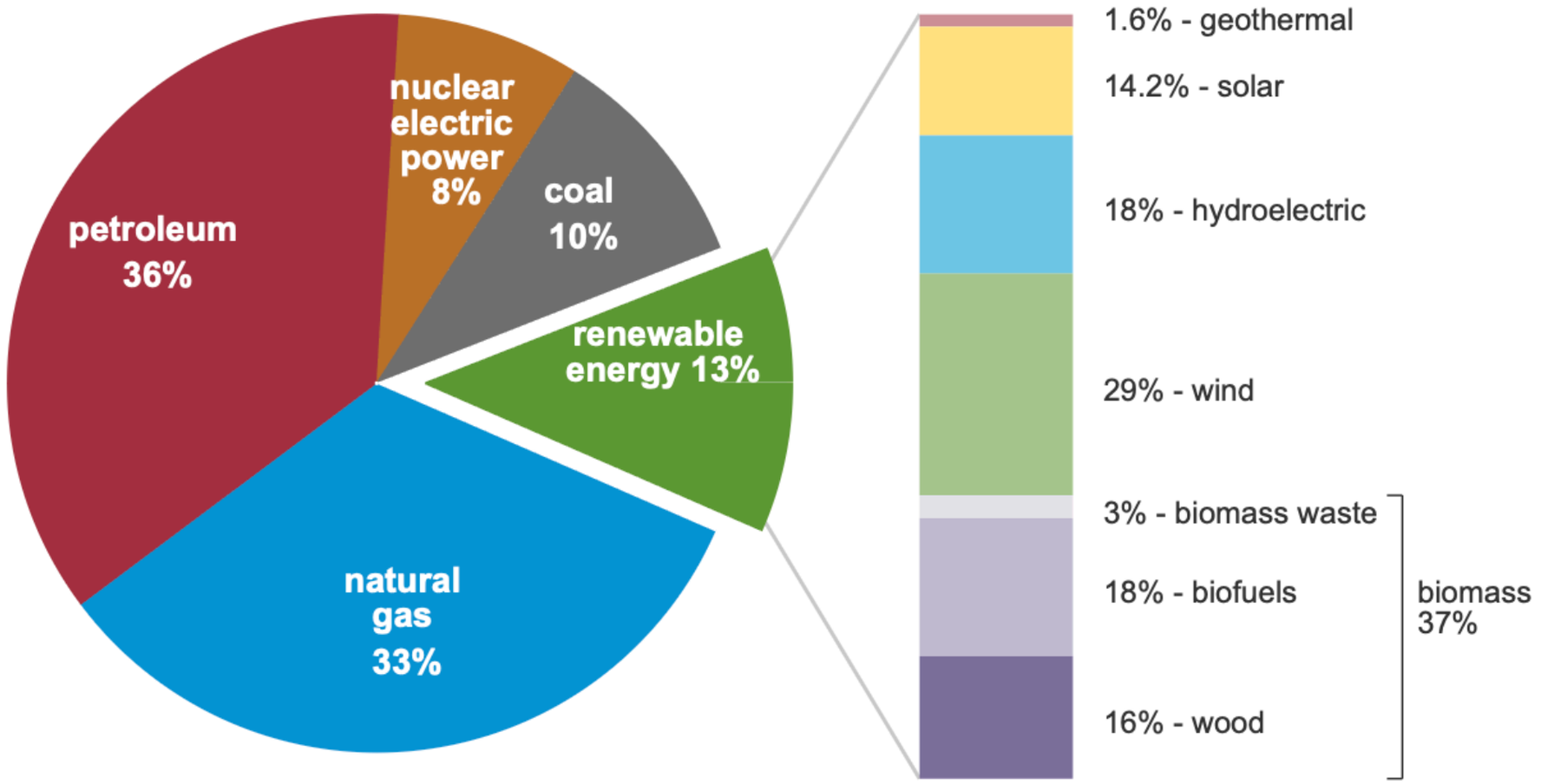


Data source: U.S. Energy Information Administration, *Monthly Energy Review*, Table 1.3 and 10.1, April 2023, preliminary data
Note: Sum of components may not equal 100% because of independent rounding.

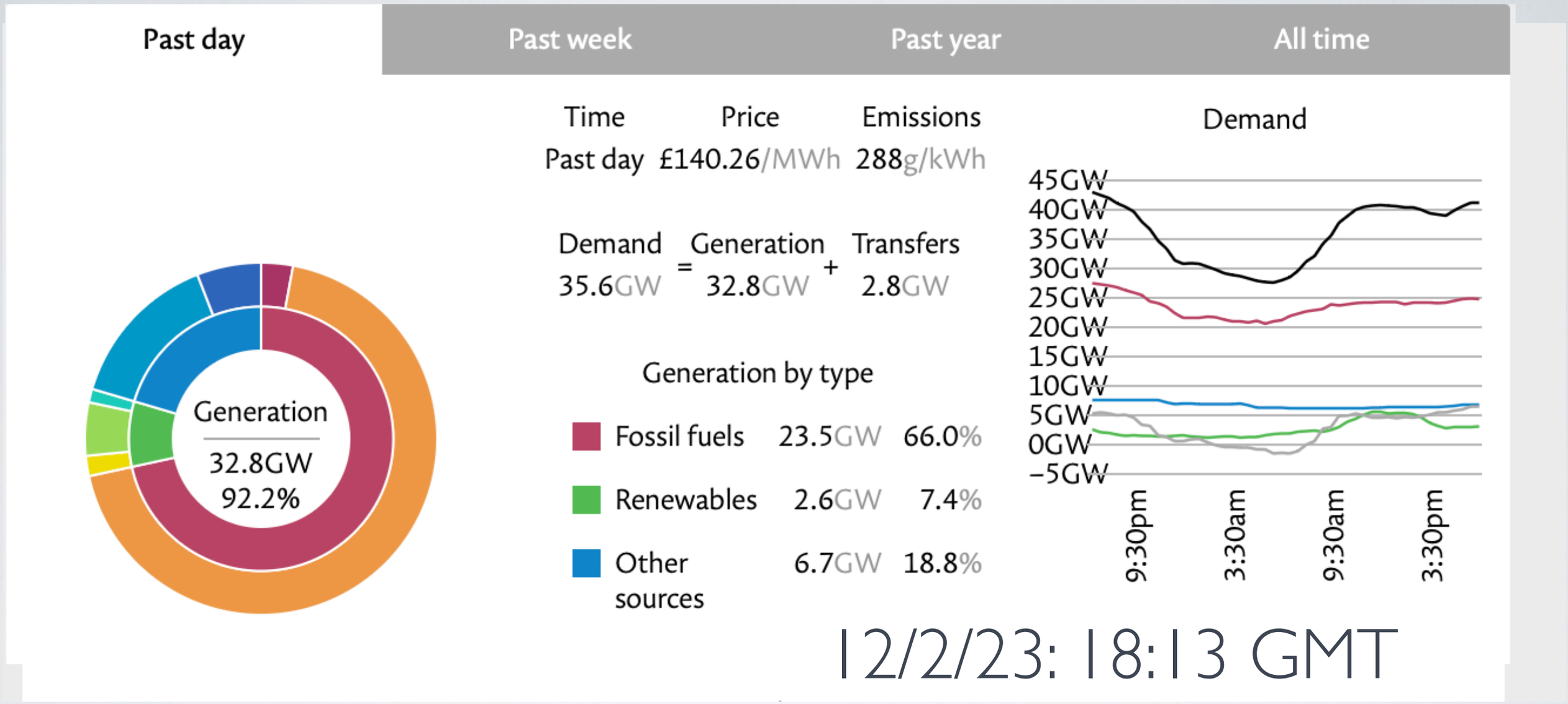
CO2 SEQUESTRATION

- We will <u>never</u> remove CO2 directly from the atmosphere with any sort of technology process!

$$\text{work}_{\text{min}} = \Delta G = -R\,T \sum_{i}^{\square} x_i \,\text{Log}[x_i]$$

- If you start with an exhaust stream of a coal or natural gas plant, technologies exist to absorb the CO2, which can be compressed and pumped into some sort of long term storage.
  - This could be accomplished with ~20% of the electricity from the power plant!
  - Plus a capital cost that is 30-40% higher.
  - Approximate doubling of wholesale electricity price.

CHALLENGE WITH WIND AND SOLAR



There are times in the winter when both wind and solar are very low

https://grid.iamkate.com/

mjm@nd.edu

chemeprof.com

GRID SCALE ENERGY STORAGE

- At the present time this is infeasible!
    - Lithium Ion:
        - way too expensive, hard to get the needed Lithium
    - Multiple other battery systems are being studied:
        - Nothing is close to commercialization
    - "Pumped-hydro" is doable where you have excess water and a working hydroelectric plant — that is not at capacity….
    - Proposed solution:
        - Convert excess electricity to hydrogen by water electrolysis — store the hydrogen
- Until this can be solved. It will be hard to get the fraction of "renewables" much higher.

ALSO THERE IS A LAND USE *DENSITY* PROBLEM

ON AN 100 ACRE SITE

- Coal to Electricity: 1000 MW
- Solar to Electricity: 30 MW
- Wind to Electricity: 0.4MW
- Corn to liquid fuel: 0.1 MW
- 10 oil wells (surface footprint): 10 GW

GREAT CHALLENGES REMAIN!

OPINION | REVIEW & OUTLOOK Follow

Car Dealers to Biden: EVs Aren't Selling

Some 3,900 sellers ask for a reprieve from his onerous sales mandate.

CLIMATE SOLUTIONS

Electric vehicles are hitting a road block: Car dealers

Some customers say auto dealers have steered them away from buying electric cars and trucks

By Shannon Osaka

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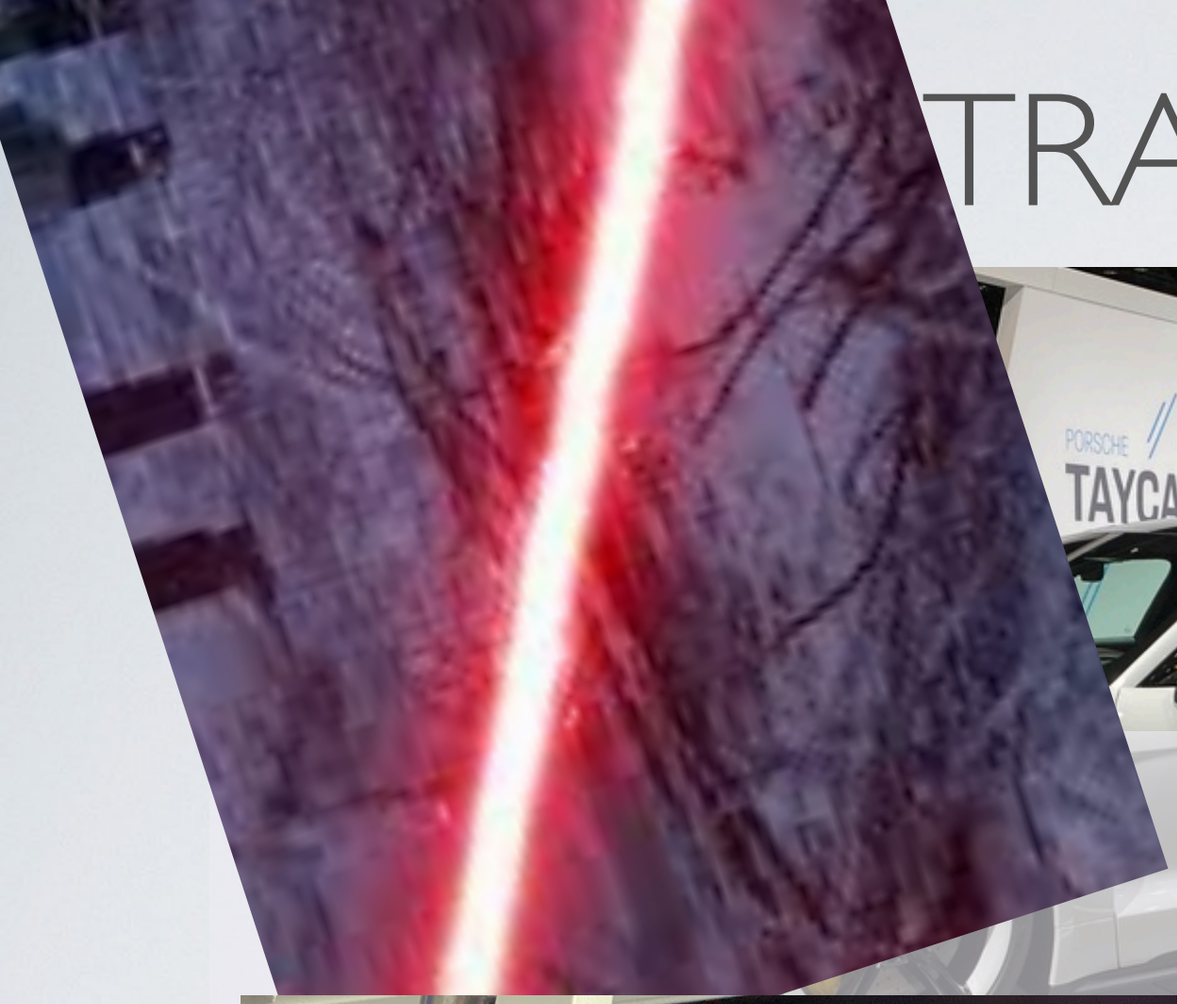
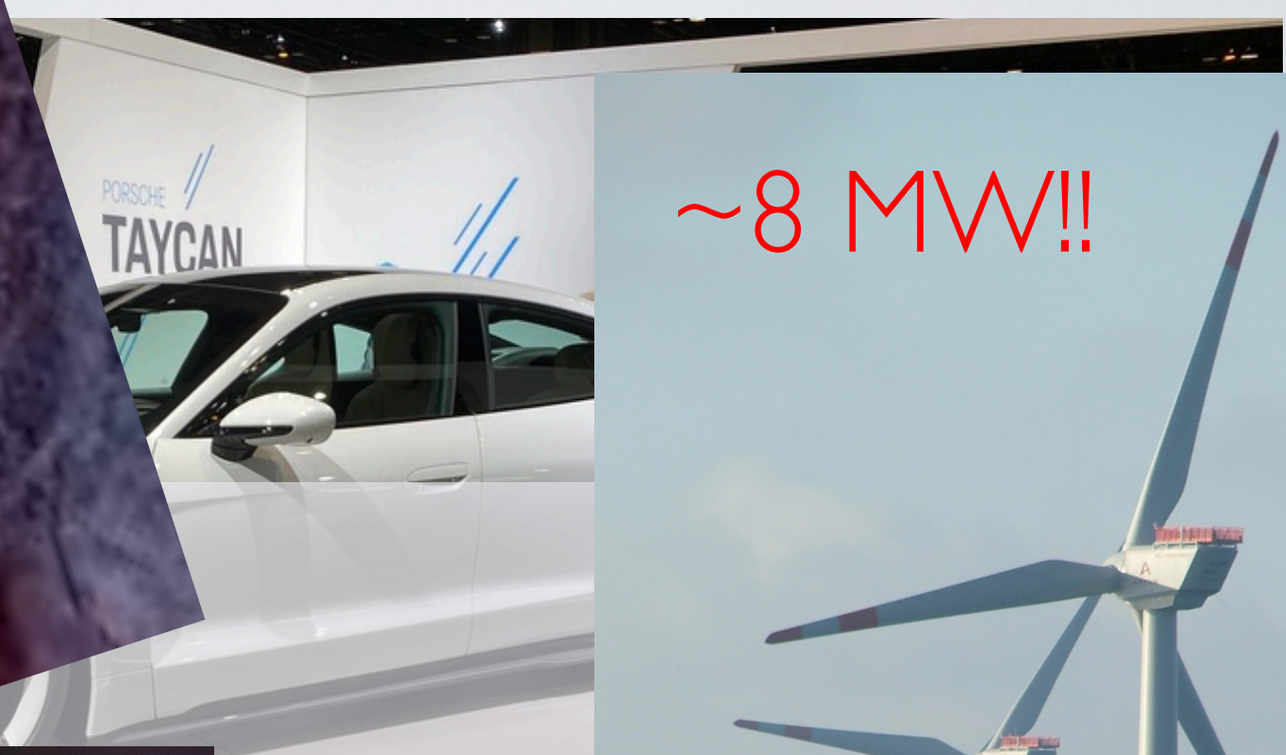
HOME > TRANSPORTATION

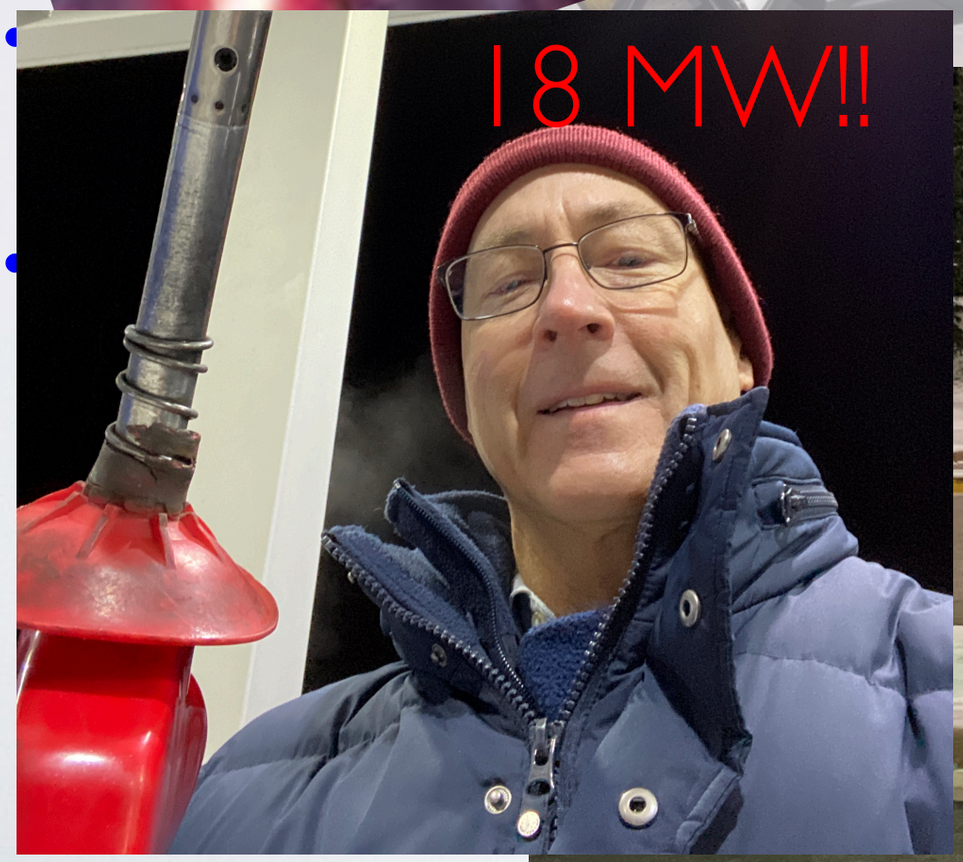
EVs are running out of customers — and some dealers don't want them anymore

Alexa St. John and Nora Naughton Aug 23, 2023, 2:06 PM EDT

TRANSPORTATION







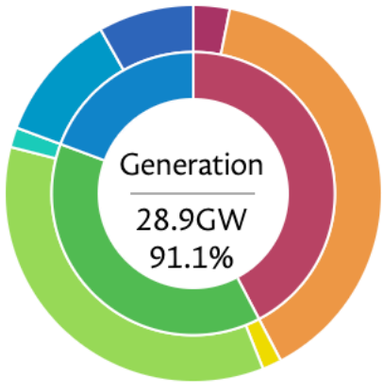
CLOSING THOUGHTS

- Your efforts to preserve history and knowledge of the past do not appear to be facing any kind of existential threat.
- Even if there is no uncertainty, Science and Scientists don't tell us what to do.
    - The path forward is a set of governmental *policy* decisions.
        - What is best based on what we know and how different paths will affect different segments of society?
        - Cost over time is a serious concern.
- Perhaps the way to view the future is to make changes that are actually possible and will have most significant impact.
    - For powering the world, nuclear appears to be the only low CO2 emission technology

CLOSING THOUGHTS

- If you got a serious medical diagnosis
- Science and Scientists don't tell us what to do.
  - That is what are the "best" policies…
- Actions of government or society are political decisions.

Past day | **Past week** | Past year | All time

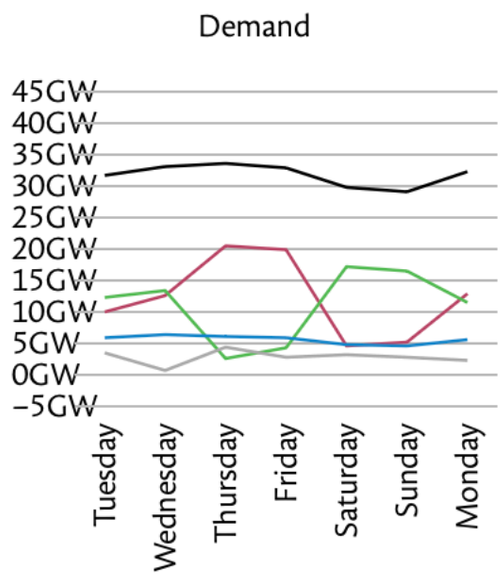


Time	Price	Emissions
Past week	£92.99/MWh	173g/kWh

Demand	=	Generation	+	Transfers
31.7GW		28.9GW		2.8GW

Generation by type

Fossil fuels	12.2GW	38.6%
Renewables	11.1GW	35.0%
Other sources	5.6GW	17.6%

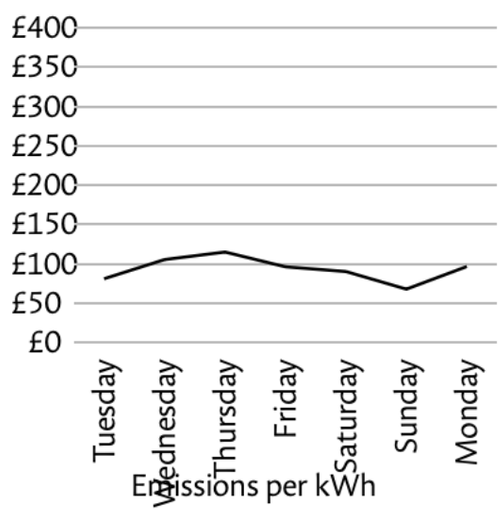


Generation by source

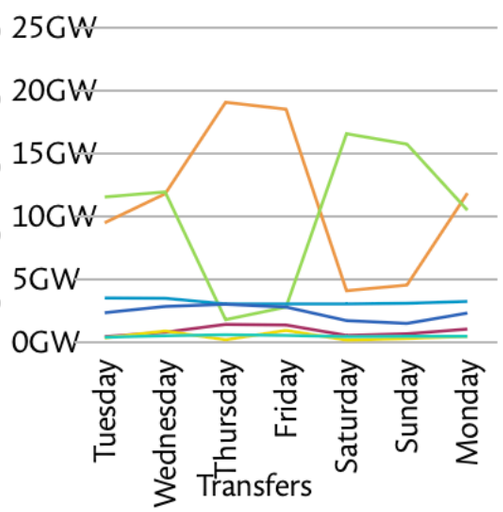
Coal	0.90GW	2.8%
Gas	11.34GW	35.7%
Solar	0.48GW	1.5%
Wind	10.13GW	31.9%
Hydroelectric	0.49GW	1.6%
Nuclear	3.22GW	10.1%
Biomass	2.37GW	7.5%

Interconnectors

Belgium	0.54GW	1.7%



Emissions per kWh



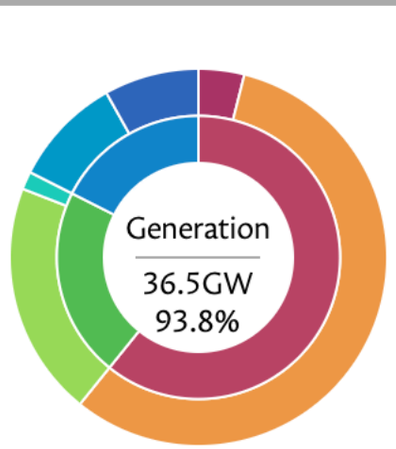
Transfers

National Grid: Live

The National Grid is the electric power transmission network for Great Britain

Time	Price	Emissions	Demand		Generation		Transfers
7:35pm	£125.39/MWh	252g/kWh	38.9GW	=	36.5GW	+	2.4GW

Generation



Note: percentages are relative to demand, so will exceed 100% if power is being exported

57.0% fossil fuels

Coal	1.43GW	3.7%
Gas	20.76GW	53.3%

20.3% renewables

Solar	0.00GW	0.0%
Wind	7.34GW	18.9%
Hydroelectric	0.56GW	1.4%

16.4% other sources

Nuclear	3.44GW	8.8%
Biomass	2.96GW	7.6%

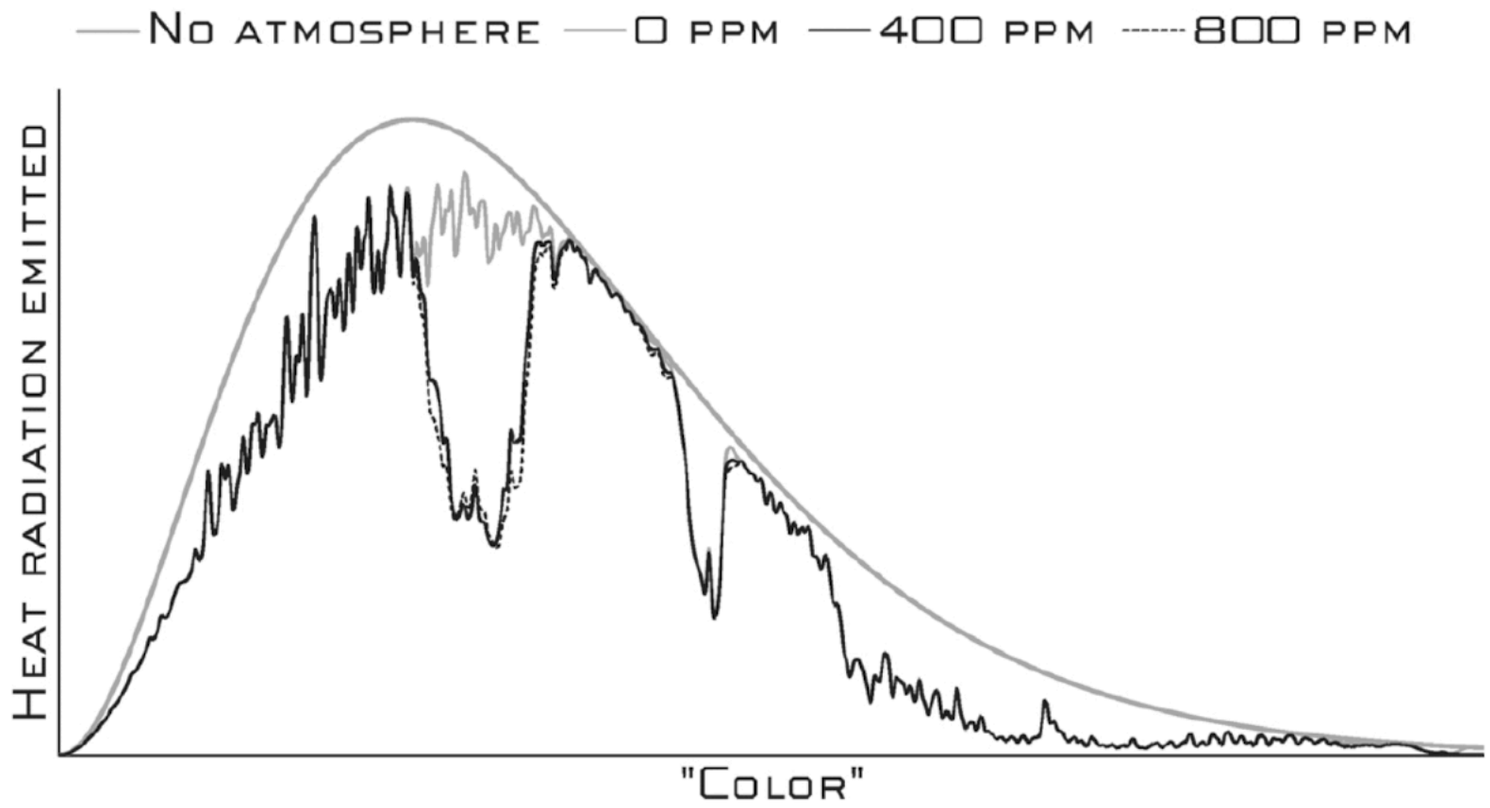
5.4% interconnectors

Belgium	0.73GW	1.9%
France	1.82GW	4.7%
Ireland	−0.75GW	−1.9%
Netherlands	0.32GW	0.8%
Norway	−0.01GW	−0.0%

0.8% storage

Pumped storage	0.32GW	0.8%
Battery storage	—GW	—%

EFFECT OF CO_2 ON THE HEAT SPECTRUM OF THE EARTH



BASIC "ASSUMPTIONS"

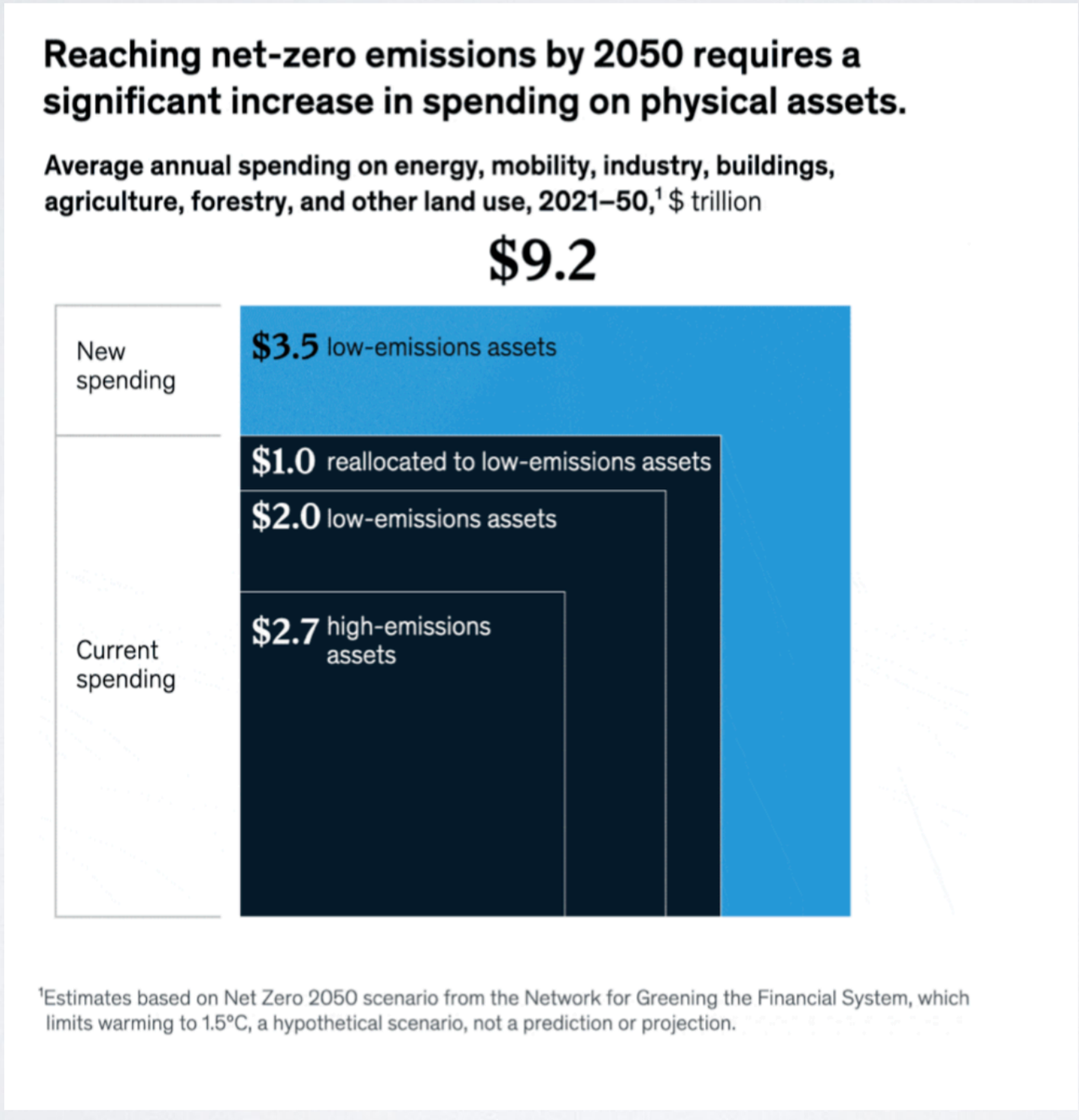
- Not sustainable if we can't afford
- Chesnuts
- Scientists like to affirm their previous results
    - Sometimes hard to go against prevailing thoughts of the establishment
- Scientists like to affirm their political views
- Academic scientist need to feed their research groups
- Other things I think are true.

GEOTHERMAL

- If you want high grade "heat"
- Drilling is expensive!
- From a 6 inch well
- 1 MW of "heat" (really stretching the values..)
- 2000 MW of chemical energy! (If an oil well)

HOW MUCH WILL NET-ZERO COST?

- McKinsey: An extra $3.5 Tril/year from now until 2050.



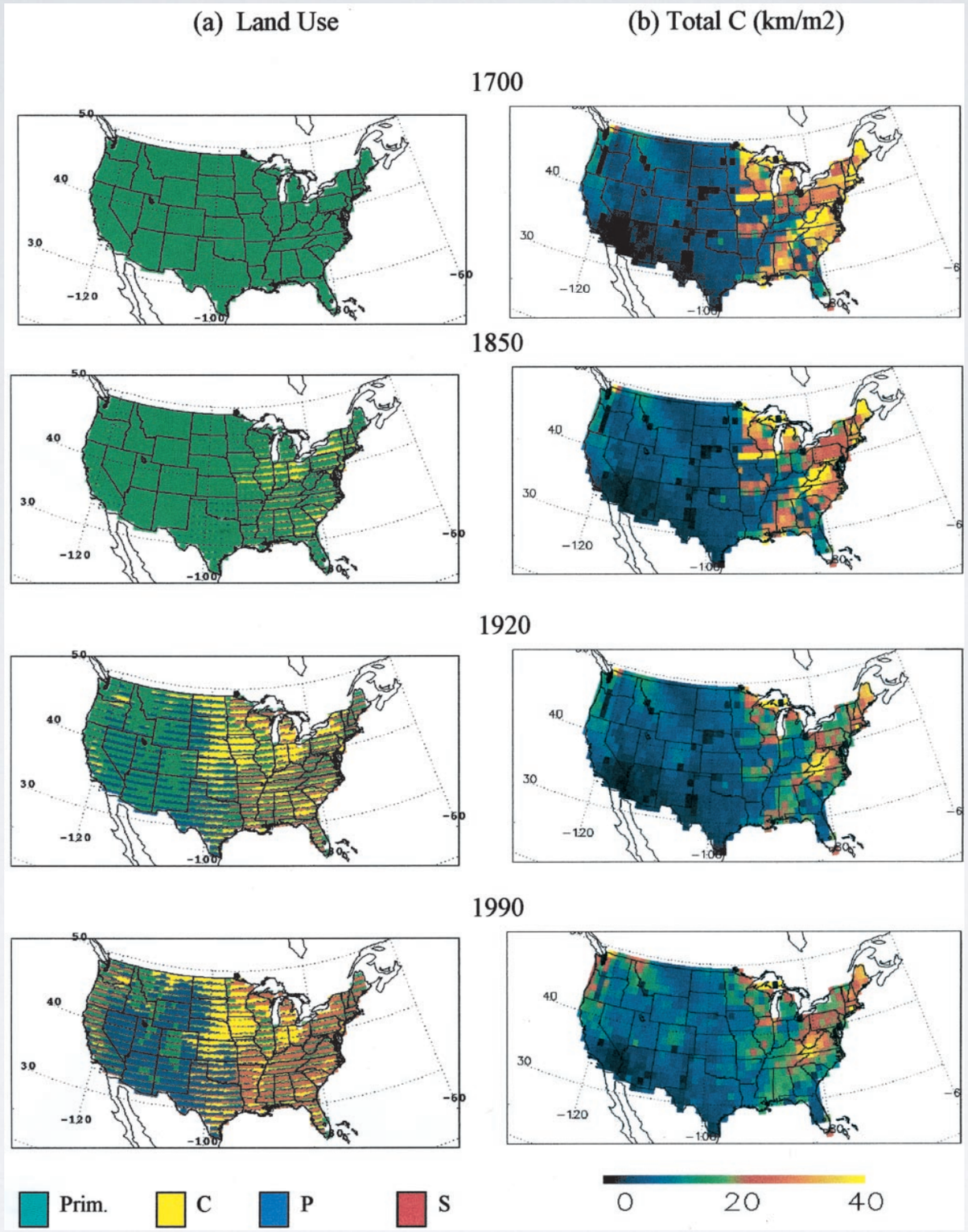


Fig. 1. ED tracks patterns of land use and carbon stocks throughout the simulation. Shown here are estimated patterns of land use and average total carbon stocks (kg C·m^{-2}) at four times in history: 1700, 1850, 1920, and 1990. In the land-use maps, each 1° × 1° grid cell is colored according to the fraction of the grid cell that is estimated to be in each of four land-use classes: primary vegetation (green), secondary vegetation (red), crop (yellow), and pasture (blue). In particular, each grid cell is shown as a stacked bar chart with colors in a fixed order. Spatial patterns of the relative amounts of land use in each of these four classes can be seen on each map. However, subgrid-scale spatial patterns and the impression of bands spanning a series of adjacent cells are the result of consistently applied coloring rules and do not illustrate spatial patterns of land use within grid cells or banded patterns of land use between grid cells.

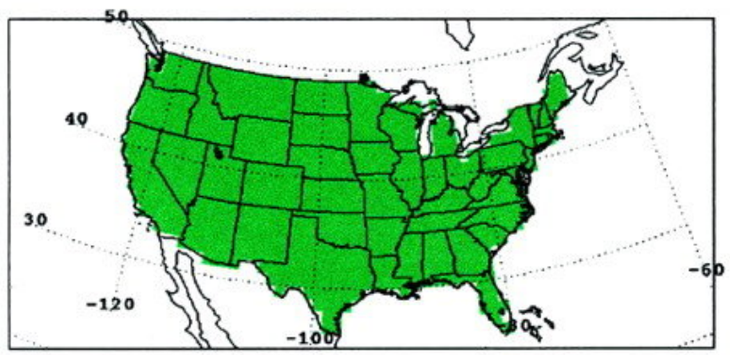
SUMMARY

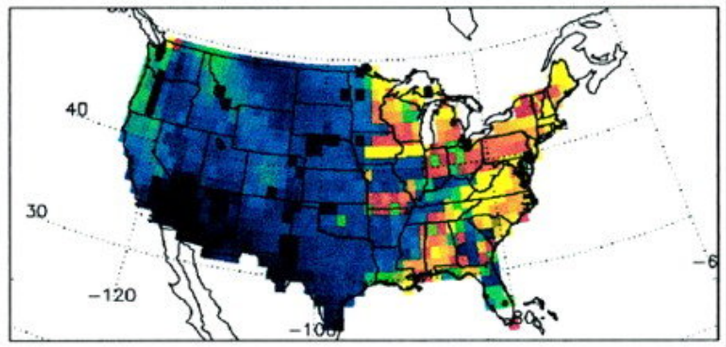
- While we have technologies that *could* allow substantial reductions in the emission of carbon dioxide into the air from the transportation and power generation sector, these are not "better" in the sense that there is a direct economic payback by using them.
    - Thus the costs would be substantial to achieve reductions that would match the predicted 2C temperature increase.
    - It is hard to see where a complete "game-changer" would come from to change this assessment. ("fusion"… still 20 years?)
- Thus an informed discussion of <u>all</u> of the issues needs to be had by society to decide a path forward.

(a) Land Use

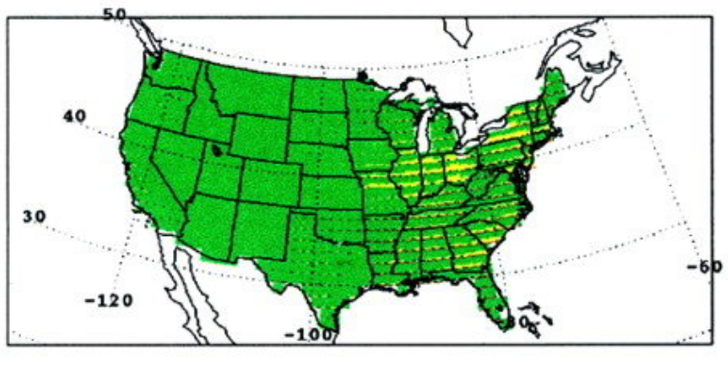
(b) Total C (km/m2)

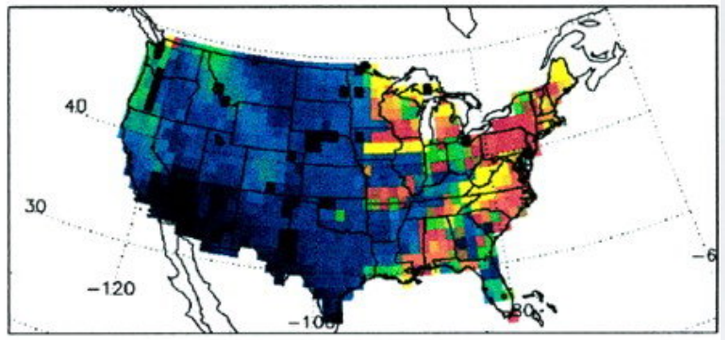
1700



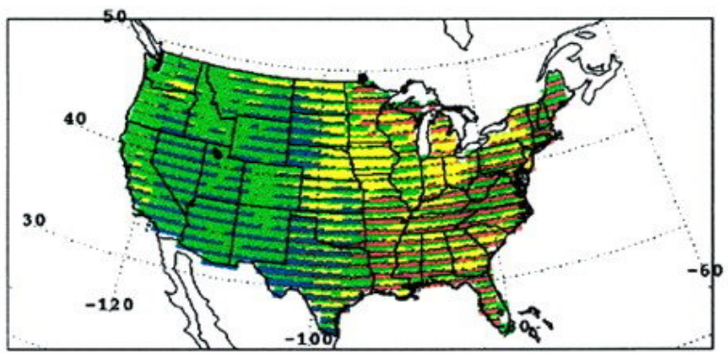


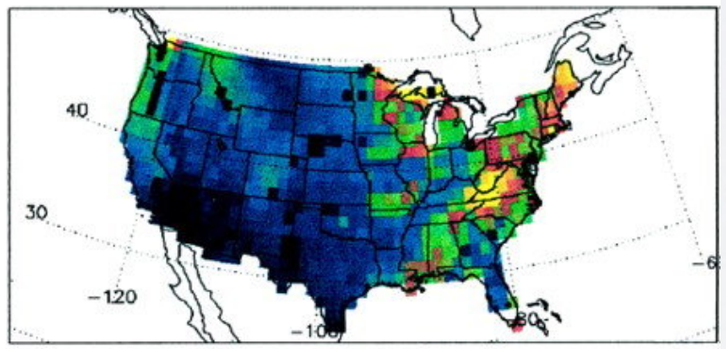
1850



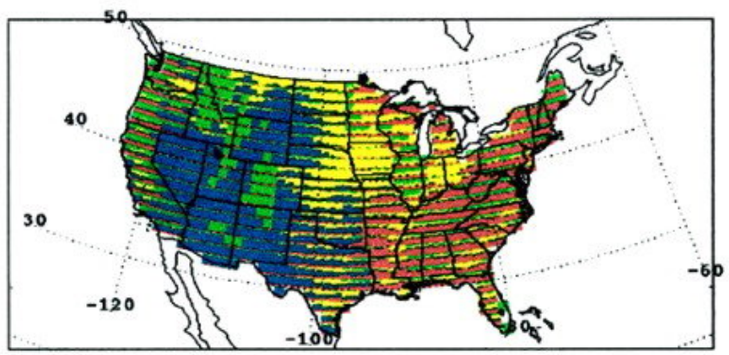


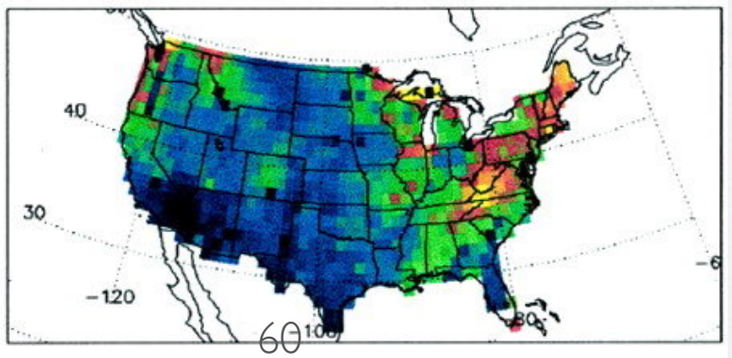
1920





1990





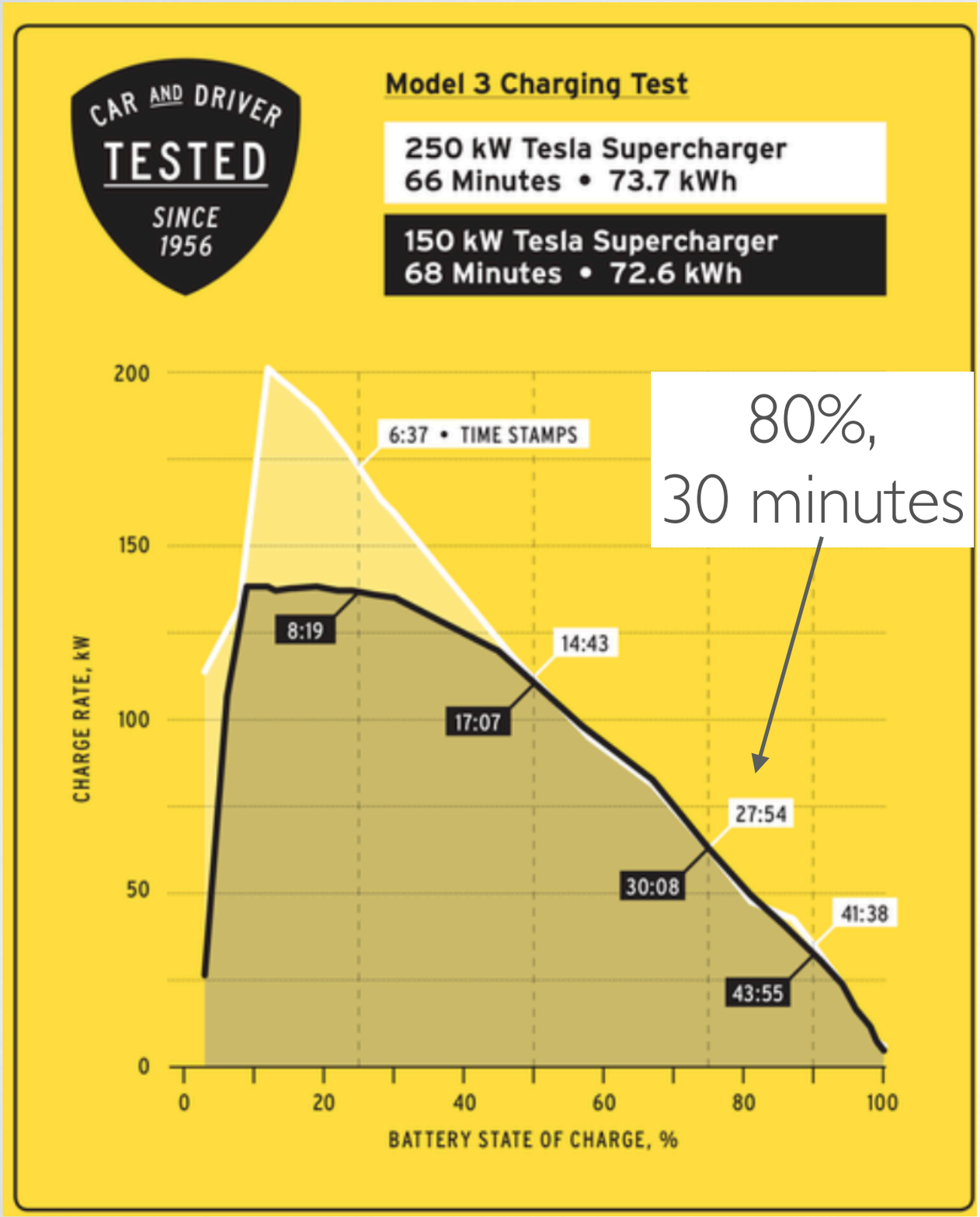
WHAT ARE THE ISSUES RELATED TO ELECTRIC VEHICLE ADOPTION?

- Can the key challenge be overcome?
- Where is the electricity going to come from?
- Will this transition be affordable?

KEY CHALLENGE

- The 12 gallons of gas in my Mazda 3 gives a range of 400 miles. Refueling takes 3 minutes
- A lithium battery pack of the same weight (32 kg) would have a range of about 40 miles.
    - Thus a Tesla or other electric car has a battery pack that weighs substantially more than the equivalent gasoline.
        - Not likely to see battery powered airplanes anytime soon!
- Recharging is also an issue.

KEY CHALLENGE



- For a maximum range of 300 miles, you could get to about 250 miles in 30 minutes

- The "super-duper" charger doesn't change this much

ELECTRIC CARS

- The difference in range, cold weather performance or charging time will be reduced over time.

- (Unsubsidized) cost differential will be reduced over time.

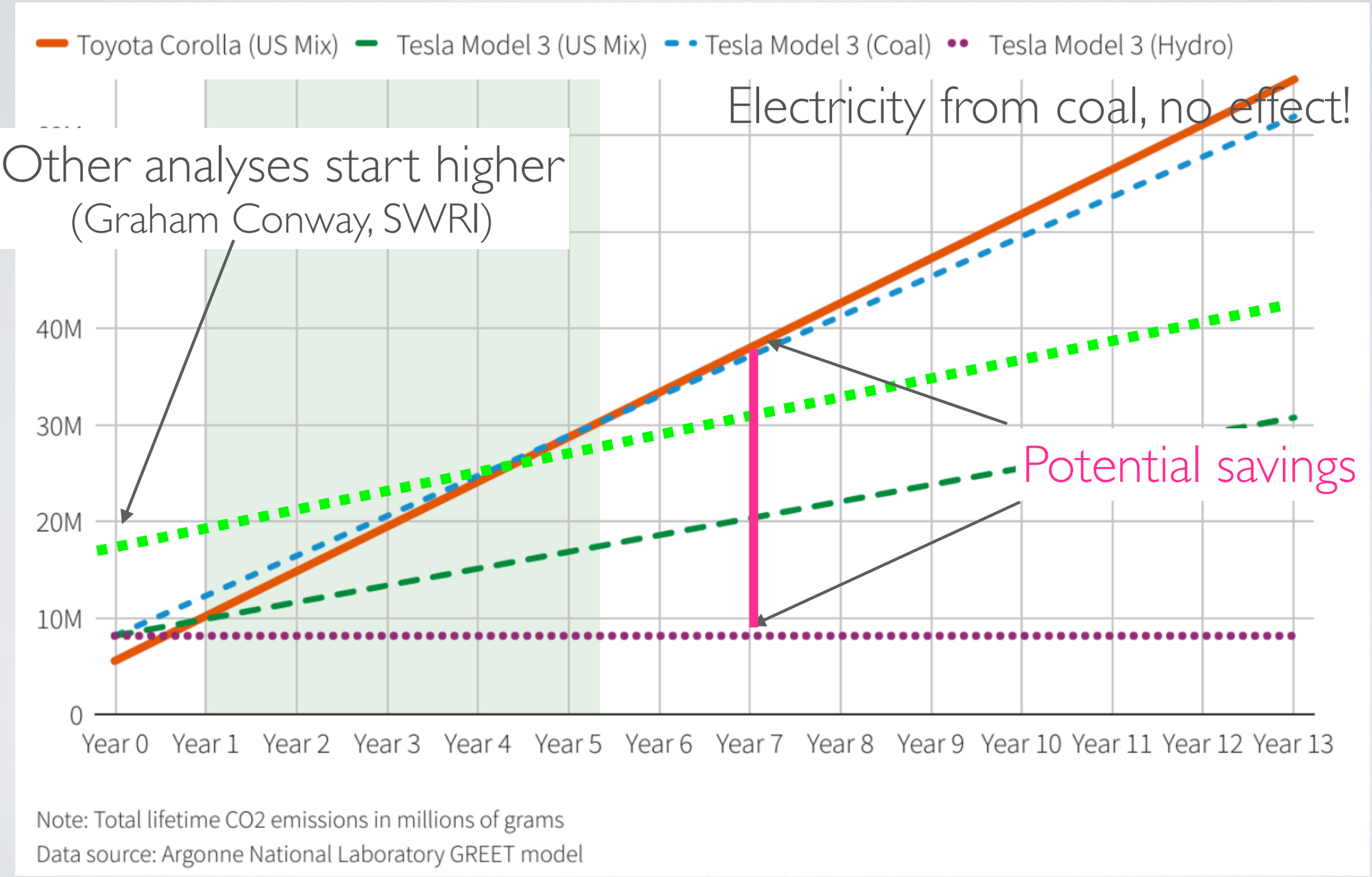
- Key materials (availability, extraction techniques) will probably remain a concern.

RECHARGING

- Indiana Toll Road + Ohio Turnpike, 392 miles, about 6 hours to drive
- On a really busy travel day, the 11 travel plazas will have backups at the gasoline pumps.
    - While there is some lost time, it takes only about 3 minutes to fill up.
    - One tank will provide enough fuel so on average, each car will stop for gas only 1 time.
- What if all cars were electric?
    - Today, a Tesla supercharger can give a car <300 miles of range in 20-30 minutes.
    - We need to provide about 9 times more charging capacity — meaning each plaza would need 144 charging ports. (OK, so every space!)
    - **Total power needed for this: 650MW! (Where from?)**

EFFECT ON CO2

ELECTRIC CAR: EFFECT ON CO2



Note: Total lifetime CO2 emissions in millions of grams

Data source: Argonne National Laboratory GREET model

ELECTRICITY GENERATION

- Almost all of the "hydro" available in the US has been tapped.

- Significant environmental pain to get more.

RENEWABLE POWER SOURCES

- Biofuels (ethanol is just barely CO2 positive compared to natural gas and diesel needed for farming)

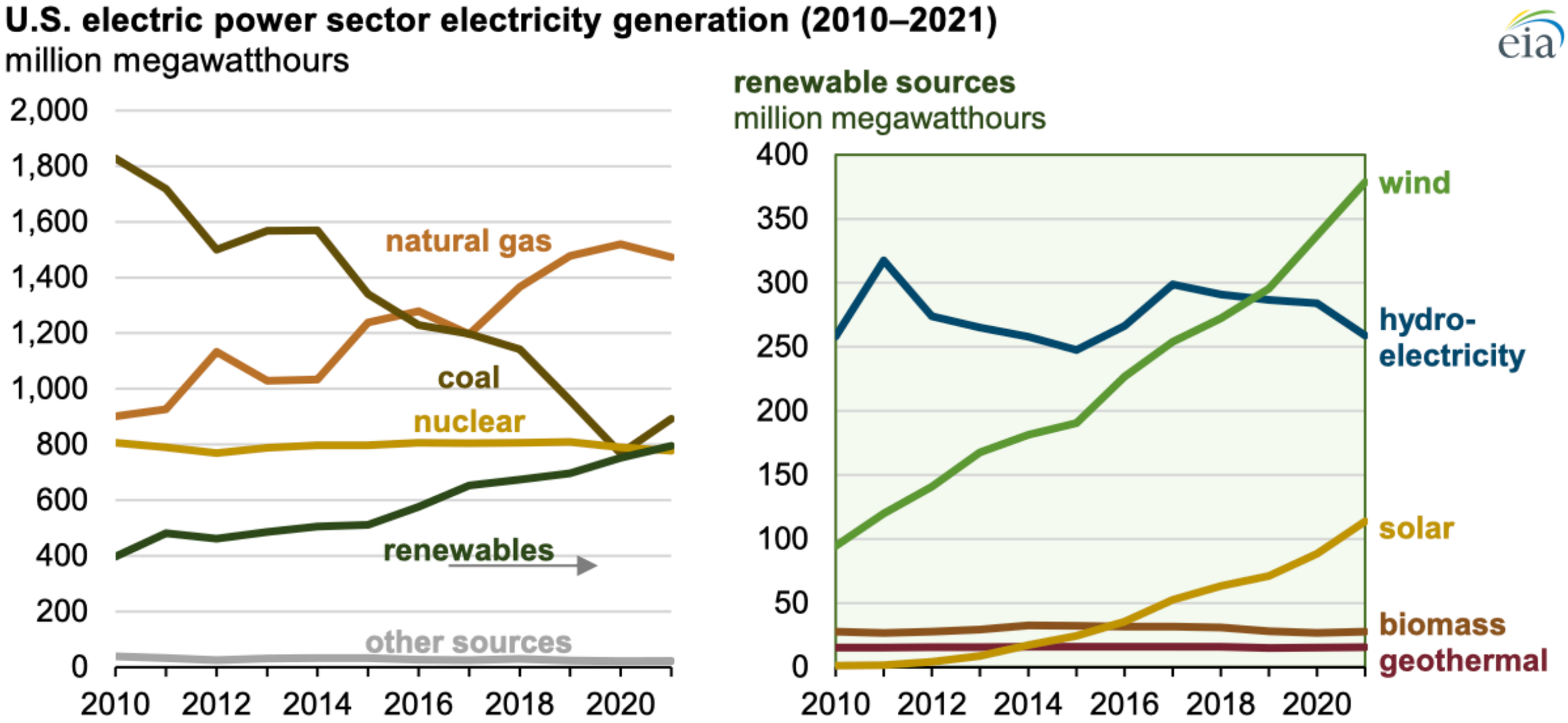
- Wind (intermittent, location dependent, birds?)

$$\text{Power} \sim V^3_{\text{wind}}$$

- Solar (intermittent, location dependent)

- Geothermal (location dependent, expensive)

ELECTRICITY GENERATION: RENEWABLES HAVE MADE GAINS….



Source: U.S. Energy Information Administration, *Electric Power Monthly*

PLASTIC RECYCLING

- Coca Cola has a very comprehensive effort
  - Thinks this is a business advantage

CHALLENGES OF RENEWABLES

- If we work out the numbers, the power density of wind is about
    - 0.004 MW/acre
- What could we compare this to (Engineers always want to make comparisons!)
- How about solar flux?
    - We can capture only part of the solar flux for useful heat, much less for electricity
        - What are these numbers?
- Solar flux averaged over the earth is ~350 W/m^2
- While nothing more energetic than a tree “runs” directly on solar, this gives a value of about
    - 0.3 MW/acre