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

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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, melting icefields, more forest fires, reduced food supply, etc.

What can be done?

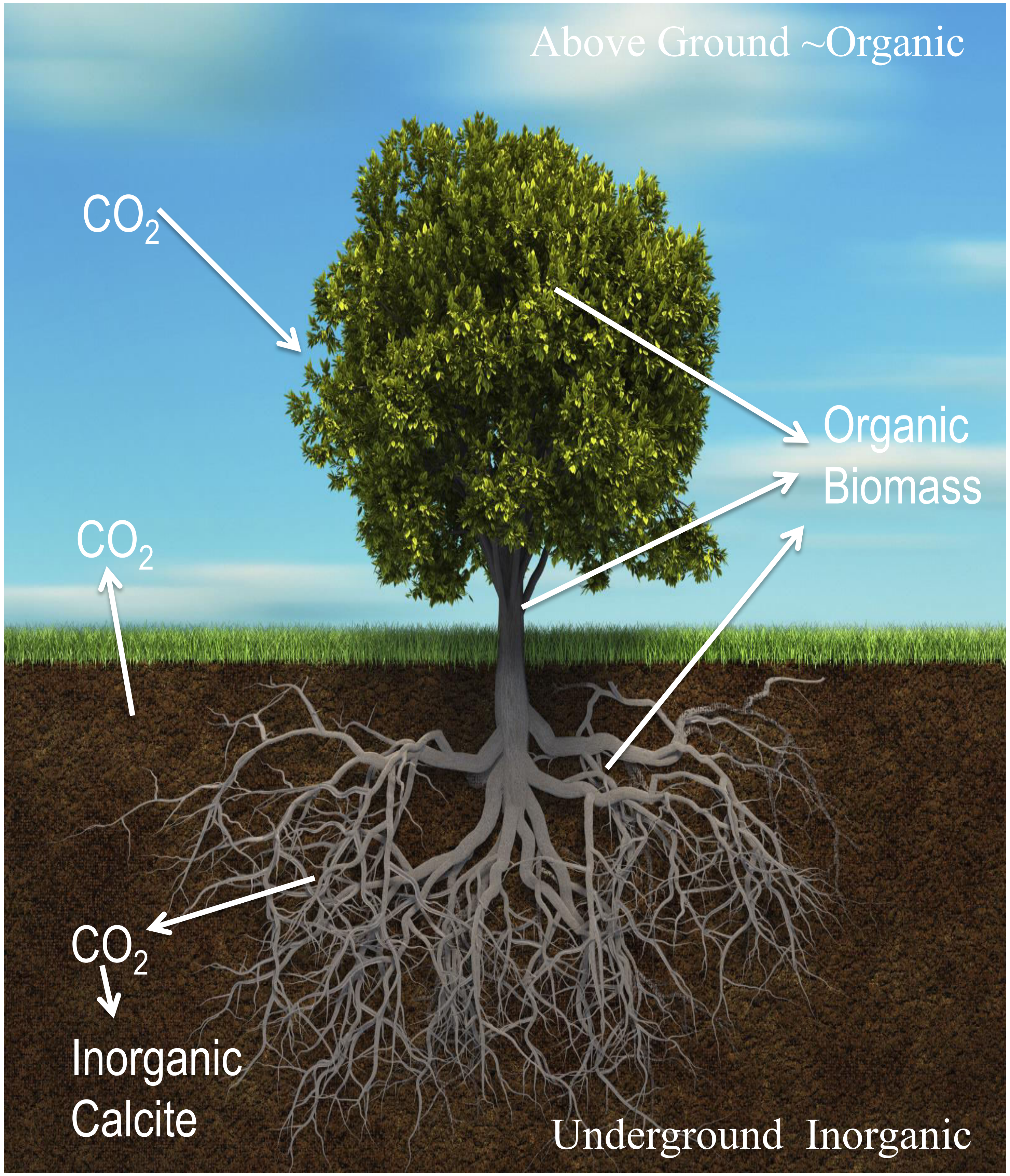
- Burn Less Fossil Fuels. (difficult to achieve)

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

- Climate engineering projects proposed for *carbon dioxide remova*l (CDR) and *solar radiation management* (SRM). (large, expensive, controversial)

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

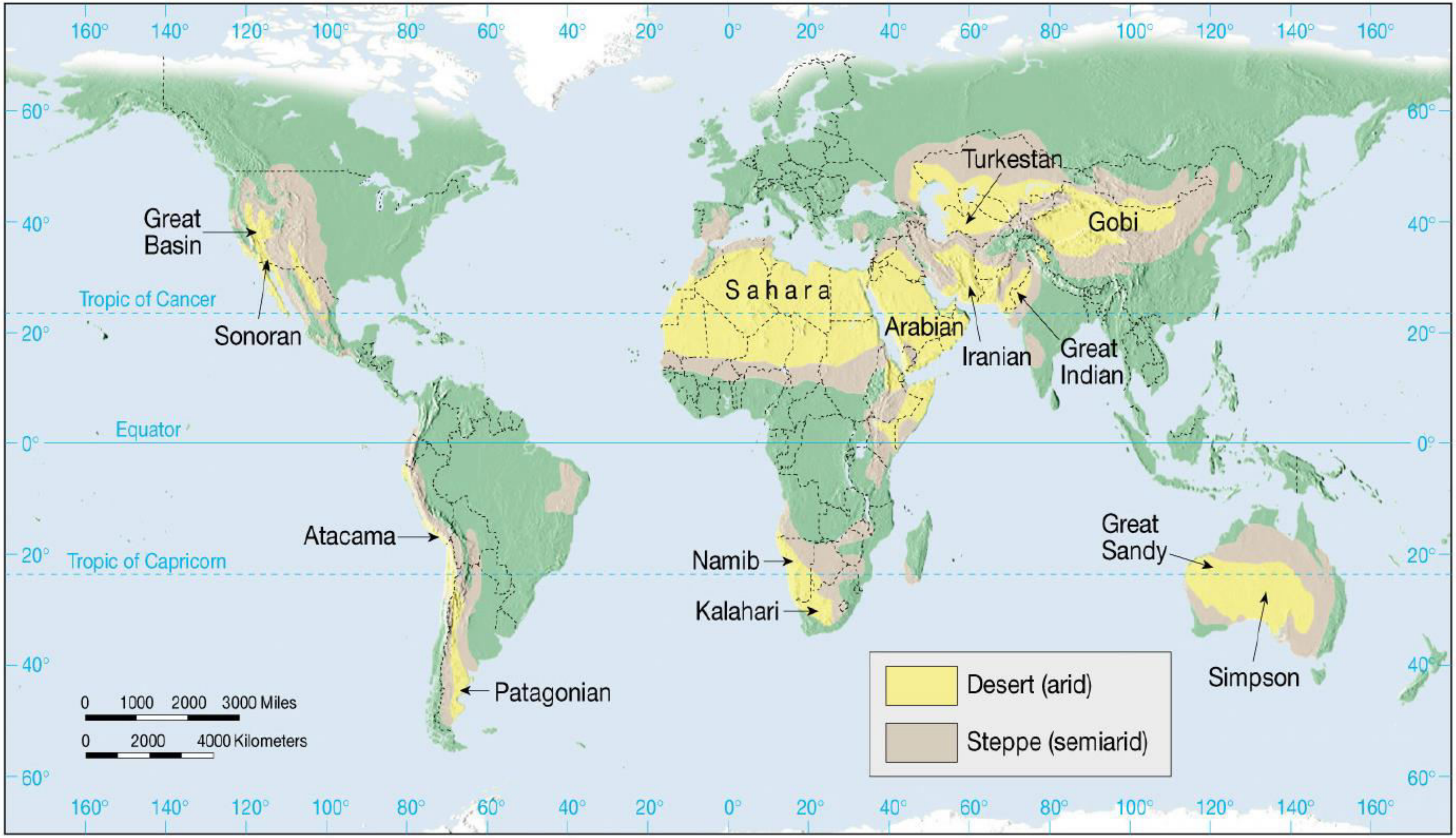
- Leaves inhale CO_2. Roots in semi-arid regions are deep. Exhale CO_2 into USZ at high partial pressure
- $CO_2 + H_2O \rightarrow$ dissolved HCO_3^- bicarbonate, combines with soil Ca^{+2}, precipitates $CaCO_3$ calcite.
- Trees in semi-arid regions sequester atmospheric CO_2 long term underground as stable calcite, low rainfall
- These trees also sequester atmospheric CO_2 short term, as organic biomass.
- But burning, decomposition of biomass reinject CO_2 into the atmosphere.



Yatir Forest in Israel → Global Extrapolation

Yatir forest, semi-arid, ~world's driest. Beginning in 1966, Keren Kayemeth LeIsrael – Jewish National Fund foresters planted four million trees at Yatir. It is now the largest forest in Israel, covering 28 km^2 (6920 acres or 2,800 hectares). ***Extrapolation: Global semi-arid forestation may remove ~2.6 billion tons of atmospheric CO_2 per year.***

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, (b) many other cation sources contribute to Eq. 3, from silicate weathering, desorption of Ca^{+2} from clay, gypsum, sea spray, etc.

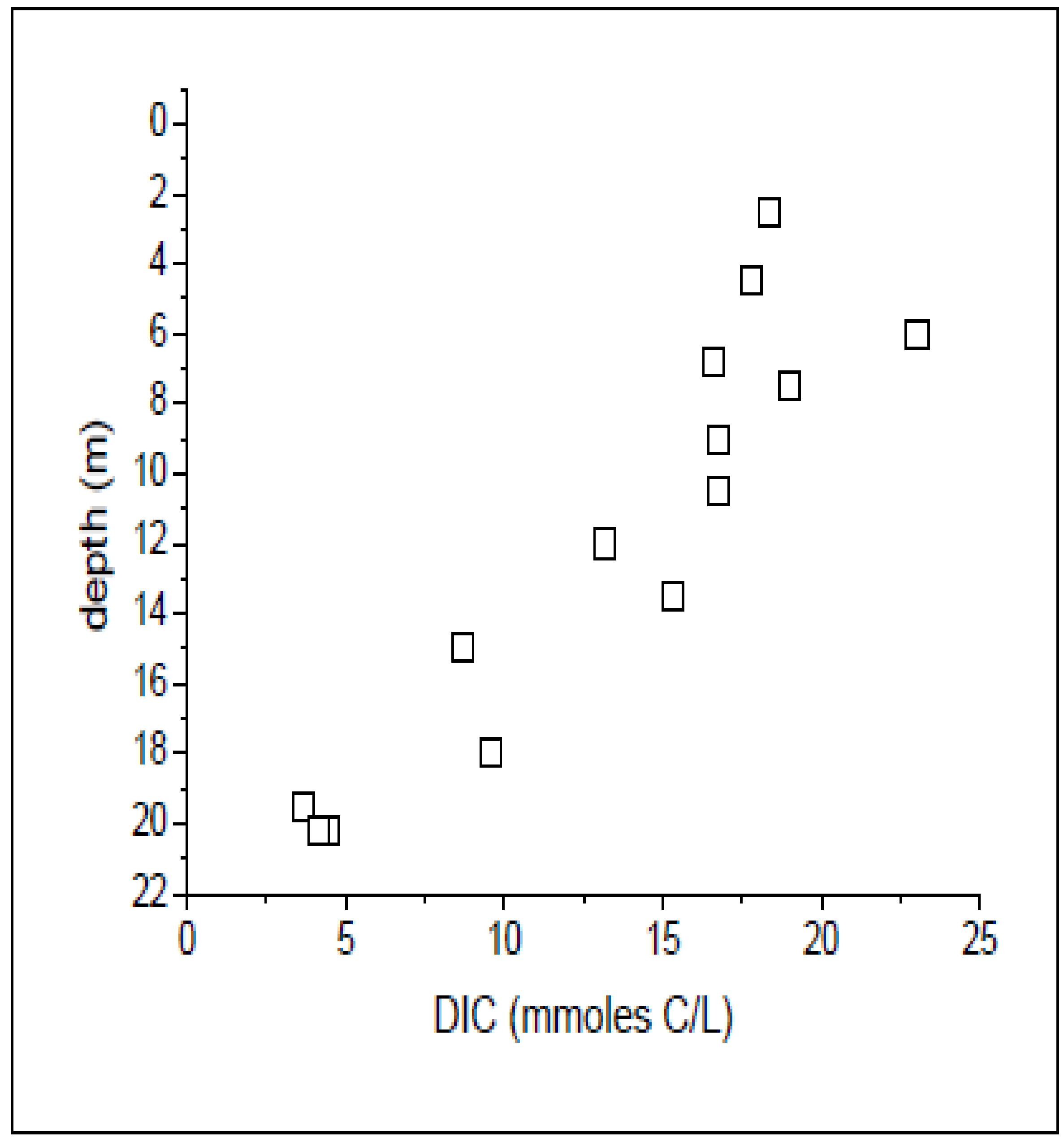
Dissolved Inorganic Carbon (DIC) vs. Depth

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



Yatir forest soil cores to 4.5 meters

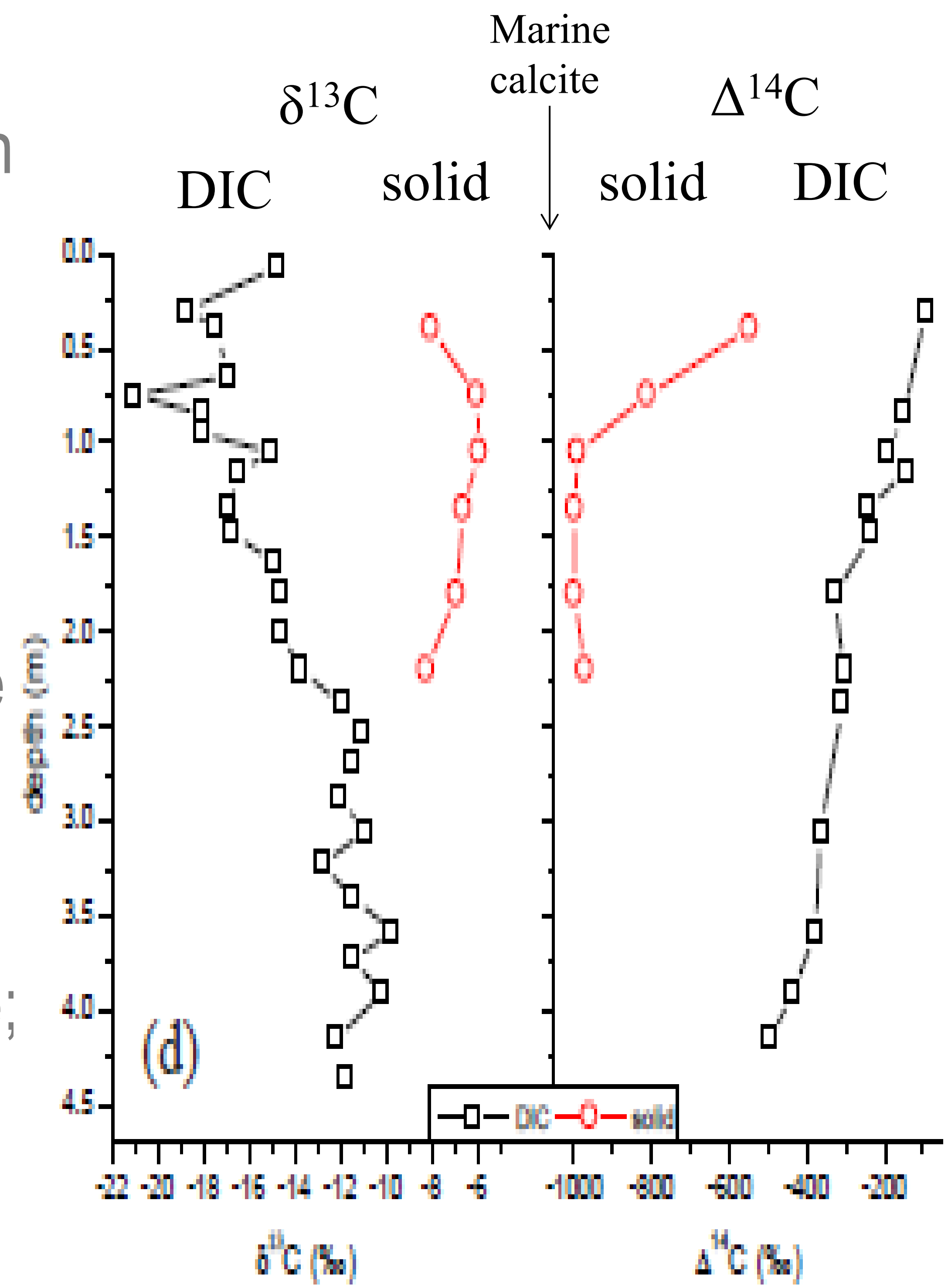
- Measure CO_2 precipitation rate (into $CaCO_3$) per cm per Liter of sediment (L_s) from decrease per cm of DIC (~1.6 mg $cm^{-1}L_s^{-1}$ at Yatir).

- 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 ~18 mg yr^{-1} L_s^{-1} of CO_2 (11 cm yr^{-1} x 1.6 mg $cm^{-1}L_s^{-1}$).

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 nodule surface.



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

Yatir forest research implications

- Until now, atmospheric CO_2 sequestration by forestation was considered only for short-term organic carbon storage (tree biomass, tree liter, soil organics).

- We prove that semi-arid forestation abstracts more atmospheric CO_2 in a manner not previously considered. More importantly, forestation provides for long-term inorganic carbon storage into the USZ.

- Our research quantifies inorganic carbon sequestration by forestation in semi-arid regions.

Global Extrapolation of Inorganic Carbon Precipitation in Forest Soil Sediment

- Consider sediment volume 1 km^2 & 6 m depth ($6x10^9$ L), trees above, roots below. Precipitation ~105 tons of CO_2 per year ($18. x10^{-3}$ x $6x10^9$ gm).

- More accurate estimates require global data on calcite precipitation rates in semi-arid forests.

- A particular global land management policy is tentatively suggested - widespread tree planting in semi-arid regions.

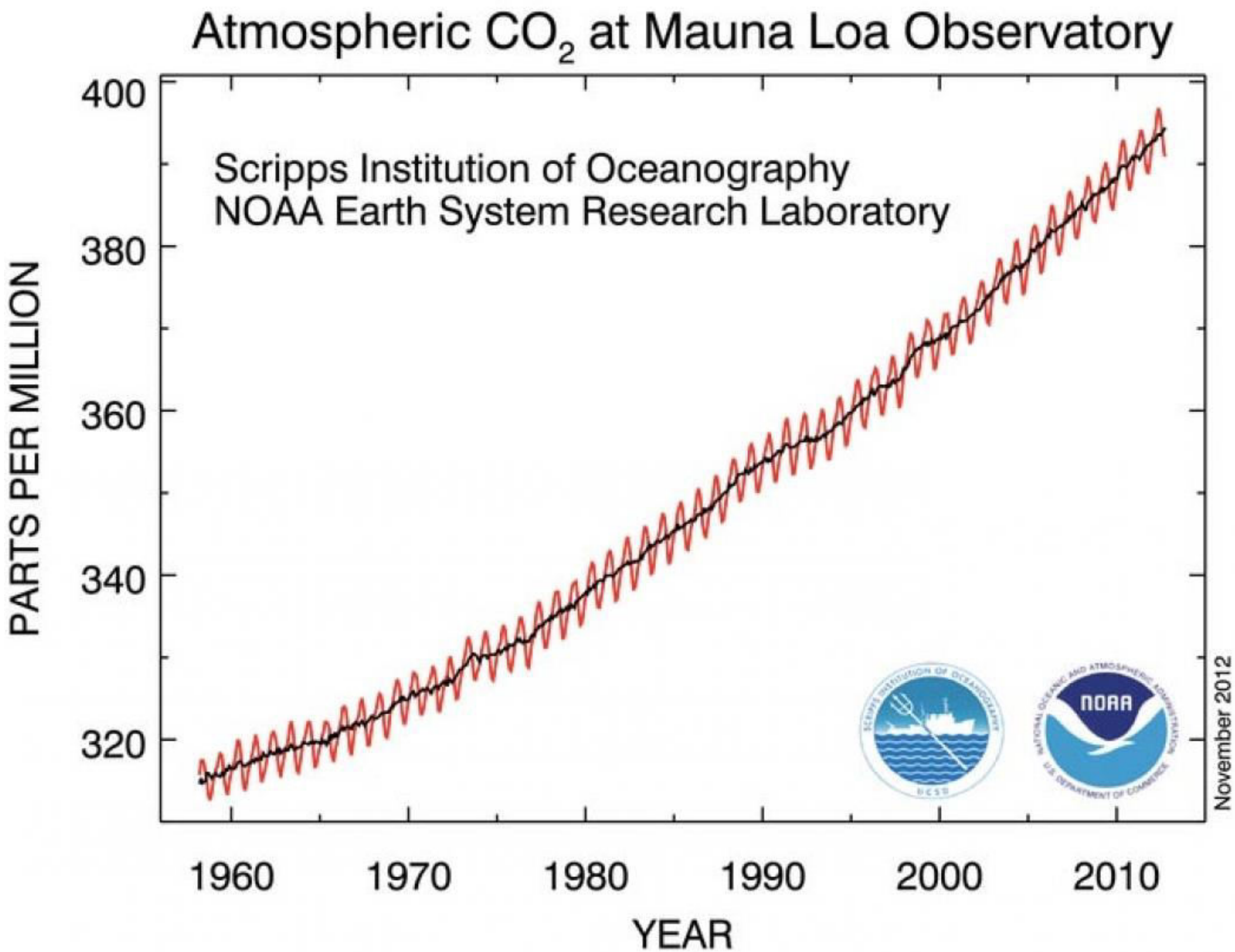
- Extrapolating semi-arid sequestration rate **globally** yields rate of ~2.6 billion tons CO_2/yr (~105 tons km^{-2} x 25 x 10^6 km^2 ~ 2.6 Pg), ~13% of the rate by which atmospheric CO_2 is currently increasing.

Summary

- Atmospheric derived CO_2 is sequestered long term as calcite in USZ.
- Yatir forest receives only ~28 cm/yr rainfall. Low rainfall precludes re-solution of calcite. Calcite sequestration much longer term than biomass carbon. Helped by deep roots compared to temperate regions.
- Semi-arid forestation does not decrease productive temperate-region agricultural land. Provide steady employment instead of marginal herding & agriculture, & useful products (lumber, charcoal, off-sets, etc.).
- Global extrapolation yields CO_2 annual semi-arid forest sequestration rate of ~2.6 billion tons CO_2/yr, ~13% of rate of atmospheric CO_2 increase.


THANK YOU!

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



Paris Climate Agreement, April & Oct. 2016

- The Paris Agreement deals with GHG emissions mitigation, adaptation and finance starting in the year 2020, to help stop the gradual warming of the Earth.
- 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.
- Many researchers now claim that such targets require "negative emissions", i.e., extraction of CO_2 from the atmosphere.
- Paris Agreement opened for signature on 22 April 2016. On 5 Oct. 2016, it reached the required 55 countries representing 55 percent of global emissions for the accord to enter into effect. But these agreements need to be followed by actions.

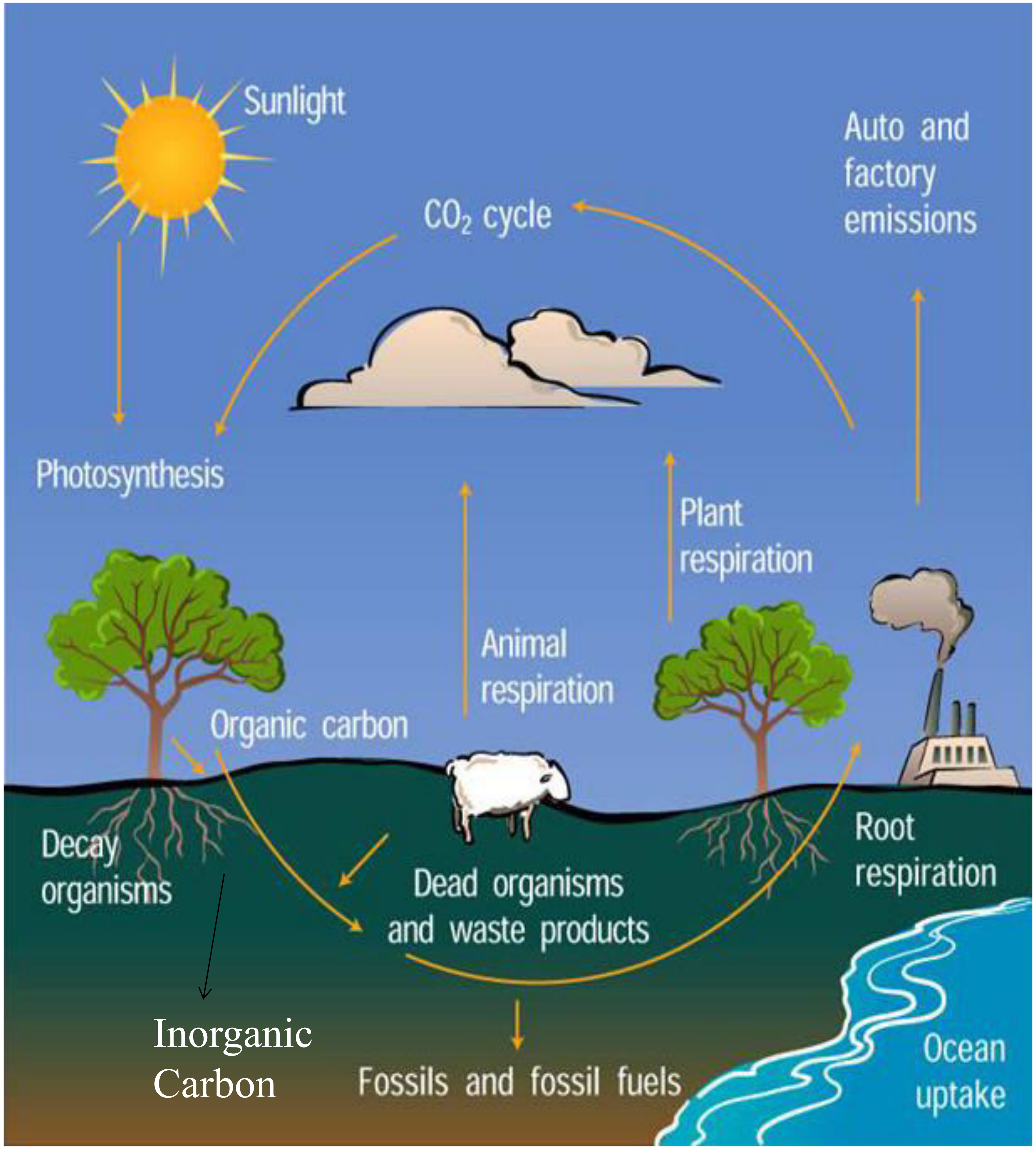
carbon dioxide removal (CDR)

- Large & expensive climate engineering projects have been proposed for *carbon dioxide removal* (CDR) and *solar radiation management* (SRM). 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 (our low cost & low tech project).

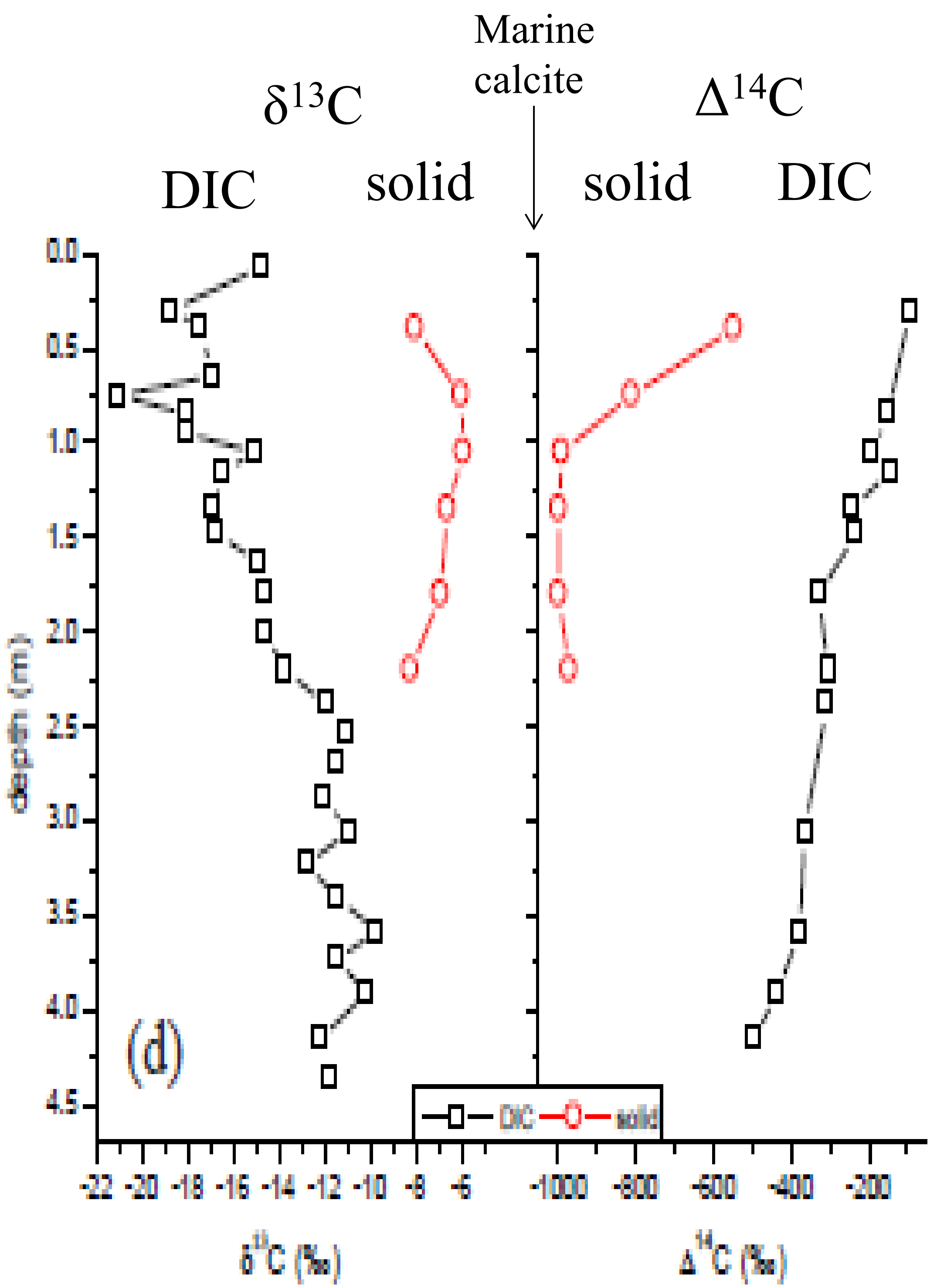
The Carbon Cycle

- 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.



Isotope exchange in Yatir (and Nizzanim) forests

- ^{13}C and ^{14}C are tracers for precipitation reaction. Continuous exchange between DIC and solid sediment in USZ as rainwater flows down. DIC concentration decreases with depth.
- $\delta^{13}C$ in solid marine calcite is a result of exchange between DIC and relict marine calcite ($\delta^{13}C$=0), and precipitation onto marine calcite surface, while DIC enriched from -20 (C3 plants).
- ^{13}C data show continuous exchange and precipitation along path from DIC into solid sediment.
- $\Delta^{14}C$ in DIC depleted with depth, while solid enriched from -1000 (no ^{14}C).
- ^{14}C exchanges demonstrate that CO_2 precipitates out of DIC as calcite. Atmospheric $^{14}CO_2$ via roots is only radiocarbon source.



Yatir forest soil cores to 4.5 meters

- 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).

- 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.

Forestation Cooling

- Green Walls are being built/proposed over extensive geographical areas (Sahel, China, India, etc.) that have thicker USZ’s than Yatir.

- But forests have reduced albedo; and therefore a warming effect. Forests can cool by evapotranspiration (ET), but do dry semi-arid forests have sufficient soil moisture?

- Further study needed to evaluate possible net climate benefits of semi-arid forestation due to carbon sequestration.