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**Preliminary Assessment of the Potential for, and Limitations
to, Terrestrial Negative Emission Technologies in the UK**

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3 Given the aspirational target of limiting global temperature rise to below 1.5°C compared to
4 pre-industrial temperatures agreed in Paris in December 2015, and the UK's recently stated
5 target of net zero emissions, there is urgency among UK policy makers to assess the technical
6 potential for, and limitations of, Negative Emissions Technologies (NETs) in the UK. In this
7 study we assess the maximum technical potential for a range of NETs, namely Bioenergy
8 with carbon capture and storage, direct air capture of CO₂ from ambient air, enhanced
9 weathering of minerals, afforestation / reforestation, soil carbon sequestration and biochar.
10 We also assess the impact of NET implementation on land, greenhouse gas balance, energy
11 requirements, water use, nutrient use, albedo and cost.
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COMMUNICATION

Preliminary Assessment of the Potential for, and Limitations to, Terrestrial Negative Emission Technologies in the UK

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Pete Smith,^{a†} R. Stuart Haszeldine^b and Stephen M. Smith^c

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The aggregate technical potential for land-based negative emissions technologies (NETs) in the UK is estimated to be 12-49 MtC-eq./yr, representing around 8-32% of current emissions. The proportion of this potential that could be realized is limited by a number of cost, energy and environmental constraints which vary greatly between NETs.

Introduction

Future increases in global average temperature will be determined largely by cumulative emissions of CO₂.¹ As a result, net global CO₂ emissions will need to reach near zero in order to limit temperature change. Negative Emissions Technologies (NETs) are likely to be important in reaching net zero emissions, or below, given the difficulty in completely eliminating greenhouse gas (GHG) emissions from all human activities. In order to avoid warming of more than 2°C with a >50% chance, most recent scenarios from Integrated Assessment Models (IAMs) include the large-scale deployment of NETs within a few decades.²⁻⁹ More stringent temperature limits imply an even greater need for NETs, deployed on shorter timescales.¹⁰ Since society must decide which mitigation pathways are desirable to tackle climate change, information on the potential risks and opportunities afforded by all NETs is necessary.

Two recent studies have examined the global technical potential for terrestrial NETs, and their impacts on land, greenhouse gas balance, energy requirements, water use, nutrient use, albedo and cost. First, Smith et al.¹¹ reviewed and analysed the biophysical and economic limits to

implementation for a number of NETs: (1) Bioenergy (BE¹²) with carbon capture and storage (CCS; together referred to as BECCS¹³), (2) direct air capture of CO₂ from ambient air by engineered chemical reactions (DAC^{14,15}), (3) enhanced weathering of minerals (EW¹⁶⁻¹⁸) where natural weathering to remove CO₂ from the atmosphere is accelerated, and the products stored in soils, or buried in land/deep ocean and (4) afforestation and reforestation (AR¹⁹⁻²¹) to fix atmospheric carbon in biomass and soils. Second, Smith²², examined other land based options, namely (5) soil carbon sequestration (SCS) through changed agricultural practices (which include activities such as less invasive tillage with residue management, organic amendment, improved rotations / deeper rooting cultivars, optimized stocking density, fire management, optimised nutrient management and restoration of degraded lands^{23,24}), and (6) converting biomass to recalcitrant biochar, for use as a soil amendment²⁵. IAMs have so far focused primarily on BECCS^{5,26,27} and AR²⁸⁻³⁰. For reasons of tractability, the analysis of Smith et al.¹¹ did not consider (7) manipulation of uptake of carbon by the ocean either biologically (i.e. by fertilizing nutrient limited areas^{31,32}) or chemically (i.e. by enhancing alkalinity³³).

Figure 1 depicts the main flows of carbon among atmospheric, land, ocean and geological reservoirs for fossil fuel combustion (Fig. 1a), BE (Fig. 1b), CCS (Fig. 1c), and the altered carbon flows for BECCS (Fig. 1d), for DAC (Fig. 1e), EW (Fig. 1f), AR, SCS, biochar, and sequestration in construction materials (Fig. 1g – the latter not assessed here), ocean fertilization (Fig. 1h – not assessed here), and biochar addition to soil as part of BECCS (Fig. 1i).

In this study, the per-t-C impacts of negative emissions derived in^{11,22}, and areas available in the UK for land based NETs, are used to make preliminary estimates of the potential for, and impacts of, terrestrial NETs in the UK. The estimates consider the use of UK land specifically; they do not consider possible imports and exports of resources from land outside the UK.

^a Institute of Biological and Environmental Sciences, Scottish Food Security Alliance-Crops & ClimateXChange, University of Aberdeen, 23 St Machar Drive, Aberdeen, AB24 3UU, UK.

^b Grant Institute, School of Geosciences, University of Edinburgh, The King's Buildings, James Hutton Road, Edinburgh EH9 3FE, UK

^c Committee on Climate Change, 7 Holbein Place, London SW1W 8NR, UK
† Corresponding author: Prof Pete Smith, Tel: +44 (0)1224 272702, Fax: +44 (0)1224 272703, E-mail: pete.smith@abdn.ac.uk

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Systemic, holistic issues need to be considered for NETS deployment³⁴ and are probably the most immediate aspects of developing these technologies which need to be addressed. It must be noted that this is a preliminary, technology focussed assessment that takes no account of such socio-political aspects of NETs deployment, which when considered would be expected to lower considerably the technical potentials estimated here. Further, whilst the best available data have been used, different technologies are at different stages of development (e.g. AF and SCS widely applied already; DAC yet to be demonstrated at scale), and the quantity and quality of data varies greatly between technologies¹¹.

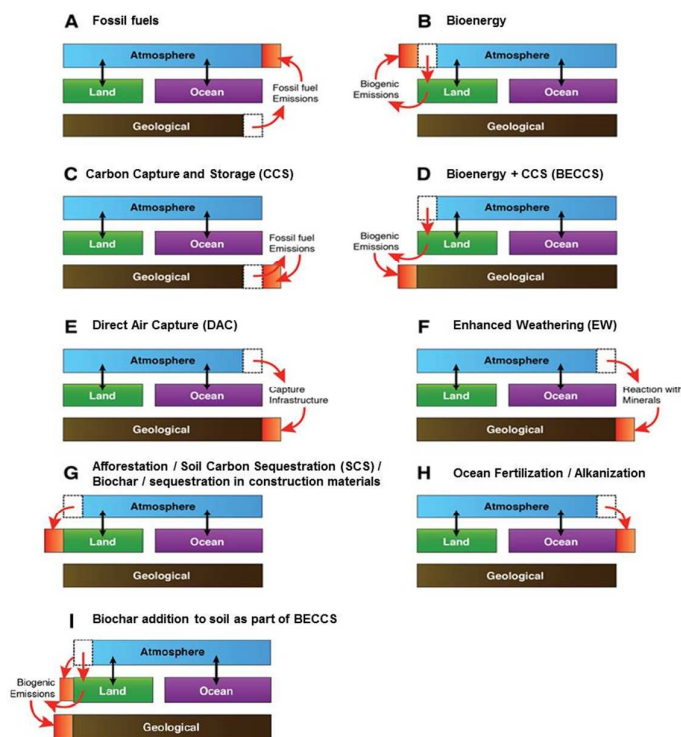


Figure 1. Schematic representation of carbon flows among atmospheric, land, ocean and geological reservoirs. See text for details (adapted from ^{11,22}).

Materials & Methods

Sources of data used to estimate impacts of NETs on a per-t-Ceq. are described in ¹¹ and ²² except for values for EW where a detailed UK study exists³⁵ and values from this study are used. For BECCS, dedicated energy crops are assumed as in ¹¹. Impact were scaled to the UK level by multiplying per-t-C-eq. impact values by available land areas for each technology defined from the UKERC spatial modelling of bioenergy study in the UK described in Lovett et al. ³⁶ using a similar approach to that used for NETs at the global scale^{11,22}. The difference in approach here is that available areas in the UK were used to constrain the potentials, rather than using exogenously estimated potentials from IAMs and / or literature values.

Available land areas³⁶ are: a) 8.5Mha for all land not excluded by all UKERC constraints, including a high naturalness score, 6.4 Mha using “a”, but also excluding all Grade 1 and 2 (prime) agricultural land, and 1.5 Mha using “a”, but also excluding all Grade 1, 2 and 3 (prime and good quality) agricultural land. To put these land grades into context, about half of all agricultural land in England is Grade 3³⁷, so including grade 3 land is realistic to avoid large scale competition with agriculture³⁵.

For EW, Renforth³⁵ lists all of the potential mineral sources in the UK. The total resource suitable for EW available in the UK is 1669 Gt rock, mostly basic silicates with a negative emission potential of 0.082 t C/t rock, and a small proportion of these as ultrabasic rocks with a negative emission potential of 0.218 t C/t rock. The total negative emission potential of the total UK mineral resource is 117 Gt C³⁵, which is a maximum technical potential; the potential that could ever be realised in reality is likely to be much lower due to a number of constraints³⁵.

The negative emission potential is largely dependent on the rate at which it is spread onto soils after comminution¹⁸. Even if spread at 50 t rock/ha/yr, the highest rate considered in Renforth³⁵ and Taylor et al.¹⁸, only 0.425 Gt mineral would be required to cover the 8.5 Mha of land available – a small fraction of the 1669 Gt rock potentially available in the UK, so the availability of suitable rock in the UK is not limiting. What limits the negative emission potential is the application rate with the rates used by Taylor et al.¹⁸ examined here:

- 0.4 t rock/ha/yr is the rate at which lime is typically applied to agricultural land³⁵
- 10 t rock/ha/yr is the “low” rate examined in Taylor et al.¹⁸, similar to nutrient poor soils, even though this is considerably larger than the typical application rate for lime in agriculture
- 50 t rock/ha/yr is the “high” rate noted in both Renforth³⁵ and Taylor et al.¹⁸. This would likely be inconsistent with agricultural use of the land, especially with mineral residues.

Results

Impacts of NETs on a per-t-Ceq. removal basis

Values for impact of NETs on a per-t-Ceq. removal basis are shown in table 1. For full details see ^{11,22}.

[Tables attached as separate file]

Table 1. Low and high per-t-Ceq. negative emissions impact values used in the calculation for UK impacts of NETs. All values for SCS and Biochar are from ²². All values for BECCS, AR, DAC and are from ¹¹, and for EW from calculations based on ³⁵, except for Potassium values for AR which were calculated from values in Ovington and Madgwick³⁸, and Potassium values for BECCS (Miscanthus) calculated from values in Roncucci et al.³⁹. All estimates are nominally for 2100 except for costs which are for 2050.

UK land available for use for NETs

Since implementation of BECCS and AR use land that can no longer be used for food production, the areas available for BECCS and AR in the UK are assumed to be those defined in the UKERC mask that excludes Grades 1-3 agricultural land (1.5 Mha). Similarly, land used for growing feedstock for Biochar cannot be used for food so is assumed to be the same (1.5 Mha). BECCS feedstock from agricultural residues would reduce competition for land, but only dedicated crops were considered here. SCS, however, can be practised on land without changing its land use, so is assumed to be any area not excluded by the UKERC mask (8.5 Mha). DAC has no land footprint (if one excludes area used to generate energy to power the process), so is not constrained by land availability. The ground rocks from the EW process can be spread onto land without changing its land use, so when applied at low rates of 10 t rock/ha/yr (thus not interfering with agricultural use of the land – though these rates are still higher than those regularly used in agriculture for liming³⁵), could be used on 8.5 Mha of land. If applied at high rates of 50 t rock/ha/yr, rock for EW could only be applied to land not used for agriculture (since the rates are incompatible with agriculture). Low and high rates are from Taylor et al.¹⁸.

[Tables attached as separate file]

Table 2. Summary of areas, negative emission potentials, impacts of NETs on water use, energy requirement, nutrient (N, P and K) requirements and albedo, and bottom-up estimates of cost in the UK. EW may supply nutrients such as P and can have variable impacts on albedo depending on the mineral used, though these effects are not quantified. See text for further details. *DAC potential is not constrained by area so impacts assessed at same level of implementation as BECCS (i.e. area of 1.5 Mha; 4.5-18 MtCeq/yr). ** EW – high rate of application (50 t rock/ha/yr) applied only to non-Grade 1-3 land = 1.5 Mha; low rate of application (10 t rock/ha/yr) applied to available Grade 1-3 land = 7.5 Mha. High and low rock application rates from Taylor et al. (2016)¹⁸.

Negative emissions potential of terrestrial NETs in the UK

Negative emissions potential for BECCS, AR and Biochar implemented on 1.5 Mha of land in the UK are: 4.5-18, 5.1, 1.73-11.25 MtC-eq./yr, respectively. SCS, implemented on 8.5 Mha of land, would deliver 0.255-8.5 MtC-eq./yr. EW can be implemented on 1.5/8.5 Mha of land, delivering 7.0-16.5 MtC-eq./yr. If 50 t rock/ha/yr is applied to 1.5 Mha of non-agricultural land, and 10 t rock/ha/yr is applied to the remaining 7.5 Mha, the combined total potential of EW is $16.36 + 6.14 = 22.5$ Mt C/yr.

The technical potential for DAC, while not assessed directly here, is high. In addition to land constraints being low, constraints from available storage sites for CO₂ are also low in the UK. Around 21 GtC (equivalent to 210 MtC-eq./yr over a century) storage potential exists in UK coastal waters⁴⁰. This would, however, be reduced for DAC by other CCS

technologies (including BECCS) requiring access to the same storage sites.

Environmental impacts of NETs in the UK

For comparison of impacts of across all NETs (as in ¹¹), DAC is compared at the same level of implementation of negative emissions as BECCS, i.e. 4.5-18 MtC-eq./yr. All other NETs are compared at the negative emission potentials described above. Table 2 summarises the impacts on water use, energy requirement, nutrient (N, P and K) requirements and albedo, and bottom-up estimates of cost (but see discussion for caveats regarding bottom-up calculation of costs).

Discussion**Total UK negative emissions potential**

The negative emissions potential for individual NETs in the UK range from ~0.3 (low estimate for SCS) to ~23 MtC-eq./yr (for EW applied to all available land). Most NETs have potential in the order of magnitude range of 1s – 10s Mt Ceq./yr, though DAC potential could be greater. Total UK emissions for all GHGs during 2010-2014 amounted to ~560 MtCO₂-eq./yr (=153 MtC-eq./yr)⁴¹, so potentials in the range of 10 MtC-eq./yr would represent around 7% of current total UK emissions. The results here for BECCS, biochar and DAC are similar to those found in another study of UK technical potential⁴²: for BECCS the estimate here of 4.5-18 MtC-eq./yr compares to 5-22 MtCeq./yr, while for biochar the estimate here of 1.7-11 MtC-eq./yr compares to 3-13 MtC-eq./yr.

Not all of the potentials of the individual NETs are additive. In particular, BECCS, AR and biochar are alternative uses of the same land / biomass resource, meaning deployment of one of these technologies precludes deployment of the others. The maximum aggregate land-based UK NETs resource is estimated to be 12-49 MtC-eq./yr (BECCS plus SCS plus EW), assuming no interaction between practices to increase soil organic carbon storage, the spreading of powdered rock onto soils for EW and the growth of biomass as a feedstock for BECCS. Though there is no literature explicitly examining potential interactions between these NETs, several can be hypothesized (such as EW raising soil pH and thereby decreasing the efficacy of soil organic carbon storage; acidity is known to slow decomposition⁴³), so the values presented here should be regarded as the maximum aggregate potential range. This optimistic aggregate technical potential for land based NETs in the UK represents ~8-32% of current UK GHG emissions. DAC could increase this total further. The potentials should be regarded as preliminary since large uncertainties remain in the data used in this assessment¹¹.

An important limitation of this study is that it excludes the potential for national negative emissions from imported and exported resources. Compared to the global per-capita average, the UK has high energy demand and low land availability. Biomass is already imported into the UK for energy generation, and proposed strategies for meeting the UK's

emissions targets include the possibility of the UK importing up to 800 PJ/yr by primary energy in the 2030s⁴⁴. To the extent that the UK does become a net importer (or exporter), and depending on where emissions savings are credited, it could have greater (or lesser) negative emissions potential.

Limitations of NETs

As for the global analyses^{11,22}, the main technical limitations of NETs in the UK are high cost and energy requirements for DAC; landscape, large areas logistics, energy requirements, and costs for EW; competition for land, water and nutrients (and potentially albedo impacts) for BECCS and AR; lower per unit potential for SCS; and albedo, land competition (and possibly) cost for biochar. For AR, changes in albedo could reduce the efficacy of the benefits through negative emissions. In Norway, about 50% of the benefit of the net C sink is lost when short vegetation is replaced by needle leaved trees (largely due to snow cover disruption)⁴⁵. At more southerly latitudes, such as the UK, one would expect the impact to be <<50% of the net C sink offset – due to both possibility of planting deciduous trees, and the decreased prevalence of snow. A full spatial assessment should be undertaken to quantify the impact.

Bottom-up costs are known to be unreliable since they do not account for the effect of lowering costs through learning during implementation and economies of scale. Nevertheless, the per-t-Ceq. estimates show the likely relative costs of each technology, suggesting that SCS is the least expensive, but with biochar also having potential for cost negative implementation (through economic benefits realised from productivity co-benefits) in part of the cost range, but also high upper estimates of cost. DAC is the most expensive NET, with upper estimates of cost also high for EW (wide cost range) and biochar. BECCS and AR have relatively low cost. Most of the costs (except for the upper estimates for DAC, biochar and EW) are in the range estimated in the AVOID programme which noted “costs in the order of magnitude of \$US 100/tCO₂”⁴², which is equivalent to ~\$US 370/tC-eq. Costs for specific technologies (converted from CO₂-eq. to C-eq.) estimated in the AVOID programme⁴² were \$US 110-150/tC-eq. for biochar; >\$US 460-550/tC-eq. for BECCS; and ~\$US 550-730/tC-eq. for DAC.

SCS and biochar provide negative emissions with fewer potential disadvantages than many other NETs, though additional nutrients could be required unless the SCS is achieved by adding organic material. Though the negative emissions potential is lower than for DAC and BECCS, it is not insignificant, and is comparable to the potential for AR¹¹.

Permanence of emissions removal

Carbon removals with any technology using liquid CO₂ for CCS are subject to the integrity of the storage reservoir. CCS demonstration projects worldwide appear to be performing well at 30 MtCO₂/yr⁴⁶. UK reservoirs for liquid CO₂ CCS have been mapped⁴⁰, and are assessed to be ready for use. Storage of captured carbon dioxide in solid form as carbonate

minerals, by injecting liquid CO₂ into basaltic rocks, may be rapid (95% in less than 2 years) and has been shown to be feasible in a small pilot study⁴⁷. Solid storage is generally considered to be more permanent with lower risk of reversal. Permanence (and sink saturation) is more of an issue for SCS, AR and biochar.

A drawback of SCS and AR is that of sink saturation. We express SCS and AR negative emission potential here as a yearly value, but the potential is time limited. SCS and AR potential is large at the outset (which trees are growing and while soil carbon stocks are increasing), but decreases as forest biomass / soils approach a new, higher equilibrium value²⁴, reaching zero when the new equilibrium is reached. This sink saturation occurs after 10-100 years, depending on the SCS / AR option, soil / tree type and climate zone (slower in colder regions), with IPCC using a default saturation time of 20 years for soil sinks^{48,49}. Since sinks derived from SCS and AR are also reversible²⁴, practices need to be maintained, even when the sink is saturated, so any yearly costs will persist even after the negative emission potential has reduced to zero at sink saturation. Sink saturation also means that SCS implemented in 2020 will no longer be effective as a NET after 2040 (assuming 20 years for sink saturation). The importance of this for NETs, is that NETs are most frequently required in the second half of this century^{3,11}, so SCS and AR, may no longer be available after 2050, or will be less effective, if they are implemented for mitigation relatively soon. The same sink saturation issues apply partly to biochar, though the issue is less pronounced as biochar is more recalcitrant, and equilibrium (if it occurs) would be expected to take much longer, so that biochar should still be effective as a NET in the second half of this century even if implemented relatively soon.

Conclusions

The aggregate technical potential for land-based negative emissions technology (excluding direct air capture and imports/exports of resources from land outside the UK) is estimated to be 12-49 MtC-eq./yr, which is around 8-32% of current total UK emissions. The proportion of this technical potential that could be realized is limited by a number of cost, energy and environmental constraints, which will need to be overcome if the full potential of NETs is to be realized in the UK. More detailed, spatially explicit studies will help to better constrain the wide ranges presented here based on literature values. Further, systemic and holistic issues relevant to NETS deployment³⁴ were not considered in this study and need to be addressed, and public acceptance for a variety of reasons (including perceived threats to health and safety) were not considered. Nevertheless, the methods applied in this study are useful in providing a preliminary technological / environmental assessment of the potential for, and limitations of, NETs at a national scale, allowing for more in-depth research and development to be targeted in future, to overcome the current barriers to implementation.

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1 *Tables*

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2 **Table 1.** Low and high per-t-Ceq. negative emissions impact values used in the calculation for UK impacts of NETs. All values for SCS and
 3 Biochar are from Smith (2016). All values for BECCS, AR, and DAC are from Smith *et al.* (2016) and values for EW were calculated from
 4 Renforth (2012), except for Potassium values for AR which were calculated from values Ovington & Madgwick (1959), and Potassium values
 5 for BECCS (*Miscanthus*) calculated from values in Roncucci *et al.* (2014). All estimates are nominally for 2100 except for costs which are for
 6 2050.

Technology	NET rate per land		Land area		Water use		Energy input		Nitrogen		Phosphorus		Potassium		Albedo impact		Cost	
	Low t- Ceq./ha	High t- Ceq./ha	Low ha/t- Ceq.	High ha/t- Ceq.	Low 1000m ³ /t- Ceq.	High 1000m ³ /t- Ceq.	Low GJ/t- Ceq.	High GJ/t- Ceq.	Low kgN/t- Ceq.	High kgN/t- Ceq.	Low kgP/t- Ceq.	High kgP/t- Ceq.	Low kgK/t- Ceq.	High kgK/t- Ceq.	Low unitless	High unitless	Low US\$/t- Ceq.	High US\$/t- Ceq.
BECCS	3	12	0.1	0.4	2	2.5	-38.6	8.7	11	20	0.8	20	5.7	22	0	0.04	132	132
AR	3.4	3.4	0.1	0.6	1.18	2.35	0	0	2	5	4	5	0.4	3.12	0.002	0.62	65	108
SCS	0.03	1	1	33	0	0	0	0	80	80	20	20	15	15	0	0	-165	40
Biochar	1.15	7.5	0.13	0.87	0	0	-50	-20	30	30	10	10	70	70	0.08	0.12	-830	1200
DAC	1818	1818	0.001	0.001	0.073	0.11	2.6	45.8	0	0	0	0	0	0	0	0	1600	2080
EW	0.82	10.91	1.22	0.09	0.0015	0.0015	3	46.2	0	0	0	0	0	0	0	0	92	5887

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5 **Table 2.** Summary of areas, negative emission potentials, impacts of NETs on water use, energy requirement, nutrient (N, P and K) requirements
6 and albedo, and bottom-up estimates of cost in the UK. See text for further details. * DAC potential is not constrained by area so impacts
7 assessed at same level of implementation as BECCS (i.e. area of 1.5 Mha; 4.5-18 MtCeq/yr). ** EW – high rate of application (50 t rock/ha/yr)
8 applied only to non-Grade 1-3 land = 1.5 Mha; low rate of application (10 t rock/ha/yr) applied to available Grade 1-3 land = 7.5 Mha. High and
9 low rock application rates from Taylor *et al.* (2016)¹⁸.
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Technology	Area applied Mha	Negative Emission Potential		Water use		Energy required		Nitrogen		Phosphorus		Potassium		Albedo		Cost	
		Low Mt Ceq./yr	High Mt Ceq./yr	Low km ³ /yr	High km ³ /yr	Low PJ/yr	High PJ/yr	Low ktN/yr	High ktN/yr	Low ktP/yr	High ktP/yr	Low ktK/yr	High ktK/yr	Low unitless	High unitless	Low B\$US/yr	High B\$US/yr
BECCS	1.5	4.5	18	9.00	45.00	-173.7	156.6	49.5	360	3.6	360	25.7	396	0	0.04	0.59	2.38
AR	1.5	5.1	5.1	6.02	11.99	0	0	10.2	25.5	20.4	25.5	2.0	15.9	0.002	0.62	0.33	0.55
SCS	8.5	0.255	8.5	0	0	0	0	20.4	680	5.1	170	3.8	127.5	0	0	-0.04	0.34
Biochar	1.5	1.725	11.25	0	0	-86.3	-225	51.8	337.5	17.3	112.5	120.8	787.5	0.08	0.12	-1.43	13.5
DAC		4.5*	18*	0.33	1.98	11.7	824.4	0	0	0	0	0	0	0	0	7.2	37.44
EW	1.5/8.5**	7.0	16.5	0.01	0.04	20.9	755.9	0	0	0	0	0	0	0	0	0.64	96.32