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1 **Deep seam and minesoil carbon sequestration potential of**  
2 **the South Wales Coalfield, UK**

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7 **Abstract**

8 Combustion of coal for energy generation has been a significant contributor to increased  
9 concentrations of atmospheric carbon dioxide. It is of interest to evaluate the potential of  
10 former coalfields for mitigating these increases by carbon sequestration and to compare  
11 different options to achieving this end. Here, carbon sequestration in residual coal seams and  
12 through reclamation of spoil tips is compared, and their carbon dioxide storage potential in the  
13 South Wales Coalfield estimated. Coal seam sequestration estimates come from an  
14 established methodology and consider the total unmined coal resource below 500m deep with  
15 potential for carbon sequestration. The most likely effective deep seam storage capacity is  
16 104.9 Mt carbon dioxide, taking account of reservoir conditions and engineering factors. Whilst  
17 many spoil tips in South Wales have been reclaimed, the focus has not been on carbon  
18 sequestration potential. Estimates of minesoil restoration sequestration capacity were based  
19 on a survey of restored minesoil and vegetation carbon stocks, mainly on sites 20-30 years  
20 after restoration; data from this survey were then extrapolated to the coalfield as a whole.  
21 Minesoil storage is estimated at 1.5 or 2.5 Mt (+ 2.2 Mt in tree biomass) carbon dioxide based  
22 on average grassland or woodland measurements, respectively; modelled data predicted  
23 equilibrium values of 2.9 and 2.6 Mt carbon dioxide respectively in grassland or woodland  
24 minesoils. If all sites achieved close to the maximum capacity in their land use class, minesoil  
25 storage capacity would increase to 2.1 or 3.9 Mt carbon dioxide, respectively. Combining the  
26 best woodland minesoil and standing biomass values, sequestration capacity increases to 7.2  
27 Mt carbon dioxide. The wider social, economic, environmental and regulatory constraints to  
28 achieving this sequestration for each approach are discussed. Coal seam sequestration has  
29 a much higher capacity but sequestration in mine sites is less costly and has fewer regulatory  
30 constraints. Findings indicate a significant combined potential for carbon sequestration in the  
31 South Wales Coalfield and highlight challenges in achieving this potential. On a global scale,  
32 ex-coalfield sequestration could contribute to broader efforts to mitigate emissions.

33 **Keywords** coal; minesoils; carbon sequestration; storage capacity

## 34 1. Introduction

35 Increasing atmospheric concentrations of carbon dioxide (CO<sub>2</sub>), caused by human activities  
36 including power generation and industry, are driving climate change. In 2017, for example, it  
37 is provisionally estimated that UK net carbon dioxide (CO<sub>2</sub>) emissions were 366.9 million  
38 tonnes CO<sub>2</sub> (MtCO<sub>2</sub>) (DECC, 2018). While the carbon intensity of the UK and wider world  
39 economy is falling, progress falls short of what is needed to limit global temperatures to 2°C  
40 above pre-industrial levels (PwC, 2016). Geological carbon (C) sequestration aims to avoid or  
41 offset the atmospheric emission of CO<sub>2</sub> and is prominent in strategies for climate change  
42 mitigation and adaptation. Of most interest for C sequestration are deep saline aquifers,  
43 depleted oil and gas reservoirs, unmineable coalbeds, and soils. There is now a pressing need  
44 to explore all options to not only reduce emissions, for example through the point source  
45 capture, utilisation and storage of CO<sub>2</sub>, but also to increase the removal of CO<sub>2</sub> from the  
46 atmosphere by introducing land management practices to enhance levels of soil C (The Royal  
47 Society and The Royal Academy of Engineering, 2018). Thus, the CO<sub>2</sub> storage potential within  
48 the South Wales Coalfield, both below-ground in coal seams and above-ground in minesoil,  
49 is of interest.

50 Carbon capture and sequestration (CCS) in coal seams is an appealing option for Wales since  
51 there are significant remaining coal reserves in proximity to large point source emitters of CO<sub>2</sub>,  
52 such as the Port Talbot steel works (c. 6.6 MtCO<sub>2</sub>/year) (Thomas & Kluiters, 2013). Coalbeds  
53 provide in principle an attractive sink for captured CO<sub>2</sub> since storage is predominantly in the  
54 sorbed phase, reducing CO<sub>2</sub> mobility and therefore its risk of leakage compared to the other  
55 candidate reservoirs. The foremost technical barrier to the deployment of C sequestration in  
56 coalbeds remains the swelling response of coal to CO<sub>2</sub> sorption, having been found in several  
57 field trials to reduce the (already low) permeability of coal to the extent where CO<sub>2</sub> injection is  
58 impractical without reservoir stimulation (e.g. van Bergen *et al.*, 2006; Fujioka *et al.*, 2010).  
59 Whilst coal swelling is beyond the scope of the present work, the nature of the sorption and  
60 swelling behaviour remains an active area of research (e.g. Liu *et al.*, 2017; Chen *et al.*, 2019)  
61 and is recognised as a constraint of the CO<sub>2</sub> storage potential of coalfields.

62 The C sequestration potential of disturbed soils, such as spoils associated with mining, is high  
63 because the level of organic carbon they contain prior to any reclamation is much lower than  
64 in natural soils (e.g. Vinduskova & Frouz, 2013). Therefore, the difference between the starting  
65 point and the saturation level of carbon in minesoils is large. Several studies have focussed  
66 on C accumulation in restored minesoils (e.g. Akala & Lal, 2001) and have highlighted the  
67 potential of these sites for C sequestration. The sequestration of carbon in soils is dependent

68 on good ecosystem functioning; this in turn depends on a wide range of interacting factors  
69 (Shrestha & Lal, 2006). Minesoils present a combination of problems limiting vegetation  
70 productivity and hence C sequestration. These include compaction (Bending & Moffat, 1999),  
71 poor water-holding capacity (Daniels & Zipper, 1997), nutrient deficiency (Palmer & Chadwick,  
72 1985), low levels of soil biological activity (Anderson *et al.*, 2008) and low pH where materials  
73 are pyritic (Martínez *et al.*, 1996). However, Littlefield *et al.* (2013) found that the rate of C  
74 accumulation in minesoils was more rapid than in natural soils where both were planted to  
75 similar forest communities. Compared with areas receiving soil cover, sites planted directly on  
76 overburden can show higher rates of soil carbon accumulation and larger final stocks, despite  
77 having lower levels of plant growth (Bending & Moffat, 1999; Jacinthe & Lal, 2007).

78 Thomas (1966) estimated the area in South Wales covered by colliery and ironstone spoils,  
79 often intermixed, to be approximately 5,800 ha; this area would have increased with  
80 subsequent mining activity and reprofiling of steep spoil slopes. For the purposes of this  
81 exercise, a final value of 6,500 ha is assumed. Up to the mid-1990's, much of this colliery spoil  
82 or land associated with coal mining, was reclaimed in the South Wales Coalfield (Griffiths &  
83 Smith, 2007), most planted directly into re-graded spoil. Many sites are approaching 30 years  
84 since reclamation and are likely close to maximum stocks of accumulated carbon (Vindušková  
85 & Frouz, 2013). Broader studies suggest that grassland and woodland have similar soil C  
86 accumulation rates and maximum carbon stocks; woodland does have higher above-ground  
87 biomass (Patenaude *et al.*, 2004).

88 The aim of this study is to evaluate and compare the CO<sub>2</sub> storage potential and practicality of  
89 deep coal seams and of minesoil, using the South Wales Coalfield as a case study. A parallel  
90 study (Sarhosis *et al.*, 2016a) generated data on coal seam sequestration potential. This work  
91 and previous studies have considered coal and minesoils as individual sinks for CO<sub>2</sub>. Here we  
92 emphasise their comparison at a regional scale and consider some of the broader issues  
93 associated with their implementation. Although the two approaches are complementary, their  
94 relative sequestration capacity, sequestration rates, practicalities, and cost effectiveness vary.  
95 Circumstances within individual coalfields differ, but our findings will indicate whether C  
96 sequestration associated with former coal mining activities can make a meaningful  
97 contribution to limiting atmospheric greenhouse gas increases.

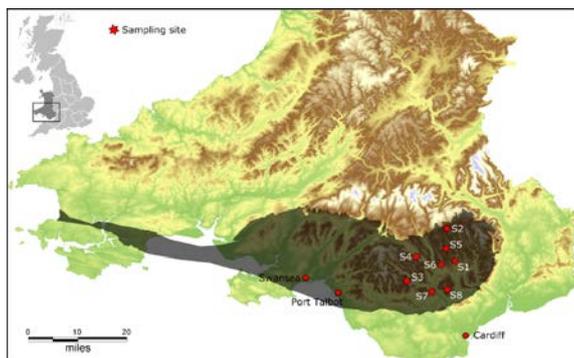
## 98 **2. Methods and approaches**

### 99 *2.1. C sequestration in coal seams*

100 An estimate of the coal seam CO<sub>2</sub> storage potential was given by Sarhosis *et al.* (2016a),

101 based on a digitised, three-dimensional geological map of the South Wales Coalfield's  
102 remaining coal resource. By considering minesoil reclamation alongside the results of  
103 Sarhosis et al., the present work determines the carbon sequestration potential of the Coalfield  
104 as a whole. A discussion of practical considerations, economics and possible regulatory  
105 constraints for each option is also provided in this work to complement the quantitative findings  
106 and provide a stronger basis for their comparison. For completeness, this section will present  
107 a summary of the approach taken by Sarhosis et al. in their estimation of the coal seam  
108 sequestration capacity of the South Wales Coalfield.

109 The main part of the South Wales Coalfield is roughly 145 km by 40 km in extent (Figure 1),  
110 with coal seams lying at depths exceeding 1800 m in the West but not reaching depths greater  
111 than 60 m in the East (Adams, 1967). The seams considered by Sarhosis et al. (2016a) for C  
112 sequestration were those of the Middle and Lower Coal Measures achieving thicknesses  
113 greater than 1.5 m and satisfying a 500 m minimum depth constraint. By collecting the  
114 candidate seams into a number of 'packages', the digitised, three-dimensional map yielded a  
115 cumulative residual coal resource of around 12,700 Mt.



116  
117 **Fig. 1.** The extent of the South Wales Coalfield and the location of field survey sites used in  
118 this study to estimate the C sequestration potential of minesoils (S1-S8 see Table 3). (Sarhosis  
119 et al., 2016a).

120 The study by Sarhosis et al. (2016a) provided an estimate of the effective C sequestration  
121 capacity of coal seams in the South Wales Coalfield by making an analogy to the reserves  
122 estimation for coalbed methane (CBM). In summary, a total '*theoretical*' coalbed methane *in*  
123 *situ* was first estimated then converted to the effective gas capacity by applying the factors  $C_f$   
124 and  $R_f$  for well completion and reservoir conditions, respectively. These factors and their  
125 assigned values are discussed in detail by Sarhosis et al. (2016a), but may be qualitatively  
126 interpreted as restricting the volume of unmined coal that can be accessed for sequestration.

127 An 'effective' CO<sub>2</sub> storage capacity was then estimated by applying an exchange ratio for the  
 128 preferential displacement of *in situ* CH<sub>4</sub> by CO<sub>2</sub>, the values for which were determined from  
 129 laboratory adsorption tests. To consider the likely range of reservoir conditions and  
 130 engineering factors, statistical distributions were defined for each input parameter (Table 1),  
 131 allowing for a Monte Carlo analysis of the effective storage capacity. The data sets and  
 132 literature supporting these values are discussed fully in Sarhosis *et al.* (2016a).

Parameter	Minimum	Most likely	Maximum	Standard deviation
Coal CH <sub>4</sub> content, $G_{CH_4}$ (m <sup>3</sup> t <sup>-1</sup> )	5.50	13.00	22.50	2.00
Completion factor, $C_f$	0.40	0.50	0.90	0.05
Recovery factor, $R_f$	0.20	0.50	0.85	0.10
Exchange ratio, $E_r$	1.10	1.40	2.00	0.20

133 **Table 1** Summary of the input values used for the Monte Carlo analysis of the effective CO<sub>2</sub> storage  
 134 capacity of the South Wales Coalfield (Sarhosis *et al.*, 2016a).

## 135 2.2. Estimating C sequestration in minesoils

136 A field survey of reclaimed minesoils in the coalfield was carried out during 2012 and 2014. A  
 137 total of 8 sites were investigated in detail (Figure 1), selected from an evaluation of 30 potential  
 138 sites for which detailed reclamation and management history was available (Steve Smith Pers.  
 139 Comm.). On each site, minesoil C stocks were estimated under grassland and woodland; on  
 140 woodland sites, in addition, C stocks in trees were estimated to provide an indication of the  
 141 total ecosystem C sequestration. Standing biomass on grassland sites was insignificant.

142 Most of the selected sites had been reclaimed between 20 and 30 years previously, although  
 143 one younger site was included. This narrow timeframe was as a result of a concerted  
 144 programme of spoil reclamation over sites in the coalfield covering a decade. The older  
 145 woodland sites were considered to have accrued much of their potential C storage capacity,  
 146 although Frouz (2017) considered that such minesoils were not C saturated after 50 years of  
 147 soil development. Measurements of C stocks on these sites were then converted to a regional  
 148 scale using estimates of the areal extent of minesoils, based on several published sources  
 149 (Griffiths & Smith, 2007; Howe *et al.*, 2005; Thomas, 1966).

150 Site observations indicated that rooting depths rarely exceeded 30 cm in either grassland or  
 151 woodland sites due to the compact nature of minesoil at depth, so this depth was taken as the  
 152 lower limit in sampling for C estimates. Intact cores (for bulk density measurement) were taken  
 153 at 10 random locations in each land use class within each site. Stone contents (> 2 mm) were

154 separated and measured, then the remaining fine earth was analysed for its C concentration.  
155 C stocks were then estimated based on fine earth C concentrations, and adjusting for stone  
156 content and bulk density.

157 Minesoils commonly contain fossil C in the form of coal fragments (Ussiri *et al.*, 2014), which  
158 complicates the estimation of recent C contents. To address this problem, coal samples were  
159 ground and ignited at a range of temperatures from 300 to 400°C to determine the maximum  
160 temperature at which no mass loss was recorded (320 °C). As this would underestimate  
161 'recent' organic matter contents, the extent of this underestimate was determined by igniting  
162 'natural' soils adjacent to the minesoils, at 320 °C and 400 °C; the difference in weight loss  
163 was used to determine a correction factor for losses at 320 °C to estimate loss on ignition at  
164 the commonly used 400 °C (Ben-Dor & Banin, 1989). Direct C measurements of coal-free  
165 samples using an Elementa C analyser, then allowed for site specific LOI to organic C  
166 conversions. It was assumed that deep minesoils did not contain any recent C. Samples taken  
167 below the rooting depth were treated similarly to detect recent C and these measurements  
168 supported the assumption that the recent C content of initial minesoil was insignificant. .

169 Planted tree species were typical of deciduous temperate woodland including (in descending  
170 order of dominance), *Alnus glutinosa/incana*, *Salix caprea/alba*, *Betula pendula*, *Fraxinus*  
171 *excelsior*, *Quercus petraea*, and *Corylus avellana*. To estimate above-ground biomass in  
172 woodland, five 5 x 5m quadrats were randomly selected across each site and within each  
173 quadrat the planting density (mean = XX), tree species and diameter at breast height (DBH)  
174 for each tree were recorded. These data were then converted to biomass data using:

$$\log(m_{bio}) = A + B \log(DBH) \quad (1)$$

175 where  $m_{bio}$  is the biomass, and A and B are parameters that varied with species as obtained  
176 from Zianis *et al.* (2005). Biomass data were then converted to carbon estimates assuming a  
177 mean C content of 47.5%, based on data reviewed by Vashum & Jayakumar (2012). Since,  
178 the partially decomposed litter layer was included in soil samples, a separate measure of litter  
179 inputs was not necessary for the purpose of measuring stocks.

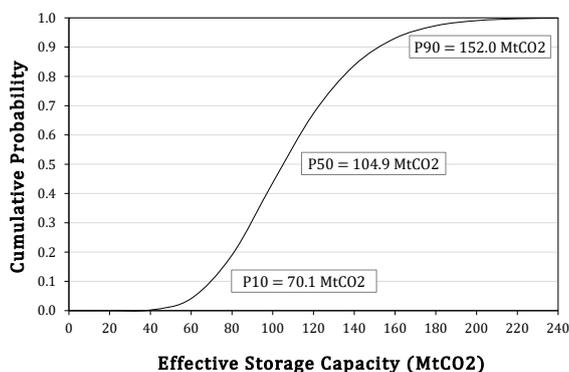
180 A meta-data analysis of carbon sequestration in minesoils was also conducted to supplement  
181 survey data. The literature was searched for reclamation studies conducted in ways similar to  
182 those in Wales, that is temperate mixed woodland or grassland, no topsoil application and  
183 where bulk densities were available, coal carbon had been accounted for and minesoil was  
184 sampled to 30cm (Akala & Lal, 2001; Jacinthe & Lal, 2007; Lorenz & Lal, 2007). For each land  
185 use class the data were analysed in Sigma Plot v12 using linear and sigmoidal 3 parameter

186 models of C stock changes with time.

### 187 3. Results and Discussion

#### 188 3.1. Coal seam storage capacity

189 The Monte Carlo analysis of the effective coal seam CO<sub>2</sub> storage capacity, performed by  
190 Sarhosis *et al.* (2016a), produced the results shown in Figure 2. The results were presented  
191 in terms of the proved, probable and possible effective storage capacities to be exceeded with  
192 confidences of 90%, 50% and 10%, respectively. The results show a proven total effective  
193 storage capacity of 70.1 MtCO<sub>2</sub>, with a probable capacity of 104.9 MtCO<sub>2</sub> and a possible  
194 capacity of 152.0 MtCO<sub>2</sub>.



195

196 **Fig. 2** Results of the Monte Carlo simulation for the effective CO<sub>2</sub> storage capacity of coal  
197 seams in the South Wales Coalfield (Sarhosis *et al.*, 2016a).

#### 198 3.2. Minesoil storage capacities and sequestration rates

199 Estimates of C stocks (and CO<sub>2</sub> equivalents) in restored minesoils are presented in Table 2a.  
200 Stocks under woodland were much higher than those under grassland ( $P = 0.004$ ). There  
201 were also significant ( $P = 0.04$ ) differences between sites, with Craig y Dyffryn and the more  
202 recent Deep Navigation holding  $< 50 \text{ t C ha}^{-1}$  compared with Cambrian and Cwm Darren where  
203 stocks exceeded  $100 \text{ t C ha}^{-1}$ . This range of C stocks is comparable to those obtained in other  
204 recent studies on woodland mine soils from China ( $51.2 - 172.2 \text{ Mg ha}^{-1}$  – Yuan *et al.*, 2016).  
205 The lower C stocks on Deep Navigation can be attributed to the shorter period since  
206 restoration whilst Craig y Dyffryn was affected by a fire several years after reclamation. On  
207 average the below-ground component in grassland contained 231 CO<sub>2</sub>-equiv t per ha and  
208 woodland 384 CO<sub>2</sub>-equiv t per ha (excluding 11 year site). Table 3 shows the estimated above-

209 ground C stocks in woodland for each site; no meaningful estimate could be made for  
 210 grassland but since it was grazed intermittently amounts are insignificant. In woodland there  
 211 was little correlation between above- and below-ground C stocks ( $r = -0.0725$ ) indicating that  
 212 factors in addition to primary productivity, such as moisture regimes, affected C accumulation.  
 213 These factors would impact not only productivity but also C losses by respiration; respiration  
 214 responses to revegetation are variable, with examples of little difference between seeded and  
 215 partially colonised grassland (Cizkova et al., 2018), but higher respiration rates in 5-year  
 216 afforested minesoils compared to both unreclaimed and reference forest sites (Ahrwal & Maiti,  
 217 2018).

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218 Soil C stocks in reference sites were broadly similar across both land uses. Minesoils under  
 219 grassland had lower C stocks than corresponding reference soils; for the older woodland sites  
 220 this difference was less consistent. It should be noted that on all reference sites there was  
 221 some evidence of rooting below the sampled depth, so C stocks for these soils may be  
 222 underestimates. Findings are broadly consistent with those of Vindušková & Frouz (2013),  
 223 who indicated that a large proportion of post-mining woodland sites reach the pre-mining SOC  
 224 stock within 20 years; since grassland minesoils contained C stocks less than those of  
 225 undisturbed soils, C accumulation may be incomplete. In addition, woodland systems have  
 226 substantial carbon stored in above-ground biomass and the estimated figures for restored  
 227 sites are shown in Table 3. The average additional sequestration above-ground is  $82.8 \text{ t C ha}^{-1}$   
 228 and this is likely to increase beyond the timescale of the present study as woodlands mature.

229 **Table 2** Minesoil C stocks (30 cm depth) and CO<sub>2</sub> equivalent in a) restored colliery sites  
 230 under grassland and woodland and b) associated reference sites where available. Data  
 231 include overall means and standard deviations for each class

232 a)

Site	Age	Stocks C t per ha		CO <sub>2</sub> equiv. t per ha	
		Grassland	Woodland	Grassland	Woodland
Bargoed (S1)	21	77.5	86.9	284.1	318.5
Bryn Bach (S2)	22	63.7	102.4	233.8	375.4
Cambrian (S3)	24	69.3	161.2	254.1	590.9
Craig y Dyffryn (S4)	24	31.3	55.1	114.9	202.3
Cwm Darren (S5)	21	84.3	140.5	309.2	515.1
Deep Navigation (S6)	11	37.6	56.1	138.0	205.7
Gelliwion (S7)	26	62.3	104.6	228.4	383.6
Windsor (S8)	22	52.9	81.9	193.8	300.2
Mean		59.9 ± 7.0	98.6 ± 14.2	219.5 ± 25.5	361.4 ± 51.9

Mean (- 11 year site)                  63.0 ± 7.1      104.7 ±14.7      231.2 ±26.0      383.7 ± 53.9

233    b)

Site	Vegetation type	Stocks C t per ha	CO <sub>2</sub> equiv. t per ha
Bargoed	Grassland	105.3	386.1
Cambrian	Grassland	93.1	341.4
Mean	Grassland	99.2±8.6	363.8±31.6
Craig y Dyffryn	Woodland	105.2	385.7
Deep Navigation	Woodland	101.1	370.7
Gelliwion	Woodland	99.2	363.7
Windsor	Woodland	117.3	430.1
Mean	Woodland	105.7±8.1	387.6±29.8

234

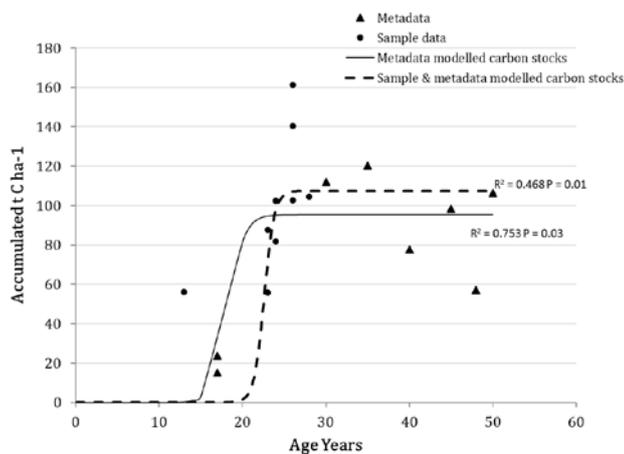
235    **Table 3** Estimated C and CO<sub>2</sub> equivalent stocks in above-ground biomass on woodland  
 236 sites. Data include overall means and standard deviations for each class.

Site	Biomass C t per ha	Biomass CO <sub>2</sub> equiv. t per ha
Bargoed	108.2	395.9
Bryn Bach	91.7	335.7
Cambrian	50.3	184.1
Craig y Dyffryn	77.9	284.9
Cwm Darren	58.7	214.7
Deep Navigation	24.2	88.5
Gelliwion	140.8	515.4
Windsor	110.4	404.1
Mean	82.8 ± 37.7	302.9 ± 138.0
Mean (- 11 year site)	91.1 ± 31.7	333.5 ± 116.0

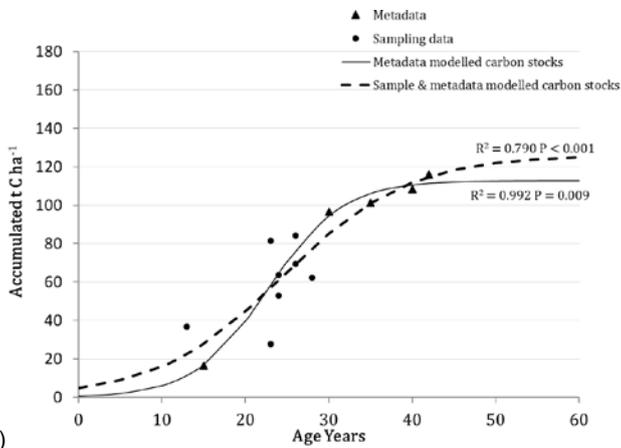
237    The model based on metadata from the literature alone and when combined with data from  
 238 this study is described in Figure 3. In all cases, for the combined data, sigmoidal regressions  
 239 had higher R<sup>2</sup> values than linear regressions, particularly for woodland (woodland linear R<sup>2</sup> =  
 240 0.085; grassland linear R<sup>2</sup> = 0.775,). The strongly non-linear relationship between C stocks  
 241 and age in woodland is expected, since C inputs would be very low after initial planting due to  
 242 limited litter production, then increase as trees grow; in contrast, grassland production and  
 243 therefore C inputs would be more consistent from the first growing season onwards. A

244 sigmoidal model would also be more applicable for predicting soil C sequestration, as net soil  
245 C accumulations have been shown to slow approaching saturation where no further  
246 accumulation takes place (Stewart *et al.*, 2007).

247 The statistical significance of the models improved for the combined data but the % of variation  
248 explained declined. Results of the combined analysis suggest higher carbon equilibrium  
249 stocks for woodland and grassland than those indicated from published data alone. The model  
250 predicts that woodland soils reach equilibrium after ca. 26 years of 107 t C ha<sup>-1</sup>, and show a  
251 rapid increase in carbon stocks after a slow initial rate of accumulation. The mean woodland  
252 soil equilibrium C stocks may be underestimated by the model as markedly higher values were  
253 recorded on two of the sites sampled; in general woodland datasets varied in relation to that  
254 predicted in the model. Our data are somewhat contradictory, in that older woodland minesoils  
255 appeared to be still in a phase of rapid C accumulation after 30 years, whereas reference soil  
256 stocks were close to the model prediction. The simple sigmoidal model here likely  
257 underestimates very early accumulation of soil carbon in woodland soil, due to the paucity of  
258 data points soon after planting. Grassland soils on the other hand accumulate carbon from  
259 soon after planting. The rate of increase of C accumulation is slower than for woodland soils  
260 but they attain a higher C storage equilibrium at 125 t C ha<sup>-1</sup> after ca. 60 years; a slower rate  
261 of C accumulation in grassland compared with woodland soils was also reported by  
262 Vindušková & Frouz (2013). The model predictions of eventual equilibrium minesoil C stocks  
263 for grassland are somewhat higher than those measured, but consistent with those recorded  
264 for the reference sites. Overall, the modelled data show that our results may have wider  
265 geographical application since the addition of data from the current study improves confidence  
266 in predictions of C stocks.



267 a)



268

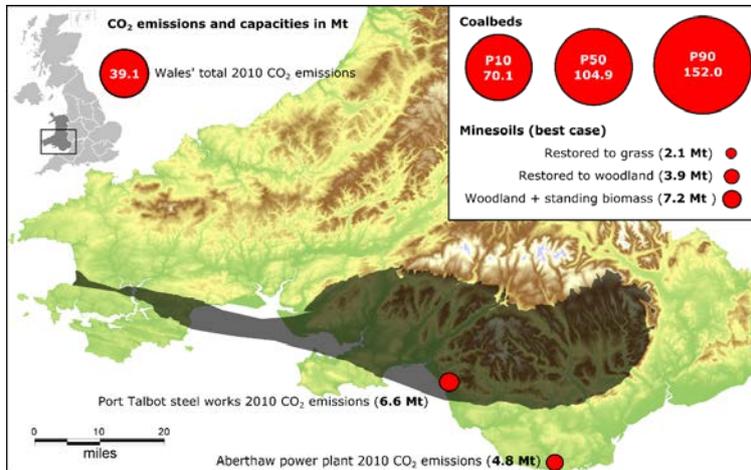
b)

269 **Fig. 3** Model of C accumulation with time in minesoils under a) woodland and b) grassland.

270 Based on modelled data, grassland minesoils for the coalfield should reach equilibrium carbon  
 271 storage of 2.9 MtCO<sub>2</sub> compared with measured data of 1.5 MtCO<sub>2</sub> after less than 30 years.  
 272 For woodland the model predicts 2.6 MtCO<sub>2</sub> compared with a measured 2.5 MtCO<sub>2</sub> in  
 273 minesoils.

### 274 3.3. Practical considerations for C sequestration

275 It is practical to correlate the potential for coalbed C sequestration with the major point source  
 276 emissions in the region. It can be seen in Figure 4 that the probable effective CO<sub>2</sub> storage  
 277 capacity of the Coalfield is equivalent to around 16 years of emissions from the Port Talbot  
 278 steel works, or 22 years from Aberthaw power plant. Following the recommendations of  
 279 Sarhosis *et al.* (2016b), there are constraints that would further restrict the storage capacity  
 280 that is accessible in practice, including social, economic, regulatory, and environmental  
 281 factors. Optimal sites would require detailed geological characterisation and engineering  
 282 design, leading to a matched capacity formed from a limited number of sites that is likely to be  
 283 less than the values presented in Figure 4.



284

285 **Fig. 4** Results of the preliminary evaluation for the coal and mine site CO<sub>2</sub> storage capacity of  
 286 the South Wales Coalfield (adapted from Sarhosis *et al.*, 2016 with emissions data from  
 287 Thomas and Kluiters, 2013).

288 Carbon stocks varied considerably between different minesoils (Table 2) of similar age.  
 289 Sequestration is determined by plant C fixation, the proportion returned to soil and the rate at  
 290 which this C is mineralised. Constraints to plant growth on minesoils include the supply of  
 291 water (compaction, rooting depth and texture (e.g. Bohrer *et al.*, 2017)) and nutrients (primarily  
 292 N and P (Bending & Moffat, 1999)). These constraints can be mitigated by good reclamation  
 293 practice, the former by effective ground preparation or loose tipping, the latter by inputs of  
 294 slow release nutrients and use of N-fixing legumes or trees (Moffat & McNeill, 1994). Allocation  
 295 of plant C into minesoils can be enhanced by species with prolific root systems, a characteristic  
 296 that would also improve acquisition of water and nutrients. Retention of C inputs can be  
 297 affected by minesoil characteristics such as texture, particularly clay contents,  
 298 drainage/aeration conditions and the depth range of C (primarily via roots but also bioturbation  
 299 (Józefowska *et al.*, 2017)) incorporation. Some low level, ongoing management of sites,  
 300 beyond the normal UK 5-year aftercare (involving nutrient inputs, replacement of failed trees  
 301 etc) period, might be justified by enhanced C sequestration benefits. Based on C data for the  
 302 best site, the potential for coalfield minesoil C sequestration is 2.1 or 3.9 (7.2 including best  
 303 standing biomass C) MtCO<sub>2</sub> for grassland or woodland respectively, under best management  
 304 practice described above. Due to the unfavourable conditions in minesoils, they are unlikely  
 305 to be subject to land use changes that might release sequestered carbon. This is important as  
 306 Angst *et al.* (2018) concluded that carbon sequestered in minesoils may be more vulnerable  
 307 to mineralisation through disturbance than is the case with 'natural' topsoil. Also, carbon

308 sequestered in woody biomass would at least in part be released through decomposition  
309 unless used in long-lived wooden products.

#### 310 *3.4. Economics, practice and regulation of C sequestration approaches*

311 Estimating the costs of these carbon sequestration approaches inevitably involves  
312 assumptions on exchange rates and inflation. Values estimated here are approximate  
313 therefore, but consistent in relative terms as the same assumptions have been applied to both  
314 sequestration scenarios.

315 The cost of capturing CO<sub>2</sub> from point sources can vary substantially. Recent studies indicate  
316 that projects are likely to cost between \$70–110 per tonne of CO<sub>2</sub>, although this is expected  
317 to reduce by up to 50% as capture technologies advance over the next decade (CCS  
318 Association, 2016). Indeed a recent report (National Academies of Sciences, Engineering, and  
319 Medicine, 2018) concluded that several technological and land management options have a  
320 current cost of \$20–100 per tonne of CO<sub>2</sub>. Requirements to run these technologies can impact  
321 the profitability of the source plant, as the separation of CO<sub>2</sub> consumes a significant amount  
322 energy (Haszeldine, 2009). There is however an economic incentive for low carbon strategies  
323 that could significantly reduce the costs of emission tariffs for energy intensive facilities such  
324 as Port Talbot steel works. The UK currently follows the EU Emission Trading System (ETS)  
325 to meet its emissions reduction targets, in addition to a carbon price floor introduced in 2015  
326 that has raised emissions tariffs further (Ares & Delebarre, 2016). Increased energy  
327 requirements and carbon capture technology costs may therefore be outweighed by the  
328 reduction in tariff expenditure.

329 Construction expenditure for the distribution pipeline will depend on the volume of gas to be  
330 transported and its composition. For pure CO<sub>2</sub>, the pipelines will be largely similar to pipelines  
331 used to transport methane in standard CBM operations, with some minor safety  
332 enhancements (Haszeldine, 2009). It was found by Ares & Delebarre (2016) that pipeline  
333 infrastructure had a very minor influence on CBM profitability. Consequently, the distribution  
334 infrastructure required for a scheme should not notably impact its economic potential in South  
335 Wales.

336 An investigation of the economic potential of recovering methane from residual coal seams for  
337 electricity production at a study area in South Wales, UK, has been undertaken by Sarhosis  
338 *et al.* (2016b). A coupled CBM-CCGT (combined-cycle gas turbine) process, using simple  
339 depressurisation techniques to capture the methane, has been suggested to yield a profit of  
340 \$108 million over a 37-year period. With CO<sub>2</sub> injection, the overall CH<sub>4</sub> recovery can be

341 significantly improved by directly displacing the methane from the coal (Ranathunga *et al.*,  
342 2017). The probable economic value of the CBM operation may therefore be taken with  
343 greater confidence and certainty by using CO<sub>2</sub> injection as a stimulant for methane desorption.  
344 A study by Pini *et al.* (2011) found that injecting pure CO<sub>2</sub>, although initially slower, can provide  
345 more effective methane displacement and a faster total recovery than for CO<sub>2</sub> with impurities  
346 (e.g. H<sub>2</sub>, CO, water, SO<sub>2</sub>, NO<sub>2</sub>). However, a CO<sub>2</sub>-N<sub>2</sub> mixture could enhance recovery whilst  
347 also reducing concerns over coal swelling around the gas injection point. An alternative to  
348 electrical power generation through a CBM-CCGT power plant would be the use of CBM for  
349 low carbon hydrogen production through steam-methane reformation combined with carbon  
350 capture. This option is part of the UK Carbon Capture, Usage and Storage (CCUS)  
351 deployment pathway (BEIS, 2018), reflecting the reliability of methane reformation in  
352 producing hydrogen at the scale required for the domestic and industrial heat and transport  
353 sectors. In any case, whilst the CBM is a valuable resource that can offset the cost of coal  
354 seam sequestration, the CO<sub>2</sub> emitted in its utilisation is required to protect the original  
355 emissions reduction.

356 Typical costs for ground preparation, planting and maintenance of restored colliery sites  
357 (excluding earthworks associated with reprofiling) in the UK were reported in the range \$6500  
358 - 8,000 ha<sup>-1</sup> (1.3 £ to US\$ exchange rate) during the mid-1990's (Goodman, 1998). Adjusting  
359 for inflation this equates to approximately \$11,700-14,000 ha<sup>-1</sup> in 2018. Cost will of course be  
360 region specific but the above estimates are not out of line with the revegetation component  
361 from other studies globally (e.g. Maiti & Maiti, 2015). Taking an average of this range and data  
362 presented here, minesoil CO<sub>2</sub> sequestration can be calculated as approximately \$55 and \$35  
363 t<sup>-1</sup> for grassland and woodland mine sites, respectively, assuming that all revegetating costs  
364 are charged to sequestration. Reclamation of colliery spoil is usually undertaken for reasons  
365 such as stabilisation, landscape, ecology, and recreation benefits. Since reclamation of  
366 minesoils is rarely considered from a C sequestration perspective, it could be argued that  
367 sequestration costs are zero. If a 25% increase in planting and maintenance costs were added  
368 aiming to obtain results as for the best of the sites surveyed (Cwm Darren), CO<sub>2</sub> sequestration  
369 costs equate to approximately \$50 and \$30 t<sup>-1</sup> overall (higher costs offset by greater  
370 sequestration) or for additional management costs alone approximately \$11 and \$7 t<sup>-1</sup> for  
371 grassland and woodland sites, respectively. In any full life cycle analysis of restoration, CO<sub>2</sub>  
372 emissions associated with energy use in planting would have to be accounted. However, even  
373 where these emissions were double those of planting on natural soils, to allow for the more  
374 difficult site conditions, they are unlikely to exceed 1.5 t<sup>-1</sup> ha<sup>-1</sup> CO<sub>2</sub> based on fuel, seed and  
375 fertiliser usage (Phillips, 2009), so would not affect significantly estimates of sequestration  
376 costings.

377 **4. Conclusions**

378 With the decline of coal extraction, there is interest in the potential of carbon sequestration in  
379 the remaining coalfields. An estimate of the carbon sequestration potential of coal seams in  
380 the South Wales Coalfield makes an analogy to the reserves estimation for coalbed methane.  
381 Taking account of the spatial variance in coal seam properties, the key input parameters  
382 needed for the evaluation were described by statistical distributions. The probable capacity  
383 was found to be 104.9 MtCO<sub>2</sub>, equivalent to 16 years of the 2011 emissions from the Port  
384 Talbot steel works. By comparison, coalfield minesoil ecosystems may sequester up to 5.9  
385 MtCO<sub>2</sub>, if all were restored to best woodland standards. Coal seam sequestration may be  
386 affected by a range of technical factors so extrapolation of findings may be more problematic.  
387 Estimates of minesite carbon stocks from this study fit well with the data from the meta-  
388 analysis, implying that the conclusions are more broadly applicable to similar climatic zones.  
389 Indeed, the predictions are not inconsistent with the findings of other studies under contrasting  
390 climate conditions (e.g. for India, Ahirwal & Maiti (2017)).

391 Although small be comparison with coal seam capacity, mine site C sequestration may have  
392 some wider advantages over coal seam sequestration. It could be considered cost free, as  
393 restoration has been considered beneficial for the economic regeneration of former coalfield  
394 areas regardless of sequestration benefits. Furthermore, sequestration in restored minesoils  
395 is unlikely to face any of the regulatory or policy constraints that might apply to coal seam  
396 restoration. In assessing the economic value of spoil reclamation schemes, there is a clear  
397 case for including carbon sequestration in this assessment.

398 The results of this evaluation indicate a potential for both approaches to contribute meaningful  
399 carbon capture and sequestration in the South Wales Coalfield. The two approaches are  
400 complementary, targeting different C sources. The former has a potential to reduce CO<sub>2</sub> inputs  
401 to the atmosphere an order of magnitude greater than the latter, although the techno-economic  
402 feasibility has not been evaluated fully. Whilst optimisation of C sequestration is likely to align  
403 with many of the broader minesite restoration and land use objectives, this may not always be  
404 the case. Our data show that there is scope to improve sequestration and that optimising C  
405 stocks in minesoils could justify additional restoration and management expenditure. There is  
406 significant potential for mitigation of CO<sub>2</sub> emissions in former coalfields for point source (larger  
407 and short-term) and diffuse emissions (smaller and medium term).

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