Sequestration of Atmospheric Carbon Dioxide as Inorganic Carbon under Semi-Arid Forests

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11 Sept. 2019

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Introductions

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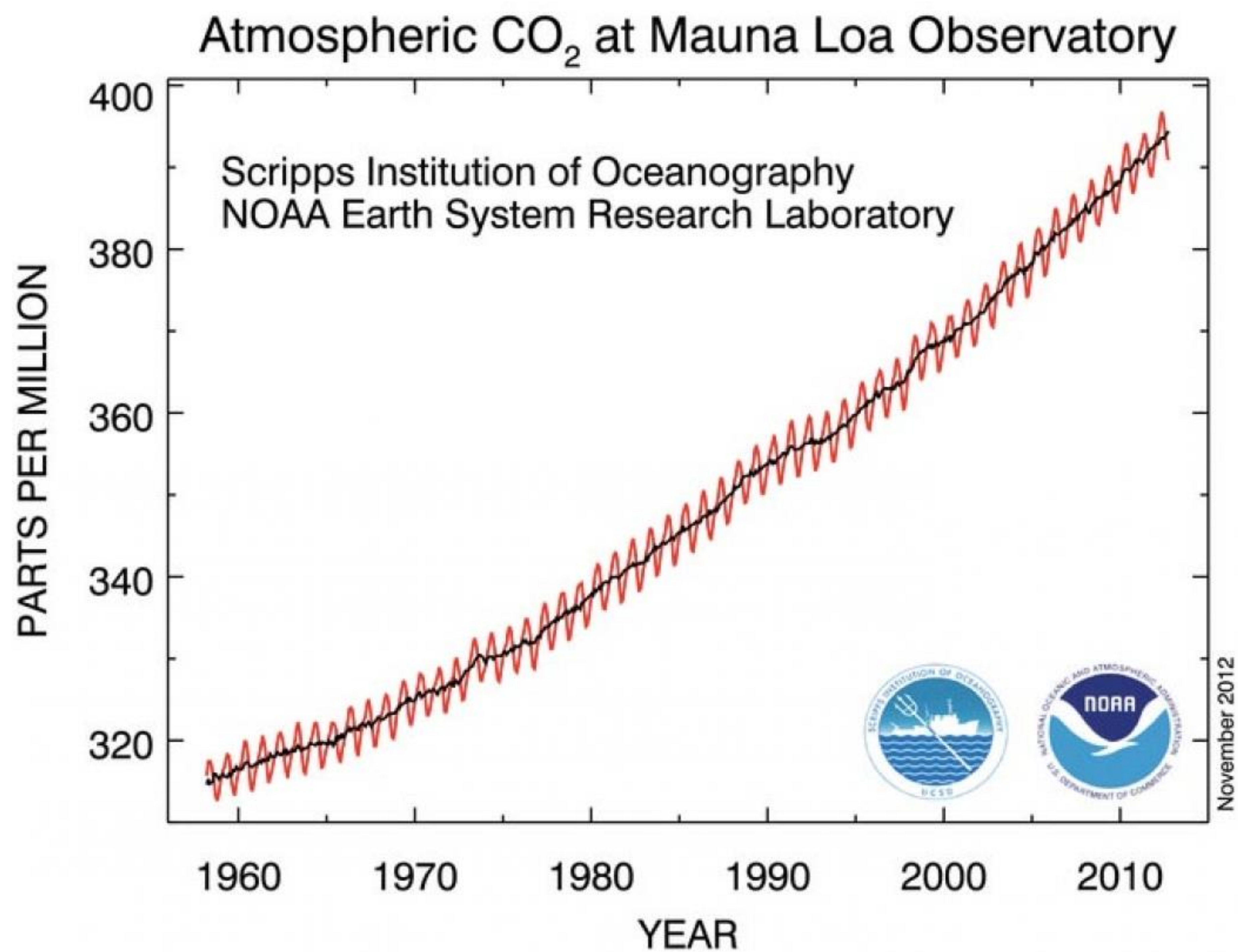
Greenhouse Gases

Atmosphere contains ~320 billion tons CO_2

Annual increase is ~20 billion tons CO_2

Excessive CO_2 greenhouse gas may cause global warming, climate change, rising sea levels, ocean acidification, ocean deoxygenation, melting icefields, more forest fires, reduced food supply, etc.

Increasing Atmospheric Carbon Dioxide



What can be done?

- Burn Less Fossil Fuels. (difficult to achieve)

- Nuclear power, develop safer reactors, deal more effectively with nuclear wastes. ("Greens" opposition)

- Stop Deforestation

- Climate engineering projects proposed for *carbon dioxide remova*l (CDR) and *solar radiation management* (SRM). (large, expensive, controversial)
  CDR captures CO_2 produced by large industrial plants, compresses it for transportation, and then injects it deep into a rock formation for permanent storage.
  SRM projects seek to reduce global warming by reflecting sunlight, for example using stratospheric sulfate aerosols

- ***Carbon reduction & storage via forestation. (low cost & low tech)***

How to prevent temperature increase?

Pinatubo eruption June 1991

↓

10 billion tons magma & 20 million tons SO_3

↓

Global Temperatures decreased 0.5°C 1991-1993

↓

Best not to count on volcanic eruptions!

How to prevent temperature increase?

Fossil fuels provide ~80% of global energy supply

Collect CO_2 and securely bury deep underground

↓

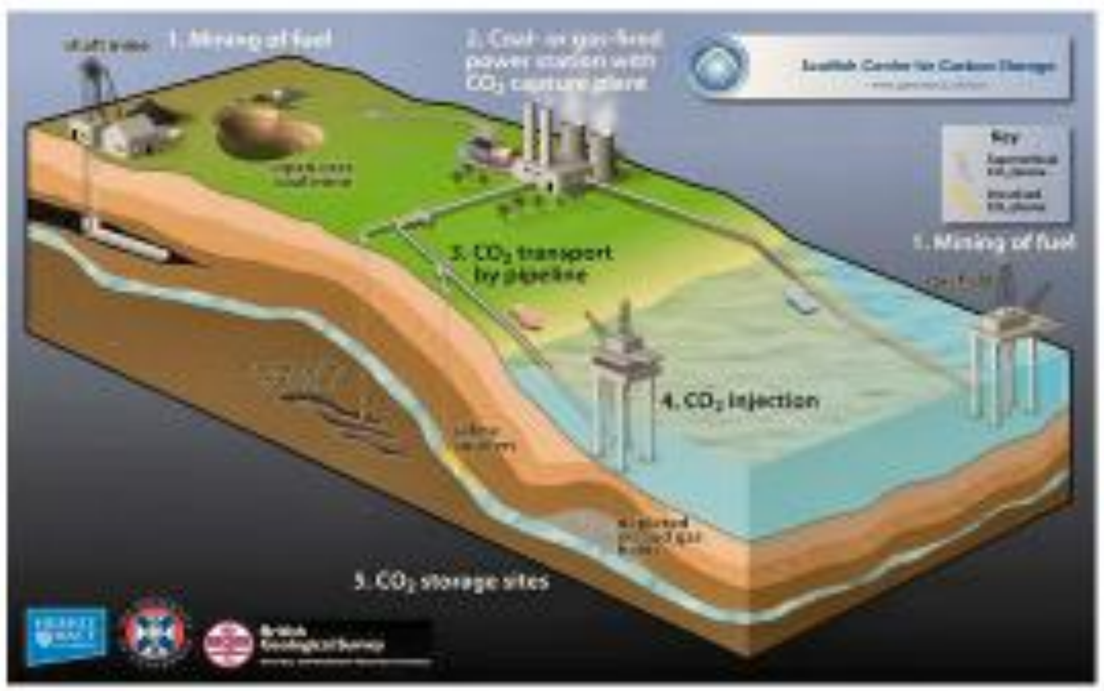
Sequester ~40% of annual CO_2 production

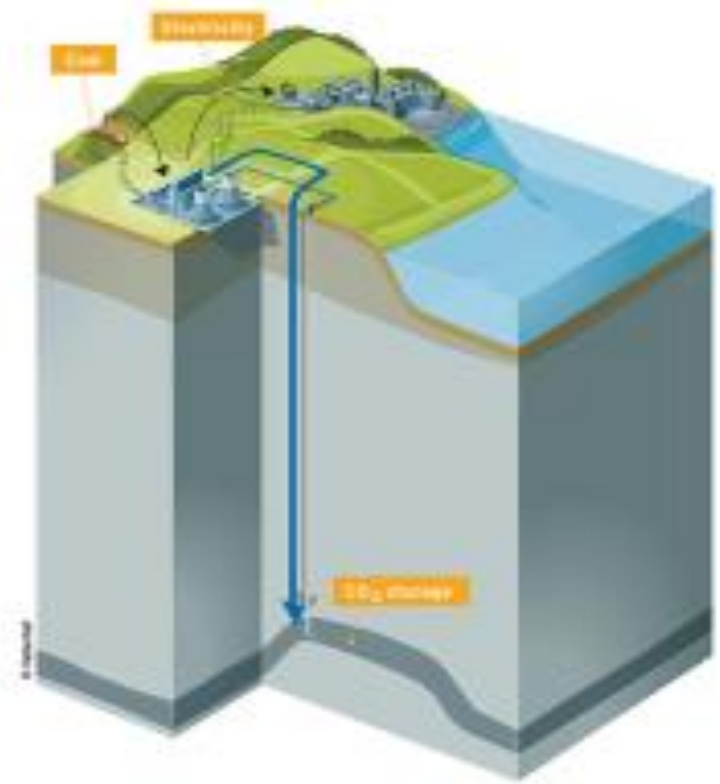
↓

complicated & expensive

Carbon Capture and Storage: What It Is

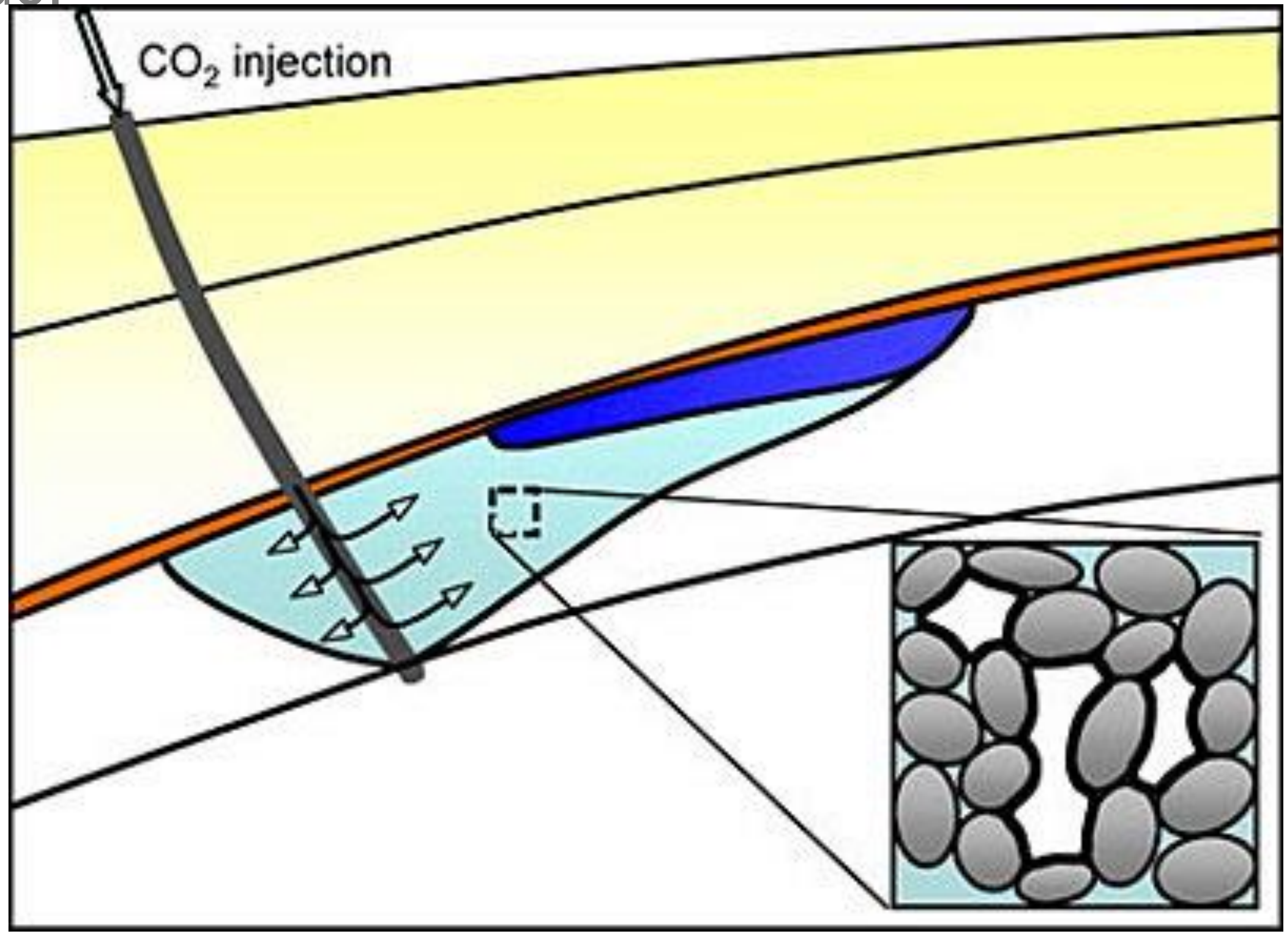
- Capture CO_2 released from burning fuels and store it elsewhere
- Reduce CO_2 emission into atmosphere
- Steps:
  1.) Capture
  2.) Transport
  3.) Storage





Technological Feasibility

- Removing the Carbon Dioxide is not the problem, it’s storing it that’s the main issue.



How to prevent temperature increase?

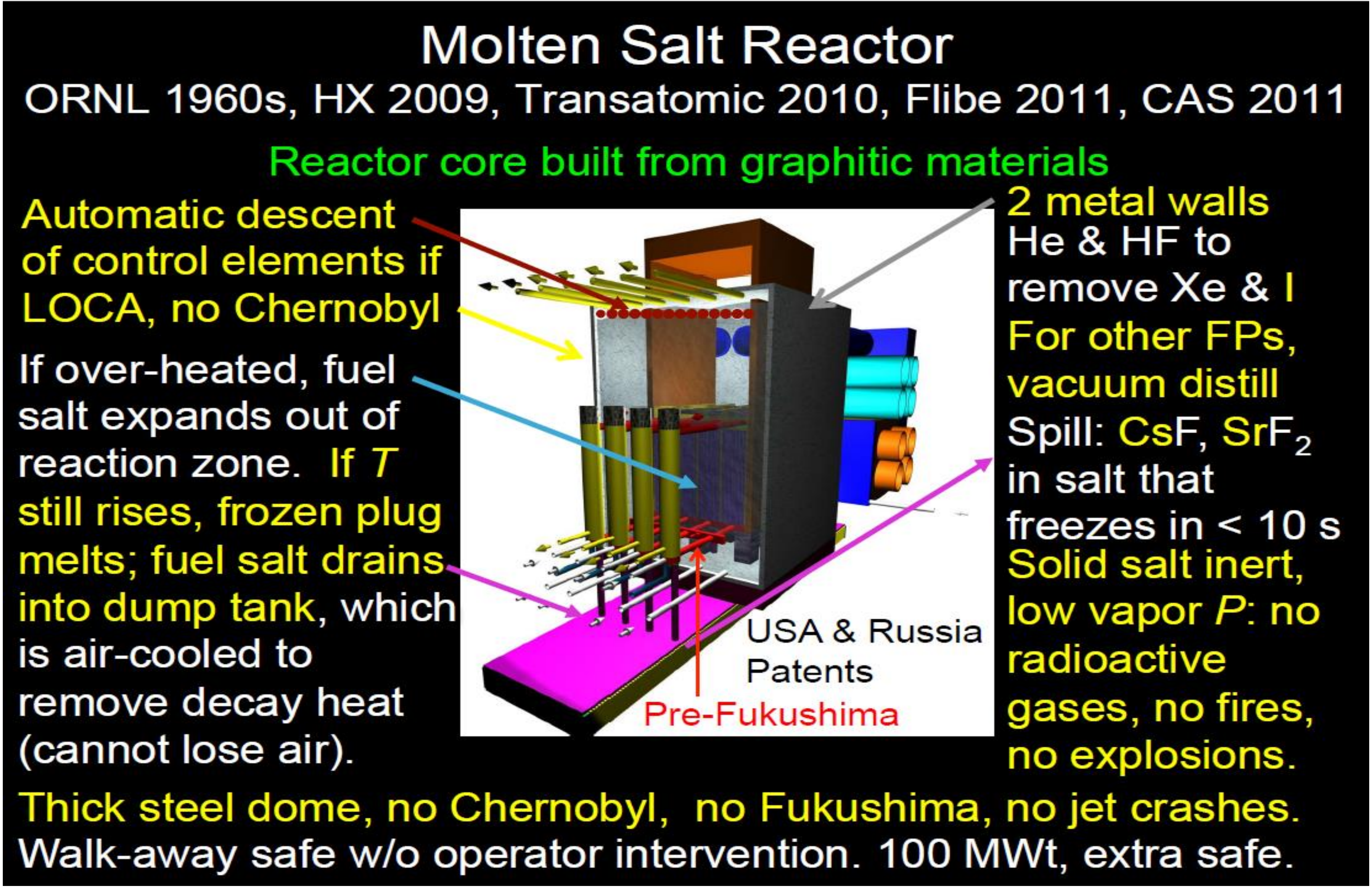
develop and use safer nuclear power,

Molten Salt Breeder Reactors, etc.

Preferred to collecting CO_2 from fossil power stations

R&D Blocked by NO NUKES

No money and No political will to develop and use safer nuclear power



Safe Reactor Design and Construction and Experience too expensive, even for those countries still interested. Safe reactors will not be ready when needed.

The Amazon rain forest is disappearing at a speed of approximately 4000 football fields per hour!

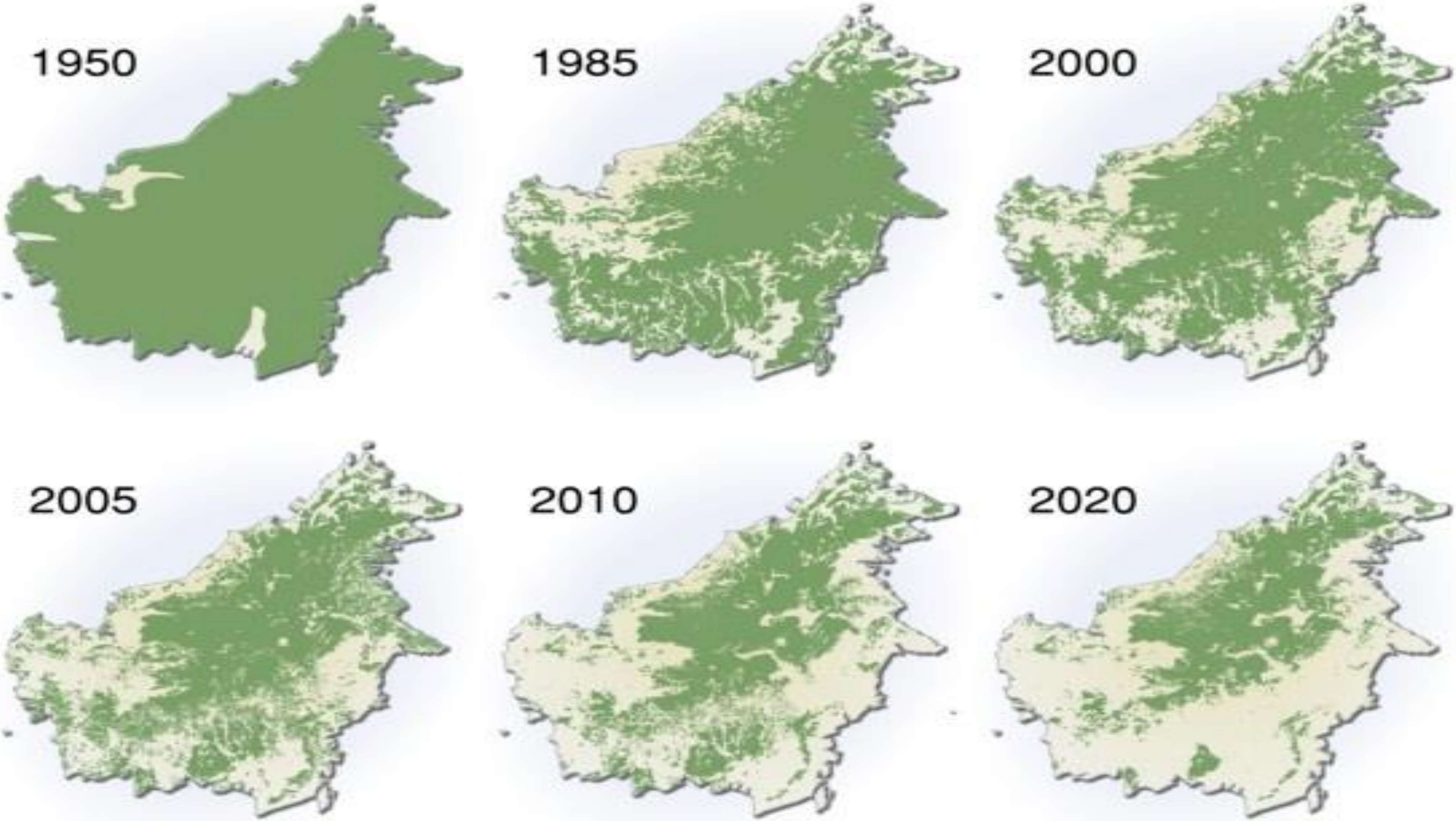
- Wood for construction and for making fires.
- Agriculture (soy) for farms.
- Land for poor farmers who have no other place to live.
- Grazing land for cattle.
- Road construction
- Oil production
- Mining

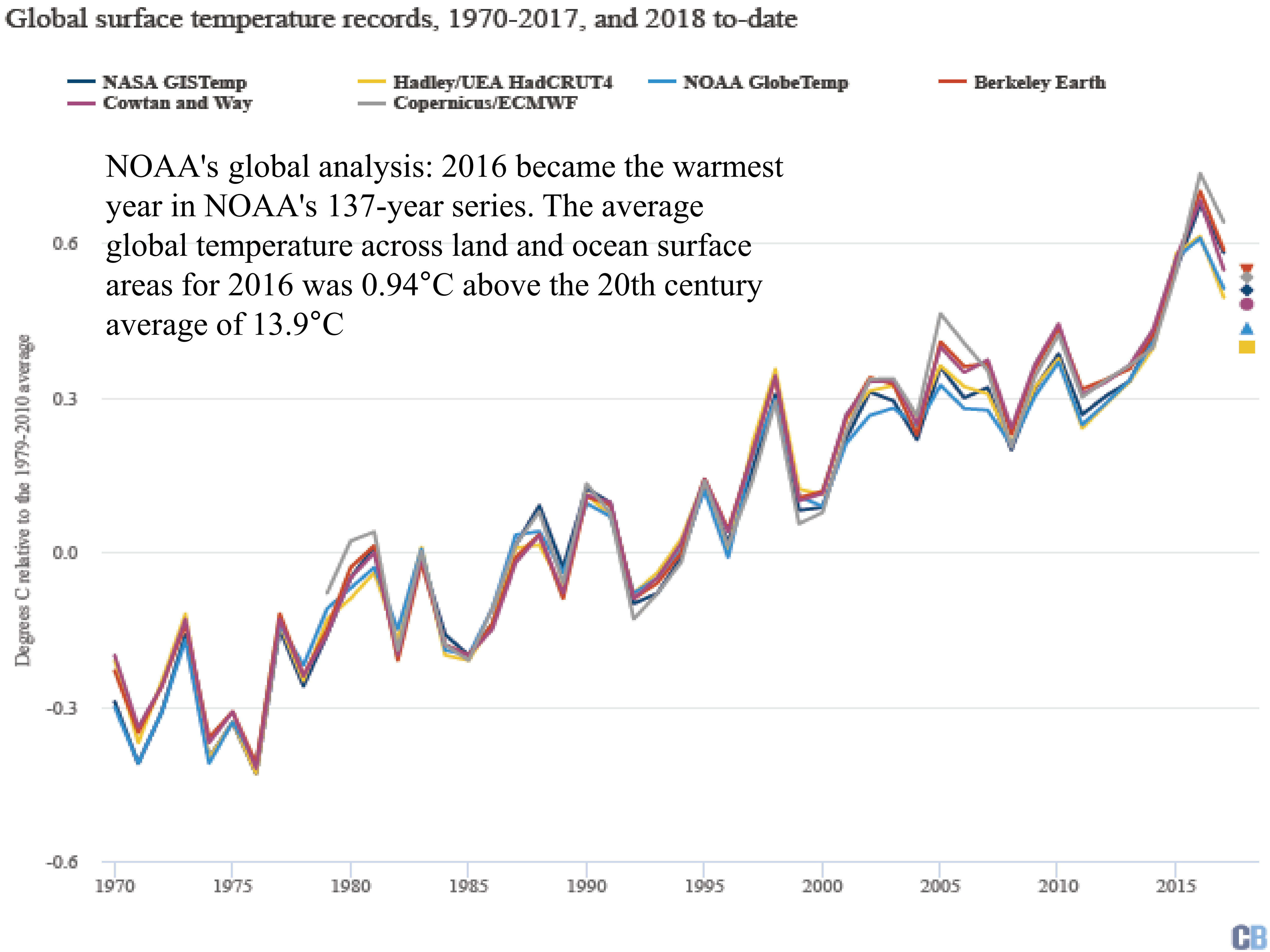
Droughts are changing the Amazon rainforest

Droughts are increasingly frequent in the Amazon rainforest, with three "100 years" droughts in the space of only 10 years. Trees have openings at the bottom of their leaves called stomata, which open and close to regulate the amount of carbon dioxide a tree absorbs and the amount of water vapor it releases. When there is more carbon dioxide in the atmosphere, stomata do not need to open so widely and, therefore, release less water vapor, and fewer clouds will form over the forest.

The Amazon rainforest suffered severe droughts that killed large amounts of vegetation in the most affected areas. Also, unfortunately, an increase in global temperature can kill many more trees.

Brazil Deforestation





Annual global mean surface temperatures from NASA GISTemp (https://data.giss.nasa.gov/gistemp/), NOAA GlobalTemp

2015 Paris Climate Agreement

- The 2015 Paris Agreement deals with GHG emissions mitigation, adaptation and finance starting in the year 2020, to help stop the gradual warming of the Earth. 2018 Santiago, Chile meeting Dec. 2018.

- Main aim is to limit the increase in the global average temperature to well below 2°C above pre-industrial levels, by reducing GHG emissions.

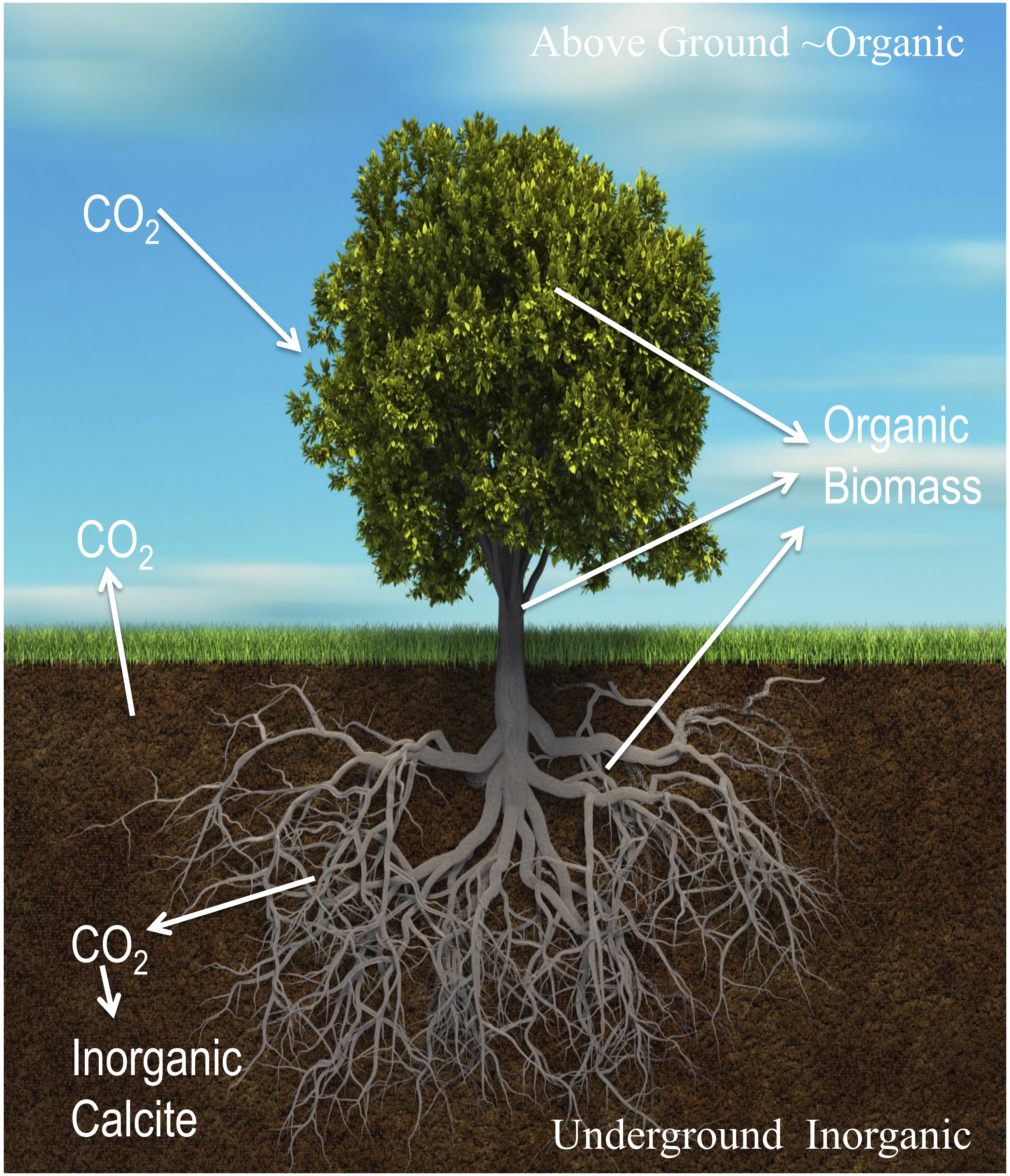
- But this target now requires "negative emissions", i.e., extraction of CO_2 from the atmosphere.

- By July 2018, 194 states and the European Union have signed the Agreement.

- **But a study published 2017 in Nature found that all major industrialized nations are failing to meet the pledges they made in the Paris Agreement.** And these pledges are anyhow inadequate. Emissions keep rising and impacts are being felt all around the world. USA, India and China were responsible for 85% of the global rise in energy-related carbon dioxide emissions over the past year.

- USA for example delivered an official notice to the UN that it intends to withdraw from the Paris Agreement 4 Nov. 2019, the earliest date that it is legally eligible to withdraw.

- Photosynthesis - Leaves inhale CO_2. Roots in semi-arid regions are deep, and also exhale CO_2 into USZ at high partial pressure
- $CO_2 + H_2O \longrightarrow$ dissolved HCO_3^- bicarbonate, combines with soil Ca^{+2}, precipitates $CaCO_3$ calcite.
- Trees in semi-arid regions sequester atmospheric CO_2 long term underground as stable calcite, low rainfall – calcite does not dissolve.
- These trees also sequester atmospheric CO_2 short term, as organic biomass.
- But burning, decomposition of biomass reinject CO_2 into the atmosphere.

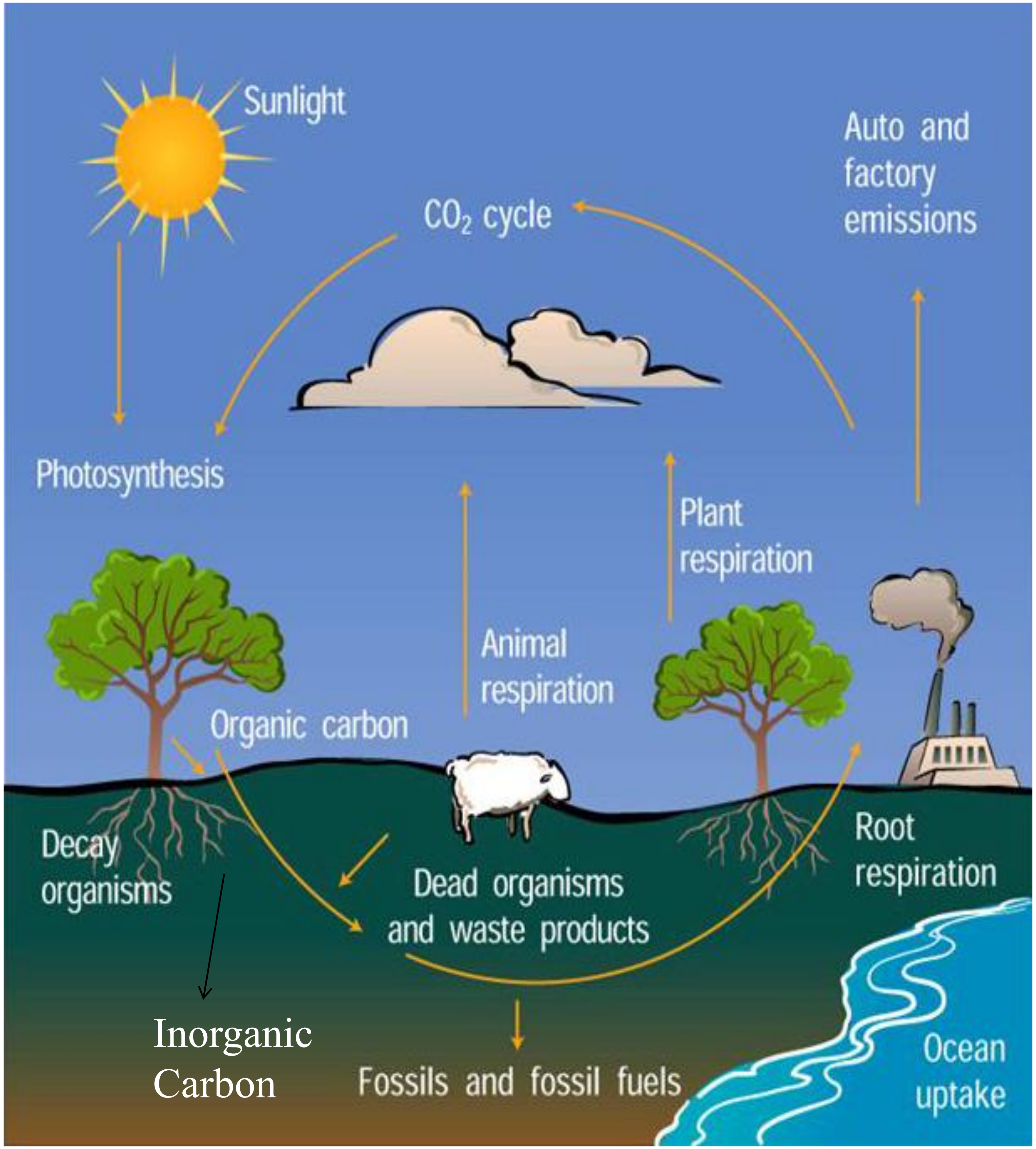


Tree Respiration

- **Why is CO_2 exhaled by the roots?**
- During the day, the tree inhales air (CO_2, O_2, etc.) through the stomata. and uses CO_2 via photosynthesis to produce O_2 and $C_6H_{12}O_6$ glucose. Some inhaled or produced O_2 is used to oxidize glucose, to produce energy for the tree's biological functions, via the reaction $C_6H_{12}O_6 + 6O_2 \longrightarrow 6CO_2 + 6H_2O$
- Not all the glucose is oxidized, but is rather used for other biological purposes. The tree's metabolism is such that the oxidation of glucose, and tree growth, work at a higher rate at night, when the tree is not occupied with photosynthesis. So the roots exhale CO_2 produced by oxidation of the glucose. Besides CO_2 sequestration, the trees supply needed O_2.

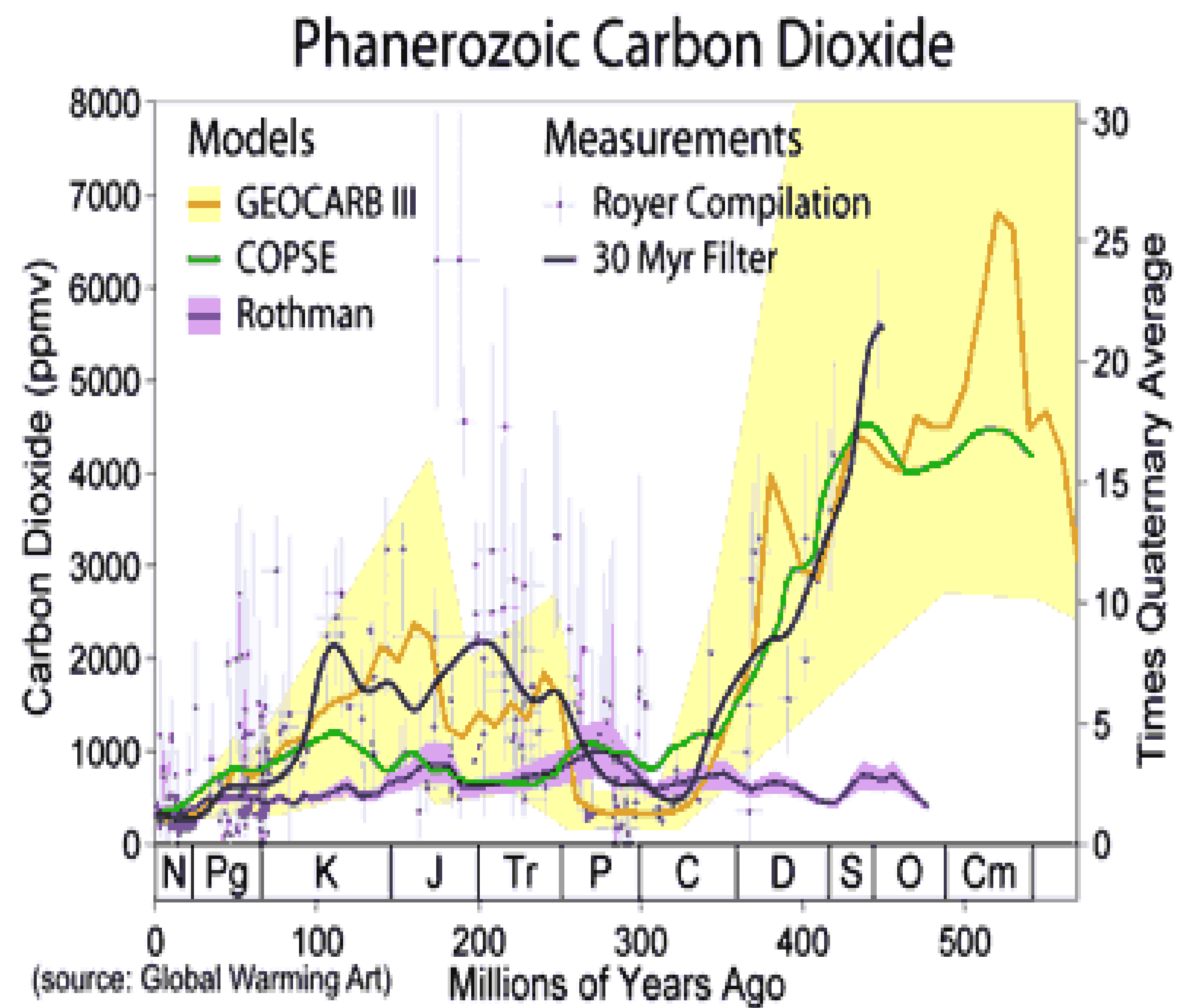
The Carbon Cycle

- Burning fossil fuels and decomposition of dead plants and animals inject CO_2 into the atmosphere.
- Organic carbon production via forestation provides useful short term organic carbon sequestration.
- Semi-arid forests remove atmospheric carbon dioxide, fixing it underground long term as inorganic carbonate salts.



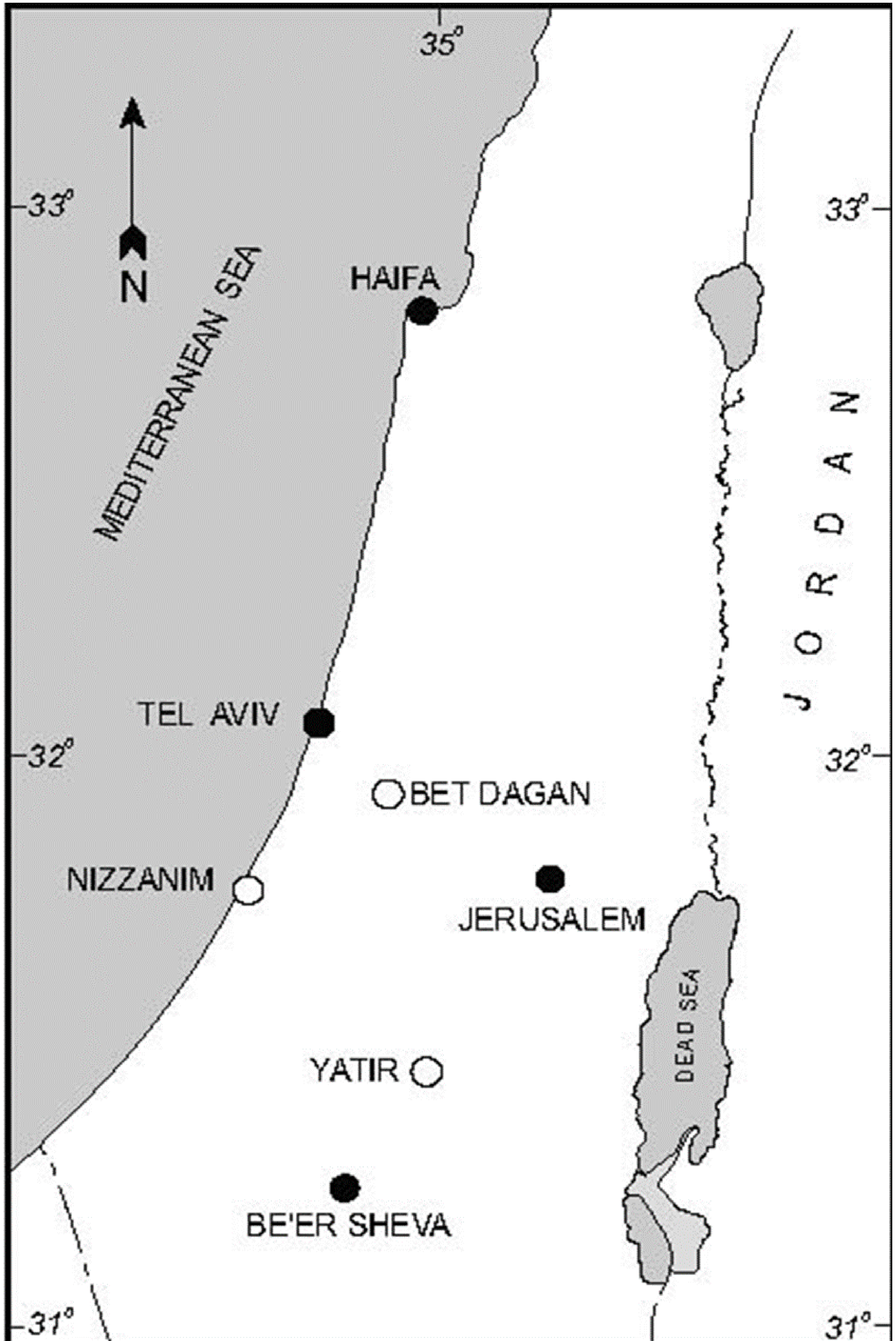
Is there evidence that forestation can efficiently sequester carbon dioxide?

Yes! Atmospheric CO_2 was ~15 times present concentrations during the middle Devonian by volcanism. During the following Carboniferous period, biomass from great forests was preserved within carboniferous coal and oil deposits. This carbon is being returned to the atmosphere as fossil fuels are burned. The transfer of CO_2 to plant biomass tapered off with the onset of the late carboniferous Permian Karoo Ice Age. The figure shows the variability of atmospheric CO_2 throughout the Phanerozoic. Notwithstanding the great increase since the Industrial Revolution, atmospheric CO_2 levels at present are relatively low on a geological time scale.



Yatir Forest in Israel

Yatir forest, semi-arid ~ world's driest - 28 cm per year - largest forest in Israel, 28 km^2 (6920 acres or 2,800 hectares), C3 Type.
Sediment is loess (windblown, fine quartz sand, clays, fine grain limestone).
Semi-arid is 18% of global land surface.


35°
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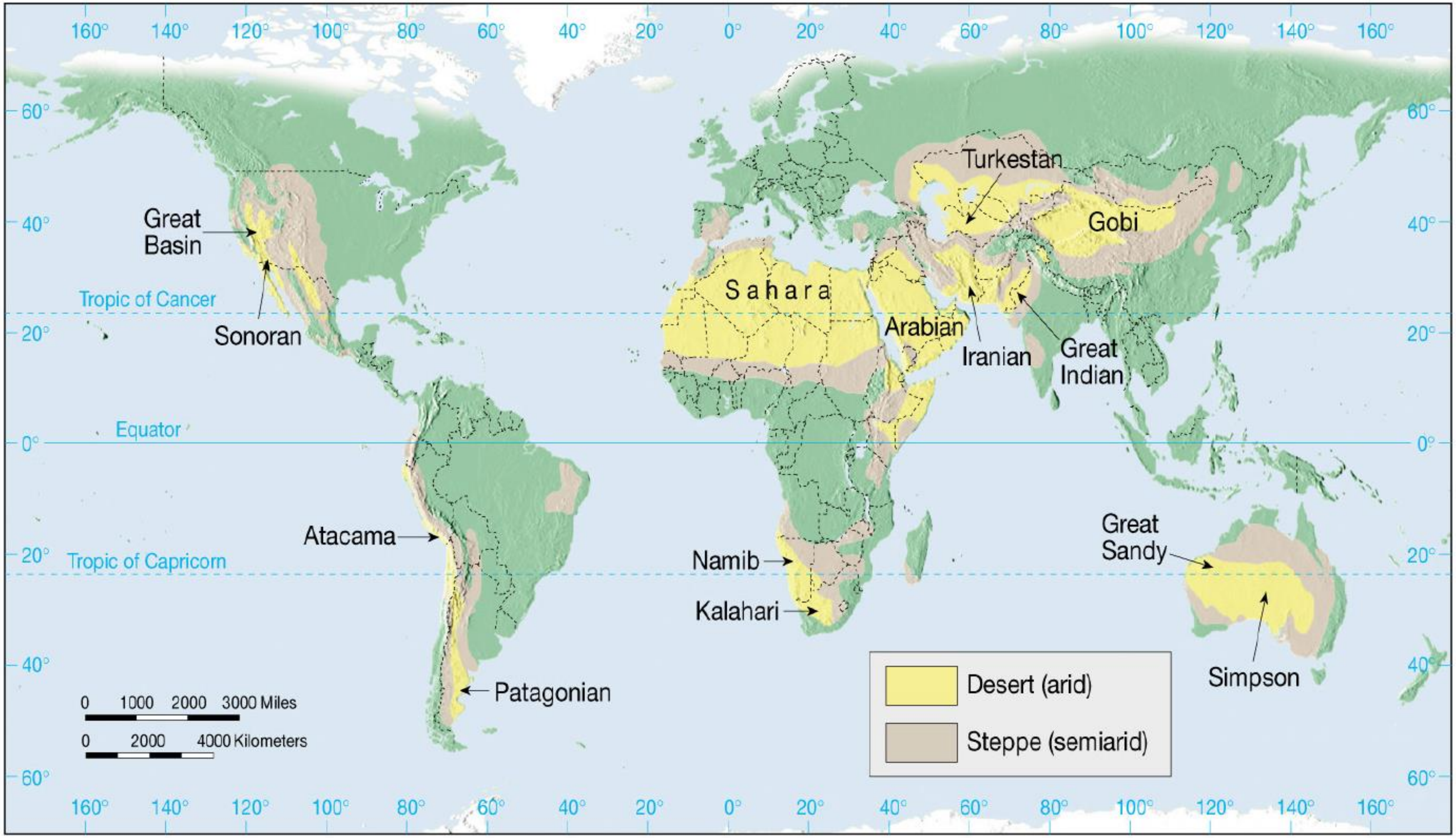
32°
BET DAGAN
NIZZANIM
JERUSALEM
DEAD SEA
YATIR
BE'ER SHEVA
31°
31°

Global distribution of semi-arid (Steppe, 17.7%) regions



Chemical Equations for Carbonate Precipitation

Soil gas dissolves into the soil moisture, forms carbonic acid.

(1) $CO_2 + H_2O \leftrightarrow H_2CO_3 \leftrightarrow H^+ + HCO_3^-$

Carbonic acid dissolves pre-existing soil calcite and releases calcium ions.

(2) $CaCO_3 + H^+ \leftrightarrow Ca^{+2} + HCO_3^-$

Released Ca^{+2} combines with the DIC, and precipitates calcite.

(3) $Ca^{+2} + 2HCO_3^- \longrightarrow CaCO_3\downarrow + CO_2\uparrow + H_2O$

Eq. 3 (idealized) implies no net sequestration. Our isotopic data show net sequestration because: (a) most CO_2 from Eq. 3 does not return to atmosphere, maybe only 20%, roots are deep, most remains in soil gas (b) many other cation sources contribute to Eq. 3, desorption of Ca^{+2} from clay, gypsum, sea spray, etc.

Yatir forest soil cores

- Porosity (~53%), Humidity (~12%), Dry sediment density (1.24 g cm^{-3}) → A Liter of sediment has 0.47 L solid + 0.12 L water + 0.41 L gas.

- Measure CO_2 precipitation rate (into $CaCO_3$) per cm per Liter of sediment (L_s) from decrease per cm of DIC (~2.0 mg $cm^{-1} L_s^{-1}$ at Yatir).

- Measure flow rate of water (11 cm yr^{-1} at Yatir) using tritium in water (HTO) as tracer.

- CO_2 precipitation rate (within calcite $CaCO_3$) at Yatir is ~22 mg yr^{-1} L_s^{-1} of CO_2 (11 cm yr^{-1} x 2.0 mg $cm^{-1} L_s^{-1}$). Calcite is derived from CO_2 exhaled by tree roots. The Carbon isotope fractionation $\delta^{13}C$ in the DIC is due Yatir's C3 type plants that exhale CO_2 with $\delta^{13}C$ ~ -22‰.

Dissolved Inorganic Carbon (DIC) vs. Depth

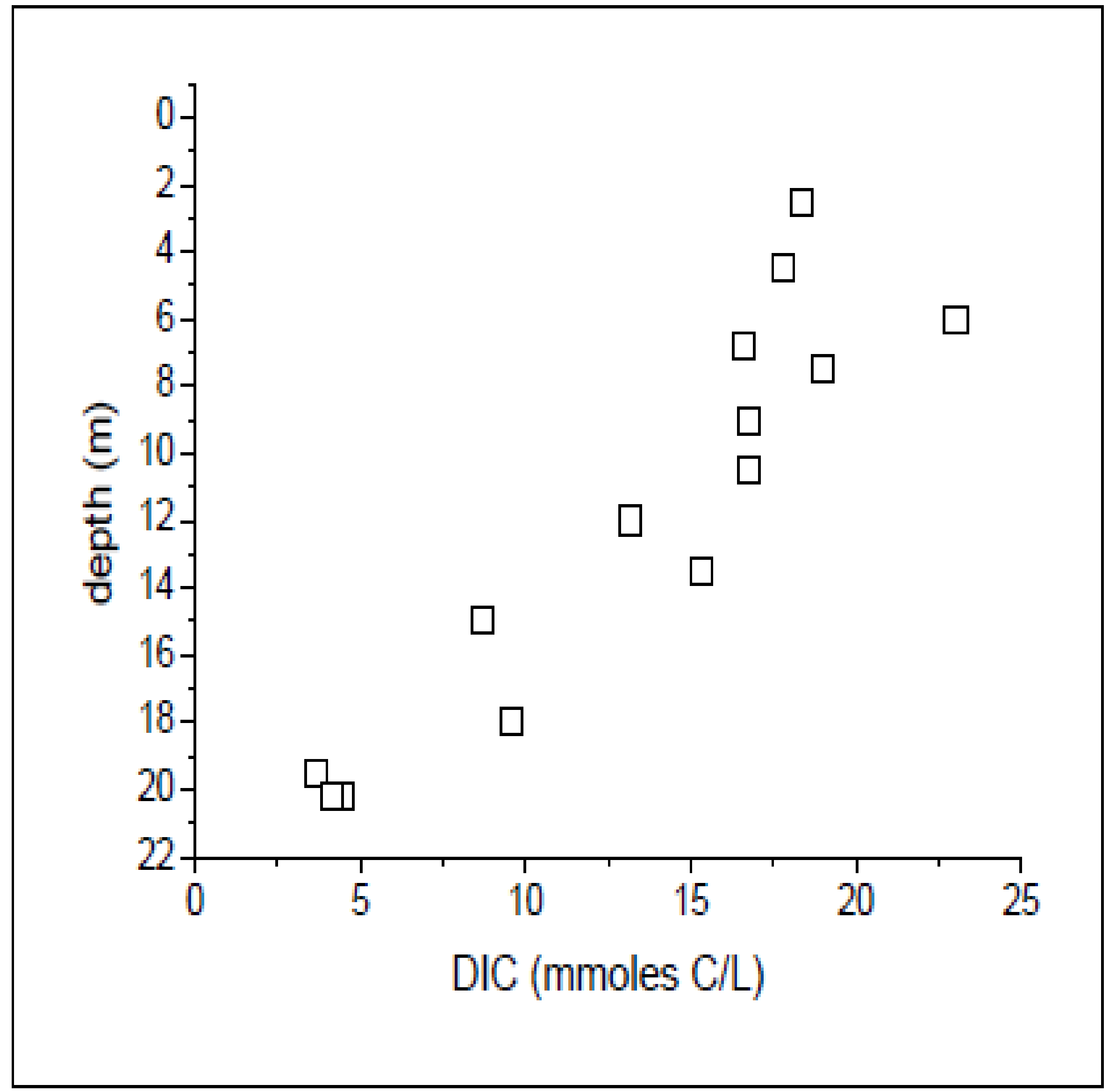
Measure DIC (as CO_2) from CO_2 mass & liters of water (L_w) extracted from USZ wet sediment by vacuum distillation (~250 mg CO_2 L_w^{-1} at Yatir)

Yatir Plants

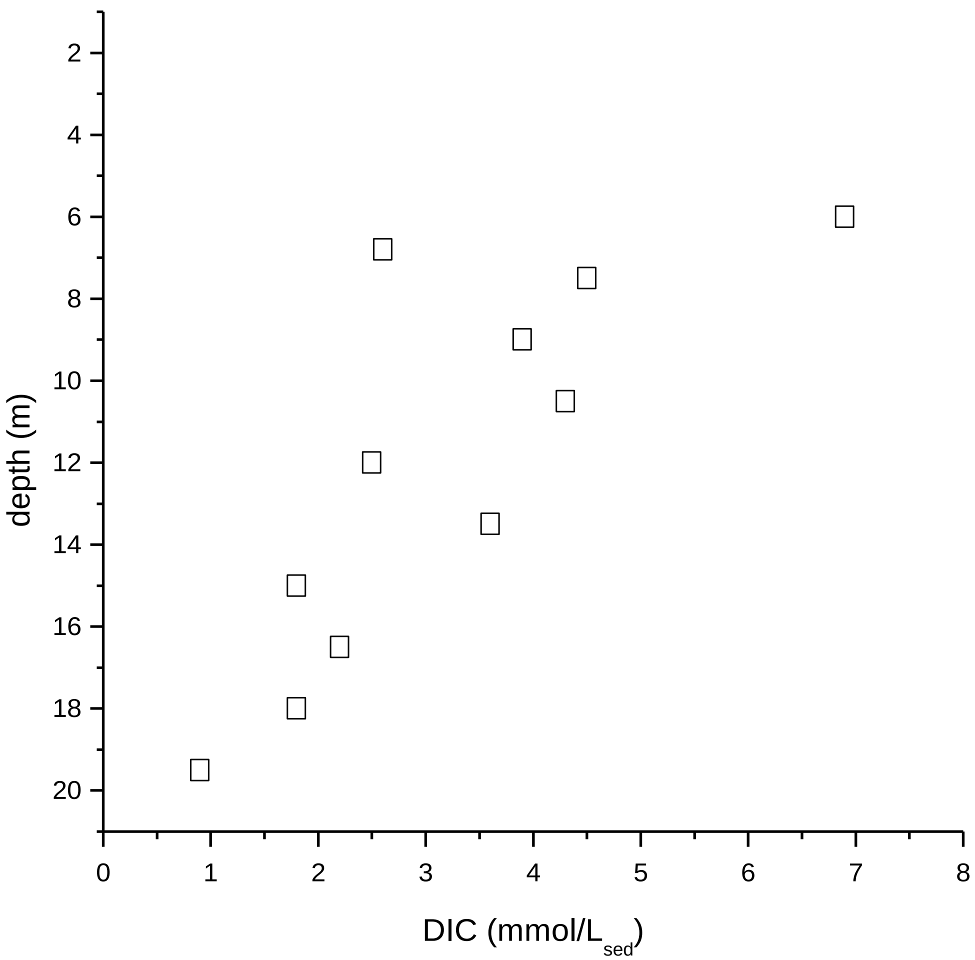
Depth (cm)	DIC (mmol C L^{-1})
30-60	4.5
60-90	3.4

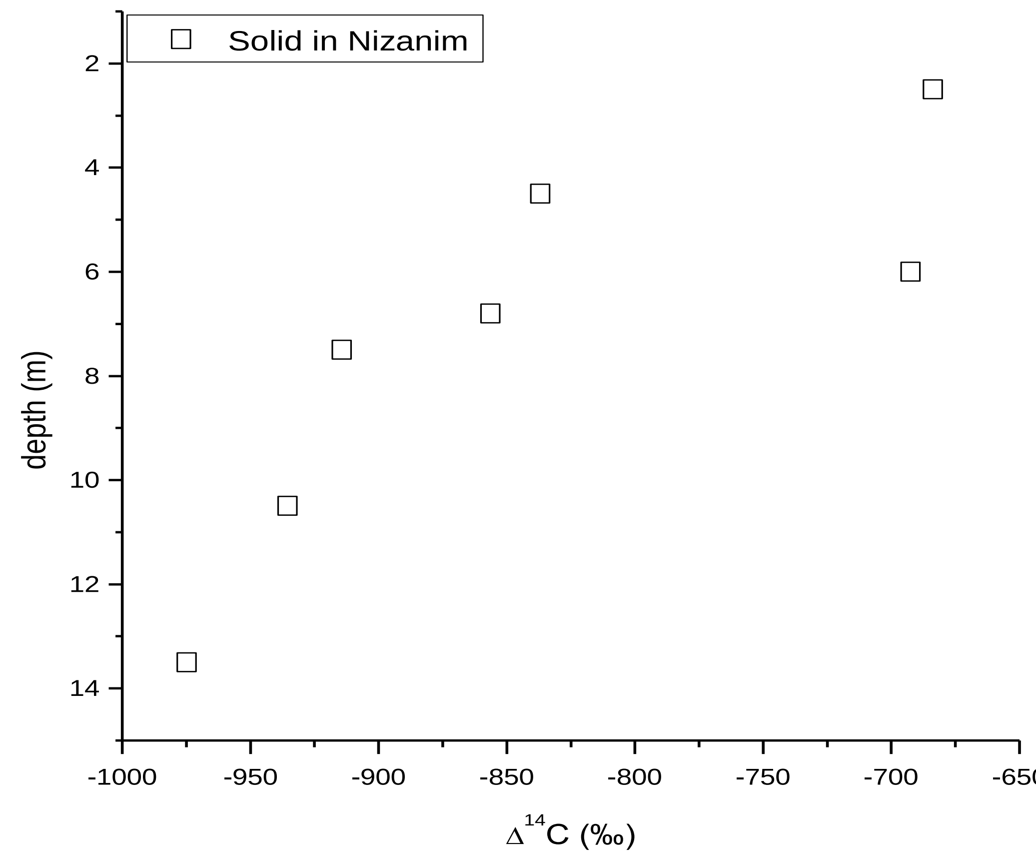
CO_2 from roots combines with soil water of unsaturated zone (USZ) to form DIC, comprised mainly of HCO_3^- bicarbonate. DIC concentration decreases with depth, as water flows down, due to $CaCO_3$ precipitation into USZ. Seen easily for plants with shallow roots, not tree roots.

Nizzanim Plants



Nizzanim DIC and ^{14}C



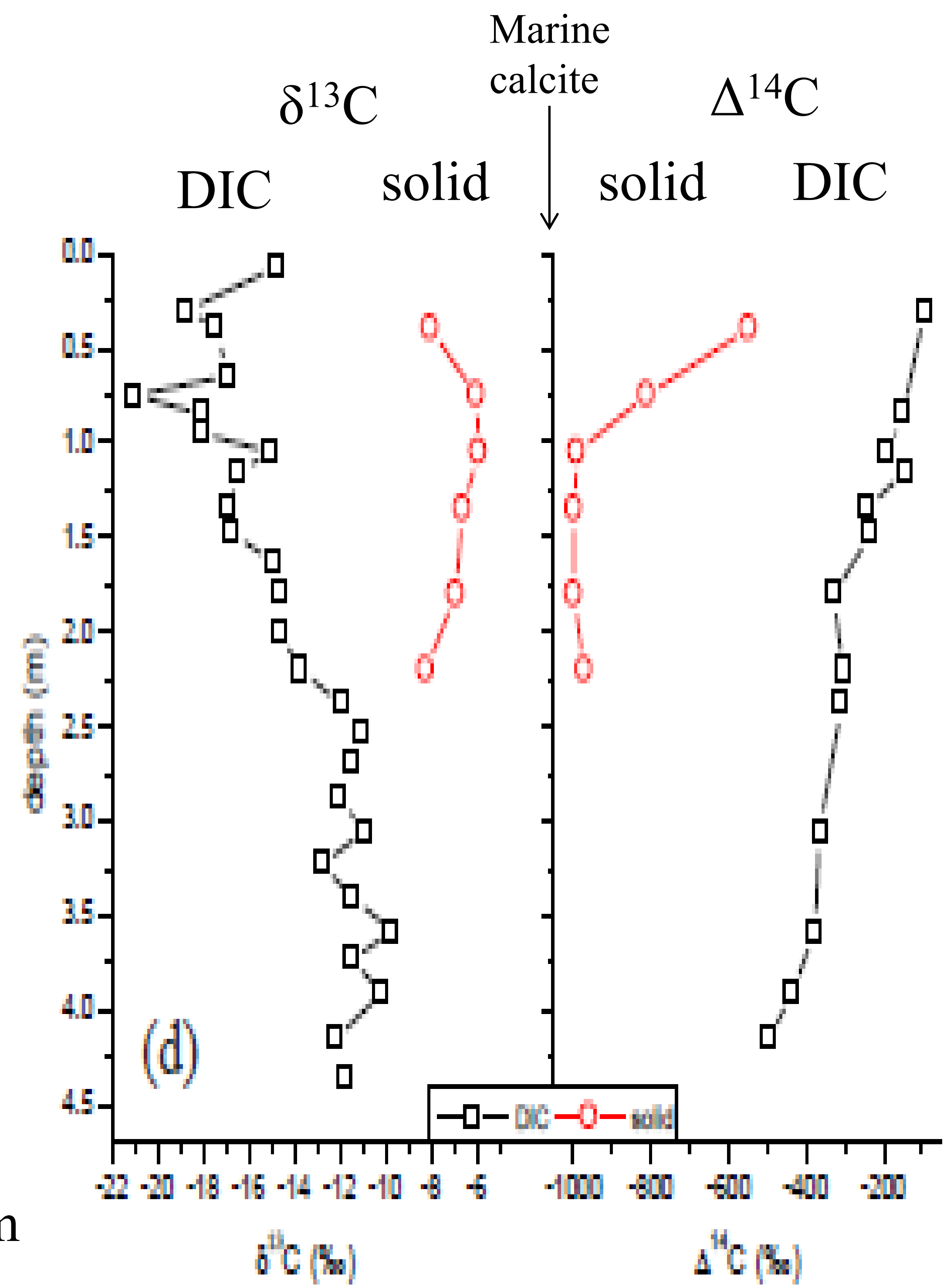


Left: DIC decreases with depth, due to removal of carbon from solution and exchange with sediment.

Right: ^{14}C activity in the sediment is from atmospheric CO_2 injected into the DIC by the overlying plants, as the host calcite is too old to contribute radiocarbon. Once $^{14}CO_2$ enters the DIC, a continuous carbon isotopic exchange and precipitation occurs between the DIC and the solid carbonate. The ^{14}C activity in the solid decreases as a function of depth, correlated with the decreasing DIC concentration,

Isotope exchange in Yatir (and Nizzanim) forests

- ^{13}C and ^{14}C are tracers for precipitation reaction
- Soil contains up to 20% relict marine calcite.
- DIC concentration decreases with depth.
- Relict calcite: $\Delta^{14}C$ = -1000 (zero ^{14}C).
- Relict calcite: $\delta^{13}C$=0 (same ^{13}C as standard)
- Continuous exchange between DIC and marine calcite in USZ as rainwater flows down.
- $\delta^{13}C$ and $\Delta^{14}C$ values in solid (nodules) vary due to exchange between DIC and relict calcite; & precipitation onto sediment nodule surface.



13C and 14C in the solid and liquid phases of the sediment. The solid phase shows that modern 14C had precipitated from the liquid on the solid phase

Isotopic evidence for CO_2 incorporation and sequestration into pedogenic carbonate

- $\delta^{13}C$ and $\Delta^{14}C$ trace the incorporation of atmospheric CO_2 from DIC into pedogenic carbonate, as DIC descends down profile interacting with relict marine limestone
- Depleted $\delta^{13}C$ values in DIC from atmospheric CO_2 - exchanges (continuous dissolution and precipitation) with $\delta^{13}C$- enriched relict marine limestone to form pedogenic calcite (**solid**) of intermediate $\delta^{13}C$ values
- Atmosphere is the sole source of ^{14}C , introduced into the USZ as $^{14}CO_2$ via roots and decay
- Pedogenic **solid** in the USZ incorporates ^{14}C, as DIC exchanges with relict limestone
- Therefore: atmospheric CO_2 tagged by radiocarbon is incorporated into pedogenic carbonate
- Not previously observed. AMS allows C14 measurement with 2 ml.

Global Extrapolation of Inorganic Carbon Precipitation in Forest Soil Sediment

- **CO_2 precipitation rate (in calcite $CaCO_3$) at Yatir is ~22 mg yr^{-1} L_s^{-1} of CO_2** (11 cm yr^{-1} x 2.0 mg $cm^{-1}L_s^{-1}$). Calcite is derived from CO_2 exhaled by tree roots. The Carbon isotope fractionation $\delta^{13}C$ in the DIC is due Yatir's C3 type plants that exhale CO_2 with $\delta^{13}C$ ~ -22‰.
- Consider sediment volume 1 km^2 & 6 m depth ($6x10^9$ L), trees above, roots below. **Precipitation ~130 tons of CO_2 per year** ($22. x10^{-3}$ x $6x10^9$ gm).
- **Extrapolating semi-arid sequestration rate globally yields rate of ~3.0 billion tons inorganic CO_2/yr** (~130 tons km^{-2} x 24 x 10^6 km^2 ~ 3.0 Pg), ~15% of the rate by which atmospheric CO_2 is currently increasing.
- In addition, the sequestration of organic carbon following global semi-arid forestation has been estimated by other investigators as ***~2 billion tons of organic CO_2 each year.*** All others only consider organic.
- **A particular global land management policy is tentatively suggested - widespread tree planting in semi-arid regions.**

Forestry Carbon Reduction Credits

- 6.2 billion tons emission allowances and offsets were traded globally in 2015; total value was €48.4 billion. 3.0 billion tons of CO_2 via inorganic sequestration are potentially worth ~$30-$90 billion in CRCs. One **carbon credit** is equal to one ton of **carbon** dioxide.
- Forests may generate carbon reduction credits (CRC) via afforestation and/or reforestation (AR), improved forest management, conservation and protection against deforestation. However, forestry sequestration activities recognized under the Clean Development Mechanism of the Kyoto Protoco (CDM) are restricted to AR. The AR CDM is a mechanism to credit carbon sequestration by forests.
- The difference between a **baseline scenario** and the **project scenario** indicates the carbon sequestration achieved through the AR activity and the resulting amount of tradable carbon credits. The baseline scenario describes the development of carbon stocks without the CDM project, through the existing or historical changes in carbon stocks in the vegetation. The project scenario estimates the effect of AR on the annual increase in carbon stocks.

Advantages of Semi-Arid Forest Sequestration

Advantages of inorganic carbon sequestration into USZ in semi-arid regions via *Forestation*

- **Trees can be harvested** for useful products (lumber, charcoal, off-sets, etc.); while **inorganic carbon deposition remains underground**. Harvested biomass will be an important future renewable energy component, as fossil fuel supplies decrease.

- Extensive thickness of USZ (deep roots) compared to temperate regions – therefore greater active volume.

- **Low rainfall precludes dissolving calcite,** as in temperate regions.
  Yatir forest receives only ~28 cm/yr rainfall. World's **driest and healthy forest**.

- Semi-arid afforestation does not reduce food supply by decreasing productive temperate-region agricultural land

- Provide steady employment in economically depressed areas instead of marginal herding & agriculture

Suggested International Collaborations

- Synergy- Tel Aviv geoscientists with inorganic carbon sequestration expertise and collaborators with forestation and organic sequestration and legal expertise can help limit global warming.

- Research aims include measurements in Israel and other countries to help achieve an improved estimate of potential global sequestration rates.

- May also lead to establishing business partnership, based on filing world wide patents, with an appropriate percentage of patent rights assigned to capital investors.

- Business objective is to develop, create and commercialize optimized method of evaluating a Forest’s Inorganic Carbon Sequestration Rate.

Sequestration Summary

- **Atmospheric derived CO_2 sequestered long-term as inorganic calcite in USZ of semi-arid forests -** much **longer-term** carbon reduction and storage compared to organic carbon biomass.

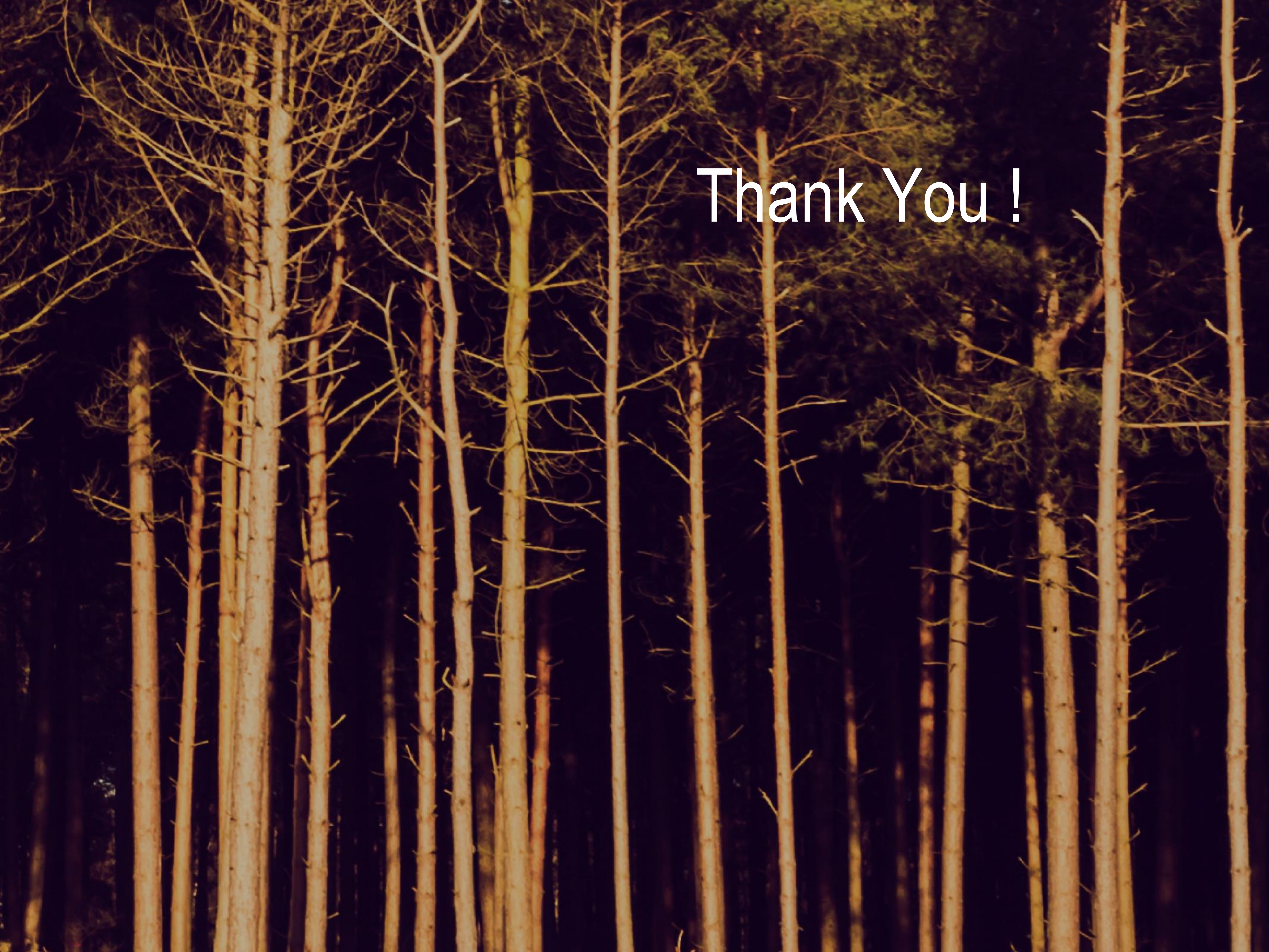
- **Global extrapolation** yields CO_2 annual semi-arid sequestration rate of ***~3.0 billion tons inorganic CO_2/yr,*** plus **~2,0 billion tons *organic CO_2/yr. The total carbon sequestration rate*** *after global semi-arid forestation then potentially represents* ***a respectable ~25% of rate of atmospheric CO_2 increase.***

- We **developed the technology to measure and certify inorganic carbon sequestration rate** of semi-arid forests.

- Forests may thereby **generate valuable annual carbon reduction credits**. Economically sustainable & profitable. **The forests also provide needed O_2**

  Semi-arid forest related biomass will be **an important future renewable energy component**, as fossil fuel supplies decrease (lumber, charcoal, biochar, etc.).

  Further measurements now in progress at Israel's Ilanot Forest – **Looking for collaborators** in other semi-arid regions. **Need more data** to better characterize the potential global sequestration rate.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