CO_2 payback time for a wind farm on afforested peatland in the UK

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SUMMARY

The siting of wind farms on natural and afforested upland peatlands presents an interesting public policy dilemma. Such locations may offer developers attractive wind characteristics amidst sparse human settlement, but the associated disturbance of carbon from soils and vegetation may reduce the carbon benefits that can be derived from wind farm operation. To examine the relative impacts, an estimate was made of the CO_2 payback time for a wind farm hypothetically sited on an afforested peatland in north-east England known as Harwood Forest. The location is representative of many potential wind farm sites, and was chosen for this study because its carbon fluxes and stores have been extensively characterised. We adjusted a published LCA for a wind farm in another location to take account of CO_2 that would be emitted or not sequestered as a result of site disturbance if it were constructed and operated in Harwood Forest. The results show that the wind farm would compensate for its life cycle CO_2 emissions in less than three years of operation in Harwood Forest, whereas the CO_2 payback time would be reduced to less than five months if it were placed at an alternative site where CO_2 emissions from disturbed soil and vegetation were not an issue.

KEY WORDS: carbon balance, forestry, LCA, life cycle assessment, peat.

INTRODUCTION

Under the European Union Renewables Directive, the United Kingdom (UK) has a commitment to derive 15% of its final energy consumption from renewable sources by 2020 (DECC 2009). Meeting this objective will necessitate an increase in renewable electricity from about 5.5% of total usage today (DECC 2009) to more than 30% (HM Government 2009). Much of this will be from onshore wind turbines, whose visual and environmental impacts have raised particular public concern. The "dash for wind" has met with opposition from local communities concerned about the industrialisation of open land in the rural landscape, and the resulting delay in implementation has hindered the pursuit of national targets. One option is to build wind farms on upland (often peatland) which has already been afforested. Here, public concern may be less significant, largely because "naturalness" has already been altered by afforestation of wilderness areas with exotic conifer species, of which Sitka spruce (*Picea sitchensis*) is by far the most common.

The construction of wind farms in forestry plantations has a number of potential drawbacks. One of these relates to the performance of the wind turbines themselves; the plantation acts as a complex obstacle to air flow, tending to reduce wind speeds, increase wind shear and create additional turbulence (Boddington 2004). Of primary interest here, however, is the associated disturbance to ecosystems and processes within the forest. Establishing the wind farm requires clearance of a considerable area of plantation to accommodate roads and turbine platforms, and the resulting disturbance of soil has been associated with a significant flux of CO_2 to the atmosphere and to drainage waters (Waldron *et al*. 2009). Moreover, because such plantations are currently significant carbon sinks (Magnani *et al*. 2007), large-scale deforestation accompanying their conversion to wind farms would negatively impact on the national greenhouse gas inventory. Some commentators (e.g. Nayak *et al*. 2010) have taken the view that the CO_2 emissions caused by disturbance of poorly selected and managed sites approach or even exceed the emissions from fossil fuel combustion averted by the wind farm over its lifetime.

This conceptual study presents a first-order estimate, using life cycle assessment (LCA), of the effect of disturbance due to wind farm development on the carbon balance of a site in north-east England where carbon stores and fluxes in soils, vegetation and trees under active silvicultural management have been extensively characterised. We use a published LCA that estimates the embedded energy, CO_2 emissions and electrical power generation of a wind farm in another location, which is hypothetically placed within the UK electrical grid, allowing us to adjust for CO_2 that would be emitted or not sequestered by the afforested peatland as a result of site disturbance during construction and operation of the wind farm. Life cycle energy and CO_2 assessments for the wind turbines and associated civil engineering works are combined with characterisations of forest and peatland carbon stores and fluxes to assess how clearfelling a parcel of forest and disturbing its soil would change the CO_2 payback calculation.

METHODS

Study site

Harwood Forest is a *ca*. 4,000 ha Sitka spruce (*Picea sitchensis*) plantation in Northumberland National Park, England. It is located at 55º 12' N, 02º 02' W, about 30 km inland from the North Sea coast (Figure 1), at an altitude of 200–400 m a.s.l. Annual rainfall is around 950 mm and mean annual temperature about 7 ºC (Zerva & Mencuccini 2005b). The soil is mostly shallow peaty gley, and the land was ericaceous moorland before it was converted to forest plantation in the 1930s. The water table fluctuates seasonally and its level varies spatially, with greater depths to water table beneath mature forest stands (average 20 cm in winter, 90 cm in summer) and shallower depths in clearfelled stands (10 cm in winter, 25 cm in summer) (Zerva & Mencuccini 2005a). The forest plantation is segmented into stands of different ages with a forest rotation of approximately 40 years. At the end of each rotation the stands are clearfelled and replanted, although silvicultural practices are now changing in order to reduce adverse impacts on carbon balance arising from the disturbance of forest.

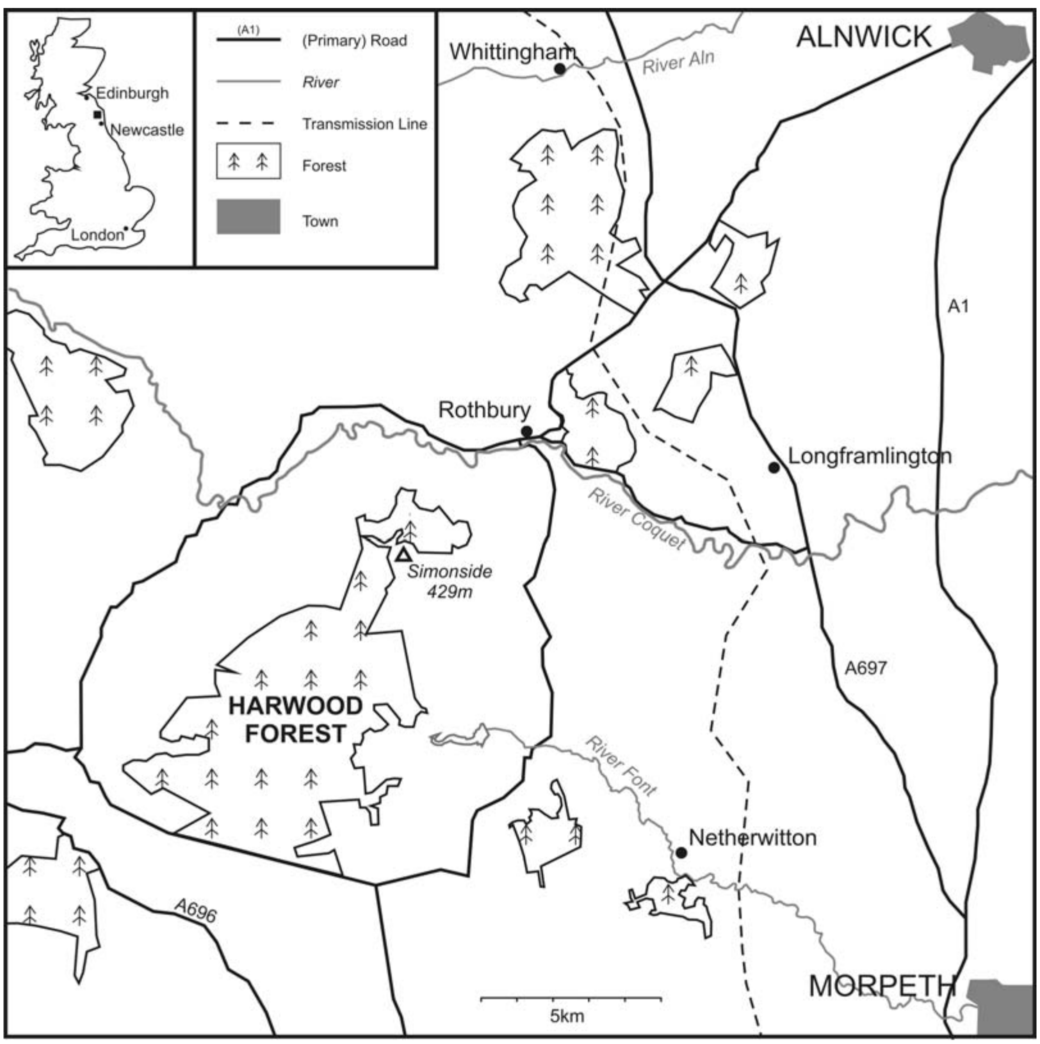

Figure 1. Location of Harwood Forest.

In this part of the country, organic soils over a large area of upland landscape are dominated by ericaceous dwarf shrubs such as *Calluna vulgaris* and *Vaccinium* spp., with notable peat deposits. The population density is low and the prevailing use of the land is for low-intensity sheep grazing, military training, amenity and forestry. The region's forests extend to about 100,000 hectares, of which the UK Forestry Commission owns and manages half. Forest resources are conceived as being for mixed use, and the region's spatial strategy (NEA 2008) lists a dozen or so forest-derived benefits including recreation, tourism, timber, ecosystem protection, CO_2 sequestration and renewable energy resources. The theoretical wind energy potential of Harwood Forest and Knowesgate has been assessed at 400–500 MW (installed capacity), but a report to the North East Assembly which balanced wind energy development in the region against preservation of the landscape recommended that this should be reduced to 100 MW (NEA 2006).

Wind farm life cycle assessment

Ardente *et al*. (2008) present a detailed evaluation of the energy and environmental performance of a non-peatland wind farm in Italy, which indicates that the lifetime CO_2 costs incurred by the development can be recovered within six months of commissioning. On this basis, wind power generation is clearly an effective strategy for reducing emissions as the remainder of the wind farm's operating life is essentially carbon free. The question remains, however, whether the CO_2 emissions and the payback time are altered significantly when the effects of disturbing ecosystem processes within a forested and/or peatland site are taken into account. To arrive at an estimate, we explore the CO_2 emissions and lost C sequestration that would result from placing the Ardente *et al.* (2008) wind farm on the afforested peatland at Harwood Forest. In order to simulate the translocation as accurately as possible, site-specific information on all facets of the wind farm's likely carbon budget was derived from literature, as described below.

Life cycle assessment of wind turbines

Life cycle assessment (LCA) is based on the principle that it is possible to estimate the total amount of energy and materials required for, and the emissions associated with, manufacturing, operating, and decommissioning an energy generating technology. While full LCA considers a wide range of impacts including global warming potential, acidification, human toxicity, *etc*., it is common to see more restricted analyses that concentrate purely on energy and CO_2 emissions. Life cycle assessments have been performed on a wide range of renewable energy sources including wind (Tahara *et al.* 1997, Lenzen & Munksgaard 2002, Ardente *et al.* 2008, Martinez *et al.* 2009, Tremeac & Meunier 2009), solar (e.g. Alsema 2000), wave (Parker *et al*. 2007) and tidal stream (Douglas *et al*. 2008) converters.

Within LCA, energy analysis concentrates on determining an energy intensity (often expressed as $kWh_{in}\ kWh_{el}^{-1}$), which relates the energy embodied within materials, manufacturing processes and the operation of a device over its lifetime (kWh_{in}) to the electricity generated (kWh_{el}) over the same period. Typical wind farms have energy intensities significantly lower than unity; that is, they generate more energy during their lifetimes than is required to manufacture, operate and decommission them. The vast majority of the energy input occurs during manufacture and installation. Lenzen & Munksgaard (2002) suggest energy intensities of around 0.03 to 0.09 $kWh_{in}\ kWh_{el}^{-1}$. Associated with this is the energy payback time, which is the time it takes a turbine to generate the primary-energy equivalent of the energy input required for its construction, operation and decommissioning. Typical energy payback times are around six months (Lenzen & Munksgaard 2002, Martinez *et al*. 2009, Tremeac & Meunier 2009), suggesting that over a 20-year lifetime a turbine would generate 40 or more times the quantity of energy consumed (Ardente *et al.* 2008).

Of more direct interest here is the CO_2 intensity, which expresses the carbon emissions associated with manufacture, operation and decommissioning of the generator per unit of electricity production over its lifetime. Typical units are g $CO_2\ kWh_{el}^{-1}$, and it can be calculated as:

$$CO_{2\text{-eq}}\ \text{intensity} = \frac{E_{CO_2}}{8760 \cdot \lambda \cdot P \cdot T} \qquad (1)$$

As there are no CO_2 emissions from fossil fuel burn, E_{CO_2} represents the indirect CO_2 emissions (kg CO_2) arising from manufacture, construction, operation and decommissioning over the life cycle of the device. The denominator is the lifetime energy production (kWh_{el}), calculated as the product of the turbine's rated power P (kW), the annual load factor λ (%) (see below), the operating lifetime T (years) and the number of hours in a year (8760).

The variability of wind means that the turbine will not always operate at its rated power. The load factor reflects this and is the ratio of the net electricity generated by the wind turbine to the net generation that would have occurred if it were to operate continuously at its rated capacity. Typical load factors in the UK are around 30% (DECC 2009), although there is considerable variation and load factors for some sites in the Shetland Isles are as high as 53.5% (Boehme & Wallace 2007). The load factor cited in Ardente *et al*. (2008) is atypically low at around 20%; this was attributed to operational problems and anomalous weather during the first year of operation. For the calculations here, we assume a load factor of 27%, which was the average for onshore wind in the UK in 2008 (DECC 2009).

In order to determine CO_2 equivalent emissions, other greenhouse gases are converted to CO_2 equivalence by their global warming potentials (Bolin *et al.* 1995), using a 100-year time horizon. Life cycle CO_2 emissions for the eleven-turbine wind farm assessed by Ardente *et al.* (2008) were in the range 2,700–3,700 t CO_2; the corresponding CO_2 intensity was calculated at 10–15 g CO_2 kWh_{el}^{-1}.

The CO_2 payback time is the time required for the CO_2-equivalent emissions avoided by displacing grid electricity with wind power generation to equal the emissions released during the life cycle of the turbine, i.e. E_{CO_2}. A typical value for payback would be around six months (Ardente *et al.* 2008) but there is substantial variability between studies. The payback time depends on the life cycle emissions and the amount of electricity generated by the turbine, but also on the assumed carbon intensity of the grid electricity displaced by the wind turbine. There is a great deal of debate over grid intensity because emissions vary significantly between electricity systems and over time, and it is not a straightforward matter to identify precisely what generation has been displaced at any one moment. A common practice in LCA is to apply an average national electricity generation mix. For the UK in 2007 this was 39% coal, 36% natural gas, 17% nuclear and 8% other (DECC 2008), giving an average intensity of around 0.52 kg CO_2 kWh^{-1}. However, UK Government guidelines recommend a CO_2 intensity figure of 0.430 kg CO_2 kWh^{-1} when calculating avoided CO_2 emissions from renewable generation; this is stated to reflect long run emissions from combined cycle gas turbines, which are assumed to be the first plants to reduce output in response to reduced electricity demand (DEFRA 2008). Alternatively, some studies assume that wind displaces marginal coal plants; a displacement value of around 0.860 kg CO_2 kWh^{-1} (IEA 1998) has been used in the UK. Nayak *et al.* (2008, 2010) offer a compromise by assuming that all thermal power plants (oil, gas, and coal) are used for grid balancing and it is their combined output that is displaced when nuclear and renewable power is generated. Their recommendation, applied in this study, is to use the emission factor of the UK's fossil fuel sourced grid mix, which was 0.605 kg CO_2 kWh^{-1} in 2008 (DECC 2009, page 125, Table 5C).

Wind farms and disturbance of forest ecosystems

The wind farm development at Harwood Forest is assumed to be identical in structure to that described by Ardente *et al.* (2008), with eleven 660 kW turbines, each with a rotor diameter of 50 m, a steel tower 55 m high and a lifetime of 20 years. The use of relatively modest turbines is justified here as, although larger turbines (~2 MW) are now common, their deployment may be blocked in this location due to visual impacts. In addition to the turbine specifications, and critically for this study, Ardente *et al*. (2008) offer a detailed breakdown and assessment of the civil engineering works that are primarily responsible for site disturbance; these include roadways, cable trenches and the turbine foundations. Despite the modest capacity of this wind farm it still requires substantial volumes of materials to build the turbines and the associated civil infrastructure (Table 1).

Table 1. Quantities (in tonnes) of major materials used in manufacture of turbines and civil works for an eleven-turbine wind farm (Ardente *et al*. 2008).

Material	**Wind turbines**	**Civil Works**
Steel	731	123
Cast iron	66	
Glass-reinforced plastic	54	
Copper	10	3
Plastics	<1	36
Aggregate		21,708
Local soil/stones		10,333
Sand		2,802
Concrete		4,097

Each tower is supported by a square, steel-reinforced concrete foundation 'pad' about 10–15 m per side (Lindsay 2005, Nayak *et al*. 2010). The pit required to accommodate the foundation is about 20 m square (Nayak *et al.* 2008, LWP 2006), although in practice the area disturbed may be greater (Lindsay 2005); here we assume the excavated area to be a 30 m square. A perimeter buffer around the excavation pit might be clearfelled to allow access to the turbine pad. This buffer area is assumed to be a 50 m square enclosing the excavated area. A hard standing area is commonly constructed for each pad site to provide a stable foundation for the cranes that are used in construction, maintenance and decommissioning of the turbine. In the case study cited by Hall (2006), the area of excavation required for each hard standing was about equal to the area needed for the turbine base itself, and this 1:1 ratio is used here. The turbine pads are connected by a network of access roads built after clearfelling trees. The roads are made of crushed stone emplaced in a roadbed approximately 5 m wide (LWP 2006). It is assumed that road construction requires excavation or destruction of the peat down to mineral soil. We estimate that 500 m of new road construction is required per turbine (Nayak *et al*. 2008, Lindsay 2005, LWP 2006) and that a 10 m buffer will be cleared of trees on each side of the access road. Crushed stone for road beds is assumed to be quarried off-site (Hall 2006, Nayak *et al.* 2008) without any need for deforestation or peat excavation. As transmission cables can be buried alongside the access roads, no additional disturbance is attributed to their emplacement. Two utility buildings, a substation and a control station are each assumed to require 2 ha of clearfelling and peat excavation (estimated visually from LWP 2006). In summary, each turbine pad can be characterised by land subject to *excavation* for construction of roads, hard standings, utility buildings and the foundation itself; and land subject to *degradation* in a buffer zone around the foundation and alongside roads. Per turbine, excavated land totals 0.79 ha and degraded land approximately 1.16 ha.

Carbon losses resulting from ecosystem disturbance

Harwood Forest provides an excellent case study location due to the existence of a series of established studies of soil and biomass carbon for forest of a range of ages on the same soil and geological substrata. Zerva & Mencuccini (2005a) report the soil and biomass carbon stocks whilst Magnani *et al.* (2007) compare the CO_2 fluxes of the entire ecosystem with other cases in Europe. Kowalski *et al.* (2004) show the magnitude of carbon losses when soils are disturbed at harvesting, with clearfelling converting a managed UK forest from a carbon sink of around 6 t C ha^{-1} year^{-1} to a source of around 1 t C ha^{-1} year^{-1} for several years because respiratory fluxes from the soil exceed photosynthesis.

Although it is likely that real turbines would be positioned in forest stands of different ages, it is assumed here that all site development occurs in 20-year-old second rotation stands, in order to simplify the estimation of carbon fluxes. This is a reasonable "typical" stand age for a forest plantation established in the 1930s with 40-year rotations. Moreover, the timing of future harvest for the 20-year-old stand is conveniently synchronous with the end of the 20-year lifetime of a wind farm; and this assumption about stand age permits the use of data collected at Harwood Forest by Phillips (2000), Zerva *et al.* (2005), Zerva & Mencuccini (2005a, b) and Magnani *et al.* (2007).

On excavated land, harvesting of trees will be followed by complete removal of the peat soil. It is assumed that the (organic) peat will be left exposed to the elements and so will decompose aerobically, with all of its carbon content being released to the atmosphere. This assumption is inaccurate because, for example, an unknown fraction of the carbon will be transported to rivers, probably over a long period. Also, the developer may temporarily stack excavated peat and later restore a portion of it to the landscape.

It is assumed that the buffer areas will be managed to encourage the development of grassland vegetation and discourage tree growth during the lifetime of the wind farm. The initial clearfelling will prolong exposure of the soil to solar irradiation and deprive it of carbon inputs from litterfall and tree roots, leading to significant loss of carbon (Zerva & Mencuccini 2005a, b). Soils alone released about 15 t C ha^{-1} in the first ten months after tree harvesting at Harwood Forest (Zerva & Mencuccini 2005a); but this loss will be partially offset by sequestration, litterfall and below-ground carbon transport as invasive grassland vegetation matures (Huotari *et al.* 2009). A value of 81 t C ha^{-1} is adopted for soil carbon loss on degraded land, calculated as the difference between the carbon stock of the second rotation 20-year-old stand (181 t C ha^{-1}) and the clearfell site (100 t C ha^{-1}) of Zerva *et al.* (2005).

Branches and roots are assumed to remain onsite after clearfelling. Roots die and decompose below ground, contributing to the soil carbon efflux. Branches decompose on the land surface, releasing all carbon to the atmosphere. Tree stems are transported from the site to sawmills and are ultimately used in construction and furniture. Following Harmon *et al.* (1990), 43% of the carbon from the stems is assumed to remain sequestered from the atmosphere for at least the lifetime of the wind farm, while the remaining 57% is released to the atmosphere in less than five years.

Phillips (2000) estimated that the carbon stored in an 18-year-old stand of trees at Harwood Forest was around 70 t C ha^{-1}, about half of which was allocated to tree stems, mirroring the allocation for stems and bark found in a plantation of Sitka spruce in Ireland (Green *et al.* 2007). Adding two years of carbon storage within trees to Phillips' (2000) estimate at a rate of 4.79 t C ha^{-1} yr^{-1} (Green *et al.* 2007) gives 79.58 t C ha^{-1} for a 20-year-old stand. This could not be reconciled with an alternative estimate (154 t C ha^{-1}) for Harwood derived by applying *R* (the ratio of below-ground to above-ground biomass) equal to 0.23 (Green *et al*. 2007) to the figure for carbon storage in fine and coarse roots of a 20-year-old stand (28.8 t C ha^{-1}, generated by allometric equations) given by Zerva *et al.* (2005). Accordingly, this study adopts an intermediate value based on careful field measurements in Ireland by Green *et al.* (2007), who estimated the total carbon stock in a 19-yr-old stand at 91 t C ha^{-1}. Adding one year's carbon accumulation to simulate a 20-year-old stand yields 95.8 t C ha^{-1} for carbon stored in trees; one-half of this for stems is 47.9 t C ha^{-1} and an equal amount is allocated for roots and branches.

Phillips (2000) noted ecosystem accumulation of carbon (in soils and forest biomass) of around 5 t C ha^{-1} $year^{-1}$ over a 40-year chronosequence. Sequestration rates in the second half of this period, when the trees had matured, are likely to exceed this figure because the ecosystem showed net carbon loss during an unknown portion of the first half. Magnani *et al.* (2007) measured maximum net ecosystem production in stands of age 3–30 years at around 5.5 t C ha^{-1} yr^{-1}; this figure is adopted for the 20-year-old forest.

Calculations

The effects of site disturbance on ecosystem CO_2 loss over the wind farm's lifetime and CO_2 payback time were calculated in the Microsoft® Office Excel spreadsheet which is published with this article at http://www.mires-and-peat.net/map04/map_04_10_calc.zip. Table 2 summarises the values of all variables used in the calculations. First, the wind farm's baseline CO_2 intensity and payback time were assessed without taking into account any impacts of site disturbance. The effects of (a) the CO_2 lost from the 8.69 ha of excavated land and (b) the CO_2 lost from the 12.76 ha of degraded land were then examined separately, and comparisons made. Finally, a sensitivity study was conducted by systematically varying key values and assumptions in turn.

Table 2. Values of variables used to calculate the effects of site disturbance on ecosystem CO_2 losses and CO_2 payback time, with literature sources.

Wind farm and grid variables	**Value**	**Reference**
Turbine capacity (kW)	660	Ardente *et al.* (2008)
Number of turbines / pad sites	11	Ardente *et al.* (2008)
Wind farm lifetime (yrs)	20	Ardente *et al.* (2008)
Load factor (%)	27	DECC (2009)
Wind farm life cycle CO_2 emissions (kg CO_2)	3,700,000	Ardente *et al.* (2008)
CO_2 intensity of grid electricity (kgCO_2 kWh^{-1})	0.605	DECC (2009)
Site disturbance and ecosystem variables		
Excavated area per turbine (ha)	0.79	Nayak *et al.* (2008, 2010); Lindsay (2005); LWP (2006)
Degraded area per turbine (ha)	1.16	Nayak *et al.* (2008); Lindsay (2005); LWP (2006)
C stock, peat soil (kg C ha^{-1})	181,000	Zerva *et al.* 2005
Soil C lost, clearfell (kg C ha^{-1})	81,000	Zerva *et al.* 2005
C stock, roots & branches (kg C ha^{-1})	50,000	Green *et al.* (2007)
C stock, tree stems (kg C ha^{-1})	35,000	Green *et al.* (2007)
C lost, tree stems (%)	57	Harmon *et al.* 1990
Ecosystem C sequestration (kg C ha^{-1} yr^{-1})	5,500	Magnani *et al.* 2007
Soil pH	4.9	Zerva & Mencuccini (2005a)
Average annual temperature (°C)	7	Kowalski *et al.* (2004)
Conversion factors		
Conversion C to CO_2	3.667	

RESULTS

Wind farm without site disturbance

Ardente *et al*. (2008) estimate that all aspects of manufacture, installation, operation and decommissioning of the eleven-turbine wind farm would incur an inherent (embedded) emissions 'cost' of 2,700–3,700 t CO_2 over its life cycle; the range indicates the uncertainty in the CO_2 burden of the materials used. Assuming a 27% load factor for Harwood Forest, annual power generation here would be 17,171 MWh, giving a CO_2 intensity of 10.8 g CO_2 kWh_{el}^{-1} based on the more conservative estimate of life cycle carbon cost (3,700 t CO_2). With a grid electricity carbon intensity of 0.605 kg CO_2 kWh^{-1}, the annual CO_2 emissions avoided will be 10,389 t CO_2 yr^{-1} and the CO_2 payback time 130 days or less than five months.

Effect of site disturbance

Table 3 shows the estimated CO_2 losses from five forest ecosystem categories affected by the wind farm over its life cycle. Overall, about 24,176 t CO_2 is released, and this is split more or less evenly between excavated and degraded land. This estimate of CO_2 emitted as a consequence of site disturbance must be added to the wind farm's embedded lifecycle CO_2 emissions of 3,700 t CO_2 to arrive at a global emissions estimate for the wind farm.

Table 4 shows the effect of combining disturbance-related CO_2 emissions with the inherent CO_2 cost of the wind farm. The overall emissions total 27,876 t CO_2 and the CO_2 intensity increases to 81.2 g CO_2 kWh^{-1}. The net impact is that the payback time increases to 979 days, or less than three years. Thus, the analysis indicates that, even when CO_2 emissions due to site disturbance are taken into account, a wind farm development on the afforested peatland at Harwood Forest could pay back embedded CO_2 emissions in a reasonable period and thus represents an effective strategy for reducing CO_2 emissions from electricity generation.

Sensitivity

Figure 2 shows the effect on CO_2 payback time of increasing some of the wind farm variables and ecosystem CO_2 loss factors by 10%. CO_2 payback time is sensitive to wind farm load factor (important in determining energy output) and assumed grid CO_2 intensity, with an increase in these variables reducing the payback time. This study adopts the historically reported UK load factor value of 27%;

Table 3. Estimated carbon losses from the forest and peat soil system at Harwood Forest due to construction and 20-year operation of the wind farm.

	Losses (t CO_2)		
Disturbance Process	**excavated area**	**degraded area**	**total**
Lost CO_2 sequestration	3,521	5,147	8,668
Excavation of peat to accommodate infrastructure	5,794	0	5,794
Degradation of peatland in buffer zones	0	3,790	3,790
Decomposition of tree branches and roots	1,533	2,241	3,774
Disposal of unpreserved stem material	874	1,277	2,151
total	11,722	12,454	**24,176**

Table 4. Comparison of estimates of CO_2 emissions, intensity and payback for the wind farm at Harwood Forest, with and without the effect of site disturbance.

	CO_2 emissions (t CO_2)	**CO_2 intensity** (g CO_2 kWh^{-1})	**CO_2 payback** (days)
Without site disturbance	3,700	10.8	130
With site disturbance	27,876	81.2	979

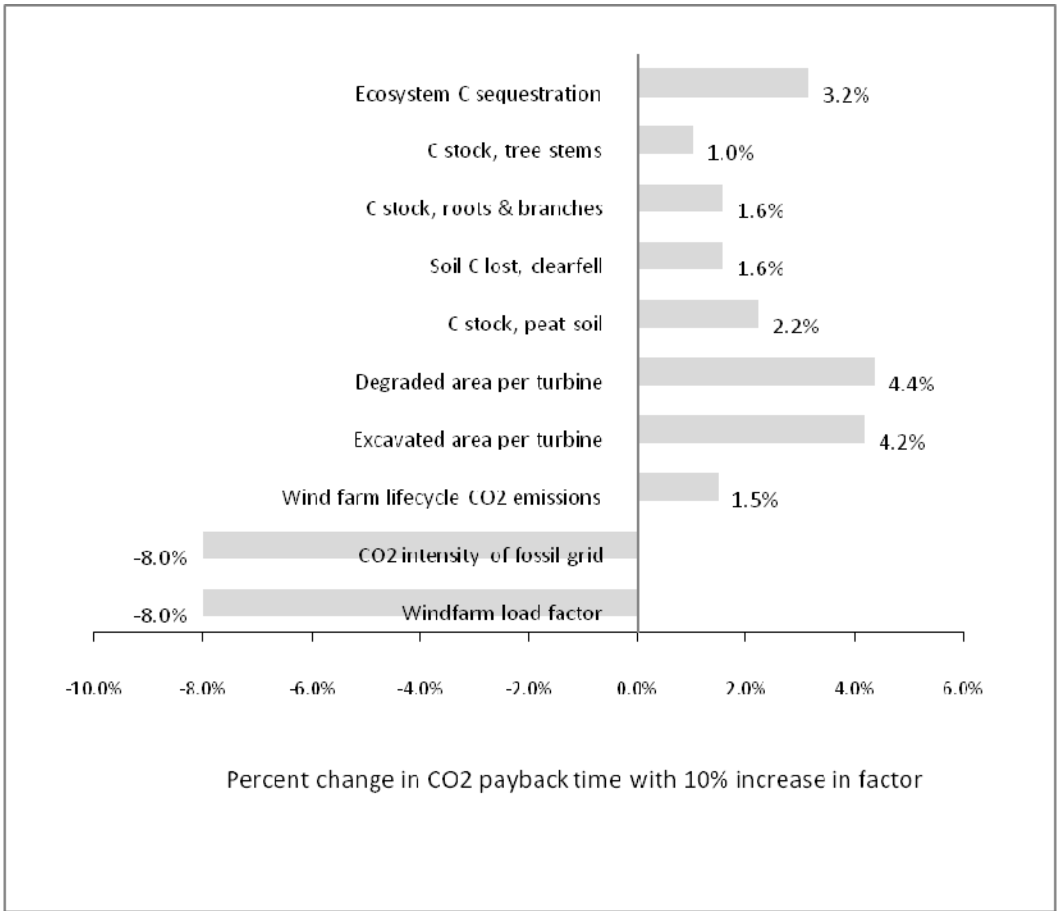

Figure 2. Sensitivity of wind farm CO_2 payback time to a 10% increase in key factors for the emissions case that includes ecosystem CO_2 release due to site disturbance. CO_2 payback time is 979 days before varying key factors.

increasing this to 29.4%, which was the UK average for onshore wind on an unchanged configuration basis in 2008 (see DECC 2009, section 7.76 and Table 7.4) would reduce the CO_2 payback time by 80 days (-8%). Likewise, increasing the assumed electrical grid CO_2 intensity to that of coal power generation, i.e. 0.860 kg CO_2 kWh^{-1} (IEA 1998), reduces payback time by 290 days (-30%). Alternatively, using a grid intensity of 0.43 kg CO_2 kWh^{-1} to represent displacement of gas turbine electricity generation lengthens the CO_2 payback time by 399 days (+40%). CO_2 payback time is also sensitive to LCA assumptions about the wind farm's life cycle CO_2 emissions; using Ardente *et al.*'s (2008) lower estimate of 2,700 t CO_2 would decrease payback time by 35 days (-4%).

Sensitivity to increases in the assumed CO_2 losses from ecosystem processes is smaller, with ecosystem carbon sequestration and disturbed area assumptions showing the largest changes. This study uses the maximum carbon sequestration value of around 5.5 t C ha^{-1} yr^{-1} for stand ages spanning 3–30 years which was measured using eddy covariance apparatus at Harwood Forest by Magnani *et al.* (2007). Taking the maximum value of 9.0 t C ha^{-1} yr^{-1} reported for a Sitka spruce plantation in Ireland by Black *et al.* (2009) would increase the CO_2 payback time by 194 days (+20%). The area excavated and degraded during wind farm development is site specific, is dependent upon developer practices, and shows significant variation in published reports (Nayak *et al*. 2008, 2010; Hall 2006). Because the water table at Harwood Forest is lower than in natural bog, a smaller allocation of hard standing per pad site may provide sufficient stable ground for turbine construction on afforested peatland. We used a ratio of 1:1 for turbine base to hard standing area, following the Environmental Statement for a Lake District proposal quoted by Hall (2006), while Nayak *et al* (2008) use a ratio closer to 1:3.5 in their case study. Using the latter allocation for hard standings lengthens payback time by 117 days (+12%). Our estimate of the area excavated for turbine bases is generous; replacement of some of the excavated peat soil immediately after construction should yield a smaller disturbed footprint and lower emissions (Nayak *et al.* 2008). Our sensitivity study indicates that change in the area degraded is relatively significant for the CO_2 calculations, but would need to increase by more than fifteen times to push the CO_2 payback time beyond the lifetime of the wind farm.

DISCUSSION

Hall (2006) performs a calculation similar to that presented here, based on information provided in an Environmental Impact Assessment for a proposed 27-turbine wind farm on a Cumbrian peatland, which returns a CO_2 payback time of 3.5 years. In a second study, the same author calculates CO_2 payback times of 8–16 years for wind farms on peatland soils in Scotland (cited by Douglas 2006). One salient difference between these estimates and the one presented here is in the assumed CO_2 intensity of grid electricity replaced by the turbines; Hall (2006) uses the gas turbine (only) figure of 0.43 $kgCO_2\ kWh^{-1}$.

Another difference is in the assumed carbon losses in natural (Hall 2006) *versus* second-rotation afforested (this study) peatland soils and ecosystems. A natural bog's hydrology is often poorly understood by planners (Lindsay 2005) and natural peatland needs to be considered as much a mounded or flowing body of water as a parcel of land. Excavations, linear cuts for roads, cable trenches and drainage ditches disrupt water flow and result in lowered water table and aeration of peat soils for a significant distance from the edge of disturbance (Boelter 1972). Calculations of CO_2 payback times for wind farms on natural peatlands assume that excavation and ditch drainage results in aeration of peat soils extending 50 m (Nayak *et al.* 2008; Hall 2006), 100 m (Hall 2006, high case) and 200 m (Lindsay 2005) from the edge of excavation. At Harwood Forest, decades of silviculture have introduced a complex of roads and drainage ditches which fundamentally modify surface water flow patterns, while the patchwork of forest stands of different ages results in differential water table drawdown. Over a 10-month period in 2002, depth to water table averaged 60 cm beneath 40-year-old forest compared to 16 cm in a nearby clearfelled parcel as a consequence of water use and evapotransporation in the forest stand (Zerva & Mencuccini 2005a). As the water table at Harwood Forest is already discontinuous and drawn down, we did not assume a halo of peat oxidation beyond the boundary of excavated or clearfelled land. Furthermore, silvicultural practices including excavation of drainage ditches and overturning of topsoil are incorporated in the carbon loss figures for a clearfelled forest in Zerva *et al* (2005).

Hargreaves *et al.* (2003) documented conversion of peatland from a carbon sink (~0.25 t C ha^{-1} $year^{-1}$) to a source (2–4 t C ha^{-1} $year^{-1}$) after it was drained and ploughed, but observed that the peatland became a carbon sink again when ground vegetation recolonised. Sedges, rushes and grasses that invade a clearfelled site at Harwood Forest within the first year after harvest (Zerva & Mencuccini 2005a) represent a significant store of below- and above-ground carbon (Huotari *et al*. 2009). We did not assume complete oxidation of soil carbon in our degraded (clearfelled but unexcavated) zone as others have done (Hall 2006, Douglas 2006). At Harwood Forest, the original conversion from natural to afforested peatland, accompanied by soil carbon loss from drainage, occurred more than 50 years ago. Soil carbon has accumulated beneath first- and second-rotation forest cover since then, but has never attained previous levels; today, an undisturbed grassland adjacent to Harwood Forest contains 274 t C ha^{-1} of soil carbon compared to 140 t C ha^{-1} in a first rotation 40-year-old stand and 249 t C ha^{-1} for second rotation 30-year-old stand (Zerva *et al*. 2005). The initial drainage during the transition from undisturbed peatland to plantation forest results in a pulse of the most labile fraction of peatland soil carbon, leaving a relatively higher fraction of recalcitrant soil carbon in the disturbed ecosystem (Laiho 2006). The response of soil carbon to site disturbance (i.e. clearfelling and soil degradation) at Harwood Forest should follow the patterns documented for disturbance to an afforested plantation by Zerva *et al.* (2005), Zerva & Mencuccini (2005a) and Phillips (2000), and would not be expected to mimic that of a drained natural peatland. For one thing, clearfelling at Harwood Forest precipitates raising rather than lowering of the water table, and soil carbon loss may be driven more by loss of litterfall and increase in solar irradiance (Zerva *et al.* 2005, Zerva & Mencuccini 2005a, Zerva & Mencuccini 2005b) than by oxidation of peat due to aeration.

Nayak *et al.* (2008, 2010) have provided the most comprehensive approach to estimating CO_2 payback times for wind farms located on peatlands, utilising published sources for estimating carbon stores and fluxes, and providing analytical tools for planners to *prospectively* estimate life cycle CO_2 emissions for peatland wind farms. Their studies underline the importance of management decisions in reducing

CO_2 payback time, and suggest that with wise site selection, management practices and peatland restoration, additional greenhouse gas emissions attributable to site disturbance can be limited to less than 10% of the total C emissions saved. Nayak *et al.* (2008, 2010) do not assume complete oxidation of drained peat soils, but rather apply equations derived empirically during development of the ECOSSE soil carbon model for CO_2 and CH_4 emissions (Smith *et al*. 2007). These equations are not directly applicable at Harwood Forest, firstly because litterfall and below-ground carbon transport from trees (and their loss after clearfelling) exceeds that of a natural peatland, making the comparison inconsistent; and secondly, because export of dissolved and suspended organic carbon in streams is greatly accelerated in the first years after clearfelling due to harvesting practices and may represent losses in the order of 5–10 t C ha^{-1} yr^{-1} (Reynolds 2007). The approach adopted here differs from that of Nayak *et al.* (2008, 2010) in that it is *retrospective*, using field measurements of carbon stores and fluxes to estimate CO_2 payback time. We support the contention of Nayak *et al.* (2008, 2010) that characterising peatland hydrology is critical in estimating the CO_2 emissions from degraded land, and that action taken to minimise the drainage of water from soils around roads, turbine foundations and building works is essential for minimising carbon loss.

CONCLUSION

Useful conclusions can be drawn from the work of Nayak *et al*. (2008, 2010), Hall (2006) and this study. First, CO_2 emissions caused by site disturbance may equal or exceed those resulting from the manufacture, operation and decommissioning of a wind farm. Secondly, although the calculations are site specific, wind farms on natural and afforested peatlands can deliver acceptable CO_2 payback times of less than four years. This relatively short payback time underlines the productivity and low carbon footprint of wind turbines over their operating lifetimes. However, there is a distinct difference between natural and afforested peatlands in terms of their responses to site disturbance. Natural peatland ecosystems are fragile hydrological complexes in which introduced features that interrupt water flow can lower the water table far from the edge of excavation, exposing the most labile carbon fraction to decomposition. In an afforested peatland, the landscape is a quilt of forest stands with drawn-down, segmented and discontinuous water table, lessening the influence of drainage on soil carbon efflux. Clearfelling at Harwood Forest results in a rise in water table, not a drop, and in any case the most labile fraction of soil carbon will have been lost during the initial conversion to plantation decades earlier. A more significant factor in the disturbance of afforested peatlands is the loss of sequestration, litterfall and below-ground carbon transport from trees, as well as the accelerated loss of dissolved and suspended organic carbon in streamflow as a result of clearfelling.

Despite the technical case that the CO_2 emissions avoided by installing a wind farm on an afforested peatland probably exceed the emissions caused by disturbance of the site, it should be remembered that CO_2 payback time is a relative measure. The case for excavating and degrading peatland soil is supportable only as a lesser of evils. A higher portion of low-carbon power in the national electricity mix would reduce its CO_2 intensity and extend the CO_2 payback time if calculated on the basis of the full grid mix, thus weakening the case for building wind farms on natural and semi-natural sites. Wind power developers should be aware of greenhouse gas emissions associated with site development and make efforts to reduce the footprints of pad sites, buffer zones, roads and building works that disturb hydrology, forests and soils.

REFERENCES

Alsema, E.A. (2000) Energy pay-back time and CO_2 emissions of PV systems. *Progress in Photovoltaics Research and Applications*, 8, 17–25.

Ardente, F., Beccali, M., Cellura, M. & Lo Brano, V. (2008) Energy performance and life cycle assessment of an Italian wind farm. *Renewable and Sustainable Energy Reviews*, 12, 200–217.

Black, K., Byrne, K.A., Mencuccini, M., Tobin, B., Nieuwenhuis, M., Reidy, B., Bolger, T., Saiz, G., Green, C., Farrell, E.T. & Osborne, B. (2009) Carbon stock and stock changes across a Sitka spruce chronosequence on surface-water gley soils. *Forestry*, 82(3), 255–272.

Boddington, R. (2004) The effect of forestry on wind regime and energy yield. *One-Day Workshop on the Influence of Trees on Wind Farm Energy Yield*, British Wind Energy Association, Glasgow, 17th March 2004. Online at: http://www.bwea.com/planning/trees.html

Boehme, T. & Wallace, A.R. (2007) Hindcasting hourly wind power across Scotland based on met station data. *Wind Energy*, 11(3), 233–244.

Boelter, D.H. (1972) Water table drawdown around an open ditch in organic soils. *Journal of Hydrology*, 15, 329–340.

Bolin *et al.* (1995) *IPCC Second Assessment: Climate Change 1995. A report of the Intergovernmental Panel on Climate Change*. IPCC, Geneva, Switzerland, 64 pp. Online at: http://www1.ipcc.ch/ipccreports/assessments-reports.htm.

DECC (2008) *Digest of UK Energy Statistics (DUKES), 2008 Edition*. Department of Energy and Climate Change, 394 pp. Online at: http://www.decc.gov.uk/en/content/cms/statistics/publications/dukes/dukes.aspx.

DECC (2009) *Digest of UK Energy Statistics (DUKES), 2009 Edition*. Department of Energy and Climate Change, 371 pp. Online at: http://www.decc.gov.uk/en/content/cms/statistics/publications/dukes/dukes.aspx.

DEFRA (2008) *Guidelines to Defra's Greenhouse Gas Conversion Factors for Company Reporting, June 2008*. Department of Environment, Food and Rural Affairs, 13 pp. Online at: http://www.defra.gov.uk/environment/business/reporting/pdf/ghg-cf-guidelines2008.pdf.

Douglas, C.A., Harrison, G.P. & Chick, J.P. (2008) Life cycle assessment of the Seagen marine current turbine. *Proceedings of the Institution of Mechanical Engineers, Part M: Engineering for the Maritime Environment*, 222 (M1), 1–12.

Douglas, E. (2006) The hidden cost of wind turbines. *New Scientist*, Issue 2559, p. 3608, July 2006. Online at: http://environment.newscientist.com/channel/earth/mg19125591.600.

Green, C., Tobin, B., O'Shea, M., Farrell, E.P. & Byrne, K.A. (2007) Above- and belowground biomass measurements in an unthinned stand of Sitka spruce (*Picea sitchensis* (Bong) Carr.). *European Journal of Forest Research*, 126, 178–188.

Hall, M.J. (2006) *A guide to calculating the carbon dioxide debt and payback time for wind farms.* Renewable Energy Foundation, 12 pp. Online at: http://www.wind-watch.org/documents/guide-to-calculating-the-carbon-dioxide-debt-and-payback-time-for-wind-farms/

Hargreaves, K.G., Milne, R. & Cannell, M.G.R. (2003) Carbon balance of afforested peatland in Scotland. *Forestry*, 76, 299–317.

Harmon, M.E., Ferrell, W.K. & Franklin, J.F. (1990) Effects on carbon storage of conversion of old-growth forests to young forests. *Science*, 247 (4943), 699–702.

HM Government (2009) *The UK Renewable Energy Strategy*, 238 pp. Online at: http://www.decc.gov.uk/en/content/cms/publications/lc_trans_plan/lc_trans_plan.aspx

Huotari, N., Tillman-Sutela, E. & Kubin, E. (2009) Ground vegetation exceeds tree seedlings in early biomass production and carbon stock on an ash-fertilized cut-away peatland. *Biomass and Bioenergy*, 33, 1108–1115.

IEA (1998) *Electricity Information 1997*. International Energy Agency, Paris, 668 pp.

Kowalski, A.S., Loustau, D., Berbigier, P., Manca, G., Tadeschi, V., Borghetti, M., Valentini, R., Kolar, P., Berninger, F., Rannik, U.L., Hari, P., Rayment, M., Mencuccini, M.O., Moncrieff, J. & Grace, J. (2004) Paired comparisons of carbon exchange between undisturbed and regenerating stands in four managed forests in Europe. *Global Change Biology*, 10, 1707–1723.

Laiho, R. (2006) Decomposition in peatlands: Reconciling seemingly contrasting results on the impacts of lowered water levels. *Soil Biology & Biochemistry*, 38, 2011–2024.

Lenzen, M. & Munksgaard, J. (2002) Energy and CO_2 life-cycle analyses of wind turbines - review and applications. *Renewable Energy*, 26(3), 339–362.

Lindsay, R.A. (2005) *Lewis Wind Farm Proposals: Observations on the official Environmental Impact Statement*. Royal Society for the Protection of Birds, 72 pp. Online at: http://www.rspb.org.uk/Images/lewiswindfarmpeatland_tcm9-133219.pdf.

LWP (2006) *Lewis Wind Farm: Non-Technical Summary of the 2006 Addendum to the Environmental Statement*. Lewis Wind Power, Stornoway, 21 pp. Online at: www.lewiswind.com/attachment.php?file=environmental/volume1/NTS.pdf&type=1

Magnani, F., Mencuccini, M., Borghetti, M., Berbigier, P., Berninger, F., Delzon, S., Grelle, A., Hari, P., Jarvis, P. G., Kolari, P., Kowalski, A.S., Lankreijer, H., Law, B.E., Lindroth, A., Loustau, D., Mancal, G., Moncrieff, J.B., Tedeschi, V., Valentini, R. & Grace, J. (2007) The human footprint in the carbon cycle of established temperate and boreal forests. *Nature*, 447, 848–850.

Martinez, E., Sanz, F., Pellegrini, S., Jimenez, E. & Blanco, J. (2009) Life-cycle assessment of a 2-MW rated power wind turbine: CML method. *International Journal of Life Cycle Assessment*, 14, 52–63.

Nayak, D.R., Miller, D., Nolan, A., Smith, P. and Smith, J. (2008) *Calculating Carbon Savings form Wind Farms on Scottish Peat Lands – A New Approach*. Report to the Rural and Environment Research and Analysis Directorates of the Scottish Government, Science Policy and Co-ordination Division, Edinburgh, 83 pp. Online at: http://www.scotland.gov.uk/Publications/2008/06/25114657/0

Nayak, D.R., Miller, D., Nolan, A., Smith, P. & Smith, J.U. (2010) Calculating carbon budgets of wind farms on Scottish peatlands. *Mires and Peat*, 4(09), 1–23.

NEA (2006) *Windfarm Development and Landscape Capacity Studies: Knowesgate and Harwood Forest*. Final Report to the North East Regional Assembly, Part 1, Ove Arup & Partners Ltd., Cardiff, 54 pp. Online at: http://www.tynedale.gov.uk/residents/docushow.asp?docid=170

NEA (2008) *The North East of England Plan: Regional Spatial Strategy to 2021*. North East Assemby, 237 pp. Online at: http://www.communities.gov.uk/planningandbuilding/planning/regionallocal/regionalspatialstrategies/regionalspatialstrategies2/

Parker, R.P.M., Harrison, G.P. & Chick, J.P. (2007) Energy and carbon audit of an offshore wave energy converter. *Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy*, 221(8), 1119–1130.

Phillips, A. (2000) An investigation of carbon stocks in the tree biomass and soils of Sitka spruce, *Picea stichensis* (Bong.) Carr. stands in England. Undergraduate Honours Dissertation, School of Geosciences, University of Edinburgh.

Reynolds, B. (2007) Implications of changing from grazed or semi-natural vegetation to forestry for carbon stores and fluxes in upland organic soils in the UK. *Hydrology & Earth Systems Sciences*, 11(1), 61–76.

Smith, P., Smith, J.U., Flynn, H., Killham, K., Rangel-Castro, I., Foereid, B., Aitkenhead, M., Chapman, S., Towers, W., Bell, J., Lumsdon, D., Milne, R., Thomson, A., Simmons, I., Skiba, U., Reynolds, B., Evans, C., Frogbrook, Z., Bradley, I., Whitmore, A. & Falloon, P. (2007) *ECOSSE: Estimating Carbon in Organic Soils - Sequestration and Emissions: Final Report*. Scottish Executive Environmental and Rural Affairs Department, Edinburgh, 166pp. Online at: http://www.scotland.gov.uk/Publications/2007/03/16170508/0

Tremeac, B. & Meunier, F. (2009) Life cycle analysis of 4.5 MW and 250 W wind turbines. *Renewable and Sustainable Energy Reviews*, 13(8), 2104–2110.

Waldron, S., Flowers, H., Arlaud, C., Bryan, C. & McFarlane, S. (2009) The significance of organic carbon and nutrient export from peatland-dominated landscapes subject to disturbance, a stoichiometric perspective. *Biogeosciences*, 6, 363–374.

Zerva, A., Ball, T., Smith, K.A. & Mencuccini, M. (2005) Soil carbon dynamics in a Sitka spruce (*Picea sitchensis* (Bong.) Carr.) chronosequence on a peaty gley. *Forest Ecology and Management*, 205(1–3), 227–240.

Zerva, A. & Mencuccini, M. (2005a) Short-term effects of clearfelling on soil CO_2, CH_4 and N_2O fluxes in a Sitka spruce plantation. *Soil Biology and Biochemistry*, 37(11), 2025–2036.

Zerva, A. & Mencuccini, M. (2005b) Carbon stock changes in a peaty gley soil profile after afforestation with Sitka spruce (*Picea sitchensis*). *Annals of Forest Science*, 62(8), 873–880. Online at: http://www.afs-journal.org/index.php?option=article&access=standard&Itemid=129&url=/articles/forest/pdf/2005/08/F5087.pdf

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