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

A Detheridge [a], L.J. Hosking [b], H.R. Thomas [b], V. Sarhosis [c], D Gwynn-Jones [a], J Scullion [a*]

[a] Institute of Biological, Environmental and Rural Sciences, Aberystwyth University, Aberystwyth SY23 3DA UK

[b] Geoenvironmental Research Centre, Cardiff School of Engineering, Cardiff University, CF24 3AA UK

[c] School of Engineering, Newcastle University, Newcastle upon Tyne, NE1 7RU UK

Abstract

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

Keywords coal; minesoils; carbon sequestration; storage capacity

1. Introduction

Increasing atmospheric concentrations of carbon dioxide (CO_2), caused by human activities including power generation and industry, are driving climate change. In 2017, for example, it is provisionally estimated that UK net carbon dioxide (CO_2) emissions were 366.9 million tonnes CO_2 ($MtCO_2$) (DECC, 2018). While the carbon intensity of the UK and wider world economy is falling, progress falls short of what is needed to limit global temperatures to 2^oC above pre-industrial levels (PwC, 2016). Geological carbon (C) sequestration aims to avoid or offset the atmospheric emission of CO_2 and is prominent in strategies for climate change mitigation and adaptation. Of most interest for C sequestration are deep saline aquifers, depleted oil and gas reservoirs, unmineable coalbeds, and soils. There is now a pressing need to explore all options to not only reduce emissions, for example through the point source capture, utilisation and storage of CO_2, but also to increase the removal of CO_2 from the atmosphere by introducing land management practices to enhance levels of soil C (The Royal Society and The Royal Academy of Engineering, 2018). Thus, the CO_2 storage potential within the South Wales Coalfield, both below-ground in coal seams and above-ground in minesoil, is of interest.

Carbon capture and sequestration (CCS) in coal seams is an appealing option for Wales since there are significant remaining coal reserves in proximity to large point source emitters of CO_2, such as the Port Talbot steel works (c. 6.6 $MtCO_2$/year) (Thomas & Kluiters, 2013). Coalbeds provide in principle an attractive sink for captured CO_2 since storage is predominantly in the sorbed phase, reducing CO_2 mobility and therefore its risk of leakage compared to the other candidate reservoirs. The foremost technical barrier to the deployment of C sequestration in coalbeds remains the swelling response of coal to CO_2 sorption, having been found in several field trials to reduce the (already low) permeability of coal to the extent where CO_2 injection is impractical without reservoir stimulation (e.g. van Bergen *et al.*, 2006; Fujioka *et al.*, 2010). Whilst coal swelling is beyond the scope of the present work, the nature of the sorption and swelling behaviour remains an active area of research (e.g. Liu et al., 2017; Chen et al., 2019) and is recognised as a constraint of the CO_2 storage potential of coalfields.

The C sequestration potential of disturbed soils, such as spoils associated with mining, is high because the level of organic carbon they contain prior to any reclamation is much lower than in natural soils (e.g. Vinduskova & Frouz, 2013). Therefore, the difference between the starting point and the saturation level of carbon in minesoils is large. Several studies have focussed on C accumulation in restored minesoils (e.g. Akala & Lal, 2001) and have highlighted the potential of these sites for C sequestration. The sequestration of carbon in soils is dependent on good ecosystem functioning; this in turn depends on a wide range of interacting factors (Shrestha & Lal, 2006). Minesoils present a combination of problems limiting vegetation productivity and hence C sequestration. These include compaction (Bending & Moffat, 1999), poor water-holding capacity (Daniels & Zipper, 1997), nutrient deficiency (Palmer & Chadwick, 1985), low levels of soil biological activity (Anderson *et al.*, 2008) and low pH where materials are pyritic (Martínez *et al.*, 1996). However, Littlefield *et al.* (2013) found that the rate of C accumulation in minesoils was more rapid than in natural soils where both were planted to similar forest communities. Compared with areas receiving soil cover, sites planted directly on overburden can show higher rates of soil carbon accumulation and larger final stocks, despite having lower levels of plant growth (Bending & Moffat, 1999; Jacinthe & Lal, 2007).

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

The aim of this study is to evaluate and compare the CO_2 storage potential and practicality of deep coal seams and of minesoil, using the South Wales Coalfield as a case study. A parallel study (Sarhosis et al, 2016a) generated data on coal seam sequestration potential. This work and previous studies have considered coal and minesoils as individual sinks for CO_2, here we emphasise their comparison at a regional scale. Although the two approaches are complementary, their relative sequestration capacity, sequestration rates, practicalities, and cost effectiveness vary. Circumstances within individual coalfields differ, but our findings will indicate whether C sequestration associated with former coal mining activities can make a meaningful contribution to limiting atmospheric greenhouse gas increases.

2. Methods and approaches

2.1. C sequestration in coal seams

An estimate of the coal seam CO_2 storage potential was given by Sarhosis et al. (2016a), based on a digitised, three-dimensional geological map of the South Wales Coalfield's remaining coal resource. By considering minesoil reclamation alongside the results of Sarhosis et al., the present work determines the carbon sequestration potential of the Coalfield as a whole. A discussion of practical considerations, economics and possible regulatory constraints for each option is also provided in this work to complement the quantitative findings and provide a stronger basis for their comparison. For completeness, this section will present a summary of the approach taken by Sarhosis et al. in their estimation of the coal seam sequestration capacity of the South Wales Coalfield.

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

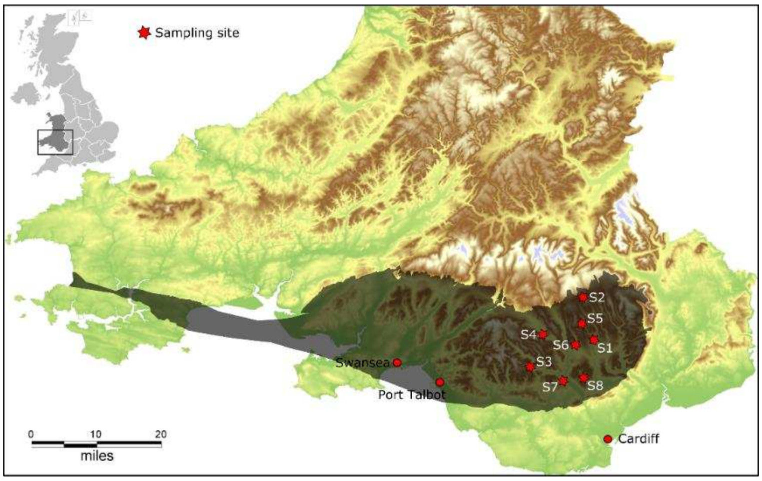


Fig. 1. The extent of the South Wales Coalfield and the location of field survey sites used in this study to estimate the C sequestration potential of minesoils (S1-S8 see Table 3). (Sarhosis *et al.*, 2016a).

The study by Sarhosis *et al.* (2016a) provided an estimate of the effective C sequestration capacity of coal seams in the South Wales Coalfield by making an analogy to the reserves estimation for coalbed methane (CBM). In summary, a total '*theoretical*' coalbed methane *in situ* was first estimated then converted to the effective gas capacity by applying the factors C_f and R_f for well completion and reservoir conditions, respectively. These factors and their assigned values are discussed in detail by Sarhosis *et al.* (2016a), but may be qualitatively interpreted as restricting the volume of unmined coal that can be accessed for sequestration. An '*effective*' CO_2 storage capacity was then estimated by applying an exchange ratio for the preferential displacement of *in situ* CH_4 by CO_2, the values for which were determined from laboratory adsorption tests. To consider the likely range of reservoir conditions and engineering factors, statistical distributions were defined for each input parameter (Table 1), allowing for a Monte Carlo analysis of the effective storage capacity. The data sets and literature supporting these values are discussed fully in Sarhosis *et al.* (2016a).

Parameter	**Minimum**	**Most likely**	**Maximum**	**Standard deviation**
Coal CH_4 content, G_{CH_4} (m^3 t^{-1})	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

Table 1 Summary of the input values used for the Monte Carlo analysis of the effective CO_2 storage capacity of the South Wales Coalfield (Sarhosis *et al.*, 2016a).

2.2. Estimating C sequestration in minesoils

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

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

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

C stocks were then estimated based on fine earth C concentrations, and adjusting for stone content and bulk density.

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

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

$$log(m_{bio}) = A + Blog(DBH) \qquad (1)$$

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

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

3. Results and Discussion

3.1. *Coal seam storage capacity*

The Monte Carlo analysis of the effective coal seam CO_2 storage capacity, performed by Sarhosis *et al*. (2016a), produced the results shown in Figure 2. The results were presented in terms of the proved, probable and possible effective storage capacities to be exceeded with confidences of 90%, 50% and 10%, respectively. The results show a proven total effective storage capacity of 70.1 $MtCO_2$, with a probable capacity of 104.9 $MtCO_2$ and a possible capacity of 152.0 $MtCO_2$.

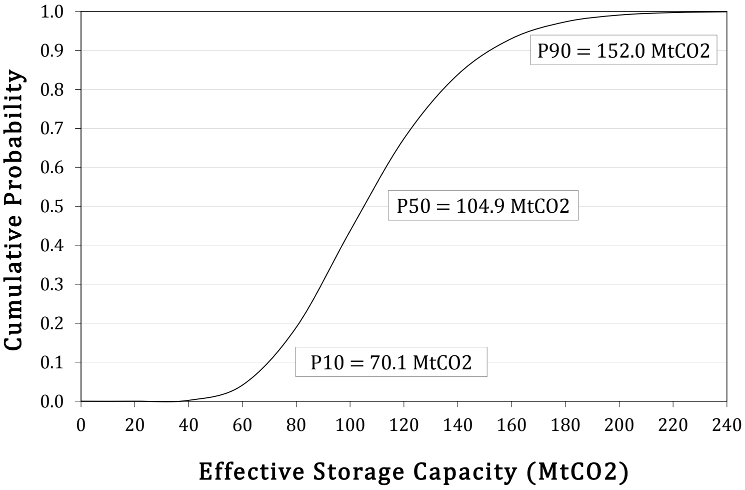


Fig. 2 Results of the Monte Carlo simulation for the effective CO_2 storage capacity of coal seams in the South Wales Coalfield (Sarhosis et al., 2016a).

3.2. *Minesoil storage capacities and sequestration rates*

Estimates of C stocks (and CO_2 equivalents) in restored minesoils are presented in Table 2a. Stocks under woodland were much higher than those under grassland (P = 0.004). There were also significant (P = 0.04) differences between sites, with Craig y Dyffryn and the more recent Deep Navigation holding < 50 t C ha^{-1} compared with Cambrian and Cwm Darren where stocks exceeded 100 t C ha^{-1}. This range of C stocks is comparable to those obtained in other recent studies on woodland mine soils from China (51.2 - 172.2 Mg ha^{-1} – Yuan et al., 2016). The lower C stocks on Deep Navigation can be attributed to the shorter period since restoration whilst Craig y Dyffryn was affected by a fire several years after reclamation. On average the below-ground component in grassland contained 231 CO_2-equiv t per ha and woodland 384 CO_2-equiv t per ha (excluding 11 year site). Table 3 shows the estimated above-ground C stocks in woodland for each site; no meaningful estimate could be made for grassland but since it was grazed intermittently amounts are insignificant. In woodland there was little correlation between above- and below-ground C stocks (r= -0.0725) indicating that factors in addition to primary productivity, such as moisture regimes, affected C accumulation. These factors would impact not only productivity but also C losses by respiration; respiration responses to revegetation are variable, with examples of little difference between seeded and partially colonised grassland (Cizkova et al., 2018), but higher respiration rates in 5-year afforested minesoils compared to both unreclaimed and reference forest sites (Ahirwal & Maiti, 2018).

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

Table 2 Minesoil C stocks (30 cm depth) and CO_2 equivalent in a) restored colliery sites under grassland and woodland and b) associated reference sites where available. Data include overall means and standard deviations for each class

a)

		Stocks C t per ha		**CO_2 equiv. t per ha**	
Site	Age	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

b)

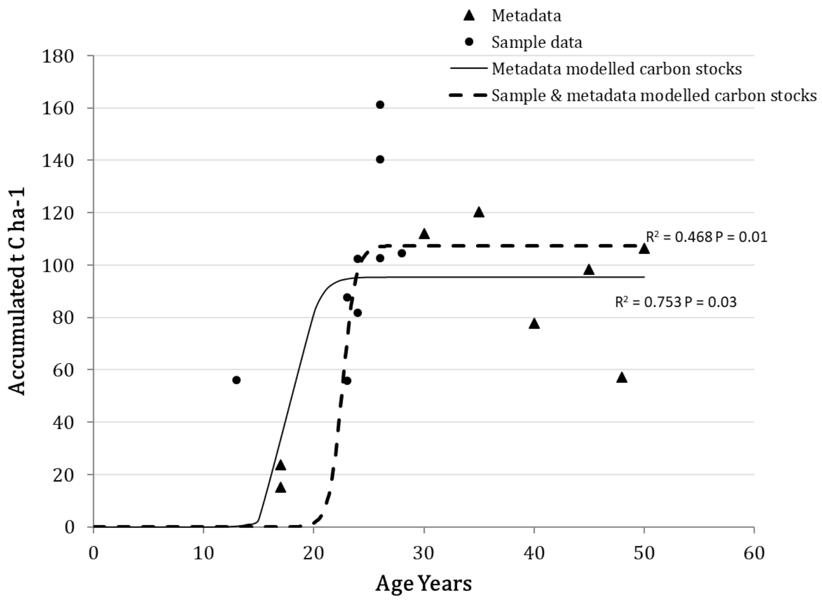
Site	Vegetation type	Stocks C t per ha	CO_2 equiv. t per ha
Bargoed	Grassland	105.3	386.1
Cambrian	Grassland	93.1	341.4
Mean	Grassland	99.2±8.6	363.8±31.6
Craig y Dyffryn	Woodland	105.2	385.7
Deep Navigation	Woodland	101.1	370.7
Gelliwion	Woodland	99.2	363.7
Windsor	Woodland	117.3	430.1
Mean	Woodland	105.7±8.1	387.6±29.8

Table 3 Estimated C and CO_2 equivalent stocks in above-ground biomass on woodland sites. Data include overall means and standard deviations for each class.

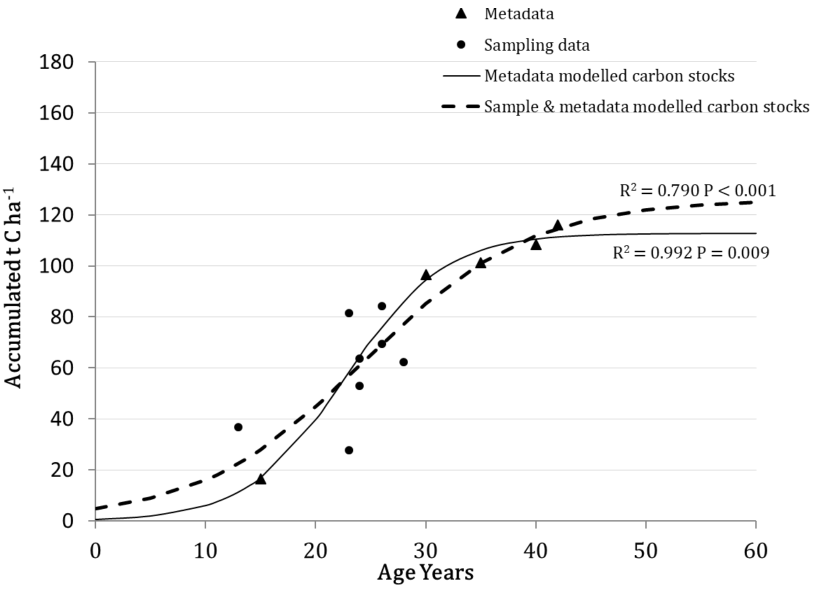
Site	Biomass C t per ha	Biomass CO_2 equiv. t per ha
Bargoed	108.2	395.9
Bryn Bach	91.7	335.7
Cambrian	50.3	184.1
Craig y Dyffryn	77.9	284.9
Cwm Darren	58.7	214.7
Deep Navigation	24.2	88.5
Gelliwion	140.8	515.4
Windsor	110.4	404.1
Mean	82.8 ± 37.7	302.9 ± 138.0
Mean (- 11 year site)	91.1 ± 31.7	333.5 ± 116.0

The model based on metadata from the literature alone and when combined with data from this study is described in Figure 3. In all cases, for the combined data, sigmoidal regressions had higher R^2 values than linear regressions, particularly for woodland (woodland linear $R^2 = 0.085$; grassland linear $R^2 = 0.775$,). The strongly non-linear relationship between C stocks and age in woodland is expected, since C inputs would be very low after initial planting due to limited litter production, then increase as trees grow; in contrast, grassland production and therefore C inputs would be more consistent from the first growing season onwards. A sigmoidal model would also be more applicable for predicting soil C sequestration, as net soil C accumulations have been shown to slow approaching saturation where no further accumulation takes place (Stewart *et al.*, 2007).

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



a)



b)

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

Based on modelled data, grassland minesoils for the coalfield should reach equilibrium carbon storage of 2.9 $MtCO_2$ compared with measured data of 1.5 $MtCO_2$ after less than 30 years. For woodland the model predicts 2.6 $MtCO_2$ compared with a measured 2.5 $MtCO_2$ in minesoils.

3.3. *Practical considerations for C sequestration*

It is practical to correlate the potential for coalbed C sequestration with the major point source emissions in the region. It can be seen in Figure 4 that the probable effective CO_2 storage capacity of the Coalfield is equivalent to around 16 years of emissions from the Port Talbot steel works, or 22 years from Aberthaw power plant. Following the recommendations of Sarhosis *et al.* (2016b), there are constraints that would further restrict the storage capacity that is accessible in practice, including social, economic, regulatory, and environmental factors. Optimal sites would require detailed geological characterisation and engineering design, leading to a matched capacity formed from a limited number of sites that is likely to be less than the values presented in Figure 4.

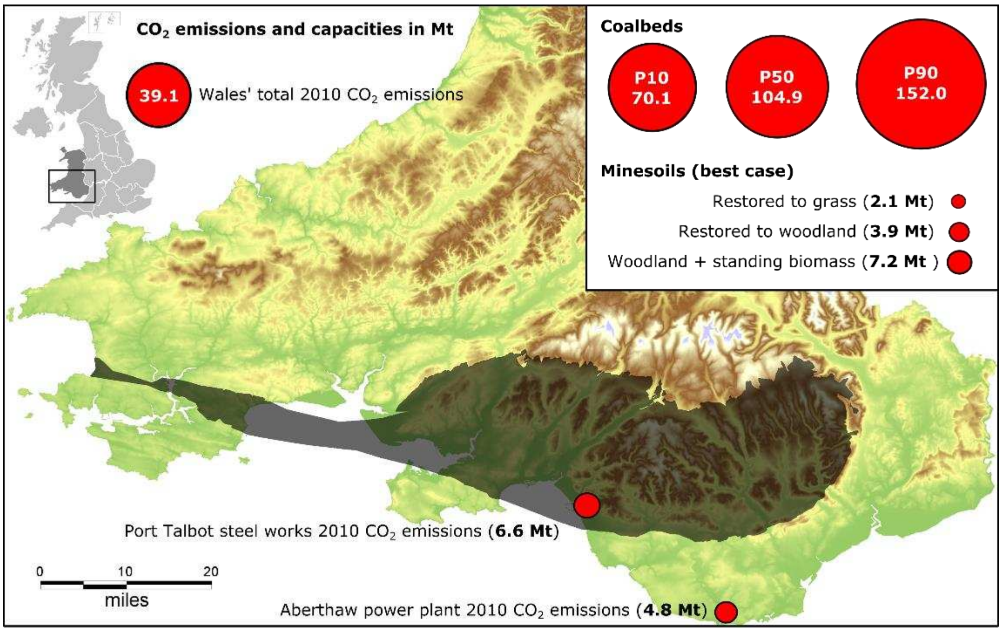


Fig. 4 Results of the preliminary evaluation for the coal and mine site CO_2 storage capacity of the South Wales Coalfield (adapted from Sarhosis *et al.*, 2016 with emissions data from Thomas and Kluiters, 2013).

Carbon stocks varied considerably between different minesoils (Table 2) of similar age. Sequestration is determined by plant C fixation, the proportion returned to soil and the rate at which this C is mineralised. Constraints to plant growth on minesoils include the supply of water (compaction, rooting depth and texture (e.g. Bohrer *et al.*, 2017)) and nutrients (primarily N and P (Bending & Moffat, 1999)). These constraints can be mitigated by good reclamation practice, the former by effective ground preparation or loose tipping, the latter by inputs of slow release nutrients and use of N-fixing legumes or trees (Moffat & McNeill, 1994). Allocation of plant C into minesoils can be enhanced by species with prolific root systems, a characteristic that would also improve acquisition of water and nutrients. Retention of C inputs can be affected by minesoil characteristics such as texture, particularly clay contents, drainage/aeration conditions and the depth range of C (primarily via roots but also bioturbation (Józefowska *et al.*, 2017)) incorporation. Some low level, ongoing management of sites, beyond the normal UK 5-year aftercare (involving nutrient inputs, replacement of failed trees etc) period, might be justified by enhanced C sequestration benefits. Based on C data for the best site, the potential for coalfield minesoil C sequestration is 2.1 or 3.9 (7.2 including best standing biomass C) $MtCO_2$ for grassland or woodland respectively, under best management practice described above. Due to the unfavourable conditions in minesoils, they are unlikely to be subject to land use changes that might release sequestered carbon. This is important as Angst *et al.* (2018) concluded that carbon sequestered in minesoils may be more vulnerable to mineralisation through disturbance than is the case with 'natural' topsoil. Also, carbon sequestered in woody biomass would at least in part be released through decomposition unless used in long-lived wooden products.

3.4. Economics, practice and regulation of C sequestration approaches

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

The cost of capturing CO_2 from point sources can vary substantially. Recent studies indicate that projects are likely to cost between $70–110 per tonne of CO_2, although this is expected to reduce by up to 50% as capture technologies advance over the next decade (CCS Association, 2016). Indeed a recent report (National Academies of Sciences, Engineering, and Medicine, 2018) concluded that several technological and land management options have a current cost of $20–100 per tonne of CO_2. Requirements to run these technologies can impact the profitability of the source plant, as the separation of CO_2 consumes a significant amount energy (Haszeldine, 2009). There is however an economic incentive for low carbon strategies that could significantly reduce the costs of emission tariffs for energy intensive facilities such as Port Talbot steel works. The UK currently follows the EU Emission Trading System (ETS) to meet its emissions reduction targets, in addition to a carbon price floor introduced in 2015 that has raised emissions tariffs further (Ares & Delebarre, 2016). Increased energy requirements and carbon capture technology costs may therefore be outweighed by the reduction in tariff expenditure.

Construction expenditure for the distribution pipeline will depend on the volume of gas to be transported and its composition. For pure CO_2, the pipelines will be largely similar to pipelines used to transport methane in standard CBM operations, with some minor safety enhancements (Haszeldine, 2009). It was found by Ares & Delebarre (2016) that pipeline infrastructure had a very minor influence on CBM profitability. Consequently, the distribution infrastructure required for a scheme should not notably impact its economic potential in South Wales.

An investigation of the economic potential of recovering methane from residual coal seams for electricity production at a study area in South Wales, UK, has been undertaken by Sarhosis *et al.* (2016b). A coupled CBM-CCGT (combined-cycle gas turbine) process, using simple depressurisation techniques to capture the methane, has been suggested to yield a profit of $108 million over a 37-year period. With CO_2 injection, the overall CH_4 recovery can be significantly improved by directly displacing the methane from the coal (Ranathunga *et al.*, 2017). The probable economic value of the CBM operation may therefore be taken with greater confidence and certainty by using CO_2 injection as a stimulant for methane desorption. A study by Pini *et al.* (2011) found that injecting pure CO_2, although initially slower, can provide more effective methane displacement and a faster total recovery than for CO_2 with impurities (e.g. H_2, CO, water, SO_2, NO_2). However, a CO_2-N_2 mixture could enhance recovery whilst also reducing concerns over coal swelling around the gas injection point. An alternative to electrical power generation though a CBM-CCGT power plant would be the use of CBM for low carbon hydrogen production through steam-methane reformation combined with carbon capture. This option is part of the UK Carbon Capture, Usage and Storage (CCUS) deployment pathway (BEIS, 2018), reflecting the reliability of methane reformation in producing hydrogen at the scale required for the domestic and industrial heat and transport sectors. In any case, whilst the CBM is a valuable resource that can offset the cost of coal seam sequestration, the CO_2 emitted in its utilisation is required to protect the original emissions reduction.

Typical costs for ground preparation, planting and maintenance of restored colliery sites (excluding earthworks associated with reprofiling) in the UK were reported in the range \$6500 - 8,000 ha^{-1} (1.3 £ to US\$ exchange rate) during the mid-1990's (Goodman, 1998). Adjusting for inflation this equates to approximately \$11,700-14,000 ha^{-1} in 2018. Cost will of course be region specific but the above estimates are not out of line with the revegetation component from other studies globally (e.g. Maiti & Maiti, 2015). Taking an average of this range and data presented here, minesoil CO_2 sequestration can be calculated as approximately \$55 and \$35 t^{-1} for grassland and woodland mine sites, respectively, assuming that all revegetating costs are charged to sequestration. Reclamation of colliery spoil is usually undertaken for reasons such as stabilisation, landscape, ecology, and recreation benefits. Since reclamation of minesoils is rarely considered from a C sequestration perspective, it could be argued that sequestration costs are zero. If a 25% increase in planting and maintenance costs were added aiming to obtain results as for the best of the sites surveyed (Cwm Darren), CO_2 sequestration costs equate to approximately \$50 and \$30 t^{-1} overall (higher costs offset by greater sequestration) or for additional management costs alone approximately \$11 and \$7 t^{-1} for grassland and woodland sites, respectively. In any full life cycle analysis of restoration, CO_2 emissions associated with energy use in planting would have to be accounted. However, even where these emissions were double those of planting on natural soils, to allow for the more difficult site conditions, they are unlikely to exceed 1.5 t^{-1} ha^{-1} CO_2 based on fuel, seed and fertiliser usage (Phillips, 2009), so would not affect significantly estimates of sequestration costings.

4. Conclusions

With the decline of coal extraction, there is interest in the potential of carbon sequestration in the remaining coalfields. An estimate of the carbon sequestration potential of coal seams in the South Wales Coalfield makes an analogy to the reserves estimation for coalbed methane. Taking account of the spatial variance in coal seam properties, the key input parameters needed for the evaluation were described by statistical distributions. The probable capacity was found to be 104.9 $MtCO_2$, equivalent to 16 years of the 2011 emissions from the Port Talbot steel works. By comparison, coalfield minesoil ecosystems may sequester up to 5.9 $MtCO_2$, if all were restored to best woodland standards. Coal seam sequestration may be affected by a range of technical factors so extrapolation of findings may be more problematic. Estimates of minesite carbon stocks from this study fit well with the data from the meta-analysis, implying that the conclusions are more broadly applicable to similar climatic zones. Indeed, the predictions are not inconsistent with the findings of other studies under contrasting climate conditions (e.g. for India, Ahirwal & Maiti (2017)).

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

The results of this evaluation indicate a potential for both approaches to contribute meaningful carbon capture and sequestration in the South Wales Coalfield. The two approaches are complementary, targeting different C sources. The former has a potential to reduce CO_2 inputs to the atmosphere an order of magnitude greater than the latter, although the techno-economic feasibility has not been evaluated fully. Whilst optimisation of C sequestration is likely to align with many of the broader minesite restoration and land use objectives, this may not always be the case. Our data show that there is scope to improve sequestration and that optimising C stocks in minesoils could justify additional restoration and management expenditure. There is significant potential for mitigation of CO_2 emissions in former coalfields for point source (larger and short-term) and diffuse emissions (smaller and medium term).

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