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Published in:
Frontiers in Ecology and the Environment
Publication date:
2019

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Download date: 07. Jan. 2021
High carbon burial rates by small ponds in the landscape

Scott Taylor¹, Peter J Gilbert², David A Cooke¹, Michael E Deary¹, and Michael J Jeffries¹*

Temperate ponds may be important sinks and sources of greenhouse gases but just how quickly ponds bury carbon (C) is poorly understood. We derived – to the best of our knowledge – the first organic carbon (OC) burial rates for small ponds of known age by digging out the whole sediment from ponds, and determined that the average C burial rate was 142 g m⁻² yr⁻¹, with a range of 79–247 g m⁻² yr⁻¹, depending on the ponds’ vegetation. Burial rates in the ponds were 20–30 times higher than rates estimated for many other habitat types, such as woodlands or grasslands, and higher than those of other natural wetlands. Although small ponds occupy a very small proportion of the landscape compared to these other habitats, their high OC burial rates result in comparable annual OC burial overall. Ponds are easy to create, can fit in with other land uses, and are a globally ubiquitous habitat. Our results indicate that ponds have the potential to be a very useful additional tool for mitigating C emissions.

The 2015 United Nations Climate Change Conference (in Paris, France) recognized the potential for vegetated habitats to buffer the effects of anthropogenic emissions of greenhouse gases (GHGs), including through afforestation and habitat restoration in areas subject to agricultural intensification (Lamb et al. 2016; Fischer et al. 2017). We argue that ponds and small wetlands can also make substantial contributions as carbon (C) sinks. Although ponds are ubiquitous throughout the world’s terrestrial biomes and are relatively easy to create, evidence of their capacity to bury C has been scarce until now (Dowing 2010).

Emerging research has described the importance of inland waters for processing organic carbon (OC), and highlights the need to include them in strategies for mitigating climate change (Battin et al. 2009). However, efforts to quantify rates of OC burial in freshwater systems have generally focused on larger habitats (eg lakes), and understanding of the efficiency of the burial process is confounded by the wide variability among habitat types (Cole et al. 2007; Kayranli et al. 2010). Current knowledge about the time required for habitats to become effective C sinks or how vegetation influences rates of OC burial (Kayranli et al. 2010) is limited. A comprehensive study on OC burial in freshwater ecosystems identified disproportionately high rates of OC burial in smaller water bodies (Dowing 2010), but these results were obtained largely from work in artificial habitats, such as agricultural impoundments. Dean and Gorham (1998) estimated OC burial rates of 34–60 Tg yr⁻¹ in larger lakes as compared to 100 Tg yr⁻¹ in the sea, despite lakes covering barely 0.007% of the area of the world’s oceans. Conversely, small natural lakes have been cited as major sources of GHG emissions due to their high rate of carbon processing and carbon dioxide (CO₂) release (Hanson et al. 2004; Torgerson and Branco 2007), even if their net C processing buries OC in their sediments.

Although the potential for small ponds to capture and store OC has been spotlighted (eg Downing et al. 2008), accurately quantified rates of OC burial are rare, leading to the question of whether ponds bury OC fast enough to be worthwhile C sinks. Gilbert et al. (2014), one of the first studies to report sediment OC and burial rates in ponds, observed an OC burial rate of ~149 g OC m⁻² yr⁻¹. This represents one of the highest rates of OC burial reported across natural habitats. Moreover, these accumulation rates, when combined with the very large numbers of small ponds (Holgerson and Raymond 2016), suggest that ponds may have a considerable overall capacity for C sequestration.

However, numerous threats could undermine their potential to buffer atmospheric C. Pond loss is a worldwide problem (Jeffries et al. 2016) driven largely by land drainage and neglect, despite the role of ponds in providing key ecosystem services, such as flood mitigation and water-quality improvement (eg Cérèghino et al. 2013). For example, small ponds constructed adjacent to streams can remove 85–90% of nitrates, phosphates, and suspended sediments from watercourses (Zedler and Kercher 2005), and networks of ponds can reduce catchment flooding during extreme weather events (Biggs 2007). Given the diversity of beneficial ecosystem services that ponds provide, creating more of them would help to meet a range of environmental policy objectives and address some of the toughest current challenges both regionally and globally, including C sequestration. Moreover, ponds are far easier to create than many other habitat types, and can be readily integrated among land uses such as urban development and intensive arable agriculture.
Inadequate information exists regarding how GHG fluxes may vary over the years as ponds develop and the climate changes. Increased emissions of methane (CH$_4$) and/or nitrous oxide (N$_2$O) – given their greater global warming potential – have the potential to offset CO$_2$ sequestration. Small ponds have been identified as potentially important sources 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$_2$O (Soued et al. 2015). Moreover, Yvonne-Durocher et al. (2017), in an unusual experimental approach, tracked CO$_2$ and CH$_4$ fluxes in experimental ponds over a period of 7 years and showed that emissions of CH$_4$ increased with warming, and that the effect was greater as the pond aged. Maintaining the effectiveness of ponds as C sinks over time therefore poses a challenge for site managers.

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, and in doing so demonstrate the potential of small ponds to help buffer C emissions. We also provide insights on the role of vegetation that 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); as such, although we focus on estimating C burial for the UK, we believe that our results have global application.

## Methods

Our experimental pond site was located at Druridge Bay, Northumberland, UK. The site was formerly an open-cast coalmine that was restored in the 1970s with clay backfill, and is now a nature reserve. Thirty ponds were constructed on the site in November 1994 to monitor ecological succession, and have exhibited similar patterns of succession (Jeffries 2008), transitioning from bare substrate supporting submerged aquatic species such as common stonewort (Chara vulgaris) and white water crowfoot (Ranunculus aquatilis), to contemporary swards of dense flora dominated by Kneiff’s feather-moss (Leptodictyum riparium), common spikerush (Eleocharis palustris), floating sweetgrass (Glyceria fluitans), and jointed rush (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 2012/2013 to identify OC storage across the early stages of succession when plant cover was very limited.

For this analysis, we used 12 of the mature ponds constructed in 1994 (which were therefore 18 or 20 years old when sampled in either 2012 or 2014) and three new ponds constructed in the winter of 2012/2013 (which were sampled 3 years later). The 12 mature ponds were chosen to represent three distinct plant succession histories. For up to 20 years, “Group 1” ponds had retained species of submerged aquatic plants (eg C vulgaris) scattered over bare substrate, 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. Four ponds from each group were sampled.

Both the original and the newly constructed ponds were dug out to a uniform size (~1 m × 1 m) and depth (~30 cm) and filled with water within a day, to provide as close to replicate ponds as is possible under natural conditions. Examples of a mature and a new pond are shown in Figure 1: note the extensive vegetation in mature ponds versus the sparse plant life of the new ponds. Knowing the exact age of the ponds, the vegetation history of each pond, and that they have a visibly distinct base of clay on which the accumulated sediment sits enabled us to make precise estimates of OC burial rates. To the best of our knowledge, no other dataset provides such precise measurements of C burial rates by small ponds.

Previous evaluations of CO$_2$ flux rates in these study ponds (Gilbert et al. 2016) showed rapid changes during the transi-
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The transition from holding water (wet phase) to drying out (dry phase) typical of temporary ponds, as well as marked spatial variations among ponds. Mean CO$_2$ flux varied between an uptake of 641 mg m$^{-2}$ d$^{-1}$ to emissions of 3792 mg m$^{-2}$ d$^{-1}$. Any CH$_4$ 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 of the 12 mature ponds (one from each of the pond groups) 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, with all accumulated sediment removed in approximately 20-cm × 20-cm × 20-cm blocks (Figure 2). Accumulated sediment was visibly different from the underlying clay (Figure 3).

Samples were dried in a cabinet at 40°C and ground in a mill; the percent OC (OC%) in each block was then determined for two 5-mg subsamples using a Flash 2000 Elemental Analyser. The OC% was combined with the mass of the block (g) to quantify the mass of OC, OC stored across the entire pond was quantified using the sum of all individual blocks. Before exhumation, the same three mature ponds were also sampled by taking three sediment cores per pond (one from the center of the pond, and the other two from halfway between the center and opposite corners, to form a straight line of three cores across the diagonal length of the pond), which permitted comparisons between OC estimates based on cores and those from the whole pond exhumations. For the remaining ponds (nine mature and three new), a single sediment core was collected. Although the number of ponds sampled was small, their biodiversity is very typical of ponds in the UK and temperate biomes globally.

Sediment cores were taken from each pond’s center using a stainless-steel corer with a beveled cutting edge to penetrate dense root layers in order to minimize compaction. An extrusion tool was fitted within the device, and the sediment was extruded and cut into 1-cm-deep slices, allowing high-resolution sampling along the entire length of the core. The OC% in each slice was determined for two 5-mg subsamples, in the same way as for the exhumed blocks.

The total amount of OC within the volume of the sediment core was calculated based on the mass of the sample, and the total OC for the whole pond was estimated by multiplying the OC measure in the core by the ratio of the area of the core to the area of the whole pond, taking the depth of sediment in the core as the depth throughout the pond. OC burial rates were then produced by dividing OC storage values by the age of the ponds at their individual time of sampling (18–20 years).

Results

Values of total OC storage from the three exhumed ponds ranged from 1565 to 2288 g OC m$^{-2}$, whereas 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 (range: 1.57–27.37% higher). Full details of OC stock estimates and burial rates are presented in Tables 1 and 2 (for the exhumed ponds and for the cored ponds, respectively).

Based on single cores taken from the other nine mature ponds, the average whole pond OC storage was 2564 g OC m$^{-2}$, and values ranged from 1413 to 4459 g OC m$^{-2}$. OC storage varied significantly between Group 1 and Group 3 ponds (analysis of variance, GLM mixed models, pond groups 1–3 as factors, samples from a core as repeat measures, individual ponds identified as random factors, differences between the three pond groups significant at $P < 0.05$). Group 3 ponds, with a history of rapid vegetation coverage, stored more OC (mean: 4077 g OC m$^{-2}$) than Group 2 (mean: 1996 g OC m$^{-2}$) and Group 1 (mean: 1618 g OC m$^{-2}$) ponds. Converting OC storage into burial rates over the 18–20 years of the ponds’ existence prior to core sampling gave an average burial rate – calculated across these 9 mature ponds – of 122.10 g OC m$^{-2}$ yr$^{-1}$. 

Figure 2. The Druridge Bay site showing ponds in situ. (a) A mature pond filled with vegetation (foreground) and a bare new pond (middle) with bare sediment. (b) Exhumation of a whole pond.
OC storage in the three newly constructed ponds was considerably lower. One of the new ponds dominated by filamentous algae retained relatively bare substrate, and no discernible layer of accumulated sediment was observed. Although thin swards of *L. riparium* were established in the other two new ponds, sediment accumulation was limited to the top 1 cm of the sediment core in both ponds. The estimated average amount of OC stored in these three young ponds was 40.73 g OC m$^{-2}$. OC burial rates in the young ponds averaged 13.58 g OC m$^{-2}$ yr$^{-1}$, a rate considerably lower than those observed in the mature ponds.

We adjusted our estimates of burial rates from the nine mature (not exhumed) ponds based on their full lifespans of 18–20 years (depending on sample date) by subtracting the mean OC burial rate measured in the new ponds during their first 3 years from the mature ponds’ rates over their whole lifespan and recalculating the rate for those mature ponds over the remaining 15–17 years, which produced an overall site average of 142 ± 19 g OC m$^{-2}$ yr$^{-1}$. Given that the lag time before extensive plant growth drives OC accumulation may be longer than 3 years in some ponds, this burial rate is likely to be an underestimate.

Spearman’s rank correlation analysis was performed on the total OC stored in each of the 12 mature (three exhumed and nine not exhumed) ponds and on each pond’s plant cover. Vegetation in each pond was recorded every summer as the percent cover of each species using a point quadrat (Jeffries 2008). For each pond, the mean cover of each plant species over the period 1994–2014 was calculated and expressed as a percentage of the maximum coverage of all vegetation observed in the pond over that same period. 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 exhibiting significant negative correlations with OC storage were *J. articulatus* ($r_s = -0.883$, $P = 0.002$) and *C. vulgaris* ($r_s = -0.683$, $P = 0.042$).

**Discussion**

Our results represent some of the highest rates of OC burial observed within natural ecosystems, exceeding those reported for many other terrestrial and aquatic habitats (e.g., boreal forests: 4.94 g OC m$^{-2}$ yr$^{-1}$; temperate forests: 4.2 g OC m$^{-2}$ yr$^{-1}$; temperate grasslands: 2.2 g OC m$^{-2}$ yr$^{-1}$; Downing *et al*. 2008) and comparable to aquaculture ponds despite receiving no artificial enhancement of productivity. The depth and vegetation of these ponds are typical of temporary ponds, which are abundant throughout terrestrial biomes, suggesting they may be globally important C sinks. Although CO$_2$ flux rates in these ponds can switch rapidly from net sink to net source as they dry (Gilbert *et al*. 2016), over the 20 years of their existence they were net C sinks, burying OC at rates higher than other terrestrial habitats. The area covered by small ponds in the UK is barely one-hundredth that of the area covered by broadleaf woodlands, but our data suggest that annual C burial by broadleaf woodlands is only three

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**Table 1. Organic carbon (OC) stocks estimated by exhuming ponds**

<table>
<thead>
<tr>
<th>Pond</th>
<th>Mean ± SD</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Whole exhumed pond</td>
<td>1861 ± 379</td>
<td>1565</td>
<td>1729</td>
<td>2289</td>
</tr>
<tr>
<td>Based on three cores per pond</td>
<td>2105 ± 284</td>
<td>1888</td>
<td>2002</td>
<td>2427</td>
</tr>
</tbody>
</table>

Notes: Estimates from exhumed ponds also include estimates using three cores taken prior to exhumation. SD = standard deviation.
times higher than the annual C burial by small ponds (Table 3). In terms of managing landscapes for OC burial, these results suggest that small ponds be integrated as C mitigation features in addition to other habitat options.

The results also provide insights into the roles played by 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 fluviatilis showed a significant positive association with OC storage, with earlier establishment and greater overall coverage enhancing OC burial. This may arise from the greater amount of refractory OC (ie that which does not readily degrade) biosynthesized by these species (Reverey et al. 2016), and vegetation cover slows the drying and wetting, respectively (Gilbert et al. 2014), and vegetation cover slows the drying and exposure of sediments to the air.

We also identified vegetation that may restrict OC burial efficiency in the ponds. The algae C vulgaris is known to be an early colonist species that prefers ponds with relatively bare substrates, but OC biosynthesized by Chara spp is preferentially degraded by microbes because of its relatively labile composition compared to vascular plant species (Reverey et al. 2016). The relative abundance of the rush J articulatus also had a significant negative correlation with OC burial rates, and Juncus spp have been associated with higher rates of C emissions in wetland environments. Juncus spp exude highly labile C from root networks, creating a rhizospheric priming effect that essentially enhances microbial activity, which promotes degradation of more refractory organic matter (Aichner et al. 2010; Dunn et al. 2015).

Methane emissions from the ponds have the potential to offset CO2 sequestration but are likely to be small for our ponds, as our upper measured limit for CH4 fluxes of 0.93 mg m⁻² d⁻¹ was equivalent to 2.3 g C (CO2eq) m⁻² yr⁻¹, which is equivalent to 1.7% of our mature pond OC burial rate (conversion equivalents from Table 2.14 in Forster et al. [2007]), and small literature estimates for other small experimental ponds range from 1.1–4.4 g C (CO2eq) 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 (CO2eq) m⁻² yr⁻¹ (1.4–19.7% of our OC burial rate; Davidson et al. 2018). Obrador (2018) reported wet-phase CH4 emissions equivalent to 4–44 g C (CO2eq) m⁻² yr⁻¹ for temporary ponds in Menorca, Spain, although emissions were below detectable limits (1.6 g C [CO2eq] m⁻² yr⁻¹) in both the wet and dry phases in the majority of ponds. Emissions of N2O from ponds are less well known; however, Soued et al. (2015) reported that fluxes were negligible as compared to those from lakes and rivers, and equivalent to a maximum of 0.8 g C (CO2eq) m⁻² yr⁻¹.

Burial or emission of C by ponds is likely to change over time in response to succession, landscape alterations, and climate change. In addition, ponds will eventually fill in; our upper measured limit for CH4 fluxes of 0.93 mg m⁻² d⁻¹ was equivalent to 2.3 g C (CO2eq) m⁻² yr⁻¹, which is equivalent to 1.7% of our mature pond OC burial rate (conversion equivalents from Table 2.14 in Forster et al. [2007]), and small literature estimates for other small experimental ponds range from 1.1–4.4 g C (CO2eq) 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 (CO2eq) m⁻² yr⁻¹ (1.4–19.7% of our OC burial rate; Davidson et al. 2018). Obrador (2018) reported wet-phase CH4 emissions equivalent to 4–44 g C (CO2eq) m⁻² yr⁻¹ for temporary ponds in Menorca, Spain, although emissions were below detectable limits (1.6 g C [CO2eq] m⁻² yr⁻¹) in both the wet and dry phases in the majority of ponds. Emissions of N2O from ponds are less well known; however, Soued et al. (2015) reported that fluxes were negligible as compared to those from lakes and rivers, and equivalent to a maximum of 0.8 g C (CO2eq) m⁻² yr⁻¹.

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also evidence that increased vegetation in small ponds mitigates CH$_4$ emissions (Davidson et al. 2018).

Late successional, filled-in ponds are often regarded — incorrectly — as supporting a degraded, species-poor biodiversity, and as such are often targeted for restoration. A more effective strategy would be for land managers to build new ponds nearby while retaining the older pond habitats and thus creating pond clusters, which would support greater biodiversity (Williams et al. 2008) and rejuvenate a site’s potential for C burial.

## Conclusions

Ponds are found throughout the world’s terrestrial habitats and are a natural fit in the landscape; they are also biodiversity hotspots that create more ecosystem benefits than many other land uses, such as the planting of new pockets of woodland. Our findings show the potential of ponds in landscape C mitigation schemes. Table 3 gives broad estimates of annual C burial for grasslands, broadleaf woodlands, and coniferous woodlands in the UK using estimates of habitat areas from the UK Countryside Survey (Carey et al. [2008]; comparable habitats are found throughout global temperate biomes), combined with estimates for ponds using the burial rates presented here. Ponds make up a much smaller area, but their very high burial rates result in total C burial not much below that of other major habitat types. Our results demonstrate the potential for ponds to be created and engineered through the introduction 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 agro-environmental policy or urban green infrastructure could contribute to the mitigation of C emissions. Ponds are easy to create, are ubiquitous globally, and can be small, versatile features readily incorporated within other land uses to provide a wealth of benefits in addition to C sequestration.

Ponds should be considered as a powerful and practical element in land management, providing a raft of ecosystem services and biodiversity benefits and helping to address some of the most difficult challenges at regional, national, and global scales.

## Acknowledgements

We thank the Northumberland Wildlife Trust for permission to use the Hauxley Nature Reserve site.

## References


Now you see me, now you don’t

The montane litter frog (*Leptobrachium montanum*) is a medium-sized, stocky frog that tends to sit among leaf litter, where its camouflage protects it from predators. The species is endemic to the island of Borneo and can be found at medium-high elevations in Indonesia, Brunei, and Malaysia. This amphibian is listed by the IUCN as a species of least concern due to its widespread geographic distribution and relative abundance across a number of locations. The frogs have large eyes that are perfect for hunting in the dark, which is when they are often encountered along roads and trails. *L. montanum* individuals are also unmistakable during nighttime amphibian surveys due to the brilliance of their eyeshine.

Montane litter frogs exhibit an interesting anti-predatory behavior that is often seen when they are approached by humans. The frogs will stand alert with their heads held high, and when they detect a potential threat, they crouch down in the leaf litter to mimic dead leaves. They quickly move their head to the ground and tuck in their front legs; the eyes usually remain open. Due to encroachment of humans in their preferred habitat, leafy hiding spots are not always available – so how effective is this behavior at preventing predation in other environments? Does crouching on concrete still help to break up their form? And with an ever-increasing presence of humans around them, it’s also worth asking: can they see us as well as we see them?

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doi:10.1002/fee.1996