Understanding Carbon Dioxide Removal and Storage (CDRS)

Paul S. Anderson, PhD psanders@ilstu.edu
This document, any updated versions, and a six-minute video about the proposed classification system are available at www.woodgas.energy/resources This is version 2021-02-18.

Summary: Multiple inadequacies in the current terminology about carbon dioxide removal (CDR) methods and negative emission technologies (NETs) are presented. An alternative, function-specific, less ambiguous system tentatively called CDRS is offered in written and graphic forms for increased understanding by the general public.

The problem

The terminology about the multiple distinct carbon dioxide removal (CDR) methods for dealing with the climate crisis is neither clearly defined nor well expressed, as is noted by both Eisenberger and Melton:

"… there is so much misunderstanding of the basic issues related to the climate challenge and the resultant diversity of solutions that are falsely considered as viable… ."

Peter Eisenberger, email to CDR Discussion Group on 29 December 2020.

"We [the general public] do not know what climate change is, or air capture, sequestration, or the jumble of alphabet soup acronyms associated with the sciences of climate change. Without a cultural background in these things, they will continue to … engender widespread skepticism… ."

Bruce Melton, email to CDR Discussion Group on 29 December 2020.

Fuller provides some advice about what to do:

"You never change things by fighting the existing reality.
To change something, build a new model that makes the old model obsolete."

R. Buckminster Fuller

This document proposes a revised classification system intended to be useful for experts and the general public about the various CDR methods that are important to help save our climate. It is tentatively called CDR<u>S</u> to emphasize the storage or sequestration aspect of carbon dioxide removal and storage. This document must not favor or oppose specific methods; it must be unbiased and objectively neutral and encompass all CDRS methods. Therefore, evaluative comments about CDRS technologies are minimized in this document that is about scientific classification systems of CDRS.

Introduction

Our urgent climate crisis that threatens the sustainability of decent life on Earth is caused by the heating of the atmosphere because of excessive levels of atmospheric greenhouse gases, of which carbon dioxide (CO_2) is the most important. CO_2 concentration in the atmosphere has risen because of land use changes (deforestation and modern agriculture) and the burning of fossil fuels for our present and past 250 years of energy consumption.

There are three known solutions for controlling our climate crisis:

1. Physical alteration of the atmosphere with solar radiation modification (SRM). This is mainly theoretical, strongly debated, and is not discussed here.

2. Reduction of our annual fossil fuel usage that currently releases about 40 gigatonnes (1 Gt = one billion tonnes) of CO_2 (or CO_2-equivalent (CO_2e)) per year. This needs to be reduced to Net Zero by replacing fossil fuels with renewable energy sources, improving energy use efficiency, and introducing changes in lifestyles. Reducing emissions is absolutely essential but is not discussed here.

3. Carbon dioxide removal (capture) from the atmosphere and (long-term) storage (CDRS) is our topic.

We, the inhabitants of Earth, must accomplish **carbon dioxide removal (CDR) with multi-century sequestration (S) of 750 to 1500 Gt** of excessive CO_2 that is either in the atmosphere or what the oceans will return to the air when (and if) atmospheric CO_2 ppm concentrations decrease from 415 ppm to a tolerable 350 ppm and possibly down to pre-industrial 280 ppm.

The long-term ***removal*** of CO_2 is no longer optional; it is a co-imperative with reduction.

Unfortunately, CO_2 removal (CDR/CDRS) concepts and methods are not well known to the general public. Furthermore, the methods of CDR are currently presented with inconsistencies in the publications on the topic. This document attempts to clarify carbon dioxide removal and storage processes and options. There are four (4) steps to attain clarity:

Step I. Clarify the basics of true removal of CO_2 with long-term storage (CDRS)
Step II. Show how current CDR explanations are deficient and/or misleading.
Step III. Offer a proposal for improved terminology.
Step IV. Encourage discussion to reach understanding, evaluation, and consensus.

Step I. Clarify the Basics of True Carbon Dioxide Removal (CDR) and Storage (CDRS)

A. True CDRS must present solutions to two distinct tasks:

1) the **capture of CO_2** from the atmosphere. Capture is mostly with transformation of the CO_2 gases into some CO_2 liquid or solid or CO_2 equivalent, including plants. *(Note: The letter "C" can stand for capture, carbon, or climate. "CC" together often means "carbon capture." We must provide clarity and/or context whenever the letter "C" is used.)*

2) the **storage or sequestration of that captured CO_2.** These two "S" words also mean holding or preventing that captured CO_2 (or the equivalent carbon in another form, e.g., in plants or fixed carbon in biochar) from returning to the atmosphere for many centuries or millennia. For TRUE removal, the duration of storage is subject to debate. Concepts of half-life, leakage, and decay need to be addressed. But in general, storage must be reasonably secure for at least a few hundred years. Short-term capture is not a viable option. Short-term holding would be like catch-and-release when fishing for sharks; it occupied your time and efforts but did not reduce the shark population.

The two tasks (capture and storage) are separate but have specific possible combinations. They require two solutions that work well together. Capture has two main categories of processes that are solutions, whereas storage has three (discussed below).

In Step III we will see that each category has some sub-categories of processes, resulting in seven (7) primary combinations of functional solutions for removal. **Capture PLUS storage constitute true REMOVAL.**

[Note that even the single word "removal" can be misleading if understood only in the context of "capture," as in "crop growth involves CO_2 removal from the air." When it is sometimes necessary to emphasize the requirement for long-term storage, a final "S" can be added to the acronym to become CDRS. But it would be nice if "removal' and "CDR" are both understood to mean that both capture and long-term storage are accomplished, which would be lasting or virtually permanent removal. For consistency in this paper and general usage, references to CDR are presented as including both the capture and storage (holding) requirements to accomplish climate impact. The word "capture" does not include "storage," but the word "removal" can include both capture and storage. The addition of an "S" to create the acronym CDRS is to provide more recognition to the importance of storage, especially long-term with climate benefits. Such language is only finalized by the societies that use the terms.]

B. CO_2 Capture:

The **capture of atmospheric CO_2** is viable with either of **two processes.** *[Excluded is a third process of dissolving atmospheric CO_2 into water, specifically in oceans, where it becomes carbonic acid. This acidification is bad for the oceans, so this process is not an option to encourage for capture. It is to be resisted and reversed. Reversal will be natural when atmospheric CO_2 is reduced, but that means additional CO_2 removal from the atmosphere will be needed.]*

1. Technology-based or engineered inorganic chemical conversion (mainly sorption) of gaseous CO_2 into liquid or solid compounds that are sufficiently stable for eventual transport and storage.

2. Nature-based organic growth of plants (by photosynthesis) to create biomass, mainly as carbohydrates that include foods, fuels, fibers, agricultural residues, invasive species, and ocean plants.

A summary of the major categories of capture is provided in Table 1:

Table 1: Major Categories of Processes of Carbon Dioxide Capture	
Engineered Solutions	**Nature-based Solutions**
Inorganic chemistry	Organic chemistry
Inorganic Compound Creation (ICC)	Photosynthesis => Plant Growth (PG)

C. Storage or sequestration of captured atmospheric carbon:

1. Destinations for storage:

After capture, there are **five main locational destinations (or "carbon sinks") for the CO_2 or CO_2 e (equivalent):**

Name	Examples
deep geology	holding supercritical CO_2 in abandoned oil wells and deep rocks
soils	where living organisms maintain the carbon content
oceans	zones of various depths, pressures, and temperatures
living plants	focused on holding what is already grown, but not new growth
constructions	long-lasting objects built with materials that secure or store CO_2.

2. Processes for storage:

There are **three processes for long-term storage** or sequestration that hold captured CO_2 or CO_2e, also known as "carbon sinks":

a. **Secure CO_2 as inorganic compounds** (especially carbonates and bicarbonates) where they cannot revert to CO_2 gas, including by injection of solids or super-critical liquid CO_2 into deep geologic structures or by creating rocks, minerals in fields, cement, or other building materials.

b. **Hold CO_2e as a <u>static amount</u> the created biomass in its organic (often living) forms or with continual renewal (as with living microbes in soils) or by preservation methods** to avoid decay and decomposition that would emit CO_2 and CH_4 (methane).

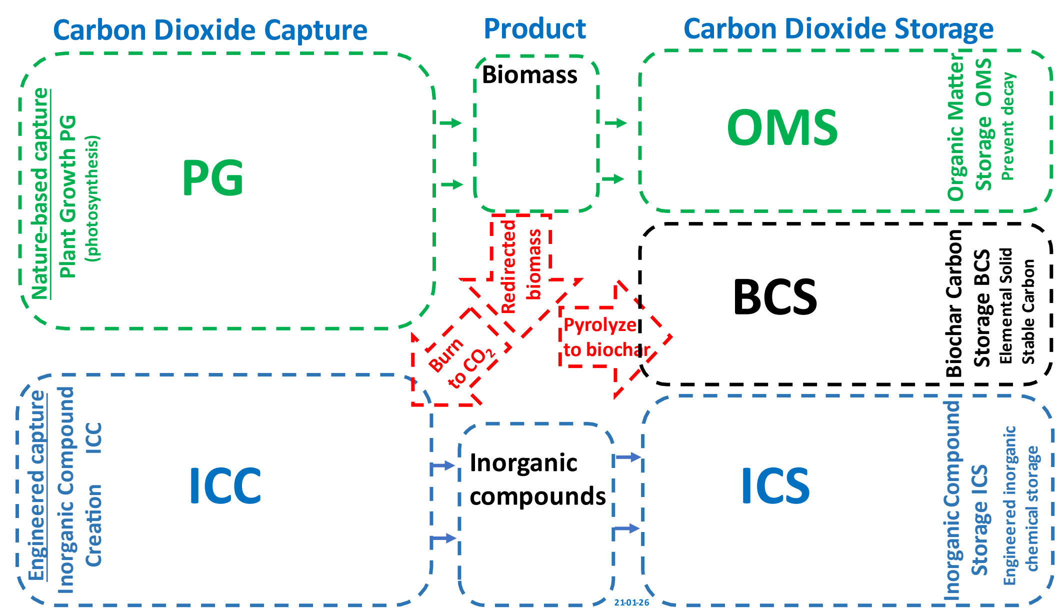
c**. Convert organic carbon of biomass into stable elemental carbon,** commonly referred to as char or charcoal, of which the significantly different major types (cooking-charcoal, biochar, and activated carbon) are the result of different temperatures (and some processing options) of thermal decomposition called **pyrolysis**. In addition to creating the stable solid carbon structures (char) that conserve about 50% of the carbon, pyrolysis liberates ~70% of the energy content of the biomass as emission gases and vapors that can be promptly collected concentrated chemicals, or burned as combustibles, or released, which is not desirable but commonly occurs in most forms of traditional charcoal production.

A summary of the major categories of storage / sequestration / holding is given in Table 2.

Table 2: Major Categories of Processes of Carbon Dioxide or CO_2e Storage		
Inorganic Compound Storage (ICS) with various types of destinations	**Organic matter storage (OMS)** that is preserved or self-regenerating without altering the carbon content	**Solid Carbon Pyrolytic Biochar Storage (BCS)** by incorporation into soils or constructions

<u>Summary of Step I:</u> ***A graphic summary of Step I is shown in Figure 1:***

Figure 1:



Step II. Show how current CDR explanations are deficient and/or misleading.

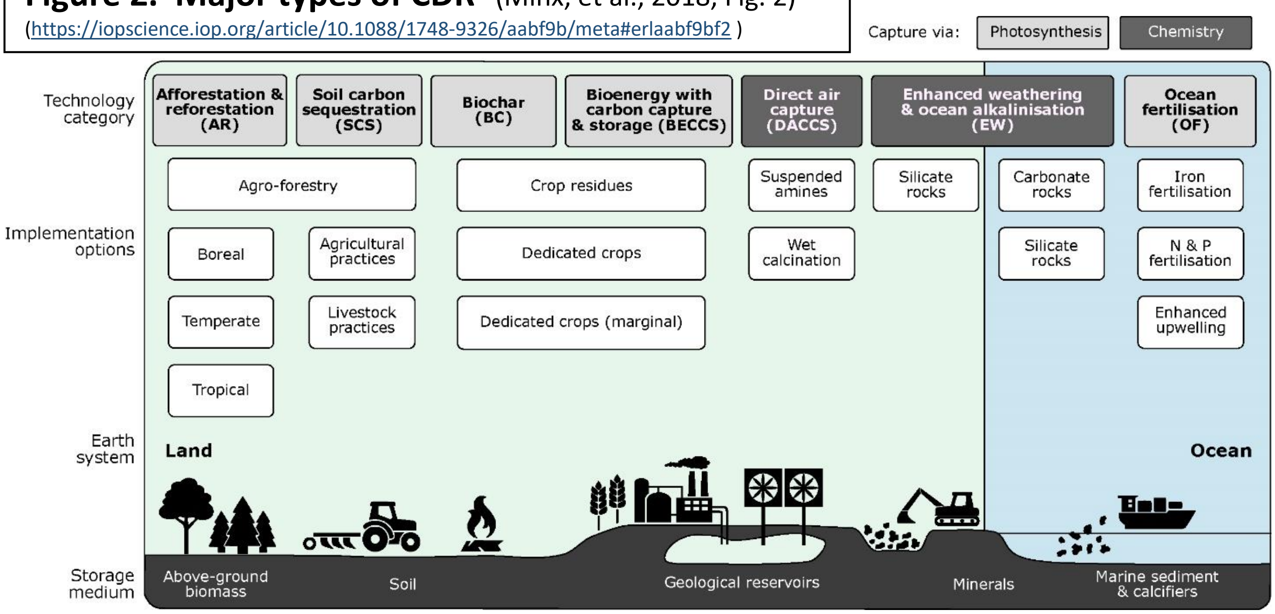
A. Recognition of current explanations

Prior to this 2021 document, most specialists (especially academic persons and organizations) have utilized a shared understanding of the CDR realm with a degree of agreement that deserves recognition. There has been strong basic agreement on the seven major CDR methods (sometimes called negative emission technologies (NETs)), as listed in Table 3. But within this core knowledge there are some unintentional imprecisions or infelicities that have been propagated in numerous publications. In particular, and for this discussion, this is seen in one exceptionally good graphic representation of current CDR terminology by Minx *et al.* (2018) in Figure 2.

Table 3: Names in 2020 of the Seven (7) Prominent Negative Emission Technologies (NETs) for Carbon Dioxide Removal (CDR):

EW	Enhanced Weathering
DACCS	Direct Air Carbon Capture and Storage
AR	Afforestation and Reforestation
SCS	Soil Carbon Sequestration
OF	Ocean Fertilization
BECCS	Bioenergy Carbon Capture and Storage
BC	Biochar

Figure 2. Major types of CDR (Minx, et al., 2018, Fig. 2)
(https://iopscience.iop.org/article/10.1088/1748-9326/aabf9b/meta#erlaabf9bf2)



B. Noteworthy "imprecisions, infelicities and errors" of CDR <u>classifications</u> (not about the CDR methods) in use through 2020:

[Note: The 22 items on the next several pages are mainly negative (discussing problems) about CDR classification systems. These items can be set aside until later if the reader is wanting to skip ahead to know the positive, new "CDRS" proposal, found in Step III. If the new CDRS terminology gains approval, this Step II will be relegated to historical archives.]

1. Photosynthesis and chemistry are the two major categories of CO_2 capture , as shown by Minx *et al.* in the two "Capture via:" rectangles in the upper right corner of Figure 2.

2. The bottom area of the Minx diagram shows the storage destinations of deep geology, soils, living plants, and oceans, but does not show long-lasting constructions (a rather recent addition to the discussions). But there is more to "storage" than location. The diagram implies a) deposition of inorganic compounds in geologic reservoirs, minerals, and marine sediment & calcifiers and b) holding at a static level the nature-based biomass either living or dead in above-ground biomass and in soil. Absent from the "storage medium" line spanning the bottom of the diagram is biochar, the solid stable carbon that is inherently different from soil organic carbon and above-ground biomass.

3. Based on notes 1 and 2 above, the Minx *et al.* diagram is "close" to the basics of true carbon dioxide removal and storage (CDRS) presented in Step I and Figure 1. **But then it falls apart in the details.**

4. The seven main CDR technologies listed in Box 3 and on the Minx-diagram (top line for "Technology category") do not give separate and clear designations of BOTH the capture and the storage processes. Both AR and SCS are being used without differentiation as terms for capture AND as terms for storage. Both BECCS and DACCS add a single letter "S" to refer to any type of storage, while more recent discussions simply change the name to DAC without reference to storage. EW, OF, and BC refer to only one of the two types of processes.

5. Capture that is by photosynthesis should also include the nine rectangles (six for Agro-forestry and three for types of Crops) in the left half of the "Implementation options" on Figure 2. Capture by biologic growth is not limited only to forests and soils. Crops should be a "Technology category" of capture, but not a means for long-term storage / holding.

6. And worse, Biochar and BECCS are not photosynthetic processes and do not capture CO_2 from the air. Biochar and BECCS depend on having a supply of biomass.

7. Actually BECCS changes the already-captured carbon in biomass back again into mainly CO_2 (which is at best carbon neutral), and then those gases need to be RE-captured with chemical technology of sorbents. Therefore, because BECCS makes its claims for carbon capture based on capture of concentrated CO_2 in chimneys by using sorbent technology, it should be in the "Chemical" category along with DACCS. The capture processes / methods for BECCS are essentially the same as if the chimney emissions came from fossil fuels (which is a self-serving reason for the fossil fuel companies to praise and promote BECCS rather than other CDRS options).

[Note: The CDR attention on BECCS is due to its inclusion in Integrated Assessment Models (IAMs), the basis for the IPCC Special Report on Global Warming of 1.5°C (2018). The analysts preferred BECCS in IAMs because it was the technology with the most available data for model parameterization at the time they were included. However, those data are based on projections of available biomass, and only had assumptions that the capture of concentrated chimney emissions (CCE) would actually work and be economically feasible, which is still unproven.]

8. "Bioenergy with Carbon Capture and Storage" (BECCS) is the only named CDR technology that implies benefits of the release of energy. Energy release or use technically has nothing to do with CDR. But if energy release is acknowledged, then Biochar should be recognized along with BECCS as a potential source of net energy (derived from plant growth) while the other CDR methods should be shown to be energy sinks of different magnitudes.

9. The representations of CDR need to include more precise recognition of biochar (BC) as a human-managed transformation of biomass that creates long-term holding of about 50% of carbon that is otherwise in rather short-duration storage in living and dead biomass.

10. SCS is a vague reference to largely unseen (difficult to observe) quantities of organic matter in soil. Those quantities of captured Soil Organic Matter (SOM) are subject to major reversals by simple actions such as plowing and use of artificial fertilizers. SCS describes neither the capture nor the holding of the CO_2e materials. Better terms are needed. [As is presented in Step III, the names SOMG and SOMS leave no doubt about referencing the Growing (increase) of the SOM or the static Storage of the SOM, respectively.]

11. There is confusion as to whether AR (afforestation / reforestation) is referring to the capture of the CO_2 through plant growth or to the holding of that CO_2 as forest biomass that must be kept alive to prevent its decay when the trees have stopped growing. For gigatonne impact, the prevention of eventual decay is a losing battle in the long term, and continual expansion of forest coverage will result in eventual competition for space for crops, biodiversity, and settlements. The use of AR to designate both capture and holding leads to confusion (or requires frequent reminding for clarification). AR is a poor choice of letters (based on forestry jargon) that do not directly indicate forests (F) or wood / woodlands (W).

12. Because of their biological nature, both AR and SCS are rather poor at long-term sequestration. AR does get some "storage" recognition because it has the longest-living plant forms, but unfortunately 100 years or even 200 years for a climax forest is not long enough storage for countering the current excess of atmospheric carbon dioxide.

13. Based on 11 and 12 above, AR and the "Trillion Trees Project" focus on growth (referring to CO_2 capture) but ultimately fall short of the needed long-term sequestration.

14. The permanence of storage by SCS is variable, and can even be shorter than for AR, and as noted earlier, can be disrupted easily and seriously with a plow or chemicals. Please note that SCS is below ground, and therefore is dependent on photosynthesis above ground to keep feeding the roots and microbes of the living soil. SCS focuses on special "living and regeneration" attributes in regenerative agriculture (as long as the soil is not overly disrupted for hundreds of years). SCS can have increased credibility if the plants above ground (crops, trees, etc.) are providing deep root structures plus additional biomass (residues after the primary harvest of grains and fibers) that can decay and leach nutrients into the soil. This is the only CDR that uses photosynthetic plant growth to support remote biological growth.

15. Shifting now to the chemical processes, we note that when EW (Enhanced Weathering) is conducted by human activities either on land or in oceans, it is the only CDRS technology that in a SINGLE STEP accomplishes both capture and storage. The pulverized rock is placed on soil or into water where chemical reactions occur to incorporate CO_2 into carbonate or bicarbonate solid compounds that essentially remain in the same location or sink to accomplish long-term storage (and pH benefits).

16. In contrast, DACCS (DAC-CS) refers to two independent processes to accomplish capture and storage separately. To shorten the name to DAC specifically emphasizes the "direct air **capture**" while ignoring or downplaying the need to also have separate (often costly) actions for transport and storage (S) of the CO_2 or CO_2e. Evaluation of DAC should also include the DAC CS aspects regarding storage. We will seek to clarify that in the proposed new terminology.

17. CCS stands for "Carbon Capture and Storage," which is both capture and holding in one name that does not clearly state how the capture is accomplished or what method accomplishes storage/holding. By conventional accepted usage by CDR experts, "carbon capture and storage" (CCS) refers directly to inorganic sorbent chemistry of DACCS and BECCS. CCS does not have the same connotation as the broad term "carbon dioxide removal" (CDR), although semantically they say the same thing, *i.e.*, to capture and store carbon. CCS is essentially smokestack scrubbing, the capture of concentrated chimney emissions (CCE) that is mediocre at best and expensive technology. CCS is advocated by the fossil fuel industries in their attempts to use sorbent chemical capture of CO_2 to whitewash the continued use of oil, natural gas, and coal, trying to become carbon neutral while not relating at all to CDR in the context of removal of CO_2 from the atmosphere. CCS is a meaningless or (worse) an ambiguous expression that should not be further used. For example, for some authors, the expression pyrogenic carbon capture and storage, or PyCCS, refers to biochar creation and storage, but CCS is interpreted as meaning CDR and not the chemical processes used in DACCS and BECCS. An expression such as CCS that carries double meanings leads to unending misunderstanding.

18. The addition of "U" to form "carbon capture utilization and storage" (CCUS) does not resolve the CCS confusion and adds a dimension of utility (including financial value) in addition to capture and storage. This opens the gates for other CDR technologies to also claim utility / value, such as ARU (use of forests for habitats), SCSU (use of soils with increased crop productivity), and BCU (the commercial value of biochar as a soil amendment). CCUS is as problematic and unclear as CCS.

19. The above comments relate to terminology of the whole community of CDR enthusiasts and are not a criticism of Minx *et al.*, which is among the best explanations available. In fact, some other prestigious publications about CDR have an additional noteworthy error. Documents by U.S. National Academies of Sciences, Engineering, and Medicine (NASEM) (2018), European Academies Science Advisory Council (2018), and Carnegie Climate Governance Initiative – C2G (2019), appear to erroneously combine SCS and biochar as if they were the same. The reasons to separate them are the fundamental differences between organic carbon in biomass that readily decays and elemental stable black carbon. Minx is correct to name biochar separately.

20. One on-flowing impact of the NASEM 2018 document is in Hezir *et al.* (2019) (https://static1.squarespace.com/static/58ec123cb3db2bd94e057628/t/5cd5968abab2200001c68cc5/1557501586386/Carbon-Removal-Comparing-Historical-Investments-with-the-National-Academies-Recommendations.pdf). They present (Figure 2 on p. 9) an organized classification system of "Technical Pathways for Carbon Dioxide Removal" in which the only link to biochar is through BECCS. BECCS in Appendix A (page 28) is indicated to include biochar (but with focus on energy and chemicals for fuels). Also, in Appendix B (pages 30 and 31) BECCS is indicated to include almost anything from living plants and involving processes of that include gasification, fermentation, biochar, and thermochemical. Perhaps this is a redefinition of the scope of BECCS, but it lacks clarity about the CDR methods.

21. The overall lack of a foundation of scientific terminology for classification of CDR is recently (28 January 2021) shown by the Innovation for Cool Earth Forum (ICEF) roadmap document entitled "*Biomass Carbon Removal and Storage (BiCRS)*". The information at www.icef-forum.org/roadmap/ states: "We introduce a new term – biomass carbon removal and storage (BiCRS) [pronounced "bikers"] -- which we believe better describes this topic than the traditional term – bioenergy with carbon capture and storage (BECCS)." But the 2 February 2021 webinar and the publication present BiCRS as including all of the CDR technologies that derive their CO_2 reduction from the growth of plants

(see the Executive Summary of Chapter 1). With the exceptions of not including DACCS and EW, the term BiCRS is defined to include BECCS, SCS, AR, BC, and OF, being all the "natural" CDR methods.

22. It is the premise of this document "*Understanding Carbon Dioxide Removal and Storage (CDRS)*" that a more scientific classification system would be more accurate, appropriate, and better for communications about CDR methods or NETs within the focused community of specialists and also to the general public. Such a system is presented in Step III for evaluation by those who are involved with any or all of the CDR methods and processes.

Earlier additional discussion on this topic by this author is located in Section III and Table 1 in the white paper *"Climate Intervention with Biochar"* found at www.woodgas.energy/resources .

Summary of Step II: ***The lack of clarity in the discussions of current carbon dioxide removal (CDR) technologies and practices stems from imprecise terminology during the past years.***

Step III. Offer a proposal for improved terminology

A. Outline of proposal: Our main objective is clarity of understanding about CDR/CDRS that can have meaning to the general public as well as to the experts. Our specific objectives include clear names and meaningful acronyms associated with the sciences of climate change. We need to arrive at such understanding without force feeding. The mission of meaningful communication is more important than extreme precision.

We start with lists of what we know about "capture" and "storage." We can add to, delete from, and modify the lists. These are not necessarily "technologies"; some are more like "situations" or "methods" or "ways."

Major categories and sub-categories of carbon dioxide **CAPTURE** (Table 4) and **STORAGE** (Table 5) are below:

Table 4: Major categories and main sub-categories of CAPTURE of carbon dioxide

Notes: The final "G" signifies Growth or Increase. BECCS is represented on the listings as the capture of "concentrated chimney emissions" (CCE).

Inorganic Compound Creation (ICC) by chemistry		**Organic Plant Growth (PG) by photosynthesis**	
Major sub-categories	Acronyms	Major sub-categories:	Acronyms
Concentrated chimney emission	CCE	Forest & woodland growth	FWG
Direct air capture	DAC	Agricultural crop growth	AGG
Enhanced weathering	EW	Weeds and wild growth	WWG
Carbon concretions in oceans:	CCO	Ocean biomass growth	OBG
		Soil organic matter growth	SOMG

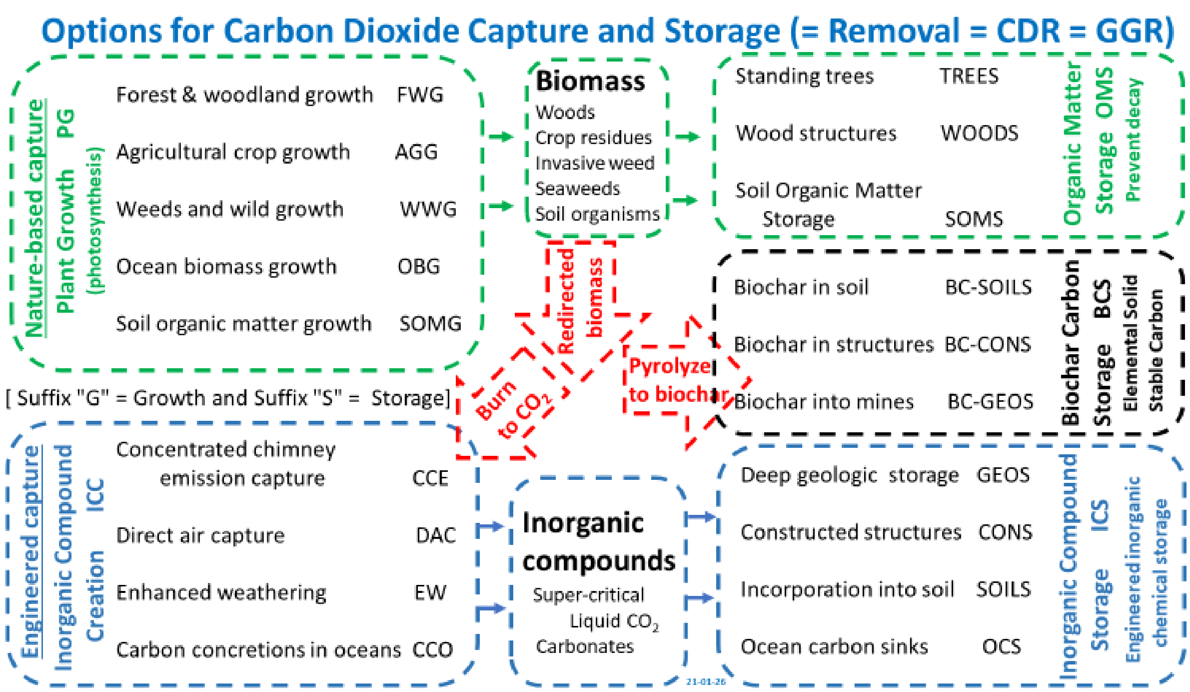
Table 5: Major categories and main Sub-categories of STORAGE of carbon dioxide

Note: The final letter "S" signifies storage, sequestration, stable and static. Because biochar (BC) is only about storage (it does not capture CO_2), it does not require but is suggested to have a final S, as in BCS.

Inorganic Compound Storage (ICS)	Organic Matter Storage (OMS)	Biochar Storage (BCS)
As chemical compounds in Locations Deep geologic storage: GEOS Constructed structures: CONS Incorporation into soil: SOILS Ocean carbon sinks: OCS	**As organic compounds** of biomass types that are **no longer growing.** Trees and other wood: TREES Soil organic matter Storage SOMS Includes "Living soil" with regeneration and growth to maintain microbes, etc. Constructed structures: CONS (mainly wood structures) *(Decomposing biomass is short term.)*	**As pyrolytic transformation of biomass** into stable elemental carbon (graphene plates, etc.) of Biochar: BC Biochar into soil: BC-SOILS Biochar into constructed structures such as concrete and asphalt: BC-CONS Biochar into old coal mines (but is unlikely) BC-GEOS

The above-named categories of carbon dioxide capture and CO_2e storage can be arranged according to their paired relationships of the two processes (both capture and long-term storage) of Carbon Dioxide Removal (CDR/CDRS). See Figure 3.

Figure 3:



There are many possible paired combinations of methods of CO_2 capture and CO_2e storage to achieve CDRS. Some are more logical or viable than others. Pairs do not create "technologies." Perhaps the pairs would be better called "methodologies" or methods or ways or paired ways. A few are listed in Table 6.

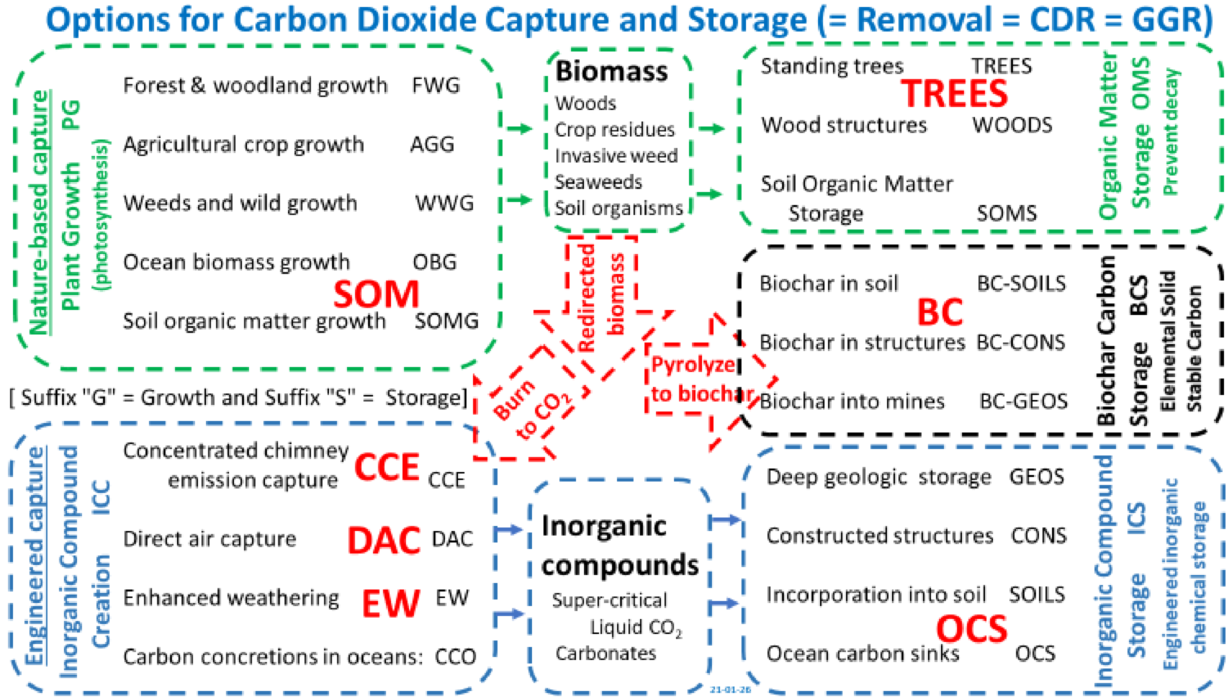
Table 6: Examples of "paired ways" to have capture and storage of carbon dioxide (CDRS)		
PG to OMS FWG to TREES SOMG to SOMS PG to SOMS AGG to SOMS	PG to BCS FWG to BC-SOILS AGG to BC-CONS	ICC to ICS DAC to GEOS CCE to GEOS EW to SOILS EW to OCS

These expressions are descriptive and long and do not "roll off the tongue" easily. More friendly names are suggested in Table 7. Some of the suggested names (acronyms) will quickly become familiar (DAC, BC, and EW) when used with some clarification of their meaning. But others (AR, SCS, and BECCS) are rejected as being inaccurate or misleading, as discussed in Step II. But acceptance of the proposed new CDRS list is ultimately accomplished by the embrace of the community of users.

Table 7: Suggested naming and characteristics of major CDRS methodologies

Names of major Divisions	Short Summary Names	Extended names	Specific Variations	Notes and Discussion
Nature-Based Plant Growth **PG to OMS**	**TREES** *(Formerly AR)* Focus is on storage	**FWG to TREES** Forest & Woodlands Growth to Tree Storage		Refers to Tree Storage, not to plural of Tree.
	SOM *(Formerly SCS)* Focus on both capture and storage	**SOMG to SOMS** Soil Organic Matter Growth (Increasing) to Soil Organic Matter Storage (Static)	**PG to SOMS** Refers to all PG including AGG (Agriculture & Crops Growing)	AGG for Ag Growth and ACG for Ag – Crops Growth could be interchangeable.
Plant Growth Transformed to Biochar **PG to BCS**	**BC** Focus is on the unique material of biochar	**PG to BCS** Plant Growth to Biochar Storage	**FWG to BC-SOILS** **AAG to BC-CONS**	Known that it comes from PG of all types.
Technology-based Inorganic Chemistry **ICC to ICS**	**DAC** Focus is on capture	**DAC to ICS** Direct Air Capture to Inorganic Compound Storage	**DAC to GEOS** **DAC to CONS**	The necessity to have functional GEOS and CONS should not be overlooked.
	CCE *(Formerly BECCS)* Focus is on capture	**CCE to ICS** Concentrated Chimney Emissions to Inorganic Compounds Storage	**CCE to GEOS** **CCE to CONS** (Fossil fuels can also provide CCE but is not even carbon neutral)	What was formerly called "BECCS" was actually 4 steps: "PG to Full-Combustion Burning to CCE to ICS."
	EW Focus on both capture and storage	**EW to ICS** Enhanced Weathering to Inorganic Compound Storage	**EW to SOILS**	EW on land is unique to have capture occur where it is also stored.
	OCS *(Formerly OF and OA)* Focus is on Oceans	**EW to OCS** Enhanced Weathering to Ocean Carbon Sinks		Ocean Fertilization & Ocean Alkalinization are special cases.

The combination of Table 7 and Figure 3 provides us with Figure 4,



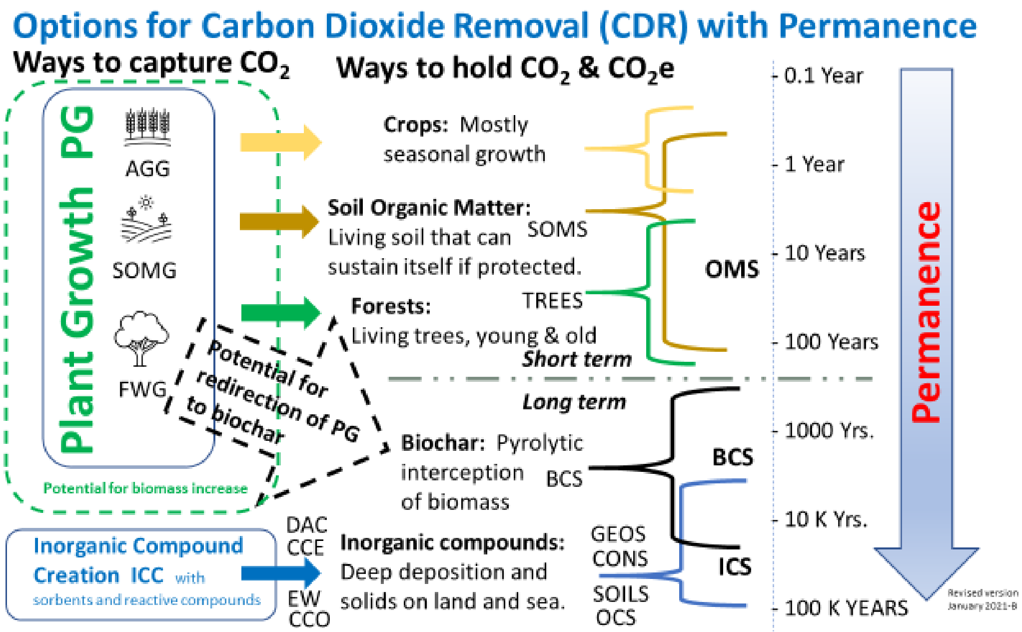
B. Using Combinations of Capture and Storage to Understand CDRS Issues:

If this reclassification system is valid, it should be useful in further discussions about all of the carbon dioxide removal with storage (CDRS) issues. One example of usage is in the following discussion about permanence accomplished by CDRS methods.

Permanence: Figure 5 shows the options for capture and storage and how they relate to permanence.

Notes:

1. The types of photosynthesis could also include biomass growth in oceans and wild plants.



2. Permanence or duration of storage / holding is measured in months, years, decades, centuries, and millennia, essentially five orders of magnitude of temporal impact.

3. The key word is "centuries" because we are today trying to pull our climate back from the brink of tipping points during the next 30 years until 2050. Even the year 2100 is only a mere 80 years away, within the life span of today's children. For example, whether the half-life of stable (80% pure) biochar is 300 or 500 or 1000 years might not matter a few generations from now if the climate crisis is not resolved.

4. Laboratory and field studies of permanence for each of the storage options will require time to reach conclusive results, but the climate crisis allows no spare time to observe such permanence in coming centuries. The brackets of years on Figure 4 could be adjusted when there is evidence.

Important topics: The various ways and methods of CDRS can be examined and objectively compared on each of numerous important issues that can be presented in text, tables and graphs. Some issues are:

1. Permanence of removal. (Example shown above.)
2. Technology Readiness Levels (TRLs).
3. Time needed to reach capabilities of significant removal levels.
4. Pace of scale up for actual implementation.
5. Cost estimates.
6. Impacts on socio-environmental issues, e.g., UN sustainable development goals (SDGs).
7. Prospects for further innovation.
8. Ownership and governance of each aspect.
9. More.

Summary of Step III: ***With proper explanations some of the older common names and acronyms can still be useful. The other ones are substituted with more logical and memorable names and acronyms that express more accurately what aspects of CDRS capture or storage are referenced.***

Step IV. Discussion of revised CDR/CDRS terminology

Comments from everyone are welcome. It is not the role of the initial author to control or exclude those comments. If specialists in the realm of CDRS can reach some shared understanding, this classificatory terminology could be useful to analyze CDR/CDRS options. This could lead to better plans and utilization of resources. And there might be hope for explaining better to the general public and to school children the options and workings of carbon dioxide removal and storage that are becoming increasingly important for resolving the climate crisis.

To initiate further discussion, several topics are introduced:

A. Peer review:

Several people can be thanked for making valuable comments about drafts, but there is no claim for "peer review" of this initial document. To have one journal and a few peers review a draft cannot legitimize a new classification system, and that peer review process would have delayed this release by several months at least. What really matters is what the full community says ultimately about this revision of classification and proposed adoption of the modified term, CDRS. Acceptances or rejections by experts in each aspect of CDRS or by recognized entities are important, but ultimately appropriate communication with society is what counts.

B. Timetable:

Following initial release in mid-February 2021 and informal discussions, the expectation is that the new CDRS system will be either embraced or tossed out by May. If and when sufficient merit is seen, there will be no reason to discuss Step II again.

Three streams of action could occur in parallel:

1. One or more credible entities could conduct evaluations and make decisions (at levels of committees, boards of directors, open reviews, etc.) about the old CDR system and the new, tentatively named CDRS proposed classifications These entities include but are not limited to:

- Carnegie Climate Governance Initiative – C2G
- Carbon 180 (www.carbon180.org)
- Institute for Carbon Removal Law and Policy (www.icrlp@american.edu)
- US Office of Fossil Energy (name is in revision) and other US government entities
- International entities, both governmental and non-governmental
- 360.org
- Environmental Defense Fund

One or more revisions could be prepared, circulated, and perhaps combined and refined. This revision process is scholarly, professional, and institutional. All of this refining can be supportive of education.

2 and 3. The second and third streams of action are education and analyses.

C. Education:

Efforts for public information and education about CDRS can start promptly. Materials (written, graphic, video, audio, etc.) will be needed at all levels. The hard science and soft sentiments about climate matters need to be translated to other languages to reach all people, including experts and educated adult populations of all societies. Also, CDRS and other climate education should be appropriately integrated at all levels of education. For example, when grade school children are introduced to plant growth (PG) with photosynthesis, give emphasis to CO_2 removal for climate care. And when continuing to explain that plants die and decompose, that is the time to discuss how charcoal can be made from plants, holding 50% of the carbon of carbon dioxide that the plants turned into wood and other biomass. Chemistry classes can instruct about inorganic compound creation (ICC) and also about the difference between pyrolysis, char gasification and complete combustion.

Note: The urgency of the climate crisis requires us to reach all grade levels promptly, and then build knowledge every year. We cannot wait for a new cycle of textbooks to be written, reviewed, and maybe accepted if the school budgets allow. Instead, there can be age-appropriate 2-side and 4-side printed or digital “inserts” for all students, with lesson-plan suggestions for the teachers.

Elmo and Oscar and Big Bird can tell the story of too much carbon dioxide in the air, so we need to take some out as well as stop putting so much carbon into the air.

Teachers / educators will accomplish what CDRS experts cannot do; they will reach the little ones whose lives will be diminished if the climate crisis is not addressed NOW. The children can help lead their parents and grandparents and the nations.

There can be video support also for the parents and general citizens.

Education about CDRS would be responsive to the opening quotation by Melton about the need for "cultural background" and understandable acronyms. Part of the response to Eisenberger's desire for "… understanding of the basic issues…[to avoid] … solutions that are falsely considered as viable…" would be by analyses that use the new CDRS classifications.

D. Analyses:

Analyses can start immediately with the eight and more issues named at the end of Step III. Advocates and detractors of each aspect of CDRS can present evidence that is as directly comparative as possible. The present and near future (five years?) data will be factual, verifiable, and enlightening. Regarding the 2030's and 2040's, there will certainly be many unknowns and assumptions for reaching Net Zero by 2050. With prospects of climatic devastation on the horizon and well within the life expectancy of today's younger generations, these analyses might help stir public opinion to advocate and authorize necessary actions, as in "vote for informed pro-climate candidates."

The next round of world temperature analyses should update the IAM projections for a more realistic understanding of the prospects of influencing the Earth's temperatures. Plant growth as a foundational carbon dioxide capture (removal) method needs to relate to the full spectrum of storage / sequestration, not just to oversimplified visions of AR (Afforestation and Reforestation) that is of insufficient permanence or to BECCS that is dependent on projected future capabilities of CCE (Concentrated Chimney Emissions) capture. Comparative analyses will help identify the best pathways for our efforts to save our climate.

The prospects of the five decades from 2050 to 2100 are open for the kind of speculation that is almost science fiction. But not quite sci-fi because anyone alive today under the age of twenty could live during that entire period of the greatest environmental transformation on Earth. And anyone age 40 or less will have their senior years after 2050.

Conclusion

This initial document is still a "work in progress" that should and can have revised editions with additional authors and inputs from everyone. This document and its approach are offered freely with no strings attached for possible sponsorship by one or more of the leading, recognized entities that are committed to solving the challenges of carbon dioxide removal (CDRS), including storage options.

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Author's statement:

I, Paul Anderson, was a university professor of geography (a physical and social science) for thirty years on four continents. Part of my job was to make things clearly understandable to facilitate the learning of unfamiliar content by college-age students, many of whom had minimal prior knowledge or interest in the subject matter.

In 2001 I was introduced to pyrolysis accomplished in what are now known as TLUD ("tee-lud") micro-gasifier cookstoves. Because those stoves have a by-product of charcoal, I was brought into the sector of biochar, and from there into carbon dioxide removal (CDR) as an important component to confront the climate crisis. Topics of climate certainly have been part of the curriculum of geography as I was taught and have taught others.

The professional, academic, and practitioner communities (especially internet discussion groups) regarding cookstoves, biochar, and CDR have contributed much to my learning and activities in retirement since the end of 2003. I thank them all. Frustrations about communications with them and others have motivated the writing of this *"Understanding Carbon Dioxide Removal and Storage (CDRS)"* document. It must first undergo the scrutiny and refining fire of the specialists. And it must be recast with added simplicity and clarity for the general public. But it will be meaningless if the individuals and societies of the world delay and eventually fail to take the necessary actions to stop and turn around (reverse) the climate crisis. Yes, turn around and reverse with active removal and storage, not just stop at Net Zero emissions.

We must undo the damage that we as residents of Earth are still continuing to make worse. This is the only home that we, our children, and future generations will ever know. Pray for them, yes, but also stop the madness of fossil fuel consumption (with subsidies!) that is certainly hurting and insidiously destroying the prospects for a desirable future. The solution would include reduction and replacement of CO_2 emissions. But we must also do true carbon dioxide <u>removal</u> and storage (CDRS). Take personal actions now. <u>Require</u> collective and corrective actions by businesses, communities, government at all levels, all organizations, your friends, your family, and yourself. Help people of all ages and cultures so that they more clearly understand carbon dioxide removal and storage (CDRS).

* * * End * * *