



Title: Direct Air Capture (DAC) Redefined- The Power of Breath

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Author Biography: Kolodji targets Million-Ton-per-Year (MMT/Y) Carbon Dioxide (CO₂) DAC by 2027, with 8-DAC patents allowed since 2021 and 3-DAC pilot facilities in Kern County, CA. Kolodji's gas-processing experience includes design/operations for high-risk Special Nuclear (weapons-grade) Materials (SNM) and live chemical (nerve/mustard) agent munitions facilities for USDOD/DOE; methyl isocyanate (post-Bhopal) and acrolein plant operations; and in 2010, the same year as BP/Macondo/Deepwater-Horizon, successfully commissioned onboard during float out and post mooring 100,000BPD/100MMSCFD O&G Production with MM+T/Y CO₂ Separation/Purification for 10,000+psig deep-water EOR injection from an FPSO offshore Brazil for Petrobras. Kolodji played management roles with petrochemical manufactures Union Carbide, Huntsman, and Baker; with O&G producers MODEC and Chevron; and engineering firms UOP, Parsons, and Worley (as Chief Process Engineer) serving Exxon, Shell, and BP. Kolodji holds a BSc in chemical engineering from the University of Southern California (USC), is a registered chemical engineer in TX/CA, authored the first USPSM legislation, lectured on Chemical Plant Risk Analysis at USC, published on HAZOPs for then fledgling Process Safety Progress, served as state Office of Emergency Services, city, and industrial Hazmat Emergency Response firefighter/trainer for real time toxics release preparedness, and was the only Carbider presenting at the 2004 (20-year anniversary) Bhopal Conference in India. Email: bkolodji@sbcglobal.net; website: K-O2.com

Deck: Kolodji, holder of 7 DAC patents and owner of three DAC pilot plants, brings attention to the urgent quintessential challenge of rapidly advancing DAC, arguably the only technology capable of achieving carbon neutrality. No better example of the challenge is with the very definition of DAC still being in flux and becoming grossly more complicated. This is epitomized by USDOE's new definition advanced as of January 2025 compared to the last USDOE pass in August 2024, making for even less agreement between other leading major organizations (IPCC, IAE, and CARB) and does a disservice in making a gauntlet for DAC innovation. In many of the major organization's definition there is a distinct and undue bias towards absorbent-based DAC with Storage (aDACs). DAC innovation and advancement is better encouraged with a broader simpler definition of DAC. This is demonstrated with a discussion on permanence as related to enhanced nature-based DAC (eDAC) and DAC with uses (DACU) such as with membrane-based DAC (mDAC) for production of low carbon sustainable renewable fuels.

Manuscript:

CARBON CYCLE MISMANAGED

In the beginning⁽¹⁾ the carbon cycle⁽²⁾ created kept atmospheric carbon dioxide (CO₂) levels in check with reversible biological/ geological chemical reactions, such as the one shown below:

Fauna Mammal/Respiration Products

Flora Biomass/Bio-Sequestration Products



From left to right, fauna (mammal) respiration products of breath, CO₂ and water (H₂O), react with energy from sunlight through flora (living plant) photosynthesis to evolve oxygen (O₂) to the atmosphere and produce carbohydrates (C₆H₁₂O₆ or biomass), building blocks of a plant and a form of bio-sequestration through natural direct air capture (nDAC). This cycle reverses (right to left) with metabolized carbohydrates (plant matter eaten and stored in a mammalian body) that react with inhaled O₂ in air to be respired with reaction products of CO₂ and H₂O in exhaled breath. The natural carbon

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cycle was “permanently” maintained with ambient CO₂ under 300 ppm, as evidenced with almost 1,000,000 years of ice core data⁽³⁾ (see Figure 1, below.) As can also be seen, this robust carbon cycle was disrupted in the industrial age with accelerating global rise in CO₂ emission rates, unabated at 40 billion tons or gigatons/year (GT/Y) in 2024⁽⁴⁾, that is still accelerating year after year at 3 ppm/year/year⁽³⁾ or 0.7 GT CO₂ equivalent/Y/Y⁽⁴⁾, because of a similar reaction to metabolism shown below:

Reactants

Products

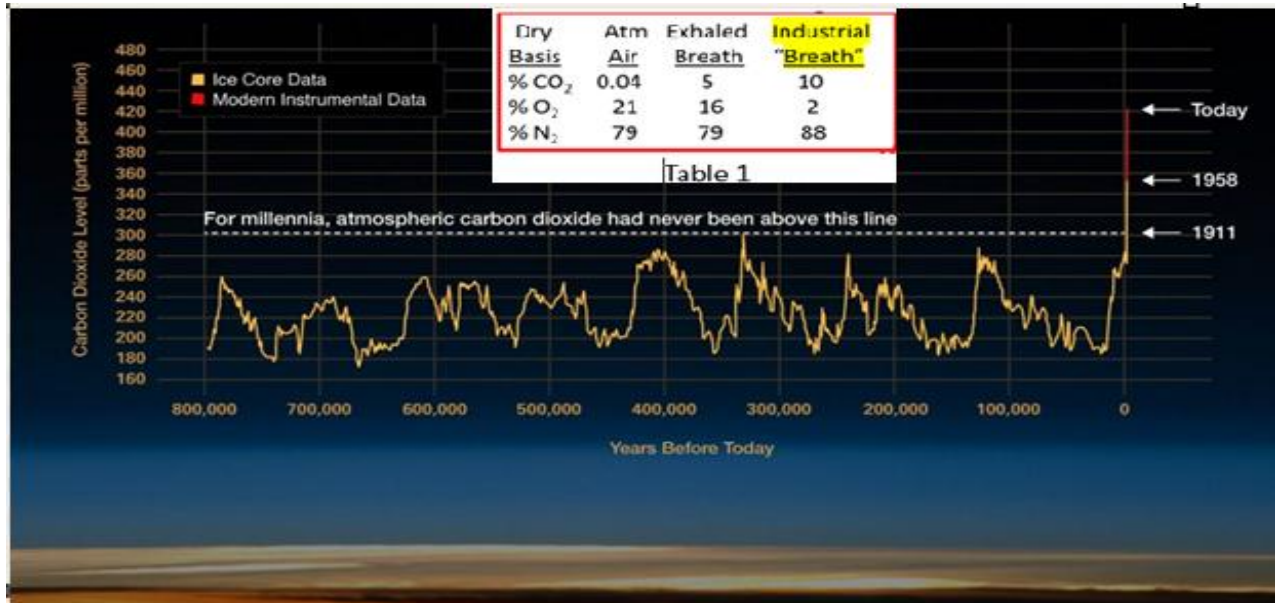
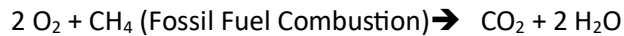


Figure 1- Atmospheric Carbon Dioxide Level in parts per million over the last 800,000 years.

Industrial emission or “industrial breath”, with the same components as that of biological breath (see dry composition in Table 1 inset on Figure 1, above), is more heavily laden with CO₂. As a result, the CO₂ concentration in the miles of upper atmosphere surrounding the globe continues an unprecedented rapid exponential rise, relative to the prehistoric time scale in Figure 1 above, leaping in less than 100 years from 300 parts per million (ppm) to over 400 ppm CO₂ today, fueled by this culprit “industrial breath” and aided by accomplices of rapid deforestation and urbanization. This rise is also the predominant cause of climate change which unabated leads to a high confidence of negative global consequences per the Intergovernmental Panel on Climate Change (IPCC)⁽⁴⁾, thus the intense interest to rapidly advance the leading and maybe only solution capable of abating this seemingly inexorable rise, Direct Air carbon dioxide Capture (DAC).

The International Energy Agency (IEA)⁽⁵⁾, United States Department of Energy (USDOE)⁽⁶⁾, and the State of California, as led by the California Air Resources Board (CARB)⁽⁷⁾ are in rare agreement regarding DAC in that it is not possible to abate this rise, that is achieve “Net Zero” or “Carbon Neutrality”, without DAC. There is also agreement regarding the maturity level of DAC. IEA states “Future capture cost estimates for DAC are wide-ranging and uncertain, reflecting the early stage of technology development.”⁽⁵⁾ USDOE states “The field of Direct Air Capture is at a relatively early developmental stage...result(ing) in uncertainties surrounding its ultimate scale, definition, and market landscape.”⁽⁶⁾ And CARB states “DAC...is under development today.”⁽⁷⁾

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Multi GT/Y DAC scale is needed to accomplish global carbon neutrality goals by 2050^(4,5,6,7). This goal appears bleak for DAC with still rapidly emerging and evolving DAC technologies not reported as successfully deployed at any significant scale, with gross capacity of around 20,000 tons or 0.00002 GT/Y reported^(4,5,6,7) to date. Not helping is the amount of contrast existing between USDOE's very specific and IEA's very broad definition. Not surprisingly, there is even more daylight between IEA versus CARB's definition. These distinctions may be a disservice to the development of such a nascent technology as DAC, through premature elimination of effective, deployable, scalable, permanent, profitable, and sustainable DAC innovation or prejudiced acceptance of DAC boondoggles that don't work.

DAC ILL-DEFINED

IEA has by far the simplest DAC definition of "removing CO₂ directly from air"⁽⁵⁾. This broad definition is the most inclusive to innovation so as to speed discovery, deployment, and scalability, and not cause the elimination of a "silver bullet" technology due to arbitrary or prejudicial whims. USDOE's DAC definition as of August 2024 was "a technology that directly separates planet-warming CO₂ from the atmosphere for permanent, safe geologic storage or the manufacture of clean, low-carbon fuels and chemicals"⁽⁸⁾ USDOE's much more complex definition as of January 2025 is "a technology that regenerates a capture medium in a closed loop and/or uses a mechanical air contactor to chemically or physically separate carbon dioxide directly from the outdoor or indoor ambient atmosphere without reliance on above-average carbon dioxide concentrations caused by nearby point sources of emissions."⁽⁶⁾ CARB likewise has a complex DAC definition with a variety of caveats, restrictions, and exclusions. CARB specifically restricts DAC to technologies "not designed to be attached to a specific source or smokestack."⁽⁷⁾ Unlike IEA for DAC, CARB specifically excludes any use of "biological sequestration or nature-based processes"⁽⁹⁾...typically accomplished through Natural and Working Lands (NWL) management and conservation practices that enhance the storage of carbon or reduce CO₂ emissions with nature-based approaches."⁽⁷⁾ This is a contradiction to California's emphasized "climate smart" goal of finding nature-based solutions.^(10,11) CARB is further prescriptive of DAC by relegation to a form of "Mechanical Carbon Dioxide Removal (CDR)... where CO₂ is removed directly from the atmosphere using mechanical and/or chemical processes⁽⁷⁾ ... that capture and concentrate ambient CO₂"⁽⁷⁾. Thus, as even USDOE doesn't do, classifying DAC only as a CDR per CARB's definition, CARB inextricably ties DAC to storage, making DAC equivalent to DAC and Storage (DACS), with the further restriction of only one form of sequestration or storage choice, that being geologic sequestration⁽⁷⁾. With this, CARB in fact specifically excludes any potential for DAC with use of CO₂ (DACU). USDOE and CARB have moved closer to each other on what the yet to be developed DAC can't be, making a tortuous gauntlet for DAC fruition efforts.

Absorption based DAC (aDAC) such as solid absorbent DAC (sDAC) and liquid absorbent DAC (lDAC) are the most highly adopted form of DAC drawing on decades of proven commercial industrial scale gas processing for CO₂ removal. With air having a CO₂ concentration magnitudes lower than industrial gases, combined with the necessity for storage of CO₂, this aDAC has become a very high capital and energy intensive challenge (\$1000+/ton) almost impossible to overcome. Nevertheless aDAC is being built today at an unprecedentedly rapid scaleup with potential of up to 1 million tons/year in 2026^(12,13). The dilemma in development is the skipping of technology readiness levels that prejudice discovery of major show-stoppers before big bucks are spent producing more CO₂ than removed while one goes broke. A most recent disclosure⁽¹⁴⁾ is telling in that the very concept of aDAC has a fatal self-defeating flaw and simply will not work because the performance of the absorbent in the aDAC facility drops dramatically as the feed concentration of the air surrounding the facility drops. Most frightening is if it did work, it does not remove CO₂ from the miles of upper atmosphere, but immediately strips the

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CO₂ only from the small sliver (100 feet) of biosphere above the earth required for life, starving plant life of the CO₂ required to sustain agricultural with the very real possibility of creating severe food security issues, see Figure 2⁽¹⁵⁾ below. Questions continue to arise as to the viability of the aDAC concept being able to work at large scale carbon removal and do no harm^(12,14). The world's largest sDAC facility built to-date at just 4000 T/Y, costing over \$1000/ton (over \$1 Billion, or \$trillions at the GT/Y scale), has recently been shuttered⁽¹³⁾ with very little fanfare.

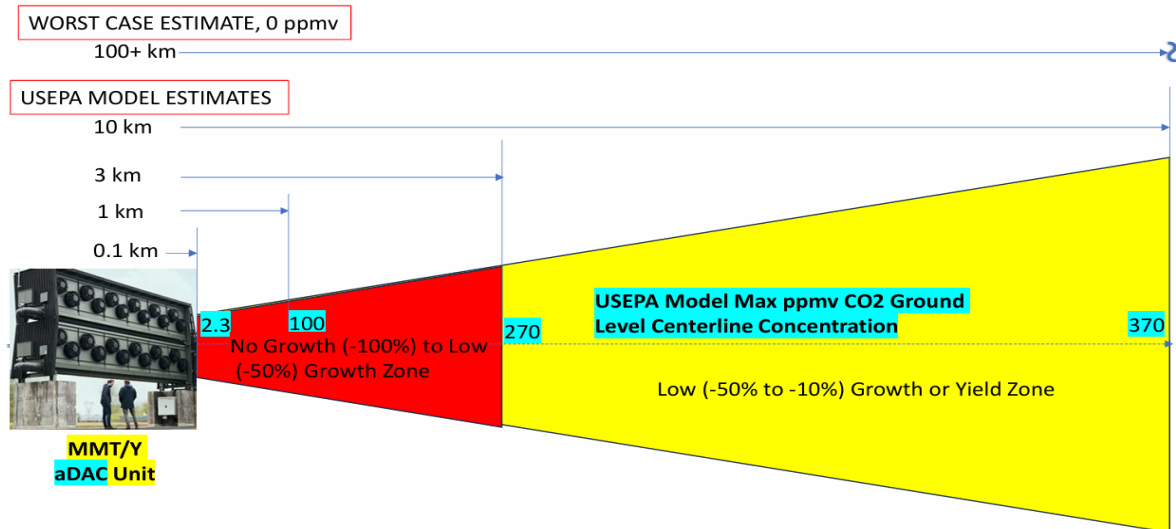
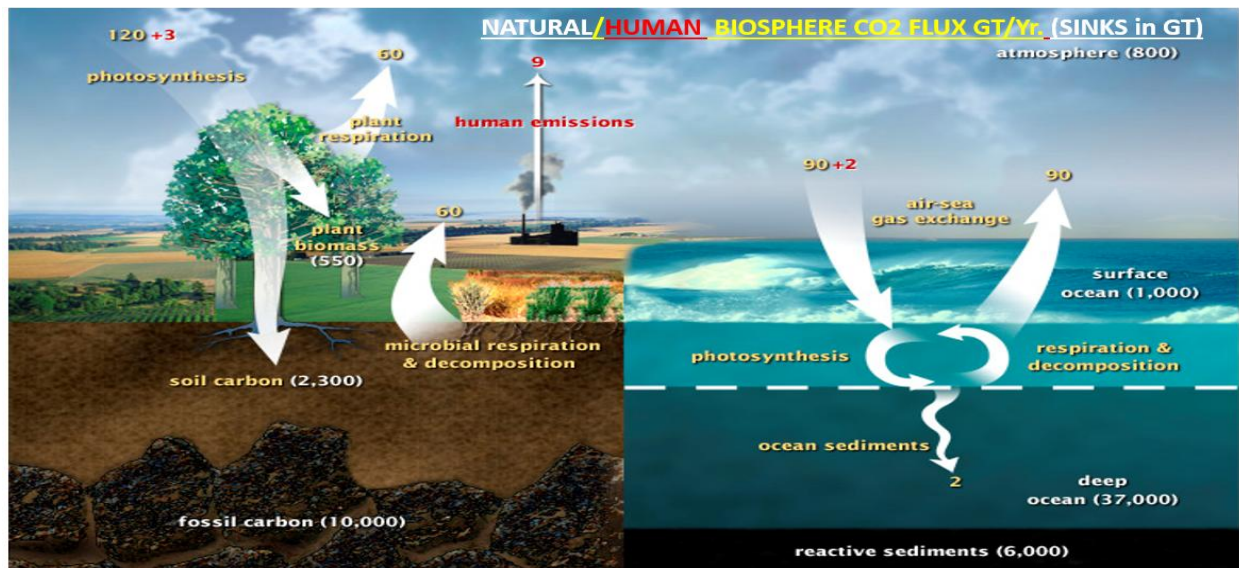


Figure 2- USEPA Model Results Showing MMT/Y aDAC Impact at 5mph wind and worst case at 0 mph.

CARBON MANAGEMENT/ DAC DEFINITION CORRECTED

Figure 1 attests to outstanding permanence for natural storage of CO₂ with a time-scale in the 100s of thousands of years. In Figure 3, the record of large magnitudes of nature's CO₂ storage scale in the air at 800 GT and in biomass at 550 GT held over the time-scale shown in Figure 1 also attest the ability of the storage to remain permanent. This extent of permanence far exceeds the permanence limits estimated by IPCC⁽⁴⁾ of 1000 GT for 10,000 years by geologic storage. Figure 3⁽²⁾ also shows how potent and rapid the buildup of nature-based DAC (nDAC) is. Photosynthesis (with plant respiration deducted) is credited with nature's only method for net removal of CO₂ from the atmosphere, and accounts for a whopping 60 GT/Y of flux or removal of CO₂ globally from ambient air, dwarfing all other efforts at DAC by man to-date. It is remarkable that CO₂ as a minority component in air with just 400 ppm is proven as the workhorse that produces the majority of a plant's biomass.



(Diagram adapted from U.S. DOE, [Biological and Environmental Research Information System](#), 12/2008)

Figure 3- Natural Global Carbon Cycle Sinks and Fluxes at normal 400 ppm CO₂

Enhancing natural photosynthesis to effect higher levels of DAC (eDAC) has the potential for climate impacting scale of atmospheric CO₂ reductions. A general form of eDAC is crop carbon dioxide enrichment, the practice of increasing the CO₂ levels in a plant's biosphere from 400 ppmv to between 600 and 1200 ppmv to effect increased growth rates, biomass production, and water utilization efficiency, as practiced for almost a century in greenhouses^(16,17). Presented in Figure 4⁽¹⁸⁾ and Figure 5^(19,20) below are published results in Open Top Chambers (OTC) showing between 100% to 200% increases in crop yields and water utilization efficiency of cotton and citrus, respectively, "with complete lack of change to elemental composition."⁽¹⁹⁾ Another form of eDAC is Free Air Carbon Dioxide Enrichment (FACE)⁽²¹⁾ which is crop carbon dioxide enrichment without enclosures, with the same results expected, as studied for over 50 years by USDOE and USDA. "What was learned from these experiments? If there is a single scientific conclusion from the many years of investigation and more than \$100 million invested, it might simply be that most of the C₃ plants and terrestrial ecosystems studied do respond positively to increased concentrations of atmospheric CO₂. This response is due to the primary effects of CO₂ on photosynthesis and stomatal aperture..."⁽²¹⁾ Over 95% of all flora are C₃ Plants, including most crops.

FACE goes counter to many elements and rules defining DAC(S). FACE can use emissions from a stack say of a power plant or other flue gas generator (post-combustion) to supply large quantities of conditioned CO₂ from flue gas to orchards, as "industrial breath" to increase biomass production. Prior to FACE, the concentrated CO₂ in flue gas never reached the orchard. With elevated high temperature buoyant discharge at high velocity, the highly concentrated CO₂ in flue gas at the release point was shot miles into the upper atmosphere and only trickled back down to the biosphere at grade after being diluted by the magnitude greater volume of upper atmosphere (see Figure 6⁽²²⁾ below). FACE feeds a conditioned higher than ambient CO₂ concentration stream into an orchard for proven increased agricultural production. FACE enhances photosynthesis and involves bio-sequestration, and is thus not a chemical or mechanical process. FACE does not capture CO₂ from air as CO₂, nor does FACE concentrate CO₂, thus geologic storage for this form of DAC is not in play. Instead, FACE uses the increased CO₂ concentration in the biosphere to directly produce more biomass in the form of carbohydrates, as has been done since "In the beginning..." The only rule FACE does not break in DAC definitions is that it

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“removes CO₂ directly from air”. In the search for the answer for a profitable, deployable, effective, scalable, permanent form of DAC, the failure to discover eDAC or FACE has been suffering from a terminal case of “not seeing the forest for the trees.” FACE is highly scalable and deployable because of profit (\$10/Ton), plug and play with existing facilities (power plants/farms) ⁽²²⁾ and nature’s effectiveness.

The enhanced nature-based DAC (eDAC) technology like FACE makes plants into little green CO₂ absorbing machines. The capture rate is estimated at 10 T/Y/Acre of crop ⁽¹⁵⁾. CARB’s 2030 DAC capture goal of 7 MMT (on page 96, Table 2-3 of the Scoping Plan for Achieving Carbon Neutrality ⁽⁷⁾) could be exceeded with just a fraction of the acreage of a single crop, that being almonds ⁽¹⁵⁾ and make a profit with increased crop yield doing so. FACE can potentially capture between 30 and 120 GT/Y of additional CO₂, while drawing down the CO₂ in the upper atmosphere by growing more biomass (see Figure 7, below.) FACE is scalable and deployable at Million Ton/Year DAC scales ⁽¹⁵⁾. As biomass production continues above that needed, the biomass is culled as a low carbon renewable and sustainable fuel and becomes a fossil-based fuel replacement with lower life-cycle emissions. “The traditional biofuel production reaction is:

Biomass + O₂ >>>> Gasification/Fischer-Tropsch >>> Hydrocarbon fuels + CO₂

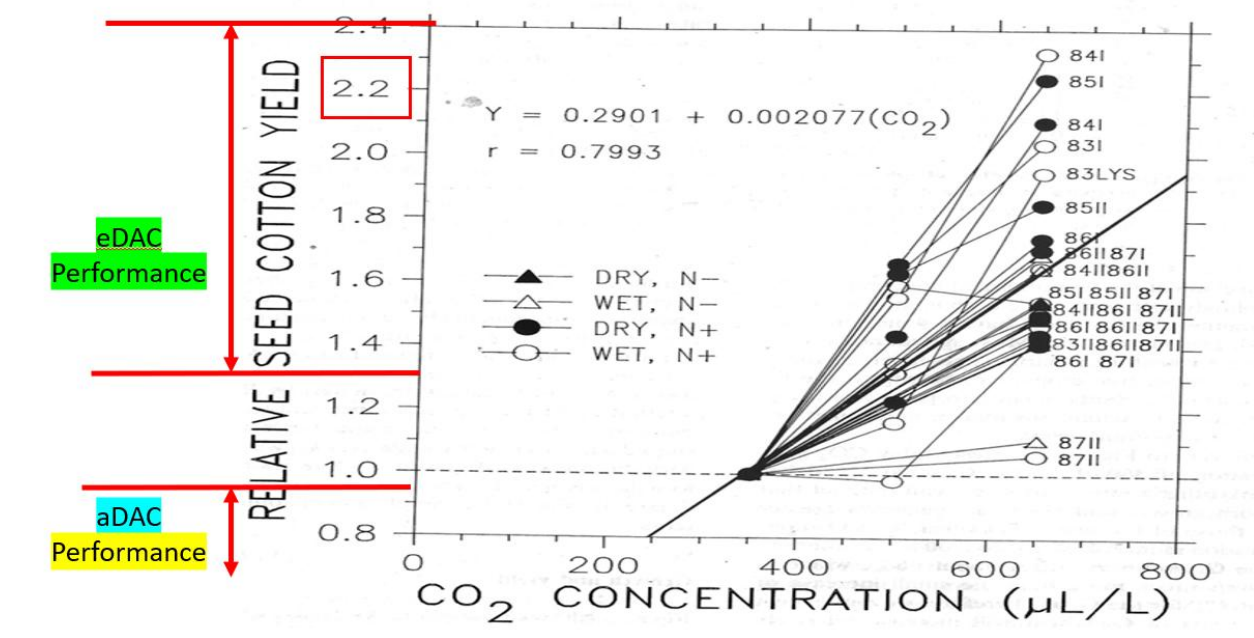


Figure 4⁽¹⁸⁾

Cotton Carbon Yield increase up to 50% at 500 PPM, up to 100% (Doubles) at Enrichment to 650 ppm



Global Change Biology (2007) 13, 2171–2183, doi: 10.1111/j.1365-2486.2007.01430.x

USDA STUDY!

Seventeen years of carbon dioxide enrichment of sour orange trees: final results

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A
Form of
eDAC

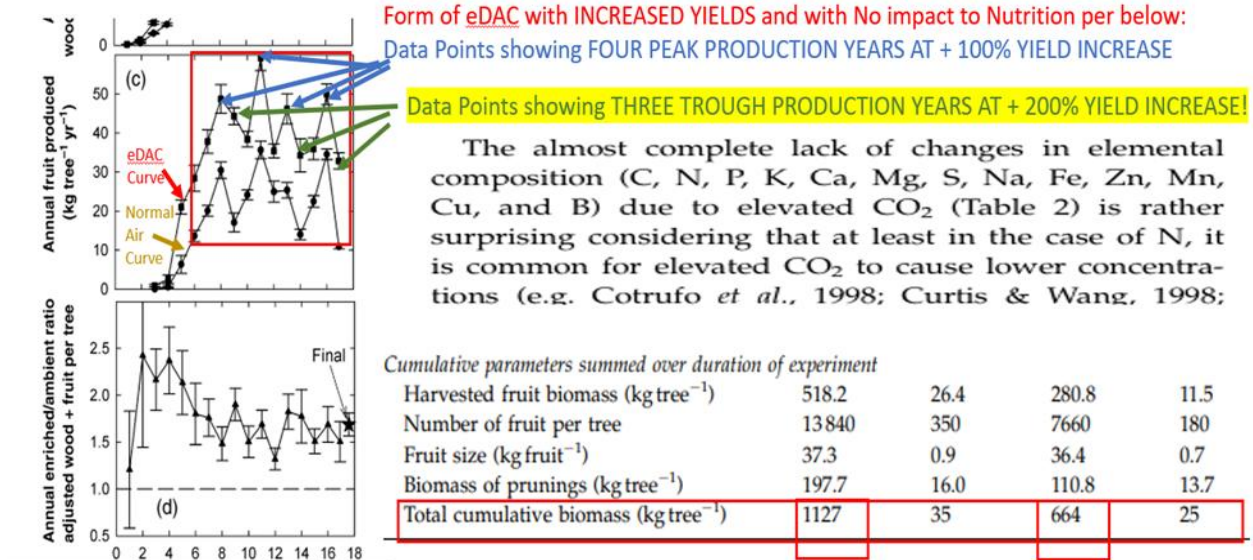


Figure 5⁽¹⁹⁾

Citrus Yield/Flux Increases 100 to 200% (Doubles and Triples) at Enrichment to 550 ppm

In traditional biofuel production, the cost of biofuels is driven by the cost of biomass.^{”(24)} FACE’s increase in biomass production makes producing sustainable renewable carbon negative fuels more economic. If the cost of oxygen production can be brought down, biofuels production becomes even more economic.

Introducing membrane based Direct Air Capture (mDAC), a technology capable of the co-capture for both oxygen and CO₂ from air. Like aDAC, mDAC is based upon leading commercial industrially proven air separation technology. mDAC is also effective when applied pre-combustion to a power plant⁽²²⁾ (see Figure 8) as a replacement to the combustion air source allowing significant reduction of fuel consumption through oxy-combustion per USDOE⁽²⁵⁾, (see Figure 9.)⁽²²⁾

Both eDAC and mDAC make a case for Direct Air Capture with Use (DACU). Per IEA, DACU demonstrates permanence and “can still deliver clear climate benefits, particularly when the application is scalable, uses low-carbon energy and displaces a product with higher life cycle emissions. In the decarbonisation path towards net zero emissions, atmospheric CO₂ will eventually need to displace the use of fossil-based carbon. While CO₂ use can deliver climate benefits under the circumstances mentioned above, it is a complement rather than an alternative to CO₂ storage, which is expected to be deployed at a much larger scale in order to reach international climate goals.”⁽⁵⁾

The goal is to further the target to net zero or carbon neutrality (Figure 10), as can only be evidenced by the halt to acceleration and the halt to the rise of CO₂ concentration in the atmosphere,

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let alone lowering of CO₂ concentration (carbon management). This can only be achieved by supplanting high carbon unsustainable non-renewable fossil fuels with low carbon sustainable renewable biofuel production as shown in the complete Black Swan Cycle (see Figure 11.)



Free Air Carbon dioxide Enrichment

FACE

FLUE GAS RELEASE POINT

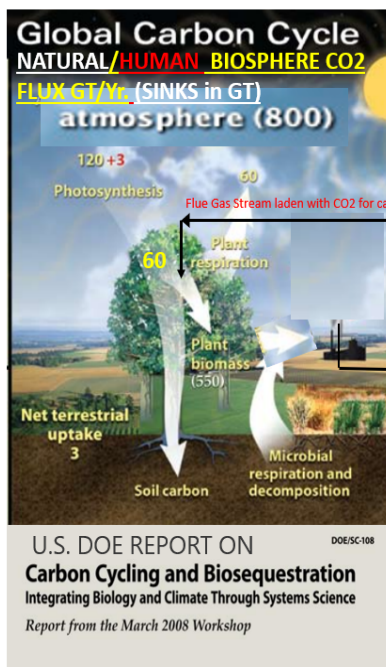
Before FACE

With FACE

- | | | |
|-------------------------|--------------|---------------------|
| 1. Release Elevation: | 100 + Ft | < 10 Ft (grow zone) |
| 2. Release Temp: | Hot (320F) | Cold (80F) |
| 3. Water Content | High | Very Low |
| 4. Density/Congestion: | Low | High |
| 5. Velocity/ Direction: | High/Upwards | Low/Downwards |

Cool, Denser than Air, Slumping Enriched Gas Lingers In Orchard

Figure 6⁽²²⁾



NOW...

... and with Global Carbon Neutrality Targets for 2035!!!

17 MILE TROPO/STRATOSPHERE ATMOSPHERIC SINK

Before FACE

With FACE

- | | | |
|-------------------------------------|---------|------------------------|
| 1. Atmospheric CO ₂ Sink | 800 GT | Target: 650 GT (-19%) |
| 2. Avg Atmos CO ₂ Conc. | 400+PPM | Target: 350 PPM (-12%) |

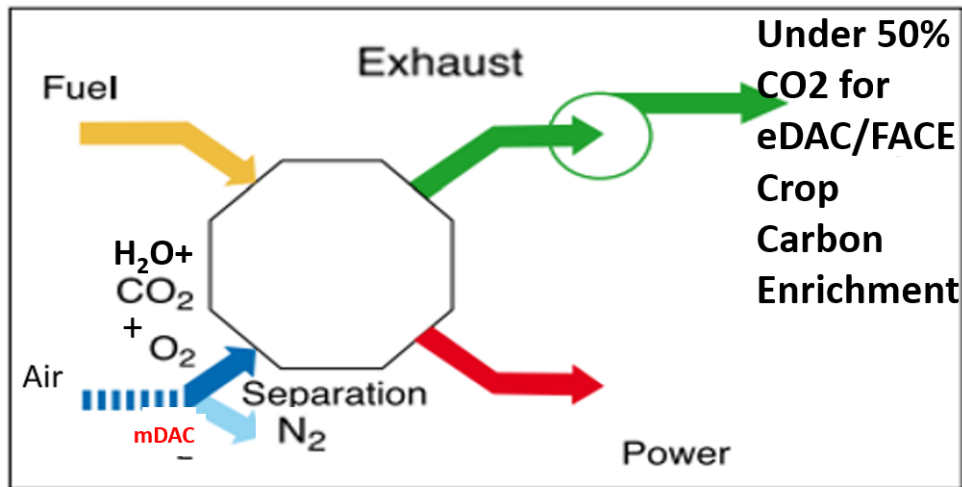
FLOOD Global Boundary (100') Layer Growing Zone

- | | | |
|---------------------------------------|------------|---------------------|
| 3. Carbon Inventory/ Flux | 0.150 GT/Y | +60 GT/Y Available |
| 4. CO ₂ Concentration, PPM | 400 | Target: 800 (+100%) |
| 5. Plant Biomass CO ₂ Sink | 550 GT | 700 GT (+19%) |
| 6. Atm to Plant Flux, GT/Y | 60 | 90 |
| 7. Biomass Fuel to Power | 0.001 GT/Y | 30 GT/Y |

Figure 7⁽²²⁾- With FACE as eDAC, carbon neutrality by 2035 can be achieved.

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BLACK · SWAN mDAC/ eDAC



SAVES CAPITAL/FUEL with CO-CAPTURE
MEMBRANE DIRECT AIR CAPTURE (mDAC) of CO2 WITH O2

Figure 8⁽²²⁾

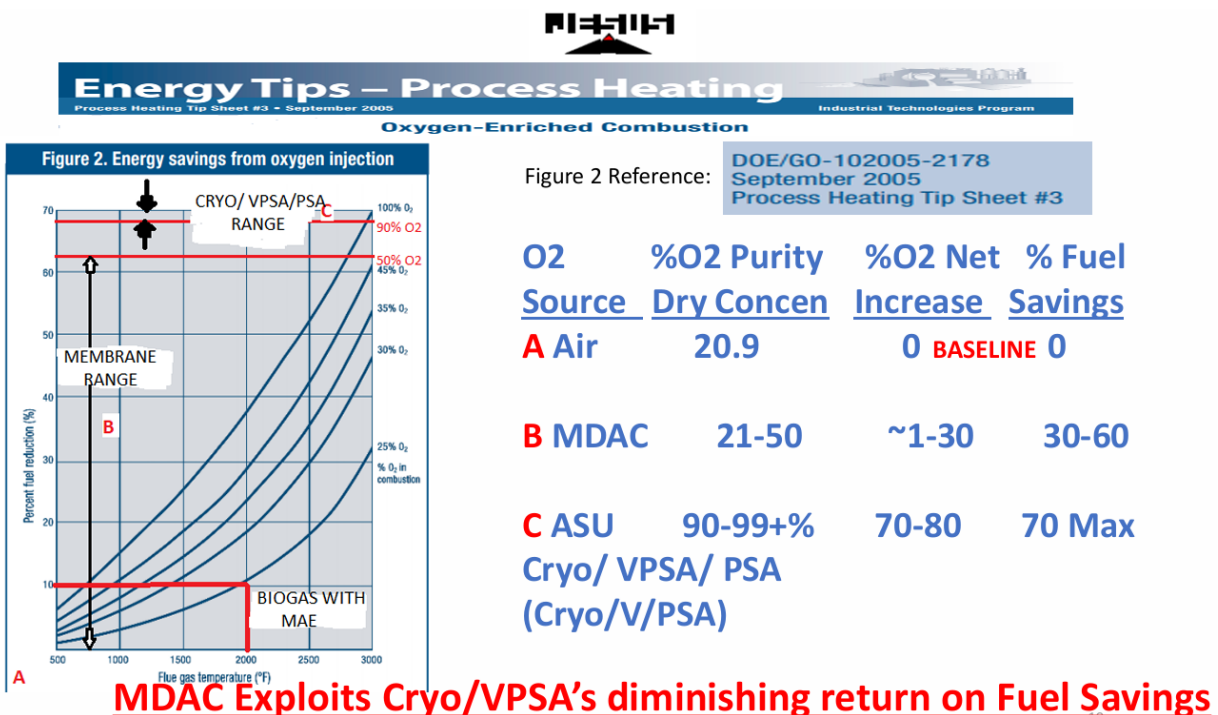


Figure 9⁽²²⁾



**"Keeling-Kimball-Kolodji" Curve
can only be achieved with eDAC that...**

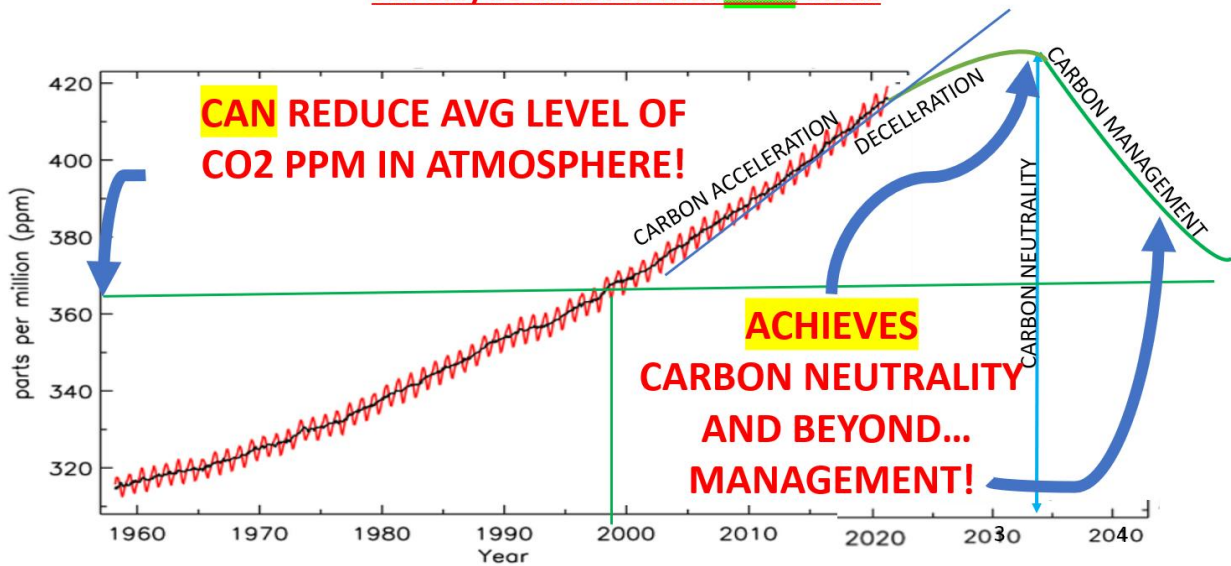


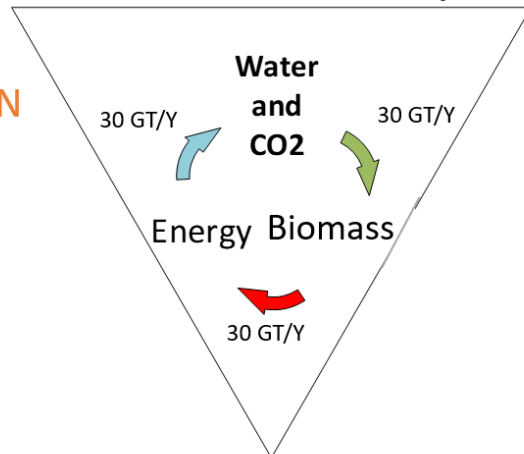
Figure 10⁽²²⁾ - Modified Keeling Curve to show process to Carbon Management



BLACK · SWAN Cycle

mDAC/
OXY-COMBUSTION

eDAC/ FACE



BIOMASS/ BIOFUEL

CARBON MANAGEMENT HARNESSSED with "POWER OF BREATH"

Figure 11⁽²²⁾

REFERENCES AND LINKS

...Peace be with you...



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- (2) [Carbon Cycling and Biosequestration | Genomic Science Program \(energy.gov\)](#)
- (3) [Evidence - NASA Science](#); [The Keeling Curve](#) UC Davis, Scripps Institute of Oceanography, and NASA related links with ICE Core Data and Keeling Curve Data.
- (4) [IPCC AR6 SYR FullVolume.pdf](#) (6a) page 45, Figure c; (6b); See note on bottom of page 86 and 2nd to last sentence in column 1 on page 86
- (5) [Direct Air Capture: A key technology for net zero \(iea.blob.core.windows.net\)](#); (7a) page 9, 2nd paragraph, last sentence; (7b) page 34, bottom paragraph; (7c) Table on page 19 and page 45, 1st paragraph, last sentence; (7d) pages 3,6,8 and 13.
- (6) [Direct Air Capture Definition and Company Analysis Report.pdf](#); by Faber, G., USDOE Office of Fossil Energy and Carbon Management, January 2025
- (7) [2022 Scoping Plan Update \(ca.gov\)](#) for Achieving Carbon Neutrality; (6a) page 92, bottom paragraph; (6b) page 84, bottom paragraph; (6c) page 96, Table 2.3; (6d) Figure 2-2 on page 84 and page 92; (6e) page 85, 1st paragraph; (6f) page 85, paragraph 1, last sentence; (6g) page 93, 2nd paragraph; (6h) page 217, Figure 4-10.
- (8) Go to USDOE link: [Direct Air Capture Factsheet August 2024.pdf](#)
- (9) [GFO-24-303 Questions and Answers ada.docx](#) see Q16 and A16 on pages 4 and 5.
- (10) [Expanding Nature-Based Solutions \(ca.gov\)](#)
- (11) [Executive Order N-82-20](#)
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