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Assessing carbon emissions for alternative ground improvement methods in peat soils at N56, Glenties, Co. Donegal, Ireland

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Abstract. The N56 project near Glenties, Co. Donegal utilised staged construction of surcharged, basally reinforced embankments up to 5.5 m high on very soft blanket peat soils in northwest Ireland to improve a 2.5 km length of national road. The 4.5 km long scheme commenced construction in March 2021 and was completed in December 2022. The adopted ground improvement methods resulted in greatly reduced requirements for peat excavation in an ecologically sensitive environment and consequent reductions in carbon emissions. The paper briefly describes the project setting, earthworks design and the Life Cycle Assessment framework and methodology adopted to estimate related carbon emissions for earthworks & pavement construction. A representative 1 km long section of embankment was assessed for comparison of the constructed surcharge treatment versus traditional excavate and replacement methods. Improved peat management alternatives including native woodland planting and deposition into bermed restoration areas are also discussed. Some conclusions are drawn about the carbon emissions from these earthworks and peat management alternatives for road construction on peat soils.

1 Introduction

Surcharging is a ground improvement technique used in road construction to enhance underlying soil properties, but its application to highly organic soils such as peat is uncommon on national road projects in Ireland and internationally. Ecological constraints precluded an excavate-and-replace approach, so surcharge loading was adopted. Given the limited published evidence on embodied carbon benefits of surcharging peat, this study addresses that gap.

The project involved upgrading the N56 national route underlain by Atlantic Blanket Bog peat and shallow Caledonian Granite bedrock with the southern half falling within the Owenea River Freshwater Pearl Mussel catchment. A 1 km aggregate total length of road constructed on shallow embankment using 2 – 2.5 m high temporary surcharge was selected for this comparative study - see Fig. 1.

Typical characteristics of peat within the 1 km section are given below. More detailed information is provided in Kissane et al [1].

- Water Table Depth – typically 0 m, but up to 0.6 m.
- Peat Depths – Typically 1 m to 5.5 m
- Natural Moisture Content – 350% to 1550% (acrotelm); 600% to 1600% (catotelm).
- Organic Content – 64% to 98%;
- Bulk Density 10.5 kN/m^3
- Von Post Humification – H3 / H5 (acrotelm); H4 / H7 (catotelm)

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Fig. 1. Temporary diversion on left and main embankment at surcharge level.

Earthworks volumes for the “as built” surcharged embankments (SU) plus excavate & replace (ER) alternative scenarios over the 1 km selected embankment length are shown in Table 1. The excavated peat volumes for scenario ER necessitated use of a peat deposition area (PDA1) (see Fig. 2) with a gross area 35,000 m^2 but only 1,545 m^2 for Scenario SU. The areas beneath the road embankments and PDA1 were degraded cutover blanket peatlands that had been cut to some extent previously and drains are visible on some of the aerial images. Peat was disposed at side slopes of 1:4 and a maximum height of 1.95 m. No planting occurred on any of the PDAs.

Table 1. Summary of Earthwork Quantities.

Earthworks	Surcharge (SU)	Excavate & Replace (ER)
Permanent Fill (m^3) above EGL	93,000	93,000
Temporary Fill (m^3) above FRL	26,000	nil
Permanent Fill (m^3) due to Settlement below EGL	12,000	nil
Excavated Peat / Permanent Fill (m^3) below EGL - ER only	nil	65,000
Geosynthetic Reinforcement (m^2) 400 kN/m grade	41,000	nil
Asphalt Pavement (m^3)	2,080	
Drainage (m^3)	3,000	

Fig. 2. Constructed road with PDA1 location highlighted.

A typical cross section for the surcharged embankment indicating the layout of geosynthetic reinforcement used in scenario SU is shown in Fig. 3.

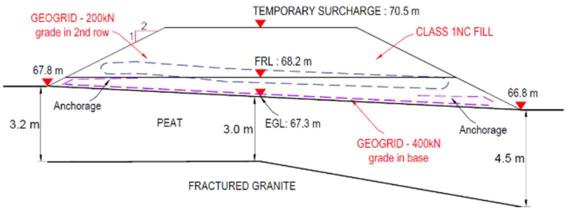

Fig. 3. Typical embankment cross-section with geosynthetic basal reinforcement.

The drainage system consists of standard 1m deep earthwork ditches along the toe of the embankments with a base width of 1 m, and a 1:1 side slope. Approximately 3,000 m^3 of excavation in peat is related to drainage ditches for both earthworks solutions.

2 LCA Carbon methodology

The Life Cycle Analysis (LCA) comparison is intended show the difference in EC between the two ground improvement scenarios, temporary surcharge versus excavate & replacement with consequent permanent excavated peat disposal. The functional unit is defined in this study as a 1 km length of road operational for 120 years. The boundary of the LCA study starts at the extraction of raw materials and ends when the design lifetime of the road foundation expires after 120 years. The calculations have been performed using LCA methodology conforming to ISO 14040 [2].

This study adopts the process analysis approach utilising a range of published EC intensities, much of which come from Hammond & Jones [3]; and DECC & Defra [4] which is applicable to this case study. Note the latest version of this database is ICE V4.1 which was published by Hammond & Jones [5]. The TII Carbon Assessment Tool [6] was used to investigate the impact of the pavement layers.

The system boundaries employed in the study for both scenarios for road construction on highly organic soil are given in Fig. 4, where the dotted line represents the system boundary and the solid black arrows indicate transport. Recurring EC in the form of maintenance, such as resurfacing roads, line painting and new signage, were not taken into account as the TII Carbon Tool at the time that these calculations were undertaken did not include them. Maintenance is now included. i.e. frequency of pavement renewals etc. Materials, transport and machinery all have cradle-to-site boundary conditions, while the peat-related factors are taken into account for the full life cycle.

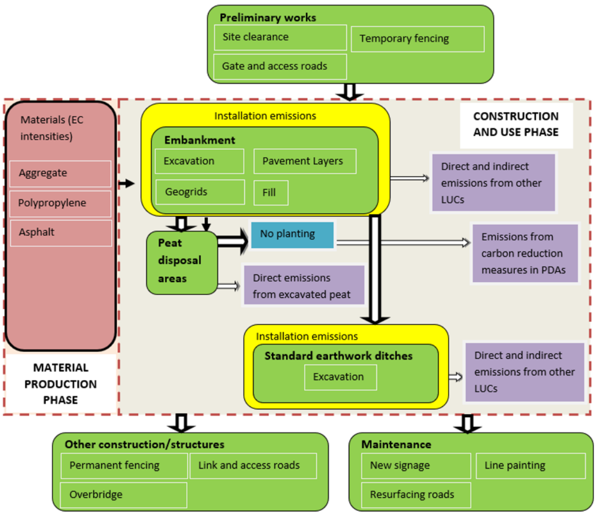

Fig. 4. Process flowchart of Scenario SU & ER.

Peat-related emissions can be sorted as follows:

- **Direct emissions from excavated peat** arise from the carbon contained in peat that is excavated during road construction. When this disturbed peat is exposed to aerobic conditions, it gradually decomposes and releases its stored carbon dioxide (CO_2) over the infrastructure's lifespan.
- **Emissions from carbon reduction measures in PDAs** are partially captured within direct emissions. However, depending on the carbon reduction measure implemented in the PDA, if all CO_2 contained in the excavated peat is released over the infrastructure's lifetime, the underlying peat beneath the PDAs will start emitting CO_2 for the remainder of the project lifecycle. These emissions are included within emissions from carbon reduction measures in PDA.

Emissions from carbon reduction measures in PDA also account for CO_2 sequestration within PDAs, which varies according to the habitat established, for example, native woodland planting or peatland restoration. In addition, they include greenhouse gas emission savings from carbon reduction measures on land outside the PDAs.

- **Direct emissions from other land use changes (LUCs)** arise from carbon released over the infrastructure's lifetime due to peatlands disturbed by construction. These include changes associated with the mainline, side roads, access tracks, drainage ditches, and pond construction. They also account for the loss of future carbon sequestration capacity in areas where peat has been excavated.
- **Indirect emissions from LUCs** arise from carbon released due to hydrological alterations associated with road drainage systems. Lowering the water table exposes previously saturated peat to oxygen, which accelerates decomposition and increases greenhouse gas emissions. Changes in water flow patterns may also affect adjacent peatlands, expanding the area influenced by drainage and contributing to further degradation.

2.1 Materials, transport and machinery

Common practice is to calculate EC intensities for materials right up to when the product leaves the factory and the life cycle profile adopted in this LCA uses intensities from Hammond & Jones [3]. The TII Carbon Tool was used to calculate the EC of the asphaltic materials required for the 7 m wide pavement.

The following assumptions were made in respect of material sources and transportation methods and distances:

- Aggregates were extracted from local quarries / borrow pits 29 km from the site. Out of the 158,000 m^3 of engineered fill required for the ER scenario and 131,000 m^3 for the SU scenario, 38,000 m^3 of the fill was excavated from elsewhere on site and reused as fill. Temporary fill required for surcharge area moved from an average distance of 2 km to replace area on another part of the scheme.
- Geosynthetics were imported from UK by road and sea over distances of 300 km and 225 km respectively;
- All transport by sea involved average weight-laden cargo ships;
- Asphalt materials were transported from a plant 50 km from the site;
- Excavated peat was transported an average distance of 2 km on a rigid truck (> 17 tonnes) fully laden but empty on return from the PDA.

The materials required for the scenarios are shown in Table 2. Table 3 gives fuel consumption rates for the use of diesel (UK average biofuel blend) [4]. For the purpose of this scenario, only the EC of excavators were examined (Table 4).

The TII Carbon Tool [6] was used to calculate the EC of the materials and transport required for the 7 m wide pavement. The pavement build-up for the road scheme was a total depth of 260 mm for base, binder and surface course. The carbon emission for the asphaltic pavement materials is 280 tCO_2eq and the transport of these materials to site was 43 tCO_2eq.

Table 2. Materials required of Scenario ER+SU.

Earthworks	Aggregate	Site Won Aggregate	Geogrid (PP)
Density (kg/m^3)	2,240	2,240	0.4 (kg/m^2)
EC Intensity (kg CO_2eq/kg)	0.0052	0.0052	3.43
Distance on land one way (km)	29	2	301
Transport Vehicle	Rigid	Rigid	Articulated
% Weight Laden	100,0*	100,0*	62
Distance by sea (km)	0	0	226
One or two-way transport	Two	Two	One
Volume (m^3)	93,000 for Scenario SU, 120,000 for Scenario ER	38,000	41,000 for Scenario SU only (m^2)

* The trucks were 100% loaded from quarry to site and returned to the quarry empty.

Table 3. Fuel consumption rates for heavy good vehicles and cargo ships [4].

Earthworks	% Weight Laden	Payload (t)	FC[1]	FC[2]
Rigid truck (> 17t)	100	9.41	0.146	0.046
Articulated truck (> 33t)	62	11.78	0.103	0.032
Average cargo ship	60		0.016	0.005
			FC[3]	FC[4]
Rigid truck (> 17t)	0	0	0.959	0.303

[1] FC = Fuel consumption ($kgCO_2eq$/t.km), [2] FC = Fuel consumption (l/t.km), [3] FC = Fuel consumption ($kgCO_2eq$/km) [4] FC = Fuel consumption (l/km)

Table 4. Fuel consumption rates and rates of work for machinery for Scenario ER + SU.

Machinery	Fuel consumption (l/hr)	Rate (m^3/hr)	Volume of peat (m^3)
16 tonne excavator	16	100	68,000 for Scenario ER, 3,000 for Scenario SU

2.2 Carbon content of peat

The loss of carbon as CO_2 from excavated peat is considered a direct emission and should be included in EC calculations [7]. Excavated peat that has been under anaerobic conditions starts releasing CO_2 and other gases when exposed to the atmosphere and aerobic conditions [8]. While water takes up the majority of the peat volume, the carbon content is part of the dry matter as shown diagrammatically in Fig.5.

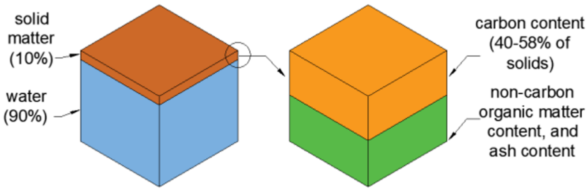

Fig. 5. Typical proportion of solid matter and water in peat (left) and typical proportions by weight of solid-matter components in peat (right).

Equation 1 is used to calculate the total carbon stock concentration, EC_{peat}, (tCO_2eq). This is the total potential CO_2 that could be released from a volume of excavated peat (V_{peat} (m^3)) over the design lifetime of the road if managed poorly. It is assumed that the total organic carbon is fully mineralised into CO_2. Given the large uncertainty associated with partitioning peat carbon into labile (easily decomposable) and stable pools (decomposes very slowly) [9], this assumption is adopted as a conservative upper-bound estimate of potential CO_2 emissions.

$$EC_{peat.} = \rho_d \text{ x } P \text{ x } (OC/100) \text{ x } (44/12) \text{ x } V_{peat} \quad (1)$$

where

- ρ_d = the average dry density of the peat (tonne/m^3).
- P = represents the percentage of carbon content derived from organic matter.
- OC = average organic content of the peat (%)
- 44/12 = relates to the molar mass of carbon dioxide (g/mol) and carbon (g/mol)

Schumacher [10] suggests estimating carbon content by applying a percentage derived experimentally, which ranges from 40% to 58% of the organic matter. This lower bound (40%) corresponds to a division factor of 2.5, while the upper bound (58%) corresponds to a division factor of 1.724. In the absence of direct measurements of carbon content in peat, an average carbon percentage of 47.4% may be used.

The peat on N56 had an average dry density (ρ_d) of 0.091 g/cm^3 and organic content (OC) of 81%. Using Equation 1, the total potential CO_2 that could be released from the volume of excavated peat for Scenario SU is 383.5 tCO_2eq and for Scenario ER is 8693 tCO_2eq. In the worst-case scenario, the percentage of carbon lost from the peat as CO_2 is assumed to be 100% due to the following considerations:

- PDAs and their sides are exposed to aerobic conditions;
- the high probability that the excavated peat will remain above the water table for the lifetime of the road.

The volume of this excavated peat will reduce as a result of primary and secondary consolidation and peat oxidation [8].

2.3 PDAs (Direct emissions from excavated peat)

Soil emissions from the PDAs are accounted for to an extent in direct emissions from excavated peat; but if all the CO_2 in the excavated peat is emitted, the peat underneath the PDAs will begin to release CO_2 for the remainder of the lifecycle and is accounted for in Section 2.4. There were no attempts to create any peatland habitat. The site was utilised as an area within the road scheme to dispose of the peat. No planting occurred on any of the PDAs.

Tier 2 country-specific emission factors (EFs) will be used where possible in the carbon assessments. However, in cases where there are insufficient studies on a particular land type, established Tier 1 EFs for CO_2, CH_4, and N_2O and loss of carbon via DOC will be taken from the IPCC guidelines [11]. This includes Tier 1 emission factors to estimate the release of CH_4 from drainage ditches. No Tier 1 data exists for POC, however, Tier 2 data exists in the United Kingdom [11]. which can be incorporated into EFs for Ireland. An EF of 15.11 $tCO_2eq\ ha^{-1}\ yr^{-1}$ (combination of Tier 1 [11], Tier 2 [12] and UK POC [13] data) representing an eroding, bare, peat area was taken from the Peatland Finance Ireland EF database [14] to characterise these PDAs. Soil emissions from excavated peat disposed in embankments will be higher than from a drained bog, as they are more exposed and more vulnerable to decomposition, hence the emission rate assumed. The rate of CO_2eq loss from these PDAs ($RATE_{PDA}$) was then calculated using Equation 2.

$$RATE_{PDA} = A_{PDA} \text{ x } EF \quad (2)$$

where

- A_{PDA} = area of the PDA (ha)
- EF = EF for the PDA for the CO_2eq flux from the soil per year. ($tCO_2eq\ ha^{-1}\ yr^{-1}$).

The duration it takes for all the CO_2 in the excavated peat to be emitted in these PDAs can be calculated using Equation 3:

$$t_{Duration\ to\ emit} = EC_{peat\ in\ PDA} / RATE_{PDA} \quad (3)$$

where

- $EC_{peat\ in\ PDA}$ = EC of peat in a PDA (tCO_2eq)
- $RATE_{PDA}$ = rate of the CO_2eq loss from the PDA (tCO_2eq/yr)

The results are tabulated in Table 5, which shows that not all of peat's carbon is released over the road's 120-year life cycle. According to this analysis, peat will have released only 279.6 and 6346.2 tCO_2eq for Scenario SU and Scenario ER, respectively.

The only direct emission given in Table 1 for option SU relates to peat excavation for drainage ditches.

Table 5. Direct emissions from excavated peat.

Earthworks	Surcharge (SU)	Excavate & Replace (ER)
Area, A_{PDA} (ha)	0.1545	3.5
V_{peat} (m^3)	3,000	68,000
$EC_{peat\ in\ PDA}$ (tCO_2eq)	383.5	8693
$RATE_{PDA}$ (tCO_2eq/yr)*	2.334	52.885
$t_{Duration\ to\ emit}$ (yrs)	164	164
Direct emissions from excavated peat in 120 years (EC_{peat}) (tCO_2eq)	279.6	6346.2

2.4 Carbon reduction measures in PDAs

Not all of the CO_{2eq} in the excavated peat is emitted, so it is assumed there are zero emissions from peat underneath the PDAs over the design lifetime of the road. No planting occurred on the PDAs, so there is no CO_2 uptake and no carbon reduction measure implemented. However, if excavated peat was not moved to the PDAs, the PDA would have produced emissions over the design life of the road. Equation 4 is used to calculate these emissions. An EF of 8.42 tCO_2eq ha^{-1} yr^{-1} (combination of Tier 1, 2 and UK POC data) was assumed for the nutrient-poor domestic cutover bog [11-14].

$$CO_2eq_{PDA\ do\ nothing} = A_{PDA} \times EF \times t_{DL} \qquad (4)$$

where

- EF = EF for the peat deposition footprint had no construction occurred (tCO_2eq ha^{-1} yr^{-1}).
- t_{DL} = design life (years)

The net emissions from carbon reduction measures in PDAs (tCO_2eq) are simply these emissions and were calculated as a net gain of -156.1 and -3536.4 tCO_2eq for Scenario SU and ER, respectively.

2.5 Drainage ditches (direct emissions from other LUCs)

Ponds and clogged drainage ditches consisting of algae and other vegetation not regularly maintained tend to produce high CH_4 emissions [15]. It is assumed that only the 1 m wide base of the infiltration ditches is covered with water all year round. There was a ditch placed on either side of the road, totalling a base area of 2,000 m^2. The lifetime on-site emissions, $CO_2eq_{drains(direct)}$, (tCO_2eq) from the drainage ditches can be calculated from Equation 5:

$$CO_2eq_{drains(direct)} = A_{drains} \times EF \times t_{DL} \qquad (5)$$

where

- A_{drains} = land area of drainage ditches, ha
- EF = EF for drainage ditches (tCO_2eq ha^{-1} yr^{-1})

A Tier 1 EF of 15.176 tCO_2eq ha^{-1} yr^{-1} was assumed for the ditches for the 120-year life cycle which is based on the IPCC EF for drainage ditches from peat extraction areas [11]. Had the peat from the associated drainage systems not been removed, they would have produced emissions over the design life of the road if constructed on a drained peatland as calculated from Equation 6.

$$CO_2eq_{drains\ do\ nothing} = A_{drains} \times EF \times t_{DL} \qquad (6)$$

where

- EF = EF for drainage ditch area (cutover bog) had no construction occurred (tCO_2eq ha^{-1} yr^{-1})

The net emissions, $CO_2eq_{net\ drains\ (direct)}$ (tCO_2eq) , effect of constructing drainage ditches as part of a road project is calculated from Equation 7 and is included under direct emissions from other LUCs.

$$CO_2eq_{net\ drains\ (direct)} = CO_2eq_{drains\ (direct)} - CO_2eq_{drains\ do\ nothing} \qquad (7)$$

The drainage ditches emission (direct emissions from other LUCs) for both scenarios was 162.144 tCO_2eq. In reality, there was a pre-existing N56 ditch system, which would offset this figure, but has been included to introduce the potential of ditches to EC calculations in earthworks

2.6 Roads (direct emissions from other LUCs)

50% of the original road was buried beneath the new N56 embankment, so the discussion below relates to the remaining 50% of the new road. When a road is built, it could be assumed that the road pavement is sealed so there are zero emissions coming from the land below it over the lifetime of the road. However, the embankment material is a free-draining, crushed rock fill which could provide an easy pathway for gases to escape into the atmosphere from the peat/fill interface in Scenario SU. As it is likely that the surcharged peat is compressed below the water table in anaerobic conditions, and to be conservative, an EF of 1.96 $tCO_2eq/ha/yr$ was assumed for this surcharged peat for the 120 year life cycle, which is based on a Tier 2 country-specific EF for a near-natural peatland [12]. This figure only includes CH_4 emissions, as the carbon sink associated with the vegetation on near-natural peatlands does not exist under the surcharged road. The lifetime on-site emissions, $CO_2eq_{roads(direct)}$, (tCO_2eq) from the road can be calculated from Equation 8. In Scenario ER, the $CO_2eq_{roads(direct)}$, (tCO_2eq) emissions are zero:

$$CO_2eq_{road(direct)} = A_{road} \times EF \times t_{DL} \qquad (8)$$

where

- A_{road} = land area of road, ha.
- EF = EF for the road footprint (tCO_2eq ha^{-1} yr^{-1}).

Had no construction occurred and the removed peat from the road not been disturbed, it would have produced emissions, $CO_2eq_{road\ do\ nothing\ (direct)}$, ($tCO_2eq$), over the design lifetime of the road (years). This is calculated from Equation 9 and is accounted for in these

EC calculations under direct emissions from other LUCs:

$$CO_2eq_{road\ do\ nothing\ (direct)} = A_{road} \times EF \times t_{DL} \quad (9)$$

where

- EF = EF for the road footprint (cutover bog) had no construction occurred ($tCO_2eq\ ha^{-1}\ yr^{-1}$).

The net effect $CO_2eq_{net\ road\ (direct)}$ (tCO_2eq), of constructing the mainline is calculated from Equation 10 below. It is noteworthy that emissions are negative for both scenarios (-426.36 tCO_2eq for Scenario SU and -555.72 tCO_2eq for Scenario ER) which is due to the land below the road emitting less through the road pavement over the lifetime of the road.

$$CO_2eq_{net\ road\ (direct)} = CO_2eq_{road\ (direct)} - CO_2eq_{road\ do\ nothing\ (direct)} \quad (10)$$

2.7 Extent of drainage (indirect emissions from other LUCs)

The lateral extent of drainage (E) (metres) due to road construction, ditches, ponds, and any other excavations in an undisturbed peatland must be calculated to understand the footprint that is now prone to decomposition and hence emissions. However, drainage due to the road construction has limited relevance for historically drained bogland as in the case of this case study, and the area will continue to be a net source of greenhouse gases regardless of construction. As a result, indirect emissions are zero.

3 Interpretation of results

The net total EC for both Scenario SU and ER for the 1km stretch of road is 4108 tCO_2eq and 6624 tCO_2eq, respectively, which is broken down by factor in Table 6. Scenario SU is 38% less than Scenario ER, mainly due to direct emissions from excavated peat which accounted for 43% of total emissions compared to only 5% in Scenario SU (Fig. 6). It highlights the significance of how excavated peat is managed.

Without further work on the PDA to increase the carbon intake of the land via additional works, Scenario SU can be adjudged to have significantly reduced the EC emissions of the project, primarily as peat arisings were significantly reduced. The on-site impact is also lower than Scenario ER due to surcharged peat remaining in-situ. Materials requirements are also lower in Scenario SU as 26,000 m^3 of the temporary surcharge fill can be used elsewhere on this project and 53,000 m^3 less permanent fill is required compared to the ER scenario.

Table 6. Breakdown of total EC for Scenario SU and ER.

Factor	EC of Scenario SU (tCO_2eq)	%	EC of Scenario ER (tCO_2eq)	%
Materials	1936	36.7	2120	14.3
Transport	2311	43.8	2053	13.9
Machinery	2	0	34	0.2
Excavated peat	280	5.3	6346	42.9
PDA	-156	3.0	-3536	23.9
Drainage ditches	162	3.1	162	1.1
Road	-426	8.1	-556	3.8
Total	4108	100	6624	100

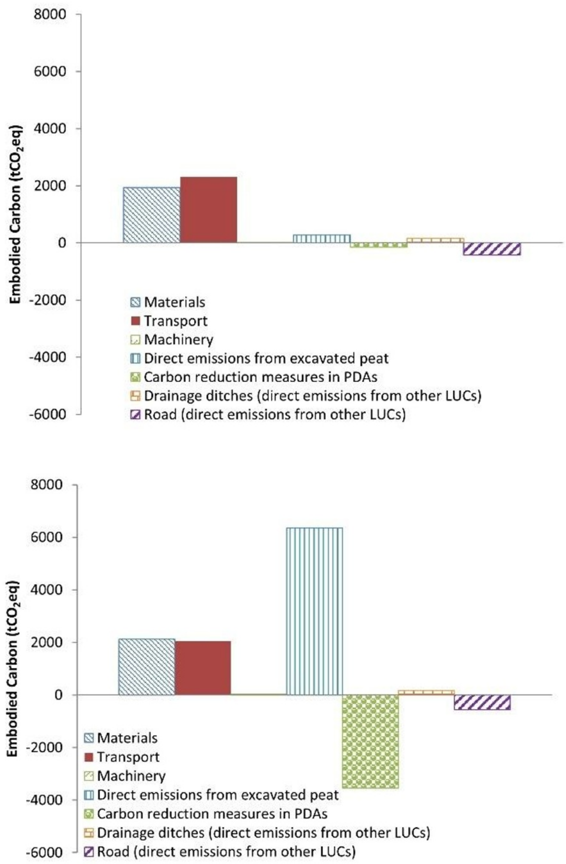

Fig. 6. Breakdown of total EC for Scenario SU (top) and breakdown of total EC for Scenario ER (bottom).

4 Alternative excavated peat management scenarios

Peat may be reused within borrow pits or material deposition areas for the purpose of rehabilitation or providing alternative habitat to blend in with the surrounding area. For a traditional raised PDA, several management options are employed, including no planting, and native woodland planting. In the no-planting scenario, the peat is typically deposited on a site that is surrounded by ditches to actively drain the site with a view to returning the site to agricultural use. This would be considered a simple PDA and was the option used on this scheme. As a result of the large volume of excavated peat in Scenario ER, two carbon reduction measure scenarios are examined to see the impact on total EC, i.e. native woodland planting (Scenario ER+1) and peat restoration (Scenario ER+2). Both assume the same PDA area as in Scenario ER.

For Scenario ER+1, the CO_2 uptake, $CO_2eq_{PDA\ do\ something\ vegetation}$, ($tCO_2eq$), over the design life of the structure can be calculated from Equation 11 and was calculated as -1827 tCO_2eq.

$$CO_2eq_{PDA\ do\ something\ vegetation} = A_{PDA} \times EF \times t_{DL} \quad (11)$$

where

- EF = EF for the PDA for the average CO_2eq intake from the woodland ($tCO_2eq\ ha^{-1}\ yr^{-1}$).

Native woodlands such as birch/willow woodlands generally have a low-yield class; consequently, soil emissions are greater than the CO_2 uptake by the woodland. Afforestation with Sitka spruce would result in greater CO_2 uptake [16], but this would be less favourable from a biodiversity perspective. A CO_2 uptake EF of -4.35 $tCO_2eq\ ha^{-1}\ yr^{-1}$ was assumed for the birch/willow woodland which comes from the Teagasc Forest Carbon Tool [16] for native birch forests on modified fen/cutaway raised peat and is the average EF for the forest over two crop rotations. For the case study, where no planting had occurred in the first set of results, $CO_2eq_{PDA\ do\ something\ vegetation}$ is equal to zero.

The net emissions from carbon reduction measures in PDAs (tCO_2eq) is then calculated by Equation 12. In this case, the net was calculated as -5363.4 tCO_2eq (-1827 – 3536.4 tCO_2eq)

$$CO_2eq_{Net\ reduction\ measures\ in\ PDA} = CO_2eq_{do\ something\ vegetation} - CO_2eq_{PDA\ do\ nothing} \quad (12)$$

For Scenario ER+2, peat restoration within PDA1 can be contained within perimeter berms comprised of low-permeability cohesive fill or lined granular fill to restrict drainage. Approximately 8,600 m^3 of additional fill would be required with an associated material and transport EC of 100 and 139 tCO_2eq, respectively. PDAs can be constructed on non-peatland areas by constructing retaining cells to receive peat by either excavating soil/stone for subsequent use in the scheme (borrow pits) and/or building berms to create raised cells to retain peat. Opportunities to exploit either solution were limited at the N56 project site.

Emissions from these restored peatlands are expected to remain relatively high until the new habitat becomes established. The period between Time 1 (e.g., pre-restoration) and Time 2 (e.g., post-restoration) represents the time ($t_{restore}$) in years required for the new habitat to establish. It can be assumed that the habitat will be functioning after 20 years which is the Tier 1 IPCC default period of restoration [17].

The soil emissions, $CO_2eq_{PDA\ do\ something\ pre}$ (tCO_2eq), in this $t_{restore}$ period can be calculated from Equation 13 below. These are the total emissions to be included in direct emissions from excavated peat.

$$CO_2eq_{PDA\ do\ something\ pre} = A_{PDA} \times EF \times t_{restore} \quad (13)$$

where

- EF = EF for the PDA (eroding, bare, peat area) prior to restoration. ($tCO_2eq\ ha^{-1}\ yr^{-1}$).

The soil emissions/removals, $CO_2eq_{PDA\ do\ something\ post}$ (tCO_2eq), after the habitat establishment, can be calculated from Equation 14. These are to be included in net emissions from carbon reduction measures in PDAs.

$$CO_2eq_{PDA\ do\ something\ post} = A_{PDA} \times EF \times (t_{DL} - t_{restore}) \quad (14)$$

- EF = EF for the PDA after restoration ($tCO_2eq\ ha^{-1}\ yr^{-1}$).

An EF of 1.38 $tCO_2eq\ ha^{-1}\ yr^{-1}$ was assumed for the new habitat which includes Tier 2 EF and Tier 1 DOC data used for a near-natural peatland [11, 12, 14]. The net emissions from carbon reduction measures in PDA (tCO_2eq) are calculated by Equation 15 and are tabulated in Table 7.

$$CO_2eq_{Net\ reduction\ measures\ in\ PDA} = CO_2eq_{PDA\ do\ something\ post} - CO_2eq_{PDA\ do\ nothing} \quad (15)$$

Table 7. Summation of Emissions for PDAs.

Factor	PDA1
Category – Direct emissions from excavated peat	
$CO_2eq_{PDA\ do\ something\ pre}$ (tCO_2eq)	1058
Category – Carbon Reduction Measures in PDAs	
$CO_2eq_{PDA\ do\ something\ post}$	483
$CO_2eq_{PDA\ do\ nothing}$	-3536
$CO_2eq_{Net\ reduction\ measures\ in\ PDA}$ (tCO_2eq)	-3054

A breakdown of total EC for all the scenarios examined is displayed in Table 8. The significance in how the excavated is managed is shown in these results, with both planting a native woodland on the PDA and creating a peat restoration site reducing total EC by 28% and 69% respectively. As a result of the relatively small volumes of peat excavation required in Scenario SU, the fluctuation in EC according to the excavated peat management scenario would be small. However, to reduce the EC cost of the job, more land could be acquired and the land use changed so as to increase the carbon intake of the land and therefore reduce the overall EC of the job.

It is also noteworthy that where peatland is already degraded, the development of a road or greenway may offer some benefit by reducing the extent of existing peat that is currently acting as a net source of emissions.

Table 8. Total EC for Scenario SU, ER, ER+1, ER+2.

Factor	EC of Scenario SU (tCO_2eq)	EC of Scenario ER (tCO_2eq)	EC of Scenario ER+1 (tCO_2eq)	EC of Scenario ER+2 (tCO_2eq)
Materials	1936	2120	2120	2220
Transport	2311	2053	2053	2192
Machinery	2	34	34	34
Excavated peat	280	6346	6346	1058
PDA	-156	-3536	-5363	-3054
Drainage ditches	162	162	162	162
Road	-426	-556	-556	-556
Total	4108	6624	4796	2056

5 Conclusions

The study describes the comparative carbon emissions estimated for two primary ground improvement techniques applied to a 1 km length of national road constructed over shallow Atlantic Bog peat in Co. Donegal, Ireland. The following main conclusions may be drawn:

- Temporary surcharge results in significant savings in permanent fill materials (assuming all temporary fill can be reused elsewhere in road construction);
- Consequently, a 38% reduction in carbon emissions over a 120 year life cycle occurs compared to traditional excavate and replace, where disposed peat is not subject to any improved management;
- Alternative peat management practices can also make significant reductions in carbon emissions, with full peatland restoration being the most effective. The costs and risks in achieving this goal over a 20 year maintenance period may be significant and hydrogeologic conditions may not be suitable.

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