Recognition of Biochar & Energy (BC&E) as a Separate Negative Emission Technology (NET) for Improving Integrated Assessment Modeling (IAM)

A Response to Fuhrman et al. (Dec 2019)
From Zero to Hero?: Why Integrated Assessment Modeling of
Negative Emissions Technologies Is Hard and How We Can Do Better
https://www.frontiersin.org/articles/10.3389/fclim.2019.00011/full

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[Author's note: This response to a published article would normally be submitted to a journal for peer review and possible publication several months later. However, in this time of isolation and delays because of the COVID-19 pandemic and with current discussion of this topic on two discussion groups (Biochar and Carbon Dioxide Removal (CDR)), this text is presented as a draft for a more prompt examination by a larger group of peers. Perhaps later there will be a more refined or expanded publication with expert co-authors, including Fuhrman et al., for rebuttal, comments or charting a course for better understanding and use of BC&E.]

Abstract

The article by Fuhrman et al. (2019) reviews Integrated Assessment Models (IAMs) as they relate to negative emission technologies (NETs). This reply addresses the three topics suggested for recommendations. First, concerning the need for better modeling of NETs, there is an error in the classification of the major NETS, specifically the placement of biochar (BC) into the same category as soil carbon sequestration (SCS). This error appears in numerous publications involving the U.S. National Academy of Sciences (2019) and the European Academies Science Advisory Council (2018), possibly including publications from earlier years. , Unfortunately, the error has been adopted and propagated byother recent authors. Therefore, this response is targeted also to several publications. Second, concerning the changing economics of NETs, attention is drawn to the major distinction between biochar and energy (BC&E) and a much-modelled NET called bioenergy carbon capture and storage (BECCS). Both result in the liberation of substantial biomass energy (BE in BECCS and E in BC&E), but they are vastly different regarding carbon sequestration (*cf.* CCS. BC). Biochar is a direct co-product of pyrolysis that is almost entirely inert carbon (as long as it is not burned) that has been removed from atmospheric CO_2 by plants. And with proper attention, biochar can be a valuable amendment to soil and other materials where it becomes virtually impossible to be burned. In contrast, CCS is not currently economical at even pilot scales. CCS is the attempt to take CO_2 gas from chimneys to make supercritical CO_2 that is to be transported for injection into deep geologic formations. The discussion of NET economics should start with the current and future favorable realities of biochar before modeling future decades based on R&D speculations about CCS. The third topic concerns tradeoffs between NETs and Sustainable Development Goals (SDGs). How BC&E is already able to help with the seventeen SDGs is discussed. After briefly pointing to the abundance of biomass in forests and croplands, several specific prospects for development of BC&E potential are introduced, along with a discussion of how the recent *Drawdown Review 2020* data relate to BC&E potential.

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Introduction:

The review article by Fuhrman et al. (2019) about Integrated Assessment Models (IAMs) of negative emission technologies (NETs) makes three recommendations for improvements to IAM modeling of NETs. This response is a contribution about one issue that relates to all three requests, namely the reassessment of NET classifications that relate to biomass and biochar.

Recommendation #1: The need to model more types of NETs:

Actually, the need is to identify the types of NETs more accurately. Smith (2016) discusses soil carbon sequestration (SCS) and biochar (BC) as NETs (plural). In 2018, Minx et al. appropriately separates BC from SCS as major types of carbon dioxide removal (CDR). But the influential European Academies Science Advisory Council (2018) and U.S. National Academies of Science Press (2019) combine BC with SCS, at least in part influencing Fuhrman et al. (email on CDR discussion group on 9 April 2020), Carnegie Council (2019), Bellamy (2020) and probably others to commit the same error which, in turn, influences the interpretation of research findings. This classification error should be corrected.

The proper classification of NETs should be focused on how carbon dioxide removal (CDR) occurs. The mutually exclusive types of carbon sequestration, their typical duration and the associated NETs are listed in Table 1:

Table 1: Types of carbon sequestration, processes, duration, associated NETs, status and comments

Type	Processes	Duration	Associated NETs	Status	Additional notes
Inorganic chemistry: mineralization and pH change	Create solid minerals on land or sea or change pH	Potentially long-term stability	Enhanced Weathering (EW) with ocean alkalinization and Ocean fertilization (OF).	Chemically possible but major application is mostly theoretical and conjecture	If applicable someday, would be expensive. An "affluent world" approach.
CO_2 capture and storage: CCS	Capture CO_2 from air or chimneys, render transportable, put into storage	Potentially long-term stability; caution with leakage issues	Carbon capture and storage (CCS) for chimneys (BECCS) and Direct air (DACCS); always with storage.	Experimental and expensive demos; some for injection to assist fracking for fossil fuel increase	If CCS works and if at scale, would be extremely expensive. Requires energy. Moral hazard. An "affluent world" approach.
Organic carbon: Living and dead biomass	Photosynthesis creates biomass from CO_2, H2O and sunlight. Decomposition makes this carbon neutral.	In soil for a few years or in forests for several decades; value is in potential volume	Soil carbon sequestration (SCS) and Afforestation and reforestation (AR). Optional to support BC&E; misleading to support BECCS.	Already part of nature and would be good agro-forestry practice if financial returns went to where the work is done.	If without guidance and support, this is agro-forestry as usual, which does not solve the problem. There are limits to plant growth. Worldwide participation.
Elemental carbon: Charcoal Biochar	Use pyrolysis of biomass to create solid carbon as charcoal / biochar with release of energy.	Multi-century or millennial. Protection from burning is required and is natural in soil.	Biochar (BC), proposed to be called Biochar and Energy (BC&E) because it increases energy supply while creating stable carbon removal.	Ready for scale-up with new methods; need increased R&D for improvements. Additional benefits being evaluated.	Intercepts organic carbon before it decomposes. Can be by both rich and poor. Liberates energy. Decentralized. Safe. Worldwide participation.

Comparing Table 1 with the above cited discussions of NETs reveals four deficiencies (or errors) in how the NETs are usually classified and subsequently used in IAM:

1. BECCS (bioenergy and carbon capture and storage) has been the only type of NET that includes a component of useful energy gain. And it does so as if the complete combustion of biomass all the way to ash and CO_2 were the only possible destiny of biomass, where all of that gaseous CO_2 is somehow captured and converted (by technology that is experimental or pilot at present) and subsequently transported as supercritical CO_2 that is then injected into geologic formations for storage. It would be beneficial for IAM procedures to separate the BE (bioenergy that is valuable) from the less than mature CCS techniques that are not yet economically viable processes for sequestration.

2. In contrast to complete combustion, pyrolysis provides us with potentially valuable bioenergy and a substance, namely biochar (BC), which is highly stable charcoal that can be irreversibly sequestered in soil or other substances. Pyrolysis is the partial combustion of biomass that liberates 70% of the energy of biomass while producing safe biochar (BC) that contains about 50% of the carbon atoms that were transformed from CO2 molecules into carbohydrates via photosynthesis. The acronym BC&E (biochar and energy) is proposed to avoid confusion with black carbon, another climate change substance designated by BC. By drawing focus to BC&E in the IAM calculations instead of BECCS, the results will improve both in realistic and beneficial climate conditions.

3. SCS (soil carbon sequestration) and BC&E should not be in the same category because their physical characteristics are fundamentally dissimilar (organic vs. elemental carbon), and their durations of sequestration are separated by orders of magnitude. Biochar into soils is recalcitrant/resident and has different functions than do the various forms of organic matter in SCS, including compost. In the Fuhrman et al. (2019) article, the paragraph on "Soil Carbon/Biochar" never mentions biochar. Bellamy (2020) and Carnegie Council (2019) also incorrectly lump BC with SCS, leading to undervaluing BC for sequestration and its additional benefits. Minx (2018) does have biochar appropriately separated as a type of CDR.

4. Both forestry (AR) and agriculture contribute to the supply of biomass for SCS and BC&E. How much biomass is available becomes a variable that IAM can use with great certainty in determining the amount of stable carbon available for sequestration, unlike the reliance on conjecture of BECCS for capture and storage.

Fuhrman et al. (p.2) acknowledge that "To date, IAMs have generally modeled the deployment of only BECCS and AR" and that of the NET approaches excluding AR, "… none [are] at anywhere near the scales required to meaningfully contribute to climate mitigation." *None are ready for scale up, except BC&E*, as is presented in this document.

Recommendation #2: The need to understand better how the economics of NETs will change with time and innovation:

How can the economics of NETs be understood when almost everything is treated as an expense? And each expense is an eighty-year projected guess with very little basis in current technology. CCS in chimney emissions are not even done well by the fossil fuel industries that have strong reasons to become carbon neutral, but instead of developing carbon neutral FFCCS (fossil fuel carbon capture and storage), they play upon the red herring (and moral hazard) of burning biomass all the way to ash in BECCS to create the CO_2 to be captured from chimneys. Methods of sequestration mentioned in Table 1 such as direct air carbon capture and sequestration (DACCS), enhanced weathering (EW) and ocean fertilization (OF) are the dreams of research scientists and start-up companies receiving R&D funding. Their potential importance is to be acknowledged, but not to the detriment of alternatives. Even models of afforestation & reforestation (AR) and SCS are questioned because of the less-than-centennial life cycle of trees or organic carbon in soils. And all of those NETs need inputs of physical energy or investment energy ($).

In contrast, BC&E already has a solid foundation and is ready for significant sponsorship for appropriate R&D work and scale up enterprises. BC&E utilizes pyrolysis, the air-controlled thermal decomposition of biomass to release combustible "woodgas" and uniquely stable charcoal. Most of existing biomass combustion (land clearing, common fireplaces, co-firing, etc.) throw away or use only a fraction of the liberated heat. But in a biomass pyrolyzer, there is a 30% reduction in energy release with 50% of the carbon atoms of the biomass retained in the form of biochar. That biochar has desirable properties and commercial value as well as perceptual "save the planet" value. When the IAM specialists incorporate those numbers into their models, the results should be quite interesting.

The IAM work already correctly imposes geographical, biological, and social limits on the supply of biomass, acknowledging that our diverse societies handle biomass supply in extremely different ways. To improve the IAM results, consider three adjustments:

First eliminate BECCS and introduce BC&E, paying attention to the valuable positive energy component as well as the CDR accomplishments of distributed biochar that require modest expenses (or are profitable) instead of conjectures about what CCS might cost decades from now if it ever becomes scalable .

Second, while preserving essential biomass for food and fiber, utilize the current world excess in biomass that fuels forest fires in California and motivates burning of crop residues in India and northern Thailand, all significantly contributing to the problem of air pollution. With emerging meso-scale pyrolysis technology, these undesirable problems can be mitigated and transformed for greatly desired CDR results.

Third, utilize the existing (and improving) methods for growing more energy crops and forests without destruction of valuable natural habitats and scenic beauty, with the additional cumulative benefits of biochar in soil. Increased biomass can become increased biochar and energy.

This topic of economic benefits continues in the third section.

Recommendation #3: The need to consider the tradeoffs between NETs and Sustainable Development Goals (SDGs):

Tradeoffs often involve winners and losers. Look instead at the potential complementary benefits between BC&E and the seventeen SDGs (named in Box A).

First, all SDGs are worthy, but seven SDGs relate especially well to the interests of the "affluent world." SDG #'s 8 – 12 and #'s 16 – 17 help the poor while strengthening the lifestyle of prosperous societies. Also, SDGs #4 and #14 are less directly impacted by NETs.

Second, , eight SDGs specifically relate to BC&E and the world's most impoverished 3 billion (40%) people. #7 is primary, #'s 1, 2, 3, 5 and 6 are directly related, while 13 and 15 are in general beneficial.

SDG #7: Affordable and Clean Energy:

Approximately 500 million households (HH) (the poorest 40%) still cook their daily meals on 3-stone fires or rudimentary, smoky cookstoves with solid biomass fuel (and some coal). There is one cookstove technology called TLUD ("tee-lud") micro-gasification (or micro-pyrolysis) that is truly a BC&E NET. It is a gas-burning stove that makes its own gases while leaving charcoal behind. It actually uses less of the same biomass fuel currently consumed for daily cooking. Use of less fuel (SDG #15), cleaner emissions (SDG #3), and proven acceptance by tens of thousands of dedicated users are already established (See Box C.).

This stove is important for NETs (and for IAM studies) because 250 million TLUD stove users (20% of world) would produce an annual removal of 2.2 Gt of CO_2 in the form of

Box A: The Sustainable Development Goals (SDGs)

(as listed in Wikipedia)

1. No Poverty
2. Zero Hunger
3. Good Health and Well-being
4. Quality Education
5. Gender Equality
6. Clean Water and Sanitation
7. Affordable and Clean Energy
8. Decent Work and Economic Growth
9. Industry, Innovation, and Infrastructure
10. Reducing Inequality
11. Sustainable Cities and Communities
12. Responsible Consumption and Production
13. Climate Action
14. Life Below Water
15. Life on Land
16. Peace, Justice, and Strong Institutions
17. Partnerships for the Goals

Box B: CO_2 removal by the poorest 20% of the world's households.

Each day each household produces 0.5 to 1.0 kg of biochar (@ ~80% fixed C). Call it one-quarter ton per year/HH as a byproduct of cooking the family meals. Per 20% of the world population, that would be 62,500,000 tons of biochar per year. Using a conversion ratio of C to CO_2 of 1:3.6, each HH could sequester (via biochar to soil) the amount of 0.9 t CO_2/yr., or [not 2.2] 0.25 Gt CO_2 /yr per poorest 20% of world's households.

sequestered biochar. (See Box B for calculations.) Raise that to 4.4 Gt if all 500 million poorest households use this BC&E stove technology while they consume less of the biomass that they currently burn to ash in their traditional cookstoves. And possibly the middle 20% of the world's households could switch from propane to the upscale TLUD stoves that have fan assistance and "refined" solid biomass fuel called pellets. (See Box C for further information about TLUD char making stoves.)

Appropriate BC&E biomass cookstoves and their fuel supply would become a world industry focused to help the poorest people (SDG #9). A pilot project has been in operation for several years with 35,000 TLUD stoves in West Bengal, India. The daily use of these stoves is generating micro-incomes (CDG #1) into the hands of women (SDG #5) from the collection and the sale of the created charcoal, displacing unclean and wasteful charcoal generation methods and becoming part of a carbon offset program that generates four offsets per stove (4 t CO_2e/year/HH). If the affluent world (the highest greenhouse gas emitters) will step up and pay a fair price (SDG #10) for offsets from millions of BC&E stoves, these carbon offsets could assure sustainability and generate funds for supporting the SDGs in general.

Box C: TLUD gasifier stoves are BC&E technology.

Figure 1. Indian woman cooking food on a Champion TLUD BC&E pyrolyzer cookstove.

For technology, terminology, video, history and usage of TLUD stoves, there are twelve key publications available in the "Quick Picks" section at drtlud.com. Concerning usage, the key document is "Case Study of Acceptance… Deganga", also directly available at drtlud.com/deganga2016.
An innovative project with carbon offsets is outlined at JuntosNFP.org/projects . An advanced TLUD stove with forced air is the FabStove, described at ekasi.energy .

For an aggressively-staged scale up to literally solve SDG #7, the affluent world (or a few billionaires) will be needed to fund these stoves (@ ~US$40 each) so that the poorest of the poor can have better lives with clean burning, fuel efficient stoves that remove true gigatons of CO_2 from the atmosphere and also can provide micro-incomes for women.

Additional values and/or benefits of biochar for all levels of society:

Separate from the issues of CO_2 removal and cookstoves for impoverished people, we must not overlook the additional value of the physical biochar that is created.

Biological and agricultural benefits of putting biochar into soil include improved water retention, improved tilth, pH adjustment to help acidic soil, strengthening of microbiota /fungi /etc., retention of nutrients (less leaching), and a general increase in food production (SDG #2 is to "End hunger [and for all societies to] achieve food security and improved nutrition, and promote sustainable agriculture," which are all aided by biochar.) Experimental work shows advantages when biochar is included (@<1%) in animal feeds, increasing growth and reducing methane release before deposition onto the soil.

Biochar can be useful for water filters, the reduction of odors (latrines), and immobilization of some toxins (SDG #6).

In summary, BC&E can provide numerous complementary benefits in addition to the SDGs for the disadvantaged. R&D about biochar deserves a major boost to have solid confirmation of its general claims.

Available biomass supply:

"Every year, plants convert 4,500 EJ (exajoules) of solar energy and 120 Gt (gigatons) of carbon [= 439 Gt CO_2] from the atmosphere into [~240 Gt of new] biomass – eight times as much as the global energy need." (World Bioenergy Association (2016)). That same document identified the annual global supply to be 56 EJ of biomass energy [about 29 Gt of biomass] in 2012, with an expected near tripling to 150 EJ by 2035 [~85 Gt of biomass]. This indicates there can be decades of increasing BC&E drawdown before we reach the planetary limit of annual biomass supply.

***** On a dry weight basis, each ton of wood or similar biomass can yield about 200 kg of stable carbon (charcoal) which represents the removal of 730 kg of atmospheric CO2. Every 1.4 billion tons of biomass can yield enough biochar for the equivalent removal of 1 Gt CO2e. *****

BC&E in the modern industrialized world:

BC&E cookstoves and barrel-size units will produce enough biochar (and energy) to impact the IAM calculations. But the world needs multiple tens of gigatons of CO_2 removal. At the large volume end of BC&E technology, there are some furnace/boilers and other biomass burners that have been adjusted to leave more char behind with the ashes. There are also sophisticated, expensive pyrolysis and gasification equipment making electricity and wood vinegar as well as biochar in moderate and small quantities. But affordable, portable and widely distributed middle or meso bracket BC&E technologies have been lacking until now.

Figure 2. 4-ft diameter RoCC kiln, rear view, preparing to unload biochar. February 2020

A 2020 invention called "rotatable covered cavity (RoCC)" kiln will fill that void. The author (Anderson) is the inventor and owner of this patent pending development, so his comments here could be biased and could have conflicts of interest. This reply to the Fuhrman et al. article is not the place to present something so new. Readers are referred to woodgas.energy/resources to access the *RoCC Kiln Manual* that discusses sizes and potential of this innovation for BC&E.

In standard practice IAM studies are based on assumptions of technologies becoming available at different times and with various capacities, so a discussion of the impact of the eventual inclusion of economically viable meso-scale BC&E technology is an appropriate topic to discuss.

There will be cases where excess biomass (such as beetle kill and forest management in mountains) is too remote to be of practical use for energy. But rather than allow the biomass to decay and eventually be carbon neutral, local pyrolysis could yield tons of carbon negative biochar which, when distributed around the forest floor, can enhance the local environment and habitat (SDG #15).

An example of what IAM could include could be based on the pyrolysis of 1.4 gigaton of dry biomass by any of numerous combinations of different-sized BC&E units. One simple example would be 1.4 million locations around the world annually doing pyrolysis of 1000 tons of biomass (~3 tons per day), providing locally useful energy (~30 GJ/day (8333 kW-h thermal)) plus ~0.6 t/day of biochar for sequestration, which is equal to ~2 t CO_2e/day that, when added together, is 1 Gt CO_2 sequestered per year. And there certainly can be ten to twenty times that amount of biomass available.

Projections and Speculations:

To some extent, IAM is the science or art of guessing/estimating/projecting the future a thousand different ways and analyzing the trends. The quality of the data concerning NETs is acknowledged to be rife with unknowns about important future technologies and even greater unknowns about the socio-political willingness to do the projected actions. We do not enter their realm except:

a) to point out in this reply that BC&E is comparatively better understood as an actual, functional technology that should replace all of the BECCS projections and

b) to provide some realistic speculations for this current decade (the 2020s). Please consider the potential impacts of the following, for which references are available and discoverable with simple internet searches of the key terms:

1. The Terraton Initiative of Indigo Ag could awaken to the potential of biochar to multiply its impact with SCS. There is no need to stop at only one teraton of CO_2 sequestration in agricultural activities.

2. The Trillion Tree Campaign could embrace the prospects of harvesting for BC&E some appropriate percentage of those trees to accomplish millennial sequestration. Photosynthesis can do best in young, fast-growing trees, but does poorly as trees age and die. Perhaps a Triple Trillion Tree Challenge will be useful to help save our planet. And each tree could be planted with some biochar to enhance its chances of survival and strong early growth.

3. The announced intentions of Delta Airlines, Microsoft, Stripe and other businesses to become carbon neutral could be converted into signed commitments to purchase the carbon offsets created by millions of impoverished households that could benefit from the clean, fuel-efficient TLUD BC&E stoves. This becomes possible because either a) the needed micro-finance could then become available from banks that only support signed contracts with major partners, or b) the relatively small funding needed for the stoves could be covered by several billionaire signers of the Giving Pledge who could each adopt one million households or more.

4. Woody and herbaceous energy crops (such as poplar, Miscanthus, bamboo and hemp) could be cultivated for their biochar as well as their energy. Specific pyrolysis kilns could receive the harvested, full-size plants (no chipping or preprocessing expenses) while the roots remain in the soil to sprout again.

5. Use of meso-size pyrolytic kilns could be matched with locations of needed heat to replace fossil fuel use at some factories, grain drying facilities, and zones with district heating and cooling. Engineering considerations would involve matching of biomass supply, heat required, and kiln size.

6. Redirect the approach of biomass-based electricity production (such as Drax power stations in the UK) from BECCS to BC&E. Certainly, that would involve expensive engineering (such as with multiple 18-ft diameter RoCC kilns or other biochar producers), but it would ultimately be less expense than the current approach that does not yet have an adequate CCS technology.

7. In reference to the *Drawdown Review 2020* (2020) update of CDR calculations at Drawdown.org/solutions, several observations can be made: (Refer to the table in the attached Appendix A.)

a) Of the top ten solutions, 1 – 3 are societal goals regarding food waste, health/education and plant-rich diets; 4, 6 – 8 are for the affluent world (mainly refrigeration); 8 & 10 are photovoltaics; 5 is tropical forest restoration (difficult to orchestrate); and only number 9 is specific for impoverished people. #9 is "Improved Clean Cookstoves," without focus on BC&E stoves, reducing CO_2e by 31.34 Gt during *thirty years* (but should be 2 to 4 Gt per year), and with Net First Cost of at least US$128.6 Billion (which is over $250 per stove for 500 million households, or six times the $40 cost of each BC&E TLUD stove in current projects). Commentary: Perhaps BC&E clean cookstoves should have a much higher ranking and be a priority for drawdown implementation.

b) Of the 82 ranked solutions, 25 specifically relate to the biosphere (crops and forests), and 12 of these are in the top 25 solutions. Activity for any of them could increase the biomass supply that could become biochar for millennial sequestration of additional carbon from the atmosphere.

c) Biomass Power (electricity) and Biochar Production are ranked only 52 and 54, respectively, with only 2.5 and 2.2 Gt CO_2 total reductions in the coming 30 years. Double counting must not be allowed, but somehow it seems that these two solutions are grossly underestimated.

8. Additional sources of biomass could become available from non-terrestrial sources such as seaweed from oceans. (Duarte et al. (2017) frontiersin.org/articles/10.3389/fmars.2017.00100/full).

9. With only five years of appropriate funding, the R&D efforts about the benefits (and limitations) of biochar and BC&E could identify the best ways for increasing agricultural production or alternative societal uses of biochar (as in construction materials), thereby adding economic value that could transform an expense into a profit.

All of the above opportunities refer only to the coming 10 years. The subsequent 20 years (2030 to 2050) should bring exciting additions. And during the second half of this century we might escape the devastation of our current route to climatic disaster.

Conclusion:

During the next 10, 30 and 80 years, the NET known as biochar and energy (BC&E) is poised to accomplish CDR in the range of 5 to 15 Gt CO_2/yr. with current technology. BC&E is not a substitute for other carbon mitigation, nor a single solution for the climate crisis. But it is a reality, and it can draw global participation, particularly if there is the political will to do so. If properly sponsored and implemented, BC&E can be an opportunity for multiple wins, including for climate, soil restoration, food production, cleaner air, renewable energy, reduction of poverty, and (we hope) greater stability and peace. IAM can help show the way.

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Conflict of Interests:

Paul Anderson is internationally known as "Dr TLUD" for his work to develop and encourage widespread adoption of TLUD cookstove technology to benefit impoverished people. Because those stoves make biochar, he has also been involved in the realm of biochar production for nearly two decades. Awareness of the lack of meso-scale appropriate pyrolysis capabilities led to his 2014 to 2020 quest with multiple experimental units that resulted in the RoCC pyrolytic kilns. His strong bias and possible conflicts of interest come from direct, hands-on involvement in these topics. He invites others to participate in the many activities involving pyrolysis for biochar, biomass energy and actions for an improved world via BC&E.

Supplementary Material:

The table in Appendix A provides a spreadsheet of selected data from Project Drawdown 2020. The unrefined, functional Excel spreadsheet is available from Dr. Anderson if someone wishes to add more data and analyses, such as for Scenario 2. The original data is found at drawdown.org/solutions .

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Appendix A follows this page.

Appendix A

Table of Drawdown Solutions (2020 edition) in Rank Order by Scenario 1 that Stops Climate Change Close to 2° C

Solution in Rank Order by Scenario 1	Sector(s)	Scenario 1 *	Net first cost Billions US$	Economic Status	Bio-sphere
1 Reduced Food Waste	Industry / Buildings	87.45	Not calculated	Everybody	
2 Health and Education	Industry / Buildings	85.42	Not calculated	Everybody	
3 Plant-Rich Diets	Industry / Buildings	65.01	Not calculated	Everybody	
4 Refrigerant Management	Industry / Buildings	57.75	Not calculated	Affluent	
5 Tropical Forest Restoration	**Land Sinks**	54.45	Not calculated		Bio-trees
6 Onshore Wind Turbines	Electricity	47.21	$632.19 – 720.77	Affluent	
7 Alternative Refrigerants	Industry / Buildings	43.53	Not yet modeled	Affluent	
8 Utility-Scale Solar Photovoltaics	Electricity	42.32	$3.4 – 5 trillion	Affluent	
9 Improved Clean Cookstoves	**Buildings**	31.34	**$128.6 – 264.42**	**Poor**	**Dependent on biomass**
10 Distributed Solar Photovoltaics	Electricity	27.98	$255 – 479.59		
11 Silvopasture	**Land Sinks**	26.58	$206.75 – 272.91		Bio-trees
12 Peatland Protection and Rewetting	Food, Agriculture, and Land Use / **Land Sinks**	26.03	Not projected		Bio
13 Tree Plantations (on Degraded Land)	**Land Sinks**	22.24	$16.67 – 72.09		Bio-trees
14 Temperate Forest Restoration	**Land Sinks**	19.42	Not projected		Bio-trees
15 Concentrated Solar Power	Electricity	18.6	$474.29 – 566.38	Affluent	
16 Insulation	Electricity / Buildings	16.97	$751.13 – 831.28	Affluent	
17 Managed Grazing	**Land Sinks**	16.42	$33.57 – 52.89		Bio
18 LED Lighting	Electricity	16.07	$-2.04 – -1.77 (Trillion)		
19 Perennial Staple Crops	**Land Sinks**	15.45	$83.13 – 190.25		Bio
20 Tree Intercropping	**Land Sink**s	15.03	$146.89 – 227.02		Bio-trees
21 Regenerative Annual Cropping	Food, Agriculture, and Land Use / **Land Sinks**	14.52	$77.9 – 115.82		Bio
22 Conservation Agriculture	Food, Agriculture, and Land Use / **Land Sinks**	13.4	$65.23 – 91.88		Bio
23 Abandoned Farmland Restoration	**Land Sinks**	12.48	$98.16 – 159.91		Bio
24 Electric Cars	Transportation	11.87	$4.48 – 5.79 (Trillion)	Affluent	
25 Multistrata Agroforestry	**Land Sinks**	11.3	$54.06 – 92.12		Bio-trees
26 Offshore Wind Turbines	Electricity	10.44		Affluent	
27 High-Performance Glass	Electricity / Buildings	10.04			
28 Methane Digesters	Electricity / Industry	9.83			
29 Improved Rice Production	Food, Agriculture, and Land Use / **Land Sinks**	9.44	Not calculated		Bio
30 Indigenous Peoples' Forest Tenure	Food, Agriculture, and Land Use / **Land Sinks**	8.69	Not calculated	Poor	Bio-trees
31 Bamboo Production	**Land Sinks**	8.27	$52.25 – 161.94		Bio
32 Alternative Cement	Industry	7.98		Affluent	
33 Hybrid Cars	Transportation	7.89		Affluent	
34 Carpooling	Transportation	7.7			
35 Public Transit	Transportation	7.51			
36 Smart Thermostats	Electricity / Buildings	6.99			
37 Building Automation Systems	Electricity / Buildings	6.47		Affluent	
38 District Heating	Electricity / Buildings	6.28			
39 Efficient Aviation	Transportation	6.27		Affluent	
40 Geothermal Power	Electricity	6.19			
41 Forest Protection	Food, Agriculture, and Land Use / **Land Sinks**	5.52	Not calculated		Bio
42 Recycling	Industry	5.5			
43 Biogas for Cooking	Buildings	4.65			Bio
44 Efficient Trucks	Transportation	4.61		Affluent	

45 High-Efficiency Heat Pumps	Electricity / Buildings	4.16		Affluent	
46 Perennial Biomass Production	**Land Sinks**	4	$230.32 – 399.92		Bio
47 Solar Hot Water	Electricity / Buildings	3.59			
48 Grassland Protection	Food, Agriculture, and Land Use / **Land Sinks**	3.35	$91.9 - 65.2		Bio
49 System of Rice Intensification	Food, Agriculture, and Land Use / **Land Sinks**	2.78	Not calculated		Bio
50 Nuclear Power	Electricity	2.65			
51 Bicycle Infrastructure	Transportation	2.56			
52 Biomass Power	**Electricity**	2.52	**$51.12 – 62.37**		Bio
53 Nutrient Management	Food, Agriculture, and Land Use	2.34			
54 Biochar Production	**Engineered Sinks (The only one)**	2.22	**$195.87 – 383.3**		Bio
55 Landfill Methane Capture	Electricity / Industry	2.18			
56 Composting	Industry	2.14	$-83.75 – -60.6		Bio
57 Waste-to-Energy	Electricity / Industry	2.04	**$134.69 – 149.92**		Bio
58 Small Hydropower	Electricity	1.69			
59 Walkable Cities	Transportation	1.44			
60 Ocean Power	Electricity	1.38		Affluent	
61 Sustainable Intensification for Smallholders	Food, Agriculture, and Land Use / **Land Sinks**	1.36	Not calculated	Poor / Female	Bio
62 Electric Bicycles	Transportation	1.31			
63 High-Speed Rail	Transportation	1.3		Affluent	
64 Farm Irrigation Efficiency	Food, Agriculture, and Land Use	1.13			
65 Recycled Paper	Industry	1.1			
66 Telepresence	Transportation	1.05			
67 Coastal Wetland Protection	Food, Agriculture, and Land Use / Coastal and Ocean Sinks	0.99			
68 Bioplastics	Industry	0.96			
69 Low-Flow Fixtures	Electricity / Buildings	0.91			
70 Coastal Wetland Restoration	Coastal and Ocean Sinks	0.77			
71 Water Distribution Efficiency	Electricity	0.66			
72 Green and Cool Roofs	Electricity / Buildings	0.6		Affluent	
73 Dynamic Glass	Electricity / Buildings	0.29		Affluent	
74 Electric Trains	Transportation	0.1			
75 Micro Wind Turbines	Electricity	0.09			
76 Building Retrofitting	Electricity / Buildings	0			
77 Net-Zero Buildings	Electricity / Buildings	0			
78 Grid Flexibility	Electricity	0			
79 Microgrids	Electricity	0			
80 Distributed Energy Storage	Electricity	0			
81 Utility-Scale Energy Storage	Electricity	0		Affluent	
82 Efficient Ocean Shipping	Transportation				

Scenario 1 Total		**992.77**
Land Sinks Total	**20**	

*** Gigatons CO2e Reduced or Sequestered (2020-2050)**