Assessing the terrestrial capacity for Negative Emission Technologies in Ireland

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ABSTRACT

Negative emissions technologies (NETs) and their potential role in meeting emission targets is a rapidly growing and contentious area of climate change mitigation research. The literature ranges in scope from general reviews of NETs options to research and development through applied case studies. Within this field, a gap exists in the application of this growing body of research to the unique limitations and opportunities of a specific nation. Ireland is a small developed island nation in the EU with a unique emissions profile, as 32% of the total comes from agriculture due to the high number of cattle. In this study we aim to assess the potential capacity of terrestrial NETs options for Ireland and review the nation-specific context for their deployment. Despite the proportionally high representation of biochar and carbon capture and storage in the international NETs research, in an Irish context afforestation and bioenergy crops are much more established practices and could readily be considered in possible emission pathways that use NETs. Higher capacities were found for NETs options that are currently unavailable (direct air carbon capture and storage and bioenergy with carbon capture and storage), while options available to deploy at scale (afforestation, soil carbon management and biochar) have capacities limited by saturation of soil carbon stock and have higher risk of reversibility due to impermanence. Hence, while we estimate a reasonable technical capacity for NETs in Ireland, emission reduction remains the highest priority for feasibly meeting a Paris-aligned carbon quota for Ireland.

Key words: Climate change, negative emissions technologies, carbon dioxide removal and storage, Ireland

Introduction

Negative emissions technologies (NETs) are any process that removes carbon dioxide from the atmosphere and stores it in the biosphere or geosphere. The international research on NETs has been growing rapidly, especially since 2005. Minx *et al.* [1] found 2900 studies published on NETs from 1991 to 2016, with the rate of publications increasing dramatically. Publications range in scope from reviewing potential, assessing feasibility and technological maturity and discussing deployment opportunities. Some of the literature addresses the deployment of specific, relatively mature, NETs options at a local case study scale, where opportunities are being actively realised [2–4].

Concerns have been raised that ungrounded optimism in NETs potential could result in delayed reductions in gross CO_2 emissions, with consequent high-risk of overshoot of global temperature targets [5]. Hence it is important that the realistic potential of NETs be carefully assessed in every context where it is considered. The literature has identified a gap between general assessments of feasibility and potential and the specific local case studies [6]. The downscaling of NETs research to a nationally relevant context is a vital next step in progressing its deployment. An outline study of this sort has recently been presented for the UK [7]. We aim to similarly present a preliminary assessment of NETs potential in Ireland, as an example of a small developed island nation at the very early stages of considering scalable NETs deployment. Furthermore, Ireland has a unique GHG emissions profile in Europe with 32% of total CO_2e emissions coming from agriculture [8], particularly due to the high and currently increasing number of cattle. Total GHG emissions are still rising and projected to do so further up to 2030 [9]. Consequently it is increasingly likely that Ireland will need to adopt negative emissions technologies if it is to avoid European fines for missing legally binding targets and to align action with the Paris Agreement limits.

International Context

Ireland has undertaken multiple interacting commitments to greenhouse gas emissions reduction, through its National Policy Position [10], its participation in EU co-ordinated climate action directives, regulations and decisions, and its ratification of the Paris Agreement [11]. Of these, the Paris Agreement temperature goals now represent the overarching constraints that all parties have committed to respect. Parties submitted statements of their separate, voluntary, Intended Nationally Determined Contributions (INDCs) in advance of the adoption of the Paris Agreement. Now formalised as NDCs under the Agreement, these have been assessed for their collective mitigation adequacy. Multiple assessments find that they are currently inadequate to the achievement of the temperature goals [12–15]. It is in this context that Ireland now has a finite remaining quota of further nett CO_2 that it can emit. It is the possibility that gross emissions of CO_2 either already have, or shortly will, exceed Ireland's remaining quota that raises the question of how much gross CO_2 removals Ireland can feasibly achieve, quickly enough, to "re-balance" its nett quota. Within the spirit of the Agreement, any remaining shortfall will have to be made up either by purchasing unused carbon quota from other parties, or purchasing the required CO_2 removal services.

Terrestrial NETs Options for Ireland

One way of classifying potential NETs approaches is according to the targeted carbon storage mechanism: either biogenic (soil organic carbon or standing plant biomass) or geological (most typically assumed to be by pumping captured CO_2, under pressure, into suitable porous rock formations, sealed below non-porous strata). While both can contribute in the short (decadal) term, concerns over saturation and permanence of biogenic storage (particularly in the face of ongoing climate impacts) mean that it is best viewed as only a temporary or transitional measure. Ultimately, only return of carbon to secure geological storage can be relied on to adequately counteract the accumulated effects of transferring carbon from geological stocks of fossil fuels to the atmosphere.

Thus, any long term programme of carbon dioxide removal (CDR) targeting biogenic storage ultimately requires the availability of geological storage, though this is not explicitly reflected in current UNFCCC mechanisms of accounting.

A second, high level classification is according to the mechanism for initial removal of CO_2 from atmosphere. Again, there are two main possibilities: either biogenic (via photosynthesis in plants) or technological (primarily in the form of what is called “direct air capture” or DAC). Table 1 presents the particular NETs technologies that will be considered further in this study, together with their respective classifications of both CO_2 removal from atmosphere, and carbon storage (whether as CO_2 or in some other form).

Table 1: NETs classification

NETs	Removal	Storage
Enhanced Soil Carbon Sequestration (SCS)	Biogenic	Biogenic
Biochar (BC)	Biogenic	Biogenic
Afforestation (AF)	Biogenic	Biogenic
Enhanced weathering (EW)	Technological	Geological
Bioenergy with Carbon Capture and Storage (BECCS)	Biogenic	Geological
Direct Air Carbon Capture with Storage (DACCS)	Technological	Geological

There is extensive prior experience in Ireland with afforestation, and more limited experience with bioenergy crop cultivation, and with enhancement of soil carbon sequestration via the use of biochar (BC) or otherwise. There is no existing experience with either DACCS or BECCS due primarily to the unavailability of carbon capture and storage (CCS). BECCS and DACCS would interact directly with the overall energy system: BECCS could contribute nett energy, whereas DACCS would require additional energy consumption. With the exception of DACCS, all the NETs mentioned in Table 1 would interact very substantially with domestic land use and agricultural practices; in some cases competing with existing land use (bioenergy crops, afforestation) and in other cases potentially being complementary to, or co-existing with, existing use (enhanced soil carbon sequestration, enhanced weathering).

There are many challenges and limitations of deploying and scaling up various NETs options in Ireland. Barriers include technical readiness, cost, storage permanence, and knowledge gaps in Ireland-specific research. A preliminary qualitative summary of these and other considerations for deploying NETs options in Ireland is presented in Table 2.

Table 2: A schematic qualitative summary of the main policy relevant considerations for utilising NETs options in Ireland ranging from green for a positive rating through yellow for medium to red for a negative rating . * denotes relatively high equivocation and uncertainty in the assessment. All options

have both opportunities and difficulties for decision-makers with significant uncertainty ranges in many cases requiring specific assessment.

	SCS	Biochar	EW	Afforestation	BECCS	DACCS
Carbon removal	*Medium* *	Medium	Medium	Medium	High	Very High
Readiness	Very High	Very High	Medium	Very High	Medium	Very Low
Cost	*Medium* *	*Medium* *	Medium	Low	Medium	Very High
Vulnerability to re-release	High	High	Medium	*Medium* *	Low	Low
Vulnerability to future climate change	Very High	High	Medium	High	Medium	Very Low
Biodiversity Risk	Low	Low	Medium	*High* *	High	Low
Energy Penalty	Low	Medium	High	*Low* *	*Very Low* *	Very High
Land Pressure	Low	Medium	Low	High	High	Very Low

This study aims to use a simplified model originally presented for the UK by Smith *et al.* [7] , also recently employed for Scotland [16], to make an approximate quantitative estimation of the technical potential carbon removal and storage capacity of NETs in Ireland, under the assumption that the aforementioned limitations, can be fully overcome and options then deployed at scale in Ireland (i.e., this analysis does not attempt to quantitatively assess the many additional economic, political and social barriers to deployment).

Methods

Smith et al. [7] presents a method to estimate the technical carbon removal capacity of various NETs options (BECCS, AF, SCS, BC, DACCS and EW) under hypothetical land area availability scenarios for the UK. To apply this model to Ireland, suitable land areas potentially available for relevant NETs option deployment had to be determined. The total land area of the Republic of Ireland is 7.0 Mha. In choosing an appropriate land area, two main resources were considered; the COFORD (Council for Forest Research and Development, Ireland) land classification scheme [17], and the discussions on land area availability for bioenergy by the Sustainable Energy Authority of Ireland (SEAI) bioenergy supply curves [18].

COFORD [17] classifies Irish land into 4 levels. The level most suitable for potential NETs deployment is level 4: 'Land most likely to have potential for forest expansion'. This is currently made up of *Farmland* (occupied by dairy, cattle, sheep, mixed livestock and tillage) with both wide and limited usage (3.5 Mha); and *Not-farmed land,* grassland and unenclosed land (0.3 Mha). For estimating the capacity of SCS and EW the same assumption as [7] was made; that these options could be applied to all of the level 4 land (3.8 Mha). For BECCS, AF and BC, a base scenario of land area availability was 0.55 Mha, representing 16% of level 4 land in the [17] classification scheme. This choice is informed by the discussion of [18] on the potential land area available for bioenergy crops in Ireland. This identifies that the EU Common Agricultural Policy (CAP) limits conversion of existing permanent grassland to arable (including bioenergy) crops to 10% (0.35 Mha) up to 2020. Further, [19] indicates an even more restrictive CAP conversion limit of 5%. Beyond 2020, [18] we identify 0.2 Mha of additional pastureland that may be eligible for conversion, subject to CAP reform. We therefore adopt the relatively ambitious assumption that 0.35 Mha of permanent grassland could be converted and attributed to a relevant NETs option (BECCS, BC or AF) up until 2020, and that post 2020 the additional 0.2 Mha may become accessible, creating a total land area estimate in Ireland of 0.5 Mha. This land area is also in a similar range to that required to achieve an 18% afforestation target by 2050 (0.51 Mha) [17]. We suggest that this area therefore represents a realistic base land use scenario for assessing the NETs capacity in Ireland up until 2100.

Two additional 'high end' scenarios were also tested to inform the current Irish policy direction of pursuing "carbon neutrality" within the agriculture sector. These two scenarios allocate 30% of level 4 agricultural land (0.97 Mha; 'high-end-1') and 75% of level 4 land that is classified as either of *Limited agricultural use* or *Not-farmed* (1 Mha; 'high-end-2') (Table 3).

Note that DACCS does not require significant land area, therefore to provide comparisons of cost, it was assumed that DACCS was deployed to the same capacity as BECCS, as with the assumptions of Smith et al. [7].

Table 3: Land area scenarios for Afforestation, Biochar and BECCS

Scenario	% of level 4 land	Area (ha)
Base	16	550,000
High-End-1	30	970,273
High-End-2	75 (limited use and unfarmed)	1,007,407

Land use emissions displacement

Additional calculations, not present in the original model of [7], were carried out to estimate the reduction of Irish emissions (largely non-CO_2) resulting from the replacement of current agricultural practices by deploying NETs. The purpose of this exercise was to more specifically inform the current policy directive of pursuing efforts towards "carbon neutrality" in the agricultural sector, as outlined in the National Mitigation Plan [20]. To estimate this displacement value, GHG emission values for Irish agricultural practices were taken from [21]. For the three land area scenarios it was assumed the NETs option was applied equally between all level 4 land use categories except tillage for the base and high-end-1 scenarios, and 75% of all 'limited agricultural use' and 'not farmed' land for the high-end-2 scenario.

Cumulative technical capacity of NETs in Ireland to 2050 and 2100

Additional work was carried out to consider the cumulative amount of carbon removed by each NETs option if deployed in Ireland up until 2050 and 2100. The purpose of this exercise was to illustrate the effect of saturation on time limitations for NETs options such as SCS, BC and AF, in contrast to the much higher storage (and therefore longer term sustained removal) capacities of BECCS and DACCS. This addresses the issue of NETs options like AF, BC and SCS being technically available to scale up to full potential now, but as an emissions management strategy is time limited and subject to saturation effects. Whereas NETs options such as BECCS and DACCS are not yet ready to deploy at scale, but are expected to be less limited by saturation due to much larger (and more secure) storage capacity. This work estimates the cumulative removals achieved by BC, SCS and AF under the assumption that Irish soils will saturate after c. 20 years. A paucity of data on Irish soil carbon deficits means the actual time to saturation cannot currently be estimated with any precision. This value of 20 years is taken on the basis of guidelines by [22]. This work also assumes that CCS storage capacity is not constraining within the given time horizons (i.e., national CCS storage capacity will not be fully used by 2100, or if it is, that there will be options to export Irish captured CO_2 to be permanently stored elsewhere). It was assumed that all NETs options were deployed to the full baseline scenario land areas by 2020, with the exception of BECCS and DACCS for which the assumed start year was 2035 (anticipating full technological readiness by then).

Results

Due to the simple nature and limitations of the model each NETs option is considered individually rather than in combination. The calculation of NETs for Ireland, based on the model of Smith et al. (7), are shown in Supplementary material (S.1). As with discussions by [7], we consider the 'low' values of the model output. We focus on the low values because the actual values are likely to be far lower than the upper end values due largely to socio-political realities. Of the low NETs capacity estimates, AF has the highest annual carbon dioxide removal capacity, followed by BECCS and DACCS, and lowest capacities are from SCS, BC and EW (Figure 1, Table S.2). To summarise, the negative emissions potential for BECCS, AR and biochar implemented on 0.55 Mha of land in Ireland are: 1.7 to 6.6, 1.9, 0.6-4.1 Mt C eq. per year, respectively. SCS, implemented on 3.7 Mha of land, would deliver 0.1–3.7 Mt C eq. per year and EW can be implemented on 0.55/3.7 Mha of land, delivering 3.1-6.0 Mt C eq. per year.

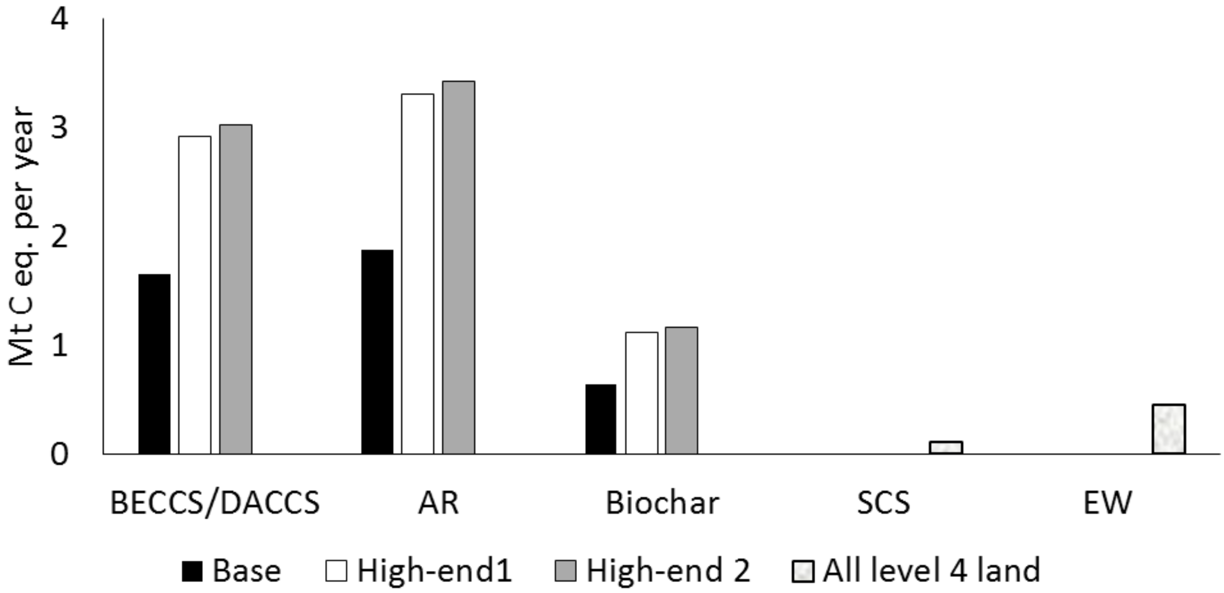

Figure 1: Estimates of annual carbon removal in Ireland under different land use scenarios (see Table 3 for land-area scenarios)

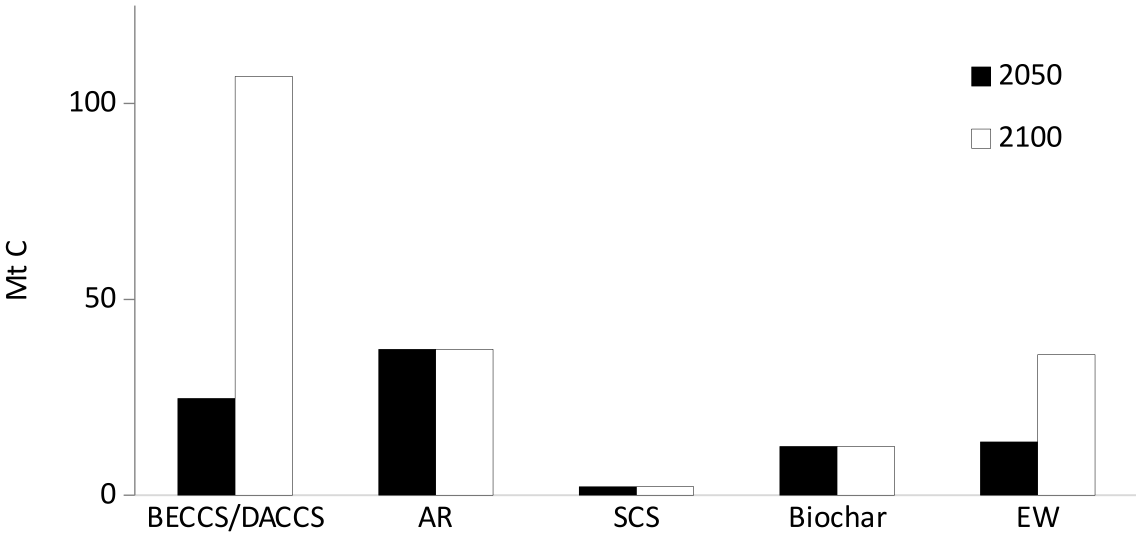

Figure 2: Annual carbon equivalent emissions reduced by conversion of land use from current agriculture practices to BECCS, BC or AF, assuming previous practice was replaced and not displaced, under three land use scenarios

Compared to total Irish emissions, under the base land area scenario, up to 11% of the 2015 emissions might be offset by a NETs option. If additional land area became available, this proportion could technically be as high as 21% (high-end-2 AF scenario, Table S.2). BC and SCS are the most economically viable options, with DACCS currently estimated as the most expensive by several orders of magnitude (Table S.2). 1-1.7 MtC could be removed per year in Ireland's land use sector by converting existing agricultural land to BECCS, AF or BC land use (Figure 2), equivalent to up to 32% of current Irish annual agricultural emissions (high-end-1 scenario, Figure 2, Table S.2). In both high-end scenarios, the combination of the carbon removals possible from AF and the emissions removed from land use replacement would result in net negative emissions in Irish agriculture and land use.

For the base scenario, maximising AF and displacing 16% of current agriculture lowers net emissions by 52% in this sector, still making a significant contribution towards the expressed policy goal of "carbon neutrality". Further reductions could be achieved by combining SCS and EW on the remaining agricultural land.

The cumulative carbon removal capacity of NETs options in Ireland up until 2050 and 2100, under the baseline land area scenario, can be seen in Figure 3. These results show the limit on carbon removal capacity of AF and BC due to soil carbon saturation. Hence, while AF showed the highest carbon removal capacity per year (Table S.2, Figure 1), this annual removal capacity will not be available long term to 2100 (Figure 3).

Taking a national carbon quota for Ireland of 766 $MtCO_2$ [23] provides a context for the cumulative capacities of different NETs options in Ireland shown in Figure 3. The cumulative capacities of NETs options in Ireland up until 2100 are as high as 400 $MtCO_2$ (BECCS and DACCS), indicating the technical potential to significantly contribute to Ireland's achievability of a net carbon quota of 766 $MtCO_2$ by effectively increasing the gross carbon quota by 52%. Up until 2050, 0.55 Mha of AF could cumulatively remove 137 $MtCO_2$, increasing the Glynn et al. nett carbon quota for Ireland [23] by 17%. However, under a base land area scenario, NETs options in Ireland are likely to fall well short of the emissions gap between the national carbon quota and current emission projections: demonstrating that, even with "anticipatory reliance" on NETs, deep, near term, reductions in gross emissions are still required.

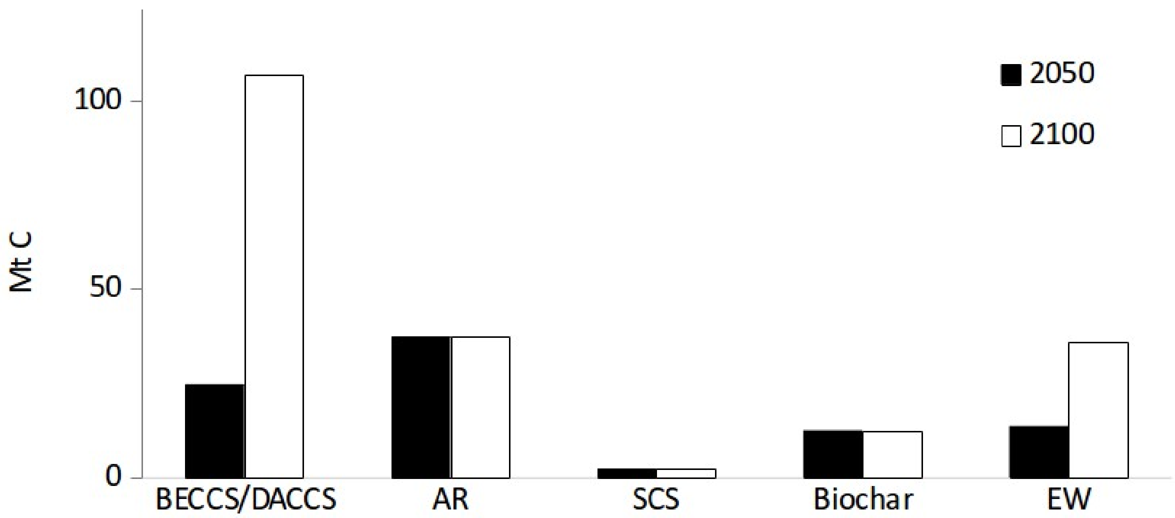

Figure 3: Estimated total cumulative CO_2 removal capacity of NETs options in Ireland, based on the (Smith et al., 2016) model under the land area assumptions of the baseline scenario, demonstrating saturation of AR, SCS and BC capacity.

Discussion

NETs Capacity in Ireland

These preliminary findings suggest that Ireland may have potential capacity to remove a significant amount of carbon from the atmosphere, even under a base land allocation scenario of 16% of level 4 agricultural land, through deployment of various NETs options. On a cumulative scale, NETs capacity in Ireland up until 2050 and 2100 may have the potential to significantly increase the achievability of an equitable nett Irish carbon quota. Each NETs option is considered individually for Ireland. While, practically, a portfolio of multiple NETs options could be deployed together, they would interact in complex ways, and significantly more sophisticated land allocation modelling, compared to the relatively simplistic scenarios presented here, would be required to assess this.

Presently, AF, BC and SCS are the most immediately suitable and ready to deploy NETs options in Ireland. Our results find that these options might remove 1.87, 0.63 and 0.11 MtC yr^{-1} respectively, offsetting up to 11% of Ireland's 2015 annual emissions (Figure 1). However, each of these options rely on biogenic and soil storage of the removed carbon, which is subject to a saturation limit and vulnerable to re-release. So while these results demonstrate significant annual removal capacity in Ireland, cumulatively these NETs capacities are estimated to be limited to 137, 46 and 8 $MtCO_2$ respectively (Figure 3). If deployed fully by 2020, this maximum capacity could be reached as early as 2050. Despite offering no further capacity, protection and management of this vulnerable captured carbon would still require significant resources into the indefinite future.

While technological maturity, cost and national capacity knowledge gaps render BECCS and DACCS difficult to deploy in Ireland in the short term future, our results find they may also have significant capacity to remove atmospheric carbon, up to the equivalent of ~10% of current annual national emissions. These options are not limited by the biogenic saturation concerns previously discussed, and in principle therefore might allow significant carbon removals post-2050, potentially increasing the gross carbon quota for Ireland by 52%. However, the current state of readiness and high costs warrant caution and prudence in relying on future availability of these technologies.

Comparisons with nearest neighbours show that, for the UK, the maximum land based aggregate NETs are estimated to be 12-49 Mt Ceq per year. This is 8-32% of current UK GHG emissions [7]. For Scotland alone the maximum NETs removal without DAC ranges from 0.06 to 6.6 Mt C per year. This is up to 90% of the annual emissions of Scotland and with a small contribution from DAC it could reach 100%. This is a consequence of a large land area available for NETs in Scotland as well as relatively low per capita emissions [16]. At 10-74% of the current emissions the contribution of NETS in the Republic of Ireland falls somewhere between Scotland and UK estimates.

Deploying NETs options in Ireland

Afforestation (AF)

The deployment of afforestation in Ireland is already well established and features heavily in existing climate change mitigation policy. Ireland currently has the lowest proportion of forested land in the EU. For successful climate change mitigation, there is a minimum stand age required to ensure a net gain of carbon, and suitable harvesting protocols are needed to protect stored carbon and ensure its permanence. The impact of afforestation on soil carbon stock depends on many factors, including climate, former land-use, forest age, forest type, soil type (clay content), nitrogen deposition and management practices [24,25].

Issues such as the permanent nature of compulsory re-plant forestry, the lack of land control and management required, as well as the replacement of traditional practices are all challenges for successful uptake by farmers [26]. A debate has emerged over competition for land between conventional farmers and afforestation-incentivised private investors [27]. There are additional concerns about the impacts of afforestation on biodiversity, especially bird species, and on the environment generally from the mono-culture blanket forestry currently being deployed under the Afforestation Grant and Premium Scheme [28].

Biochar (BC)

The international literature highlights many co-benefits of BC including increased yield [29], improved soil quality [30] and reduced soil emissions of other GHGs [31-34]; Some constraints identified in using BC include concerns about albedo changes, reduced air quality, heavy metal pollution and site-specific effects [35–37].

There is little Ireland-specific BC research, but much of the international research is transferable to an Irish context. BC has recently been introduced to market in Ireland for its fertilisation, disease protection and water retention benefits but it does not feature strongly in current Irish climate mitigation policy and research. The limited Irish-specific research on BC focuses on its potential to suppress other GHG emissions from soils [38–40] and improving soil quality and yields [41]. Improving geographically explicit data of local soil BC amendment capacity and strategically targeting soils with the largest capacity would be the most appropriate way to deploy BC applications in Ireland. For indigenous production of biochar, Kwapinski *et al.* [42] identify multiple potential feedstocks, suggesting the best resources may be manure (dairy, poultry, pig) and waste. Biomass from bioenergy crops can also be used to make biochar. This could reduce the life-cycle emissions of bioenergy crop production by increasing the amount of carbon transfer to soil sequestration, reduce fertiliser and land requirements and suppress soil GHG emissions [43–47].

Soil Carbon Sequestration (SCS)

Unfortunately, there is a paucity of data regarding the maximum stock (saturation) capacity, and corresponding existing carbon deficit, of Irish soils. However the grey literature report [48] suggests that most Irish soils have a significant carbon deficit. This is based on international findings in Europe and other regions with similar climate and soils to Ireland (e.g. New Zealand), where [49,50] have found most soils to have a saturation deficit. A case study for estimating soil saturation deficits at a national level has been presented by [51] for New Zealand. This work might facilitate a similar analysis in Ireland. In principle, such analysis could allow targeting of soils with the highest saturation deficit to achieve the most effective increases in soil carbon stock. [52] consider the “four per mille” ambition for global SCS enhancement, and suggest that Irish soil carbon sequestration rates of 0.6, 0.4 and 0.6 tC $ha^{-1} yr^{-1}$ should be possible for grassland, arable land and forested land, respectively.

Carbon Capture and Storage (CCS): enabling technology for BECCS and DACCS

The maximum potential capacity (total of practical, effective and theoretical capacity) estimated for Ireland to store CO_2 long term is 93 $GtCO_2$ (25 GtC) but there is a large uncertainty range for this figure due to the paucity of geological data. The Kinsale gas field is the most likely first suitable storage site with an estimated possible capacity of 330 $MtCO_2$ (90 MtC), but would require an investment of c. €80 million to properly assessed [53]. A more recent assessment of the Central Irish Sea Basin found it was unsuitable for storing CO_2 due to high leakage risk. The same study found the south Celtic Sea Basin may have some limited storage potential [54]. Ireland is most likely to pursue CCS after it has been commercialised by other countries – though it has currently stalled in the UK where one billion pound investment in 2015 was cancelled due to economic unviability at current carbon prices and concerns over responsibility for long-term storage risks. If Ireland does not pursue its indigenous carbon storage potential it may need to consider the potential to capture, store and transport carbon to an external storage facility such as those in Iceland and Norway.

Bioenergy Crops (for BECCS)

Trade-offs exist for expanding bioenergy crops in Ireland between GHG emissions and energy demand, acidification, eutrophication and biodiversity [55–58]. Future policies should endeavour not to undermine existing policies in these areas [59]. There are additional barriers to expanding bioenergy production in Ireland. These include:

- Cultural preferences in the agricultural community towards food production [60] and hesitance to adopt energy crops [61] [62].
- *Miscanthus* takes two years to establish and willow takes four [63]. The longevity of the bioenergy system must be incorporated into policy incentives for the mitigation potential and all co-benefits to be acquired. The long term commitment required with uncertain market and policy is off-putting [64].
- There is uncertainty concerning Irish specific yields and reliable production strategies [64,65]

Direct Air Capture and Carbon Storage (DACCS)

While DACCS does not have the same land area requirements as other terrestrial NETs options considered herein, it is currently prohibitively expensive and requires high energy input to operate and therefore would need a low carbon energy supply. One theoretical scenario would be to integrate DACCS with very high penetration of renewable energy sources in the Irish electricity system. In principle, this could align well with the relatively abundant indigenous wind energy resource in Ireland, both onshore and offshore [66].

Conclusions

In Irish policy terms NETs can be framed as aiding the proposed progression of Irish agriculture towards "carbon neutrality" in the first instance [67]; and displacement of current high emissions intensity ruminant food production with bioenergy cultivation would further support this. Displacing 16% of available agricultural land with AF may achieve additional emissions saving, relative to current agriculture, of 1 MtC (19% of 2015 agricultural emissions). Two additional 'high-end' scenarios indicate a technical potential to go beyond "carbon neutrality" and achieve net negative emission within Irish agriculture and land use sector, albeit this would also depend on a significant change in future policy direction to remove current restrictions and incentivise much more extensive land conversion to forestry and/or bioenergy cultivation for use in BECCS.

Based on these results, a preferred strategy that emerges for deploying NETs in Ireland appears to be to maximise AF, with minimal harvesting, in the immediate term (perhaps up until 2035) while supporting the development of BECCS, with the view of allocating AF harvest biomass to BECCS when CCS costs are lowered and/or AF stocks (land, biomass and soil) have saturated. However, it must be emphasised that this would rely on little or no harvest of the accumulating forest biomass during this period (for any purpose that could not guarantee the continued long term preservation of the captured carbon stock), which would imply fundamental changes in current AF support policies. However, if BECCS does not become ready or remains infeasibly expensive, the use of AF becomes limited by saturation and unavailability of further additional land, after which no further removals can be achieved. Additionally, carbon removed by AF is stored biogenically (biomass and soil carbon) which is all vulnerable to re-release and will require continued maintenance, monitoring and protection. Hence, while this work may inform policy discussions about the potential capacity for NETs in Ireland, the limitations imposed by permanence and saturation render NETs options that are immediately available (AF, BC and SCS) at some significant level of risk. Furthermore technological uncertainty and high costs render alternative options (BECCS and DACCS), presently unavailable, at an even higher level of risk. Additionally, Irish NETs capacities estimated herein fall well short of the implied requirements of the current gap between estimated Irish CO_2 quotas and current projected cumulative Irish emissions. Therefore, while our results indicate that NETs in Ireland may have potential carbon removal capacity and contribute towards achieving future net emission targets, the highest priority and emphasis of Irish climate mitigation actions should be immediate, significant, and sustained reductions in gross emissions.

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