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Quantifying the land-based opportunity carbon costs of onshore wind farms

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ABSTRACT

The development of onshore wind energy impacts the land where it is constructed, together with competition for natural resources between the energy and land sector. The loss of terrestrial carbon stocks and ecosystem services from land use change to wind farms can be interpreted as the opportunity cost that landowners give up by choosing to construct wind farms on their land. Here, we spatially quantify the impact onshore wind farms have on land when we factor in the opportunity carbon (C) costs. We found that, the construction of 3848 wind turbines in Scotland generated 4.9 million tonnes of carbon dioxide (CO_2) emissions from land use change. On average the emission intensity of land use change in peatland is 560 g CO_2 kWh^{-1}, in forestry is 88 g CO_2 kWh^{-1}, in cropland is 45 g CO_2 kWh^{-1}, and in pastureland is 30 g CO_2 kWh^{-1}. In the worst land use change scenario, the displacement of Dystrophic basin peat habitats generated 1760 g CO_2 kWh^{-1}, which is comparable to the life cycle emissions of fossil-fuel technologies such as coal and gas-fired electricity generation. In arable land, the loss of harvestable crop to wind power was forfeited for a gain in opportunity costs up to £15.4 million over a 25 year operating life. Considering the short-term value of CO_2 in the trading market, the opportunity carbon costs of onshore wind farms can range from £0.3 to £65.0 per MWh of electricity generated per year. These findings highlight that the preservation of terrestrial carbon stocks and crop production in the land sector require the development of new payment schemes that can compete economically against the monetary benefits that landowners can access from lease agreements agreed with energy companies. This ensures also that wind turbines are geographically placed to protect ecosystem C stocks, and to minimize the carbon intensity of the electricity generated.

1. Introduction

The strategy of reaching net-zero emissions by 2050 became legally binding in June 2019, and since then the United Kingdom (UK) has been committed to decarbonize the energy system to a net-zero carbon (C) target. In 2019, greenhouse gas (GHG) emissions from electricity generation were down 72% on 1990 levels (BEIS, 2020a). Three quarters of these emission reductions have been ascribed to the reduced burning of coal for electricity generation and the progressive introduction of renewable energy sources in the energy mix (BEIS, 2017; DECC, 2015a, 2015b). The amount of renewable capacity connected to the UK energy grid has increased from 8 GW in 2009 to 48 GW in 2020, producing 37% of the total electricity generated in 2020 (BEIS, 2020b). Despite the progress made, the decarbonisation of the energy sector will require a four-fold increase in low C electricity generation, with offshore and onshore wind farms and solar photovoltaics being the key technologies of the future UK generation mix (BEIS, 2019b).

The 2030 Agenda of Sustainable Development (UNGA, 2015) recognised the central role that renewable energy underpins in reducing GHG emissions and contributing to economic and social development at global scale. In particular, Sustainable Development Goals (SDG) number 7, comprises specific targets on clean energy, recommends the universal access to affordable, reliable and modern energy services (7.1), and the increase of renewable energy share in the global energy mix (7.2). However, the construction of onshore wind farms is not C neutral as they are underpinned by, and impact upon, the land where they are constructed (Kiesecker et al., 2019). The environmental impact of onshore wind farms on natural capital and ecosystem services can result in a number of trade-offs between different SDGs. Fuso Nerini (2019) highlight 31 environment-related trade-offs with SDG 7. This means that as part of broader efforts to increase low C electricity generation and its sustainability, analysis must use frameworks that consider the use and losses of natural resources across all the life cycle stages of onshore wind farms (Bateman et al., 2011; Holland, 2016; Kiesecker et al., 2019).

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The distribution of onshore wind farms is mostly driven by the preferences and restrictions imposed by local stakeholders, which dictates their land eligibility (Ryberg et al., 2020). The European Environmental Agency (Coppens, 2009), for example, evaluates the land eligibility of onshore wind farms considering only the avoidance of protected areas as a constraint, leading to a land availability of 82% across Europe. By considering more restricting land eligibility frameworks (including suitability factors depending on land cover type and constraints based on protected areas, terrain slope, elevation, forests, settlement areas and water bodies), the land eligible for onshore wind farms range from 23% to 40% in Europe (Mckenna et al., 2015; Bosch et al., 2017; Eurek et al., 2017). However, land use change (LUC) (during construction and after decommissioning of wind energy systems) can plays a critical role in the social acceptance and environmental impact of both conventional and renewable electricity generation (Fthenakis and Kim, 2009; Zaunbrecher et al., 2018). Any onshore wind energy installation results in the change or loss of habitat areas, either directly through the occupation of land by the overhead infrastructures, or indirectly due to species avoiding the areas around wind power facilities (Gasparatos et al., 2017). Habitat loss was reported to influence the presence and distribution of bids and bats species (Tabassum-Abbasi et al., 2014; Wang et al., 2015). Habitat change, instead, reduces biodiversity due to the collision of bats and birds with the structure of the wind turbines (Devereux et al., 2008; Villegas-Patraca et al., 2012), and the decrease of landscape connectivity that plays an important role in connecting dispersed ecosystems (Roscioni et al., 2014; Oloo et al., 2018; Guo et al., 2020). Shepherd et al. (2021) showed that, out of the 21 terrestrial habitats identified in Scotland, 14 habitats were affected by the construction of onshore wind farms.

The extent to which onshore wind developments contribute to GHG emissions from LUC across different landscapes has not received much research attention. Understanding the environmental trade-offs from LUC to wind energy is important for identifying coherent and integrated approaches to land use decisions between the energy and Agriculture, Forestry and Other Land Use (AFOLU) sectors, as well as new financial instruments to support activities that reduce the overall cost of mitigating GHG emissions to society. In this study, we aim to spatially quantify the land use change (LUC) emissions that derive from the construction of onshore wind farms in peatland, forest, arable and other land use types. We selected Scotland as it is one of the most important administrative areas in Europe for onshore wind energy developments. In Scotland, onshore wind power represents about 70% of the renewable energy capacity, and approximately 50% of the turnover (£1.5 billion) generated from onshore wind farms in the UK (ONS, 2018). In our LUC analysis, we use the current locations of wind farms as a reference scenario driven by the economic benefits for landowners of leasing land for wind power. We compare the reference scenario to a future scenario in which we assume that landowners and farmers can access C-based schemes aiming to increase soil C sequestration, and protect terrestrial C stocks and current levels of crop production in arable land. We discuss the results in terms of potential opportunity C costs (C_{OC}), which correspond to the CO_2 emissions that land could have been sequestered if no LUC would have occurred to wind farms. In the calculation of C_{OC}, we exclude the GHG emissions from activities for which landowners have no visibility of, such as: i) the development of the overhead wind farm infrastructure, ii) transmission and distribution, iii) backup power generation, and iv) improvement of habitat after the wind farm decommissioning.

2. Material and methods

2.1. Overview of the land use change CO_2 emissions from wind farms

We assessed LUC CO_2 emissions from the construction of onshore wind farms placed on arable land, forests, peatlands, grasslands and other land uses. The location of the onshore wind farms in Scotland is derived from the UK Renewable Energy Planning Database quarterly (BEIS, 2019a), and includes geographical and technical information of wind farms that are awaiting construction, under construction and already constructed across Scotland for the year 2019. LUC emissions are calculated following the methodology reported in Nayak et al. (2010). This includes the calculation of direct (*D*) and indirect (*I*) emissions of CO_2 arising from the loss of above- and below-ground organic C stock, and coincides with the construction of the borrow pits, access track, and turbine hard-standing foundations of wind turbines. The conversion of CO_2–C (t C) to CO_2 (t CO_2) is given by Equation (1):

$$\mathrm{CO_2 - C \rightarrow CO_2} = \text{molecular weight of } \mathrm{CO_2}(44)/\text{atomic weight of C } (12) = 3.667 \tag{1}$$

Due to limited information available on the environmental impact of wind developments, we exclude reforestation elsewhere, active measures to limit drainage in peatland, and the re-introduction of plant species and re-surfacing of peatland. To include peat restoration in the calculations, it requires information on the hydrological conditions before the construction of the wind farm and after its decommissioning, and to demonstrate a high probability that peat hydrology can be restored across the sites (Nayak et al., 2010). Given the above limitations, we assume that at the end of their life time the majority of the wind turbines will be replaced with new ones.

2.2. Land use change emissions from peatlands

We focussed on the locations where wind farms were constructed on nationally important deep peat and priority peatland habitats. This included areas likely to have a high conservation value (Class 1), areas with potentially high conservation value and peatland restoration potential (Class 2), and carbon-rich soils classified as non priority peatland habitat, but associated with occasional peatland habitats (Class 3). These peatland areas were identified by the Scottish Natural Heritage through a consolidation of existing soil and vegetation data from the James Hutton Institute 1:25,000 and 1:250,000 scale soil data and Land Cover Map Scotland 1988 (see Section S.1 of the Supplementary Information). It is plausible to assume that the onshore wind farms considered in this study were developed after the Land Cover Map of Scotland 1988) was produced. However, here we assumed that the land use types impacted by the construction of the wind turbines correspond to the land use types that are reported in the land cover map of Scotland.

The direct CO_2 emissions (*DE*) due to the construction of borrow pits (*bp*), access track (*tr*) and turbine hard-standing foundations (*hs*) is estimated using Equation (2):

$$DE_{bp,\,tr,\,hs} = \left(\left(l_{ij} \times w_{ij} \times D_p\right) \times \left(CO_2 - C \rightarrow CO_2\right) \times SOC\right) N_T \tag{2}$$

were l and w are the length and width (m) of the ith type of construction (borrow pits, tracks or hard - standings) varying with the jth generation capacity of the wind farm (Table 1), D_P is the mean peat depth removed (m), *SOC* the organic C stock (t C ha^{-1}) at the location of development, and N_T the number of turbines in each wind farm

Table 1
Input data used to calculate the direct and indirect CO_2 emissions of wind farm in Scotland.

Input (i)	Wind farm capacity (j)		
	<10 MW	≥10 < 50 MW	≥50 MW
Average length (l) of turbine foundations (m)	10	15	22.18
Average width (w) of turbine foundations (m)	10	15	22.18
Length of access track (m) [a]	418	6513	32490
Width of access track (m) [a]	5.66		
Floating road depth (m)	0.53		
Length (l) of the hard-standing (m)	37.99		
Width (w) of the hard-standing (m)	32.29		
Extent of drainage around drainage features at site (m)	60		

[a] Input used also for floating roads.

development. The details of the spatial data set used in the calculations of D_p and SOC across Scotland is described in Section S.1 of the Supplementary Information.

The indirect emissions (IE) of CO_2 due to the drainage of peat during the construction of the borrow pits (bp), floating road (fr), and hard – standings (hs), were estimated calculating the drainage volume varying for each ith type of construction and jth generation capacity of the wind farm:

$$IE_{bp,\ hs} = \left(0.5\ \times D_p \times \left(\left(\left(2 \times e_{drain}\right) + l_{ij}\right) \times \left(\left(2 \times e_{drain}\right) + w_{ij}\right)\right) - \left(l_{ij} \times w_{ij}\right)\right) \times N_T \tag{3}$$

$$IE_{fr} = 0.5\ \times D_p \times \left(l_j \times \left(\left(2 \times e_{drain}\right) + w_j\right)\right) \tag{4}$$

where l and w are the length and width (m) of the ith type of construction, e_{drain} is the average extent of the drainage at site (m) (Table 1). Finally, the total indirect CO_2 emissions from peatland (IE_P) was calculated using Equation (5):

$$IE_P = D_p \times 3.667 \times \left(I_{bp} + I_{hs} + I_{fr}\right) \tag{5}$$

2.3. Land use change emissions from forest

The distribution of forest vegetation across Scotland is obtained using the National Forest Inventory (NFI) 2016 (Forest Commissions, https://www.forestry.gov.uk/inventory), which reports the location and area of woodlands above 2 ha distinct into eight forest types (broadleaved, conifer, mixed vegetation mainly broadleaved, felled and shrub). Table 2 summarises the total above- and below-ground C stock of each forest system for different forest components and their potential C sequestration rates (Morison et al., 2012).

In the calculations, C stocks of conifer forest are assumed to correspond to Silka spruce forest managed for thinning and felling with 50 year rotation. C stocks of broadleaved forest correspond to Oak forest managed for minimum intervention. C stocks of felled forest correspond to Oak forest for thinning and felling on an 80 years rotation. C stocks of mixed vegetation mainly broadleaves comprised 70% broadleaved and 30% conifer. Finally, the C stocks of shrub vegetation is estimated using the IPCC Tier - 1 method, which applies the IPCC default values provided for above-ground biomass and the root to shoot ratios (Ruesch and Gibbs, 2008).

The CO_2 emissions associated with wind farm construction in forest includes: a) the potential losses of C stored in trees and soil as a result of forestry clearance, b) the increase of over 10% of soil C stock due to change land use from forest to pastureland (Guo and Gifford, 2002), and 3) the emissions related to the loss of C-fixing potential in forest trees during the 25 years lifetime of the wind farms. The presence of extensive areas of forestry in the vicinity of the wind farm site significantly reduces the yield of wind energy (Nayak et al., 2010). However, no site level information was found on the area of forest cleared to construct the wind turbines. Therefore, we assumed that the extension of the LUC in forestry corresponds to 1 ha per turbine.

Table 2
Total C stock (t CO_2 ha^{-1}) and C sequestration (t CO_2 ha^{-1} yr^{-1}) in forest and shrub land used to estimate the LUC emission from the construction of wind farm. (a) Average biomass C stock calculated across the polygon map where the vegetation is located. (b) Average SOC at 1 m depth calculated from the National Soil Map of Scotland (Soil Survey of Scotland Staff, 1981).

	Forest component	C stock	C sequestration rate	
			0–5 years	5–25 years
Broadleaved	Tree	583	0.1	3.7
	Litter	27.2	0	0.3
	Soil	309.3	8	−0.7
	Harvested wood	0		
	Forest operations	−0.1		
Conifers	Tree	169.1	0.4	3.1
	Litter	22.3	0.1	0.1
	Soil	791.6	−23.5	−3.8
	Harvested wood	12.9		
	Forest operations	−4.2		
Mixed vegetation mainly broadleaved (70% broadleaved – 30% conifer)	Tree	458.83	0.19	3.52
	Litter	25.73	0.03	0.24
	Soil	453.99	−1.45	−1.63
	Harvested wood	3.87		
	Forest operations	−1.33		
Felled	Tree	226.7	0.7	3.8
	Litter	58.4	0.1	0.3
	Soil	265.3	8	−0.7
	Harvested wood	14.5		
	Forest operations	−2.4		
Shrub	Tree	27.1–11 [a]	0.7	0.7
	Litter		0.1	0.1
	Soil	228 [b]	8	8

[a] Average biomass C stock calculated across the polygon map where the vegetation is located.
[b] Average SOC at 1 m depth calculated from the National Soil Map of Scotland.

The direct CO_2 emission from forest clearance and soil C removed by the turbine infrastructure is calculated applying Equation (6):

$$DE_F = \left(\left(B_k + L_k + H_k - O_k\right) \times A\right) + \left(SOC \times 3.667 \times \left(l_{ij} \times w_{ij}\right) \times N_T\right) - \left(SOC \times 3.667 \times 0.1\right) \tag{6}$$

where (DE_F) is the total direct emission, A is the deforested area based on the number of turbines N_T in the wind farm, SOC the soil C stock up to 1 m depth, and l and w are the length and width (m) of the ith type of construction (borrow pits, tracks or hard - standings) varying with the jth generation capacity of the wind farm (Table 1). B, L, and H correspond to the C stock accumulated during the forest cycle in standing biomass, litter, and harvested biomass respectively, and O is the CO_2 emissions from forest operations for each kth vegetation type (i.e broadleaved, conifers, mixed vegetation, felled, and shrubs) (Table 2)

The CO_2 emissions from potential forest C sequestration during the 25 years lifetime of the wind farms are classified as indirect emissions (IE_F), and estimated from the sum of the C sequestrated in vegetation in the initial 5 years, and from 5 to 25 years of the forest management cycle:

$$IE_{F5} = ((AI_{Bk} + AI_{Lk} + AI_{Hk} + AI_{Ok}) \times 5) \times A \quad (7)$$

$$IE_{F20} = ((\mathrm{AI_{Bk}} + \mathrm{AI_{Lk}} + \mathrm{AI_{Hk}} + \mathrm{AI_{Ok}}) \times 20) \times \mathrm{A} \quad (8)$$

In Equations (7) and (8), *AI* correspond to annual C stock increment (t CO_2 ha^{-1} yr^{-1}) of standing biomass, litter, harvested biomass, and CO_2 emitted from forest operations (*B*, *L*, *H*, and *O*) for each kth vegetation type (broadleaved, conifers, mixed vegetation, felled, and shrubs). In mixed vegetation forest *AI* is estimated considering 70% of the C sequestered derived from the main vegetation type (broadleaved) and the remaining 30% of contribution derives from conifer vegetation (Table 2).

2.4. Land use change emissions from arable and other land use types

The information on the location use of cropland in Scotland is derived from the spatial data set of Edina agricultural census (EDINA, 2018), using the 2 km^2 resolution grid map of 16 crop types and 12 vegetables types for the year 2015. Crop production (yield) and market price are derived from the UK National Statistics on Agriculture for the year 2019 (National Statistics, 2019) (Table 3).

Scottish crop information was extracted considering the extent of the agricultural parishes used in the Agricultural Census for the payment of farming grants and subsidies. In particular, we focused our analysis on the most representative arable crop types cultivated within the parishes; thus most likely to be affected by the development of wind farms. Production losses was estimated only for the crops and vegetables explaining more than 80% of the parish arable land. In addition, as cropland fields are in general located in the proximity of farm buildings already serviced by access tracks we assumed a conservative length of 418 m for the permanent access tracks to the turbine (Table 1).

Direct soil CO_2 emissions from soils (*DE*), associated with wind farm construction of borrow pits, access track and turbine hard-standing foundations, is estimated using Equation (9).

$$DE_{bp,\ tr,\ hs} = SOC \times 3.667 \times \left(l_{ij} \times w_{ij}\right) \times N_T) \quad (9)$$

where *SOC* is soil C stock up to 1 m depth, and *l* and *w* are the length and width (m) of the ith type of construction (borrow pits, tracks or hard - standings) varying with the jth generation capacity of the wind farm.

The loss of crop production value (British Pound, £), due to the loss of agricultural land and covering the lifetime of the wind farm, is calculated using Equation (10):

$$L_{Prod} = Y_i \times P_i \times A_j \times 25 \quad (10)$$

where *Y* is the yield (t ha^{-1}), *P* the price (£ t^{-1}) for each ith crop type, *A* is the area of the turbine foundation jth (borrow pits, access tracks, or hard-standings) related to the dimension of the turbines.

2.5. Carbon payback time of the wind farms

Net reduction of CO_2 emissions from wind farms occurs when the emissions due to the wind farm development is less than the C savings achieved by avoiding fossil fuel use (Smith et al., 2014). This is expressed as the C payback time ($t_{Cpayback}$, years), and includes the CO_2 emissions from both the development of the infrastructure overhead of the wind farms (E_{inf}), and as described in the previous sections the construction of the wind turbines.

Table 3
Information on the potential area (mean ± sd), and production level (yield and market value) of five major crop types directly affected by the construction of the wind farms in Scotland for the year 2019. The category 'vegetables' includes only the fresh vegetables for human consumption and cultivated in the open.

Type	Area (%)	Yield (t ha^{-1})	Value (£ t^{-1})
Wheat	15.1 ± 11.4	9	162
Barley	67.1 ± 16.3	7	147
Oats	4.4 ± 4.2	5.8	148
Oilseed rape	7.1 ± 3.9	3.3	334
		Value (£ ha^{-1})	
Vegetables	1.8 ± 2.2	9965	

E_{inf} is estimated using Equation (11) (Nayak et al., 2010):

$$E_{inf} = 934.35 \times C_{turb} - 467.55 \quad (11)$$

where C_{turb} corresponds to maximum rate of energy generation of the turbine capacity.

$t_{Cpayback}$ is formulated as the ratio of the total C losses (E_{tot}) to the annual C savings ($\mathrm{S_{turb}}$):

$$t_{Cpayback} = \frac{E_{tot}}{S_{turb}} \quad (12)$$

$$S_{turb} = \left(24 \times 365 \times \rho_{cap} \times n_{turb} \times C_{turb}\right) \times EF \quad (13)$$

where E_{tot} is the sum of E_{inf} and any direct and indirect LUC emission from the construction of the wind turbines, ρ_{cap} is the average capacity factor of the wind turbines in Scotland (30%), n_{turb} is the number of turbines, C_{turb} is the maximum capacity factor of the turbines, and *EF* is the emission factor based on a C intensity of the UK energy grid of 0.222 t CO_2 MWh^{-1} (BEIS, 2020b) for the year 2020. If $t_{Cpayback}$ is more than the life time of the wind farm, then no net reduction in C emissions is achieved (Ruesch and Gibbs, 2008).

2.6. Opportunity costs of wind farms

The LUC emissions from wind farms in peatland, forest, arable land and other land use types are reported in term of opportunity C costs (C_{OC}) and economic opportunity cost (E_{OC}). C_{OC} and E_{OC} correspond to the environmental and economic benefits that landowners give up by choosing to construct a wind farm on their land. The calculation of C_{OC} excludes CO_2 emissions from the development of the overhead wind farm infrastructure, transmission and distribution losses, backup power generation, and as mentioned above the potential C saving from the improvement of habitat after the wind farm decommissioning. Therefore, C_{OC} refers only to the CO_2 emissions that land could have sequestered if no LUC would have occurred. C_{OC} of the wind farms is reported both as total CO_2 emissions (t CO_2), and CO_2 emission intensity based on the potential wind power generated every year (g CO_2 kWh^{-1}) following conversion:

$$\mathrm{COC} = \frac{CO_2/(n_{turb} \times C_{turb})}{\rho_{turb} \times 24 \times 365} \times 1000 \quad (14)$$

In the calculation of E_{OC} we used the current scenarios of wind farms in Scotland as a reference scenario driven by the economic benefits for landowners of leasing their land for wind power. The reference scenario is compared to a future scenario in which landowners and farmers can access incentive-based C schemes in a form of auctioned contract to landowners to protect the permanence of C stock in soils, avoid deforestation, and secure current level of crop production. E_{OC} of the wind farms is calculated multiplying the total CO_2 emissions from LUC related to the construction of wind turbines by the C price in the UK trading market. The valuation of CO_2 is based on the marginal abatement cost estimates provided by BEIS (2019b), which suggests a range of CO_2 values (low, central and high) for consideration in project appraisals. Here, we applied the central (£20.54/t CO_2) and high (£37.04/t CO_2) short-term traded CO_2 values for the year 2021. E_{OC} excludes any grant funding available to landowners for afforestation, peat restoration, or sustainable agriculture (i.e. C additionality).

3. Results

3.1. Opportunity costs of wind farms in peatlands

The calculation of C_{OC} of wind farms in peatlands included the modelled depth of peatlands found in Scotland (see Supplementary Information). The Geographic Weighted Regression model used 232 soil depth measurements carried out in peatlands classified between Class 1 and 3, and spatially simulated the potential peat depth (D_P) using a bandwidth distance of 80,523 m. Across all type of peatland, D_P was on average 1.25 ± 0.52 m (mean ± sd), and 17% lower than the measured values (1.51 ± 1.55 m). At the location where wind farms were constructed, D_P resulted 1.4 ± 0.5 m. In addition, D_P resulted to have an overall fitness (adjusted R^2) of 0.25, with low R^2 coinciding with peatlands located in the north-east of Scotland affected by low number of soil depth measurements (see Fig. S1 in Supplementary Information).

Fig. 1 shows the 60 wind farms located in peatland across Scotland, and Table S1 in the Supplementary Information summarises the wind farm capacity, peatland depth and the CO_2 emissions generated from the construction of the wind farms. The average payback time ($t_{Cpayback}$) of the wind farms in peatlands ranges from 2.1 years in Peaty gleyed podzols with dystrophic semi-confined peats to 9.3 years in Dystrophic basin peats. The total CO_2 emission from wind farms constructed in peatland is 4,013,230 t CO_2, and average C_{OC} of 560.3 ± 396.1 g CO_2 kWh^{-1} (Fig. 2 and Table 4). Approximately 90% of the CO_2 emissions in peatland derives from the construction of 24 wind farms located in Dystrophic blanket peats and Peaty gleyed podzols (Table S1, Supplementary Information). However, Dystrophic basin peat are the habitat with the highest C_{OC} (1759.6 g CO_2 kWh^{-1}), and Peaty gleyed podzols with dystrophic semi-confined peat are the habitat with the lowest C_{OC} (151.7 g CO_2 kWh^{-1}). E_{OC} of wind farms in peatlands depends upon the traded C value applied (central £ 11.5 ± 8.1 MWh^{-1} and high 20.8 ± 14.7 MWh^{-1}), and varies from £3.1 for each MWh generated per year in Peaty gleyed podzols with dystrophic semi-confined peat up to £65.2 MWh^{-1} in the Dystrophic basin peats habitats (Fig. 2, Table 4).

3.2. Opportunity costs of wind farms in forest

34 wind farms were constructed in forest (Fig. 1) with an overall capacity of 1956 MW. Based on the assumption that the construction of each turbine required 1 ha of forest to be cleared, the total area of forest directly land displaced by the wind turbines was approximately 783 ha. In particular, the areas cleared varied across the five forest types as: felled > conifer > broadleaved > mixed mainly broadleaved > shrub (see Table S2 in the Supplementary Information). The direct (*DE*) and indirect (*IE*) CO_2 emission from the construction of the wind farm in forest is 367,400 and 139,904 t CO_2, respectively (Fig. 2 and Table 4), which corresponds to a $t_{Cpayback}$ of 1.7 ± 0.1 years. Felled forest is the habitat with the highest land area affected by wind farms with an overall C_{OC} of 264,501 t CO_2, of which 58% derives from direct emissions (*DE*) and 38% from indirect emission (*IE*). Mixed mainly broadleaved forest is the system with the highest C_{OC} intensity (128.3 g CO_2 kWh^{-1}), of which 80% derives from *DE* and 20% from *IE*. The average C_{OC} of wind farms in forest is 88 ± 42.3 g CO_2 kWh^{-1}, and approximately 3.2 times lower than the emissions related to the development of the overhead infrastructure of the wind farms (E_{inf} = 283.7 ± 13 g CO_2 kWh^{-1}). Depending on the forest type and traded C value applied, E_{OC} over the life time of the wind turbines ranges from £0.3 MWh^{-1} in shrub land, up to £4.8 MWh^{-1} per year in mixed mainly broadleaved (central £ 1.8 ± 0.9 MWh^{-1} and high 3.3 ± 1.6 MWh^{-1}) (Table 4, Fig. 2).

3.3. Opportunity costs of wind farms in cropland and other land use type

We found 68 wind farms constructed or under construction in cropland and distributed across 45 agricultural parishes (Fig. 1 and Table S3 in the Supplementary Information). In these parishes, the cultivation of barley, wheat, oilseed rape, oats and vegetables for human consumption represents 95.5% of the cultivated arable land in Scotland. These crops can be cultivated in different seasons in rotation, and based on their spatial occurrence in Scotland their area is ranked as: barley > wheat > oilseed rape > oats > vegetables for human consumption (Figure S2 in the Supplementary Information). On a per hectare basis, wheat is the crop with the highest productivity and the crops with the highest market value are vegetables for human consumption (Table 3).

The total LUC CO_2 emissions from wind farms constructed on arable land is 37,858 t CO_2 (Fig. 2), with an average $t_{Cpayback}$ of 1.2 ± 0.2 years (Table 4 and Table S3). Due to the seasonality of the cultivation, it was not possible to partition the C_{OC} of wind farms across different crops. However, the C_{OC} of wind farms on cropland is on average 44.9 ± 1.2 g CO_2 kWh^{-1}, which is 5.9 times lower than E_{inf} (262.7 g CO_2 kWh^{-1}). Depending upon the traded C value applied, E_{OC} from arable soils ranges from £ 777,605 up to £ 1,402,263. Whereas the E_{OC} deriving from the loss of crop yields ranges from £1,716,073 in Oats up to £15,398,669 for vegetable crops (see Table S3 in the Supplementary Information). The total economic losses related to the crop yield displaced from wind farms ranges from £2 MWh^{-1} in oats up to £13.3 MWh^{-1} per year in vegetables for human consumption (central £ 4.4 ± 4.7 MWh^{-1} and high £ 4.9 ± 4.7 MWh^{-1}) (Table 4, Fig. 2).

The category 'other land uses' comprises nardus-molinia grasslands, dry and wet heather moor, montane vegetation, undefined mixed woodland, pasture land, low scrubland, and smooth grasslands (see details in the Supplementary Text, Table S.7). Across these land uses we found 137 wind farms with approximately 3687 MW of capacity. The construction of these wind farms produced LUC CO_2 emissions of 312,844 t CO_2, and an average $t_{Cpayback}$ of approximately 1.4 ± 0.1 years (Table 4, Fig. 2). Across the category other land uses, C_{OC} varies from 18.6 g CO_2 kWh^{-1} in undefined mixed woodland to 39.9 g CO_2 kWh^{-1} in nardus molinia grass. Finally, the E_{OC} of wind farms constructed in other land use types ranges from £0.4 MWh^{-1} in undefined mixed woodland to £1.5 MWh^{-1} per year in nardus-molinia grassland, (central £ 0.6 ± 0.1 MWh^{-1} and high 1.1 ± 0.2 MWh^{-1}) (Table 4, Fig. 2).

4. Discussion

The competition for natural resources between the energy sector and the AFOLU sectors may pose conflicts between their net zero strategies. In the UK, payment schemes such as the Renewable Obligation, Feed-in Tariff, Feed-in Premiums, and quota obligations have significantly contributed to the development of onshore wind energy (Kitzing et al., 2012; Hall et al., 2020). These support instruments have made onshore wind power production an attractive investment for landowners. Landowners can access opportunities based on annual lease agreement, ranging from £4000 to £5000 per megawatt (MW) of installed capacity (NFU, 2015) that covers the lifetime of the development. On the contrary, there are no national policies that directly target the protection of terrestrial C stocks beyond the provision of information and advice for land managers (CCC, 2020a). In this complex policy landscape, the European Green Deal (EC, 2019) made clear that the land sector needs more and improved financial instruments for managing terrestrial C stocks and enhancing C sequestration. GHG mitigation strategies need to be driven by incentives which consider the opportunity cost that can be derived from new climate mitigation strategies in AFOLU (Radley, 2021; CCC, 2020a).

In the UK, the wind farm regulatory framework is mostly focussed on planning the construction and operation of onshore wind farms (Topham and McMillan, 2017), and there is no requirement to specifically consider the impact from LUC on GHG emissions and ecosystem services (Hall et al., 2020). However, the climate change mitigation benefits generated by wind energy depend also on its impact on the land where it is constructed (Kiesecker et al., 2019). At global scale, the development of wind and solar energy can potentially affect more than 11 million hectares of natural lands, resulting in 3.1 million ha in habitat

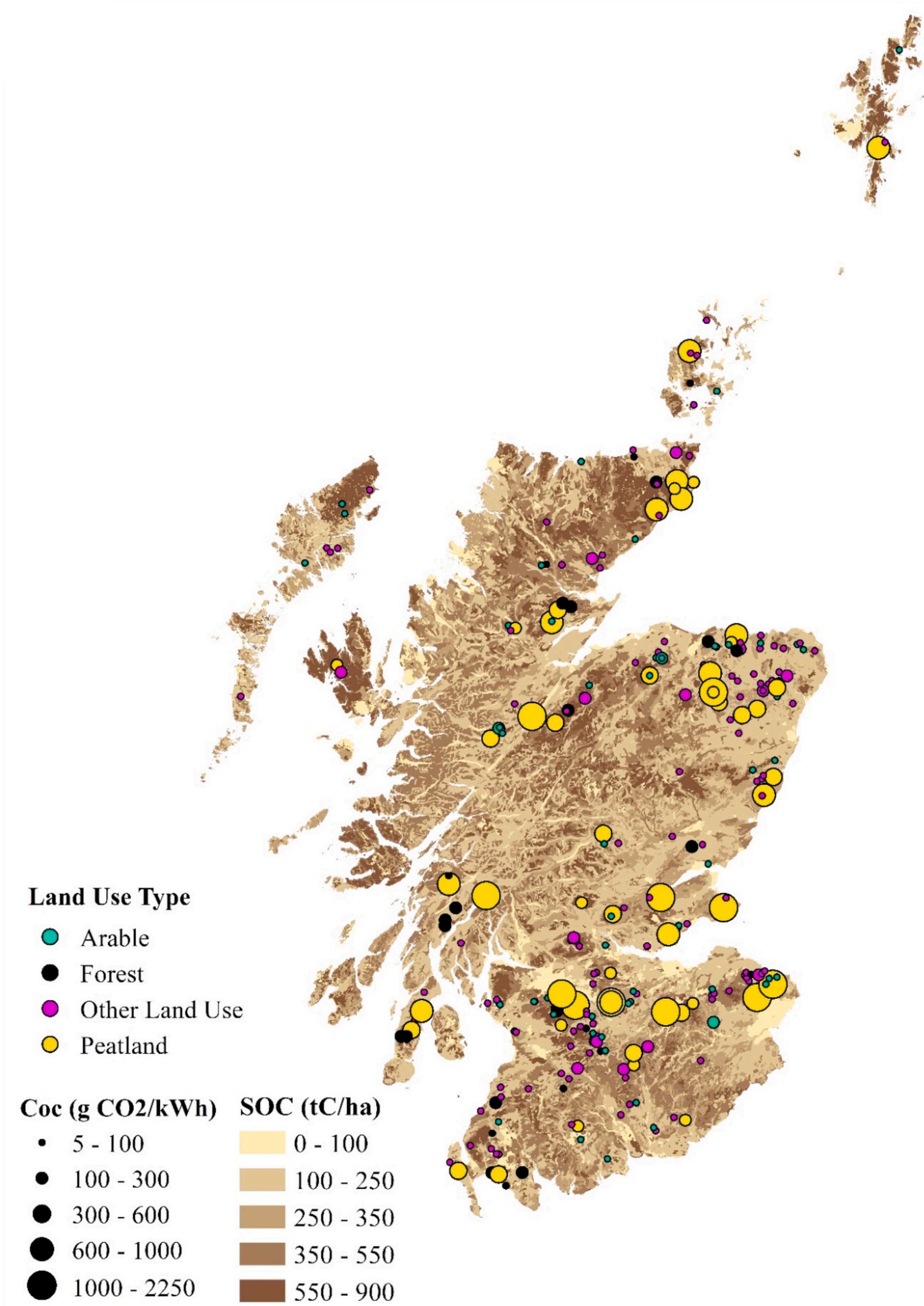

Fig. 1. Soil organic C stock density (t C ha^{-1}) to 1 m depth, and the distribution of onshore wind farms in arable land, forest, peatland and other land use types in Scotland. The opportunity C cost (C_{OC}, g CO_2 kWh^{-1}) corresponds to the CO_2 emissions that landowners could have avoided if the initial land use was not displaced by the wind farms.

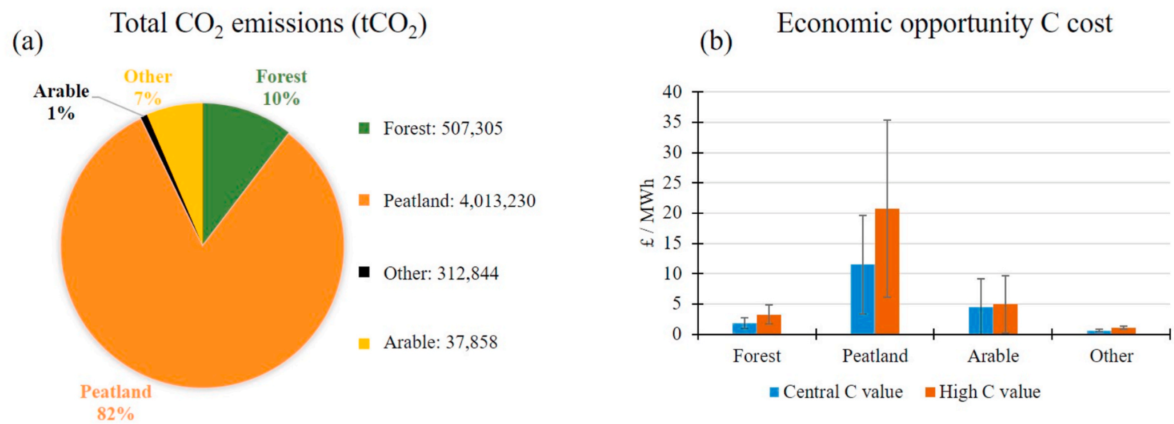

Fig. 2. Opportunity Carbon Costs of onshore wind farms. (a) Total land use change CO_2 emissions related to the construction of wind farms in forest, peatland, arable, and other land use types (i.e. grassland, pastureland). (b) Economic opportunity cost of CO_2 emissions calculated multiplying the total CO_2 emissions from LUC by the short-term traded value of CO_2 for the year 2021, which ranges from £20.54/t CO_2 (central) to £37.04/t CO_2 (high).

Table 4
Summary of the opportunity C costs from onshore wind farms constructed in peatland, forest, cropland and other land uses. Capacity corresponds to total generation capacity of the wind farms, E_{inf} is the CO_2 emission from the development of the infrastructure overhead of the wind farms, C_{OC} is the C opporunity cost conciding with the CO_2 emissions from the construction of wind turbines, and E_{OC} is the economic opportunity cost per each MWh of wind power generated per year, and based on carbon prices (£/t CO_2) corresponding to the central and high short-term traded C values for the UK for the year 2021 (BEIS, 2019b).

	Definition	*Capacity* (MW)	E_{inf} (g CO_2 kWh^{-1})	C_{OC} (g CO_2 kWh^{-1})	$tC_{payback}$ (years)	E_{OC} (£) (central – high)
Peatland	Dystrophic basin peat	51	303.2	1759.6	9.3	36.1–65.2
	Dystrophic blanket peat	1106	277.0	743.7	5.8	15.3–27.5
	Dystrophic semi-confined peat & peaty rankers	8	270.8	626.9	4.0	12.9–23.2
	Peaty gleyed podzols	401	280.1	519.4	3.8	10.7–19.2
	Peaty gleyed podzols & dystrophic blanket peat	7	278.2	280.6	2.5	5.8–10.4
	Peaty gleyed podzols & dystrophic semi-confined peat	22	306.1	151.7	2.1	3.1–5.6
	Peaty gleyed podzols & peaty gleys	25	210.3	895.4	5.0	18.4–33.2
	Peaty gleyed podzols & peaty gleys & dystrophic blanket peat	73	280.3	410.4	3.4	8.4–15.2
	Peaty gleyed podzols & peaty gleys & peaty rankers	3	296.2	396.4	3.1	8.1–14.7
	Peaty gleys & dystrophic blanket peat	92	263.1	416.4	2.7	8.6–15.4
	Peaty gleys & dystrophic blanket peat & peaty gleyed podzols	181	279.0	587.4	4.3	12.1–21.8
	Peaty gleys & dystrophic semi-confined peat	294	261.2	301.0	2.7	6.2–11.1
	Peaty gleys & peaty gleyed podzols & dystrophic blanket peat	141	293.6	373.0	2.9	7.7–13.8
	Subalpine podzols & dystrophic blanket peat	149	300.5	382.9	2.7	7.9–14.2
Forest	Broadleaved	147	297.3	98.1	1.8	2.0–3.6
	Conifer	750	281.0	99.8	1.7	2.0–3.7
	Felled	1027	277.4	98.0	1.7	2.0–3.6
	Mixed vegetation mainly broadleaved	24	266.6	128.3	1.8	2.6–4.8
	Shrub	9	296.2	16.0	1.4	0.3–0.6
Other land use	Dry heather moor	625	289.0	27.1	1.4	0.6–1.0
	Improved pasture	1148	265.0	30.9	1.3	0.6–1.1
	Montane vegetation	376	282.6	26.2	1.2	0.5–1.0
	Heather moor	720	287.6	38.4	1.3	0.8–1.4
	Nardus-molinia grassland	512	266.3	39.9	1.4	0.8–1.5
	Wet heather moor	95	284.0	26.3	1.4	0.5–1.0
	Low schrub	18	296.2	34.6	1.5	0.7–1.3
	Undefined mixed woodland	18	278.2	18.6	1.3	0.4–0.7
	Smooth grassland	175	281.4	29.8	1.4	0.6–1.1
Cropland	Barley	479	262.7	44.9	1.2	2.3–2.7
	Wheat					2.9–3.4
	Oats					2.0–2.5
	Oilseed					2.2–2.7
	Vegetables					12.8–13.3

loss and approximately 1.5 gigatonnes (Gt) of CO_2 emitted from LUC (Kiesecker et al., 2019). In this study, we showed that the construction of 3843 wind turbines in Scotland generated approximately 4.8 million tonnes of CO_2 emissions from LUC. Depending on the value of CO_2 in the trading market, these GHG emissions represent opportunity costs ranging from £127.2 to £210.2 million (i.e. medium or high short-term traded CO_2 values).

4.1. Opportunity costs from land use change in peatland

Peatlands cover a significant proportion of Scotland, and are mostly located in uplands areas that are the best for developing wind energy. However, a number of studies have increased awareness about the high C emissions that can be generated from the construction of wind farms on peatland soils (Nayak et al., 2010; Smith et al., 2014). The longevity of the pools of C held in forest is much shorter than that of C held in the peat soils, hence the LUC emissions of wind farm constructed in peatland has C implications that last well beyond the life time of the wind farm (Smith et al., 2014). In our analysis, we determined that the payback time of wind farms in peatland is on average 60% longer than in forest, and approximately 70% longer than in cropland or pasture lands. We found that CO_2 emissions from LUC in peatlands are approximately 87–92% higher than in forest and other land uses, respectively. In addition, the opportunity C cost of wind farms in peatland ranges from 151.7 to 1759.6 g CO_2 kWh^{-1}. This means that, in the best case scenario the opportunity carbon costs of wind farms in peatland are comparable to the life cycle emissions of combined cycle gas turbines (CCGT) with carbon capture and storage (CCS), which were reported to vary from 140 to 200 g CO_2 kWh^{-1} (Viebahn et al., 2007). By contrary, in the worst LUC case scenario the opportunity carbon costs of wind farms constructed in peatland are higher than the life cycle emissions of coal and gas-fired electricity generation without CCS, which can vary from 786 to 990 g CO_2 kWh^{-1} (Nie et al., 2011; Odeh and Cockerill, 2008). In the presence of a voluntary-based C scheme for landowners, the preservation of peatland habitats could generate economic opportunity costs ranging from £3.1 up to £65.2 MWh^{-1} per year, depending on the value of traded value of CO_2 in the market. Based on the high traded value, the overall CO_2 emissions from wind farms constructed in peatlands can generate economic opportunity costs ranging from £115,752 in Peaty gleyed podzols to £80.1 million in dystrophic blanket peats. By contrary, assuming annual lease agreements between the wind energy companies and the land owners of £5000 per megawatt (MW) of installed capacity, over the 25 years of life time of the wind farms economic the benefits for landowners would be approximately £319.1 million. The profits from the voluntary C market schemes could be summed to the social return of peatlands, which in lowland and upland sites has been estimated to generate between £13,000 and £190,000 for every hectare affected by the wind farms (CCC, 2020a). However, based on the value of CO_2 in the trading market, the preservation of peatlands would provide less than 50% of the economic benefit given by the auctioned contracts for wind power.

4.2. Opportunity costs from land use change in forest

In the UK, C sequestration in forestry is expected to decline due to the dramatic reduction in tree planting in recent years to an average of 9000 ha per year since 2010 (Brandmayr et al., 2019). At the same time, to place the AFOLU sectors on a pathway to net zero by 2050, the Committee on Climate Change advocated that forestry cover in the UK will need to increase from 13% to at least 17% by planting around 30,000 ha of broadleaf and conifer woodland each year (CCC, 2020b). However, in the standard framework of land eligibility for wind energy developments (Serrano-Gonzalez and Lacal-Arantegui, 2015) the opportunity costs related to the loss of forests C stocks are not taken into consideration. The Scottish Ministers by Forestry and Land Scotland, for example, reported that since the year 2000 the area of forest that has been cleared for the development of onshore wind farm is 6994 ha (FOI/EIR release, 2020). Assuming an average forest biomass C stock of 200 t CO_2 ha^{-1} (Table 2), in Scotland the direct emission from deforestation due to LUC to wind farms is approximately 1.4 Mt CO_2. In this study, we found that the total LUC emissions from the construction of wind farms in forest is 507,305 t CO_2. However, the emissions from our calculation are conservative as they reflect only 1 ha of forest land cleared to construct the borrow pits, access track and turbine hard-standing foundations. Based on these conditions, we found that the opportunity C costs of wind farms in forestry correspond to 88 g CO_2 per kWh of electricity generated per year. This means that, the opportunity C costs of wind farm constructed in forest is similar to the life cycle emissions of solar photovoltaic (PV) systems, which has been reported to vary from 75 to 116 g CO2 kWh^{-1} (Allen et al., 2008). The permanence of the forest C stocks removed by the wind farms could generate economic benefits over the life time of the wind farms ranging from £7755 in shrubland up to £9.8 million in conifer forest. By contrast, over the life time of the wind farms the economic benefits from the contracts with the energy companies would generate £244.5 million.

4.3. Opportunity costs from land use change in cropland and other land use types

We found that on average the opportunity C costs of wind farms constructed in cropland (44.9 g CO_2 kWh^{-1}) is in general higher than the in other land use types (30.2 g CO_2 kWh^{-1}). In Scotland, these results are partially explained by the use of arable land as temporary grassland in long leys sometimes longer than cultivation, which tends to increase SOC stocks in arable soils. Therefore, the LUC emissions of wind farms in arable and grasslands are comparable to the emissions from LUC of solar energy, which was reported to vary from 11 to 53 g CO_2 kWh^{-1} (van de Ven et al., 2021). However, the reduction of GHG emissions in the energy sector should not be achieved at the expense of producing less food crops. Furthermore, any risks of C leakage due to changes in agricultural production should be included in the regulatory frameworks of wind farms. Our analysis showed that the economic opportunity costs of the wind farms constructed in grasslands and pasture would range from £0.40 up to £1.50 per every MWh generated per year. By contrast, the opportunity costs from the loss of crop production, which depends on the crop type displaced by the wind turbines, range from £2 up to £13.3 per MWh generated per year. This means that, based on the current values of CO_2 in the trading market, the opportunity cost of wind farms do not provide the monetary support in agriculture that can economically compete with the financial benefit generated by wind energy.

5. Conclusions

In its Sixth Carbon Budget published in December 2020, the Committee on Climate Change advocated the increase of onshore wind capacity in the UK to 25–30 GW by 2050 (CCC, 2020c). At the same time, new contingency policy plans have been set out to improve the design and implementation of net zero policies that cut across several different economic sectors (CCC, 2020b). This means that, the need to increase onshore renewable energy sources as part of a response to the decarbonisation of the energy sector must be reconciled with net zero strategies in the AFOLU. In this study, we showed that the potential LUC emissions due to onshore wind energy can play an important role in the life cycle emissions of the wind farms, and deserve a higher level of consideration in the regulatory frameworks for land eligibility, investigation and decommissioning. Emissions from LUC to wind energy are variable across different land cover types, and in the worst land use change scenarios these are comparable to the life cycle emissions of fossil-fuel energy technologies. To limit the trade-offs from LUC, it is essential to set aside land specifically for the development of onshore wind energy systems (Obane et al., 2020). This ensures also that wind turbines are geographically placed to protect ecosystem C stocks, and to minimize the carbon intensity of the electricity generated.

At present in the UK, landowners make land use decisions based on what they are paid for, and leasing land for wind power offers great opportunities for income. By contrast, there are no compliance C schemes financially support landowners for climate mitigation actions in AFOLU sectors (Radley, 2021). Forest landowners, for example, are not compensated for any land management abatement costs (Juutinen et al., 2018), and farmers can only access C credits in the voluntary C market for mitigation actions aiming to protect soil C stocks that in the medium-term risk reducing their agricultural production. Here we showed that, in the presence of a voluntary C trading scheme, the permanence of the forest C stocks removed by the wind farms could generate economic benefits over the life time of the wind farms up to £9.8 million in conifer forest. Over the same time frame, in cropland the loss of crop yield can be as high as £15.4 million. In the near future, the introduction of the Environmental Land Management System may provide the support instrument for protecting and restoring natural capital and ecosystem services in the AFOLU sectors. Over time, it is hoped that the gaps between the economic benefits from onshore wind farms and land-based climate change mitigation strategies will close due the rising concerns over climate change impact on the environment and food security (Arneth et al., 2019).

CRediT authorship contribution statement

Fabrizio Albanito: Conceptualization, Data curation, Formal analysis, Writing – original draft, Writing – review & editing. **Sam Roberts:** Data curation, Writing – review & editing. **Anita Shepherd:** Writing – review & editing. **Astley Hastings:** Funding acquisition, Project administration, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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