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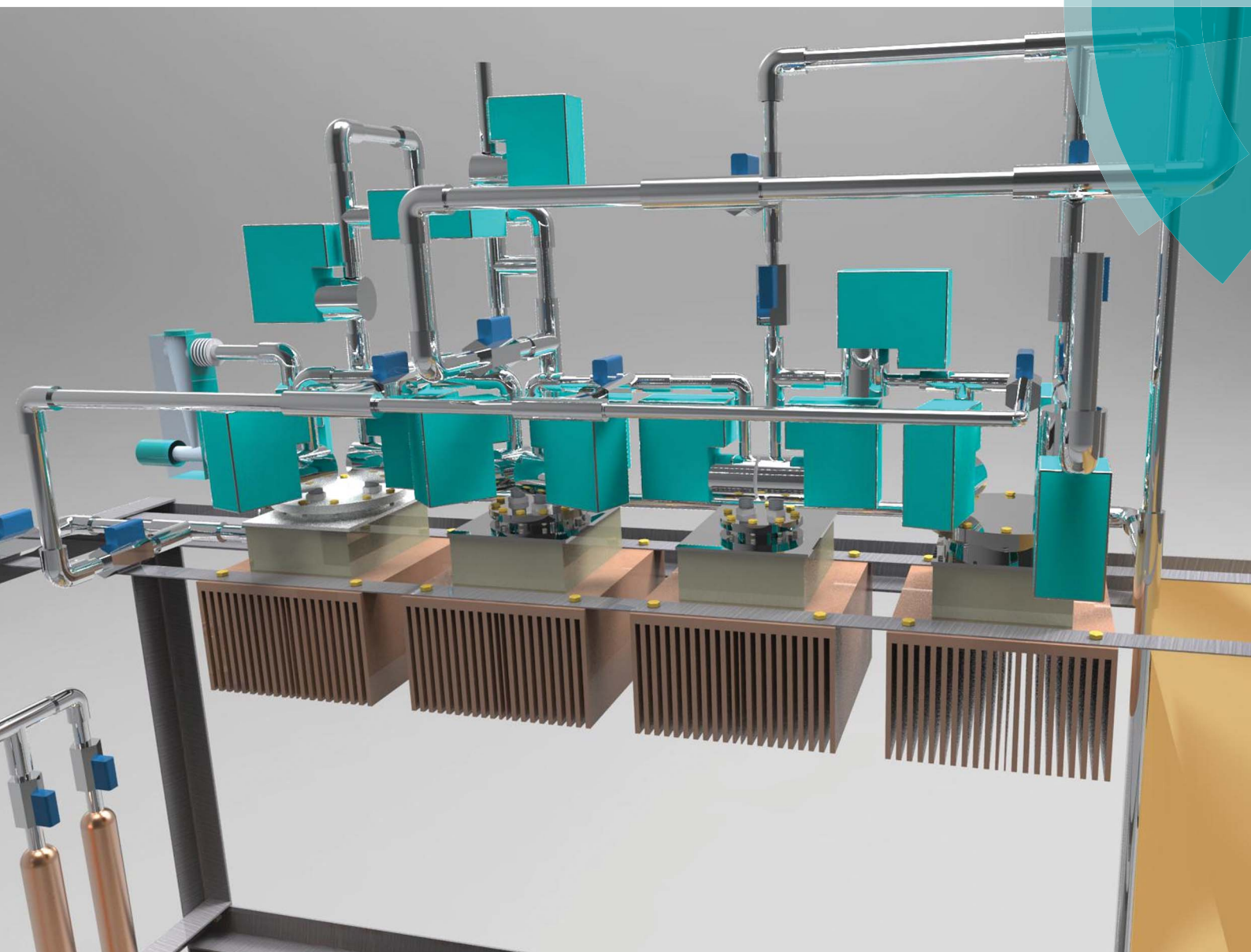
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Pete Smith *et al.*
Preliminary assessment of the potential for, and limitations to, terrestrial negative emission technologies in the UK

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Preliminary assessment of the potential for, and limitations to, terrestrial negative emission technologies in the UK

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The aggregate technical potential for land-based negative emissions technologies (NETs) in the UK is estimated to be 12–49 Mt C eq. per year, 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 CO_2.[1] As a result, net global CO_2 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 (BE[12]) with carbon capture and storage (CCS; together referred to as BECCS[13]), (2)

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Environmental impact

Given the aspirational target of limiting global temperature rise to below 1.5 °C compared to pre-industrial temperatures agreed in Paris in December 2015, and the UK's recently stated target of net zero emissions, there is urgency among UK policy makers to assess the technical potential for, and limitations of, Negative Emissions Technologies (NETs) in the UK. In this study we assess the maximum technical potential for a range of NETs, namely bioenergy with carbon capture and storage, direct air capture of CO_2 from ambient air, enhanced weathering of minerals, afforestation/reforestation, soil carbon sequestration and biochar. We also assess the impact of NET implementation on land, greenhouse gas balance, energy requirements, water use, nutrient use, albedo and cost.

direct air capture of CO_2 from ambient air by engineered chemical reactions (DAC[14,15]), (3) enhanced weathering of minerals (EW[16–18]) where natural weathering to remove CO_2 from the atmosphere is accelerated, and the products stored in soils, or buried in land/deep ocean and (4) afforestation and reforestation (AR[19–21]) to fix atmospheric carbon in biomass and soils. Second, Smith,[22] 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 amendment.[25] IAMs have so far focused primarily on BECCS[5,26,27] and AR.[28–30] 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 alkalinity[33]).

Fig. 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

1400 | *Environ. Sci.: Processes Impacts*, 2016, **18**, 1400–1405

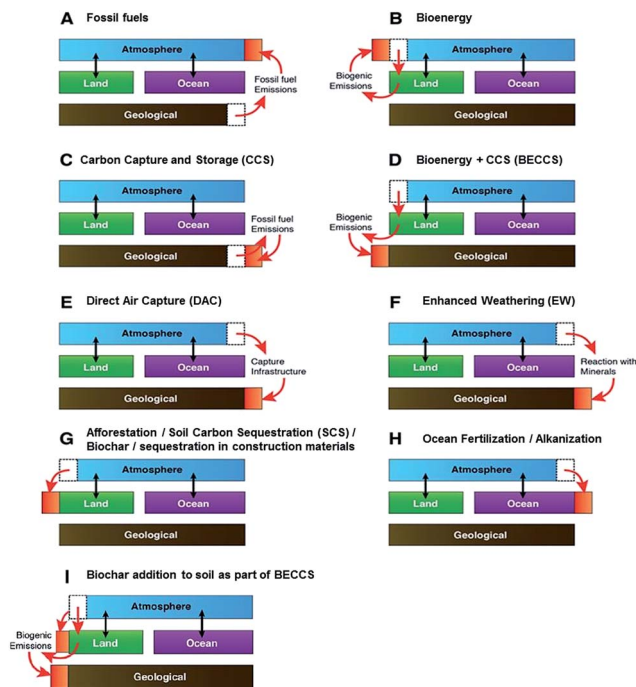This journal is © The Royal Society of Chemistry 2016

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

(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.

Systemic, holistic issues need to be considered for NETS deployment[34] 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 technologies.[11]

Materials & methods

Sources of data used to estimate impacts of NETs on a per t C eq. are described in ref. 11 and 22 except for values for EW where a detailed UK study exists[35] and values from this study are used. For BECCS, dedicated energy crops are assumed as in ref. 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 areas[36] are: (a) 8.5 Mha for all land not excluded by all UKERC constraints, including a high natural-ness 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 3 (ref. 37), so including grade 3 land is realistic to avoid large scale competition with agriculture.[35]

For EW, Renforth[35] 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 per t rock, and a small proportion of these as ultrabasic rocks with a negative emission potential of 0.218 t C per t rock. The total negative emission potential of the total UK mineral resource is 117 Gt C,[35] 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 constraints.[35]

The negative emission potential is largely dependent on the rate at which it is spread onto soils after comminution.[18] Even if spread at 50 t rock per ha per year, the highest rate considered in Renforth[35] 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 per ha per year is the rate at which lime is typically applied to agricultural land.[35]

• 10 t rock per ha per year 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 per ha per year is the "high" rate noted in both Renforth[35] 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 C eq. removal basis

Values for impact of NETs on a per t C eq. removal basis are shown in Table 1. For full details see ref. 11 and 22.

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

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Environ. Sci.: Processes Impacts, 2016, **18**, 1400–1405 | **1401**

Table 1 Low and high per t C eq. negative emissions impact values used in the calculation for UK impacts of NETs. All values for SCS and biochar are from ref. 22. All values for BECCS, AR, DAC and are from ref. 11, and for EW from calculations based on ref. 35, except for potassium values for AR which were calculated from values in Ovington and Madgwick,[38] 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

Technology	NET rate per land		Land area		Water use		Energy input		Nitrogen		Phosphorus		Potassium		Albedo impact		Cost	
	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High
	t C eq. ha⁻¹	t C eq. ha⁻¹	ha t C eq.⁻¹	ha t C eq.⁻¹	1000 m³ t C eq.⁻¹	1000 m³ t C eq.⁻¹	GJ t C eq.⁻¹	GJ t C eq.⁻¹	kg N per t C eq.	kg N per t C eq.	kg P per t C eq.	kg P per t C eq.	kg K per t C eq.	kg K per t C eq.	Unitless	Unitless	US$ per t C eq.	US$ per t C eq.
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	0.073	0.11	−50	−20	30	30	10	10	70	70	0.08	0.12	−830	1200
DAC	1818	1818	0.001	0.001	0.001	0	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

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 per ha per year (thus not interfering with agricultural use of the land – though these rates are still higher than those regularly used in agriculture for liming[35]), could be used on 8.5 Mha of land. If applied at high rates of 50 t rock per ha per year, 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]

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 Mt C eq. per year, respectively. SCS, implemented on 8.5 Mha of land, would deliver 0.255–8.5 Mt C eq. per year. EW can be implemented on 1.5/8.5 Mha of land, delivering 7.0–16.5 Mt C eq. per year. If 50 t rock per ha per year is applied to 1.5 Mha of non-agricultural land, and 10 t rock per ha per year is applied to the remaining 7.5 Mha, the combined total potential of EW is 16.36 + 6.14 = 22.5 Mt C per year.

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 CO_2 are also low in the UK. Around 21 Gt C (equivalent to 210 Mt C eq. per year over a century) storage potential exists in UK coastal waters.[40] 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 ref. 11), DAC is compared at the same level of implementation of negative emissions as BECCS, i.e. 4.5–18 Mt C eq. per year. 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 Mt C eq. per year (for EW applied to all available land). Most NETs have potential in the order of magnitude range of 1 s–10 s Mt C eq. per year, though DAC potential could be greater. Total UK emissions for all GHGs

1402 | Environ. Sci.: Processes Impacts, 2016, **18**, 1400–1405

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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 K so 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 Mt C eq per year). ** EW – high rate of application (50 t rock per ha per year) applied only to non-grade 1–3 land = 1.5 Mha; low rate of application (10 t rock per ha per year) applied to available grade 1–3 land = 7.5 Mha. High and low rock application rates from Taylor et al. (2016)[18]

Technology	Area applied (Mha)	Negative emission potential Low (Mt C eq. per year)	High (Mt C eq. per year)	Water use Low (km³ per year)	High (km³ per year)	Energy required Low (PJ per year)	High (PJ per year)	Nitrogen Low (kt N per year)	High (kt N per year)	Phosphorus Low (kt P per year)	High (kt P per year)	Potassium Low (kt K per year)	High (kt K per year)	Albedo Low (Unitless)	High (Unitless)	Cost Low (B$US per year)	High (B$US per year)
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	0.33	1.98	-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*	4.5*	18*			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

during 2010–2014 amounted to ∼560 Mt CO_2 eq. per year (=153 Mt C eq. per year),[41] so potentials in the range of 10 Mt C eq. per year 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 potential:[42] for BECCS the estimate here of 4.5–18 Mt C eq. per year compares to 5–22 Mt C eq. per year, while for biochar the estimate here of 1.7–11 Mt C eq. per year compares to 3–13 Mt C eq. per year.

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 Mt C eq. per year (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 decomposition[43]), 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 assessment.[11]

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 per year by primary energy in the 2030s.[44] 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 replace 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.

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Environ. Sci.: Processes Impacts, 2016, **18**, 1400–1405 | **1403**

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 C eq. 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 per t CO_2,"[42] which is equivalent to ~\$US 370 per t C eq. Costs for specific technologies (converted from CO_2 eq. to C eq.) estimated in the AVOID programme[42] were \$US 110–150 per t C eq. for biochar; >\$US 460–550 per t C eq. for BECCS; and ~\$US 550–730 per t C 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 AR.[11]

Permanence of emissions removal

Carbon removals with any technology using liquid CO_2 for CCS are subject to the integrity of the storage reservoir. CCS demonstration projects worldwide appear to be performing well at 30 Mt CO_2 per year.[46] UK reservoirs for liquid CO_2 CCS have been mapped,[40] and are assessed to be ready for use. Storage of captured carbon dioxide in solid form as carbonate minerals, by injecting liquid CO_2 into basaltic rocks, may be rapid (95% in less than 2 years) and has been shown to be feasible in a small pilot study.[47] 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 value,[24] 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 reversible,[24] 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 Mt C eq. per year, 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 deployment[34] 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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Environ. Sci.: Processes Impacts, 2016, 18, 1400–1405 | 1405