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High carbon burial rates by small ponds in the landscape.

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Abstract

Temperate ponds may be important sinks and sources of greenhouse gases, but just how quickly ponds bury carbon is poorly understood. We present the first organic carbon (OC) burial rates for small ponds of known age by digging out the whole sediment from ponds. The average carbon burial rate was 142 g m^{-2} yr^{-1}, with a range from 78 and 247 g m^{-2} yr^{-1}, depending on the ponds' vegetation. Burial rates in the ponds were 20-30 times higher than estimates for habitats such as woodland or grassland and higher than other natural wetlands. Although small ponds occupy a tiny proportion of the landscape compared to these other habitats their high OC burial rates results in comparable annual OC burial overall. Ponds are easy to create, can be fitted in amongst other land uses and are a globally ubiquitous habitat. These new results show that ponds have the potential to be a very useful additional tool to mitigate carbon emissions.

Introduction

The Paris Climate Change Conference 2015 recognised the potential for the creation and manipulation of habitats as a buffer against anthropogenic emissions of greenhouse gases, e.g. afforestation or habitat restoration in areas of agricultural intensification (Fischer et al., 2017; Lamb et al., 2016). Here we argue that ponds and small wetlands can also make a significant contribution as carbon sinks. Ponds are ubiquitous throughout the world's terrestrial biomes and relatively easy to create but evidence of their capacity to bury carbon is limited (Downing, 2010).

Emerging research has identified the importance of inland waters for processing organic carbon (OC), highlighting the need for their inclusion in strategies to mitigate climate change (Battin et al., 2009). However, quantifying rates of OC burial in freshwaters has focused on larger habitats, e.g. lakes, and our understanding of the efficiency of the process is confounded by the variability between habitat types (Cole et al., 2007, Kayranli et al., 2010). We have only limited knowledge about the time taken for habitats to become effective sinks or how vegetation influences rates of OC burial (Kayranli et al., 2010). A comprehensive study on OC burial in freshwater ecosystems identified disproportionately high rates of OC burial in smaller water bodies (Downing, 2010), but these results came largely from artificial habitats such as agricultural impoundments. Dean and Gorham (1998) estimated OC burial in larger lakes of between 34- 60 Tg yr^{-1} compared to 100 Tg y^{-1} in the oceans, despite lakes covering barely 0.007 of the area of the seas. Conversely, small natural lakes have been cited as significant sources of greenhouse gas emissions (Hanson et al., 2004, Torgerson and Branco, 2007), even if their net carbon processing buries OC in their sediments.

While the potential for small ponds to capture and store OC is apparent, accurately quantified rates of OC burial are scarce: do ponds bury OC fast enough to be worthwhile carbon sinks? Gilbert et al. (2014) was one of the first studies to report sediment OC and burial rates in ponds observing rates of OC burial of ~149 g OC m^{-2} yr^{-1}. This represents some of the highest rates of OC burial observed across natural habitats. Moreover, these rates, when combined with the very large numbers of small ponds (Holgerson and Raymond, 2016) and their higher intensity carbon processing compared to large lakes (e.g. Holgerson and Raymond, 2016; Polishchuk et al., 2018), suggests a significant overall carbon sequestration capacity.

However, ponds face global threats undermining their potential role for buffering atmospheric carbon. Pond loss is a world-wide problem (Jeffries et al., 2016) driven by land drainage and neglect. The role of ponds in providing key ecosystem services, such as flood mitigation and water quality improvement, is becoming clear (e.g. Céréghino et al., 2013). For example, small ponds constructed next to streams can remove 85% to 90% of nitrates, phosphates and suspended sediments (Zedler and Kercher, 2005) and networks of ponds can reduce catchment flooding during extreme weather events (Biggs, 2007). Given the wealth of beneficial ecosystem services that ponds provide, their creation would help meet a range of environmental policy objectives and address some of the toughest challenges currently nationally and globally, including carbon sequestration. Ponds are much easier to create than many habitats, and can easily be integrated into larger land-uses.

A more novel challenge is that we have little information on how fluxes of greenhouse gases may vary over the years as ponds develop and climate changes. Increased emissions of CH_4 and/or N_2O have the potential to significantly offset any CO_2 sequestration, given their greater global warming potential. Small ponds have been identified as a potentially important source of CO_2 (Abinoza et al., 2012; Holgerson and Raymond, 2016), CH_4 (Bastviken et al., 2004; Holgerson and Raymond, 2016, Wik et al., 2016) and N_20 (Soued et al., 2015). Moreover, Yvonne-Durocher et al. (2017) presented a rare experimental approach, tracking CO_2 and CH_4 fluxes in experimental ponds over seven years and showed that emissions of CH_4 increased with warming, and that the effect was greater as the pond aged. This could be a challenge for site managers to maintain the effectiveness of ponds as carbon sinks.

In this communication we present data on rates of OC burial in small ponds of precisely known age and vegetation history in a temperate lowland area in the UK, demonstrating the potential of small ponds to help buffer carbon emissions. We also present insights on the role of vegetation which can inform the construction and engineering of ponds to target OC burial. The agricultural lowland landscape and the ponds in which this study was conducted are characteristic of lowlands across

Europe, North America, temperate South America, China and Russia (Jeffries et al., 2016), therefore, while we focus on the estimating carbon burial for the UK, results will have global application.

Methods and materials

This study used an experimental pond site located at Druridge Bay, Northumberland, UK. The site was formally an open cast coal mine, restored in the 1970s with clay back fill and now a nature reserve. We constructed thirty ponds on the site in November 1994 to monitor ecological succession.

Figure 1

The ponds displayed similar patterns of succession (Jeffries, 2008) transitioning from a bare substrate supporting submerged aquatic species, e.g. *Chara vulgaris* and *Ranunculus aquatilis,* to a contemporary sward of dense flora dominated by *Leptodictyum riparium*, *Eleocharis palustris*, *Glyceria fluitans* and *Juncus articulatus* overlying ~10 cm of accumulated sediment on top of the clay backfill. Our study also involved the construction of three new ponds in the winter of 2012/13 to identify OC storage across the early stages of succession when plant cover was very limited. We used 12 of the mature ponds constructed in 1994, 18-20 years old when sampled in 2012/2014, and the 3 new ponds constructed in 2012/13. The 12 mature ponds were chosen to represent three distinct plant succession histories. Group 1 ponds had retained species of submerged aquatic plants, e.g. *C. vulgaris*, scattered over bare substrate for up to 20 years, whereas group 3 ponds had established thick swards of the moss *L.riparium* with emergent species *G.fluitans* and *E.palustris* within 2-3 years. Group 2 ponds were an intermediary group between groups 1 and 3, with 4 ponds sampled in each group.

Figure 2

Both the original and the newly constructed ponds were constructed to a uniform size (~1 m x 1 m) and depth (~30 cm), to provide as close to replicate ponds as is possible under natural conditions.

Because we know the exact age of the ponds, their vegetation history and they have a visibly distinct base of clay on which the accumulated sediment sits, we are able to make precise estimates of OC burial rates. We know of no other data set that provides such precise measures of carbon burial rates by small, natural ponds.

We have measured CO_2 flux rates from these study ponds (Gilbert et al., 2016), which showed rapid changes during the transition from a dry to wet phase, and marked spatial variation between the ponds. Mean CO_2 flux varied between an intake of 641 mg m^{-2} d^{-1} to emissions of 3792 mg m^{-2} $d^{-1.}$ Any methane flux was below detectable limits (equivalent to 0.93 mg m^{-2} d^{-1}, based on the Gasmet 4030 detection limit for CH_4 of 0.06 ppm(v) (Rõõm et al., 2014) and the sampling parameters given in Gilbert et al., (2016)).

Three mature ponds, one each from groups 1-3, were exhumed in their entirety, in 2012, by digging a trench immediately alongside the pond to below the base of the sediment, then working sideways into the pond, removing all the accumulated sediment in blocks of ~20 x 20 cm (see figure 1). Accumulated sediment was visibly different in contrast to the underlying clay (Figure 3).

Figure 3

The samples were dried in a cabinet at 40ºC, and OC% in each block was determined for two 5 mg subsamples via CN analysis on a Flash 2000 Elemental Analyser, which was combined with the mass of the block (g) to quantify the mass of OC. OC stored across the whole pond was quantified using the sum of all individual blocks. Before exhumation, these same 3 ponds were also sampled by taking 3 sediment cores from each pond: one in the centre of the pond, the other two half way between the centre and opposite corners, allowing OC estimates based on cores to be compared to those from the whole pond exhumation. For the remaining ponds (9 mature, 3 new) a single sediment core was taken. Although the number of ponds sampled is small their biodiversity is very typical of ponds in the UK and temperate biomes globally.

Sediment cores were taken with a stainless steel core, with a bevelled cutting edge to penetrate dense root layers in order to minimise compaction. An extrusion tool was fitted within the device, and the sediment extruded and cut into 1 cm slices, allowing high-resolution sampling, down the length of the core. OC% in each slice was determined in the same way as the exhumed blocks.

Using OC density and the overall sediment depth a total value for OC within the sediment core was calculated and then extrapolated over the area of the pond to give an estimate of whole pond OC. OC burial values were then produced by dividing OC storage values by the age of the ponds at their individual time of sampling (18-21 years).

Results

Values of total OC storage from the three exhumed ponds ranged from 1565 to 2288 g OC m^{-2}, while the estimates of OC storage for the same ponds based on the average of three cores taken prior to exhumation ranged from 1594 to 2817 g OC m^{-2}. The estimates of OC storage in the ponds based on sediment core samples versus exhumation of the whole ponds were therefore on average 13.09% higher, ranging between 1.57 to 27.37% higher. Table 1 gives full details of OC stock estimates and burial rates.

Based on single cores taken from the other 9 mature ponds, values of whole pond OC storage were on average 2564 g OC m^{-2} ranging from 1413 to 4459 g OC m^{-2}. OC storage varied significantly between group 1 and group 3 ponds (ANOVA, GLM mixed models, pond groups 1-3 as factors, samples from a core as repeat measures, individual ponds identified as random factors. Differences between pond groups difference $P<0.05$). Group 3 ponds, with a history of rapid, vegetation coverage stored more OC, on average 4077 g OC m^{-2}, more than either group 2 (mean: 1996 g OC m^{-2}) or group 1, (mean: 1618 g OC m^{-2}). Converting OC storage into burial rates over the 18-20 years of the ponds' existence prior to core sampling gave an average burial rate of 122.10 OC m^{-2} yr^{-1}.

Table 1

OC storage in the three newly constructed ponds was considerably less. One pond, dominated by filamentous algae, retained relatively bare substrate and no analytically discernible layer of accumulated sediment was observed. The other two ponds established thin swards of *L.riparium* but sediment accumulation was limited to the top 1 cm of the sediment core. The estimated average OC storage value in these ponds was 40.73 g OC m^{-2}. OC burial rates in the young ponds were considerably less in comparison to rates observed in the mature ponds and were on average 13.58 g OC m^{-2} yr^{-1} .

We adjusted our estimates of burial rates from the mature ponds based on their whole lifespans of 18-20 years (depending on sample date) by subtracting the OC burial rates measured in the new ponds during their first three years from the mature ponds' rates over their whole lifespan and recalculating the rate for the mature ponds over remaining 15-17 years, to give an overall site average of 142.44 ± 18.65 g OC m^{-2} yr^{-1} . The lag time before extensive plant growth drives OC accumulation may be longer than three years in some ponds so this burial rate would be an under-estimate.

Spearman's rank correlation analysis was performed on the total OC stored in each of the 15 mature ponds and their vegetation cover. Vegetation in each pond was recorded every summer, as the % cover of each species, using a point quadrat, (Jeffries, 2008). The mean cover of each plant species across the years 1994-2014 was calculated and was then transformed to the percentage of the maximum coverage of all vegetation observed in each pond. Plant species displaying significant positive correlations with OC storage were *L. riparium* (Spearman's correlation, r_s = 0.800 p = 0.010) and *G. fluitans* (r_s= 0.686 p = 0.041). Species with significant negative correlations to OC storage were *J. articulatus* (r_s = -0.883 p = 0.002) and *C. vulgaris* (r_s = -0.683 p = 0.042).

Discussion.

The results show some of the highest rates of OC burial observed within natural ecosystems, higher than other terrestrial and aquatic habitats, e.g. boreal forest 4.94.2 g OC m^{-2} yr^{-1} temperate forests, 4.2 g OC m^{-2} yr^{-1} temperate grassland 2.2 g OC m^{-2} yr^{-1} and comparable to aquaculture ponds (see Downing et al., 2008), despite receiving no artificial enhancement of productivity**.** The depth and vegetation of these ponds are typical of such habitats, which are abundant throughout terrestrial biomes, suggesting they may be globally significant carbon sinks. CO_2 flux rates in these same ponds can switch rapidly from sink to source as they dry (Gilbert et al., 2016), nonetheless in over the 20 years of their existence they were net carbon sinks, burying OC at high rates compared to other terrestrial habitats. The area of small ponds in the UK is barely one hundredth that of broadleaved woodland but our data suggest that annual carbon burial by these woodlands is only three times higher than in the ponds (Table 2). In terms of managing landscapes for OC burial, these results confirm that small ponds could be integrated as carbon mitigation features in addition to other habitat options.

Table 2

Results also provide insights into the significance of different plant communities in the ponds. The ponds studied are as close to replicate systems as is possible under natural conditions, separated only by their individualistic development of vegetation communities. The moss *L. riparium* and grass *G. fluitans* showed a significant positive association with OC storage, with earlier establishment and greater overall coverage enhancing OC burial. This may arise from the more refractory OC biosynthesised by these species (Reverey et al., 2016). Previous studies (Gilbert et al., 2014) noted that the establishment of *L. riparium* swards kept the sediment damp, with anoxic conditions often apparent under degrading vegetation: the development of the moss sward, usually covering the bed of the ponds after 3-4 years, therefore created a switch in ecosystem functioning, indicating the start of sedimentation and accumulation of OC. These ponds can switch between being net sources or sinks of carbon within days of drying or wetting, respectively (Gilbert et al, 2016); a cover of vegetation resists drying and exposure of sediments to the air.

The correlation also identified vegetation that may restrict OC burial efficiency in the ponds. The algae *C. vulgaris* is known to be early colonist species preferring ponds with relatively bare substrates. The nature of OC biosynthesised by *Chara* species is preferentially degraded by microbes given its relatively labile composition in comparison to vascular based plant species (Reverey et al., 2016). The rush *J. articulatus* also had a significant negative correlation with OC burial. *Juncus* species have been associated with higher rates of carbon emission in wetland environments. *Juncus* species exude highly labile carbon from root networks, creating a rhizospheric priming effect, essentially enhancing microbial activity which promotes degradation of more refractory organic matter (Dunn et al., 2015; Aichner et al., 2010).

CH_4 emissions from the ponds, which have the potential to create a significant offset to CO_2 sequestration, are likely to be small for our ponds: our upper measured limit for CH_4 fluxes of 0.93 mg m^{-2} d^{-1} is equivalent to 2.3 g C (CO_2eq) m^{-2} yr^{-1} or 1.7% of our mature pond OC burial rate (conversion equivalents from Forster et al. 2007) and literature estimates for other small experimental ponds range from 1.1 - 4.4 g C (CO_2eq) m^{-2} yr^{-1} (0.7 - 3.1% of our OC burial rate) (Yvon-Durocher et al. 2017) to 2.0 - 28.5 g C (CO_2eq) m^{-2} yr^{-1} (1.4 - 19.7% of our OC burial rate) (Davidson et al. 2018). Obrador (2018) has reported wet phase CH_4 emissions equivalent to 4 – 44 g C (CO_2eq) m^{-2} yr^{-1} for temporary ponds in Menorca, although for the majority of ponds, emissions were below detectable limits (1.6 g C (CO_2eq) m^{-2} yr^{-1}) in both the wet and dry phases. N_20 emissions from ponds are less well studied however Soued et al. (2015) assessed fluxes as being negligible compared to lakes and rivers: equivalent to a maximum of 0.8 g C (CO_2eq) m^{-2} yr^{-1}.

The ponds' burial or emission of carbon are likely to change over the years in response to succession, changes to landscape and climate. The ponds will fill in; they had already accumulated ~10cm of sediment in their 30cm profile in twenty years. As they become shallower the length of the dry phase and exposure of sediment will increase, which typically increases greenhouse gas emissions. Mitigating against this the ponds with denser vegetation cover showed lower CO_2 emissions as they dried out (Gilbert, 2017) and all the ponds became increasingly vegetated over time. There is also literature evidence that increased vegetation in small ponds mitigates against CH_4 emissions (Davidson et at, 2018).

Late successional, filled in ponds are often regarded, incorrectly, as poor quality and targeted for restoration. A better strategy would be for land managers to create a brand new pond nearby, retaining the older pond habitat and creating pond clusters, which are much better for biodiversity (Williams et al., 2008) as well as rejuvenating a site's potential for carbon burial. Ponds are also found throughout the world's terrestrial habitats, a natural fit in the landscape, and biodiversity hotspots creating multiple benefits than other land-uses such as planting new pockets of woodland.

Conclusion.

Our findings show the potential of ponds in landscape carbon mitigation schemes. Table 2 gives broad estimates of annual carbon burial for grassland, broadleaved and coniferous woodland in Great Britain using estimates of habitat areas from the UK Countryside Survey (Carey et al., 2008. Comparable habitats are found throughout the temperate biomes), combined with estimates for ponds using the burial rates presented here. Ponds make up a very much smaller area but their very high burial rates result in total carbon burial not much below that of the other major habitat types. Our results demonstrate the potential for ponds to be created and engineered through the planting of selected plant species, to enhance the process of natural succession and promote conditions conducive to OC storage and burial. Our estimates suggest that the inclusion of ponds in agri-environmental policy or urban green infrastructure could contribute to mitigating carbon emissions. Ponds are easy to create, ubiquitous globally and can be small, versatile features readily incorporated amongst other land uses, to provide a wealth of other benefits in addition to carbon sequestration and are a globally distributed habitat.

It is clear ponds should be considered as a powerful and practical element in land management to provide a whole raft of ecosystem services and biodiversity benefits, addressing some of the most adverse challenges currently faced on national and global scales.

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Figures & tables

Table 1. Organic carbon stocks and burial rates estimated by exhuming ponds or coring. Estimates from exhumed ponds also include estimates using 3 cores taken prior to exhumation. Burial rates are given for mature ponds over their full life span of 20 years and new ponds over 3 years

	Mean	Pond		
		1	2	3
OC stock estimates, 3 exhumed mature ponds & 3 cores before exhumation, g OC m^2				
Whole exhumed pond	1861.02	1565.17	1729.13	2288.77
Based on 3 cores per pond	2105.49	1887.78	2001.95	2426.73

	Mean	Min	Max
OC stock estimates, 9 mature ponds, 1 core per pond, g OC m^2			
All 9 ponds, storage over ~21 years	2564 ± 335	1413	4459
Group 1 ponds, (n=3)	1618.33 ± 211.80	1521 ± 199.09	1747 ± 228.68
Group 2 ponds, (n=3)	1996.33 ± 261.32	1413 ± 184.96	2368 ± 309.97
Group 3 ponds, (n=3)	4077.33 ± 533.722	3320 ± 434.59	4459 ± 583.68
OC stock estimates, 3 new ponds, 1 core per pond, burial over ~ 3 years	40.73 ± 4.30	24.21 ± 2.59	57.24 ± 6.04
OC burial rates g OC m^2 yr^{-1}			
Mature pond burial rate, ~20 years	122.10 ± 13.89	67.0 ± 8.77	212.0 ± 27.75
Burial rates in new ponds over ~ 3 years	13.58 ± 1.78	8.07 ± 1.06	19.08 ± 2.49
Mature pond burial rate adjusted to remove negligible first 3 years	142.44 ± 18.65	78.5 ± 10.28	247.2 ± 32.36

Table 2. Estimates of annual organic carbon burial across major habitat types in Great Britain, and in ponds. Habitat area estimates are taken from the Countryside Survey, (2008). Area of ponds are estimates of area taking pond numbers from Countryside Survey (2008) and median area from the four pond size classes in the Countryside Survey raw survey data. The burial estimates use our mature pond rate estimate, 122.1 g OC m^{-2} yr^{-1} . The burial rate values for woodlands and grasslands from Downing et al (2008), multiplied across the Countryside Survey estimates of habitat areas.

	Area of Great Britain		Mean OC burial, 000s Tonne yr^{-1}
Habitat	1000s ha	% of total area	
Broadleaved & mixed woodland	1406	6.0	59.1
Coniferous woodland	1319	5.7	64.6
Grasslands	8316	35.6	183.0
All ponds (0.25m^2 up to 2ha)	28.0	0.0012	34.2
Small ponds only, i.e. <0.2 ha	14.1	0.0006	17.2

Figure 1. The Druridge Bay site showing ponds in situ, (a) a mature pond filled with vegetation nearest and a bare new pond in the middle with bare sediment and (b) exhumation of a whole pond.

Figure 2. Examples of (a) a mature pond and (b) a newly dug pond. The mature pond is full of the floating grass *Glyceria fluitans*, over a thick moss sward. The newly dug pond is ~ two years old and still has very little vegetation except filamentous algae.

Figure 3. Panorama of the accumulated organic carbon rich sediment in a mature pond overlying the original smoother. The sediment was exposed as we exhumed the pond, with 1m rule included for scale.