Carbon storage in river and floodplain systems: A review of evidence to update and inform policy development for riverine Nature based solutions.

David Sear, Imogen Speck, Ben Pears.

Department of Geography & Environmental Science,
University of Southampton,
Highfield,
Southampton, UK
SO17 1BJ

This report was co-funded by the University of Southampton Faculty of Environment and Life Sciences with additional funding from Natural England. We are very grateful to both funders.

The Report is published by the University of Southampton. It is not an official / commissioned Natural England Report.

The authors acknowledge the National Trust Coleshill Estate and Holkham Estate for permission to access their land. Luke Everett, Charles Rangeley-Wilson OBE and Duncan Hornby are thanked for their technical assistance and advice. Lu Webb, Jessica Elias and Mike Morecroft at Natural England are thanked for their constructive reviews of an earlier draft which greatly improved the final version. All errors are those of the authors.

Citation for the Report should be:

Sear,D.A., Speck, I.R. and Pears, B.R. (2023) *Carbon storage in river and floodplain systems: A review of evidence to update and inform policy development for riverine Nature based solutions*, Southampton: University of Southampton, 39p. https://doi.org/10.5258/SOTON/P1124

Introduction

The threat of climate change is increasingly motivating goals that seek to achieve net zero emissions in the next few decades (Rutter and Sasse, 2022). In the UK, net zero is a statutory requirement that must be met by 2050 (Gregg et al., 2021). An important element of this strategy is determining how nature can contribute to achieving Net zero – largely via carbon sequestration and storage (Gregg et al., 2021). The degradation of many natural systems has impacted natural carbon stores and so the role of nature-based solutions is increasingly being implemented with the beneficial aims of both increasing biodiversity as well as supporting climate change mitigation (Gregg et al., 2021).

Decomposition and combustion of organic material releases CO_2 to the atmosphere, while accumulation of biomass and soil organic carbon (SOC) sequesters CO_2 (Hoffmann 2021). Wetlands such as peatlands, swamps, marshes, estuaries and floodplains provide optimal conditions for the sequestration and long-term storage of carbon although the precise timing of storage will depend on erosional (turnover) time of the specific habitat/system. Low oxygen concentrations support anaerobic conditions that reduce decomposition, whilst overbank sedimentation buries organic matter protecting it from further decomposition. On floodplains, the high clay content of deposits provide sites for chemical bonding with organic matter further reducing loss of carbon through decomposition and gaseous emission (Hoffman 2021).

Research to date all points towards a substantial role for rivers and floodplains in the global carbon cycle (Whol and Knox 2022, Hoffman, 2021). An increasingly expanding literature consistently demonstrates that riparian ecosystems and floodplains can store a significantly larger amount of carbon per area compared to surrounding land (Suftin et al., 2016; Whol and Knox 2022). Floodplains cover 0.5–1% of the global land area but have been suggested to account for a range of 0.5–8% of global SOC storage. River networks contain significant portions of terrestrial C with greatest retention occurring in floodplain riparian ecosystems D'Elia et al., (2017).

Although, there is a large range of estimated values of OC in watersheds (0.5 to 1.5 Pg (Aufdenkampe et al., 2011) and 0.9 Pg (Regnier et al., 2013)), some estimates in mountainous headwater streams in the USA, indicate that riparian areas including floodplains may store about 25% of the total OC while occupying less than 1% of watershed area (Wohl et al., 2012). Sutfin et al., (2016) reported 22% of carbon entering headwater streams is unaccounted for after quantifying delivery to oceans or losses to outgassing as carbon dioxide (CO_2), suggesting there is a substantial reservoir of carbon in riparian systems derived from sediment deposition.

The role of rivers in carbon sequestration has often been interpreted as a conduit between terrestrial and marine carbon stores (Gregg et al., 2021). Carbon can be stored in the floodplain in many forms including above ground vegetation (Dyabla et al., 2019), and soil (Wohl et al., 2017), as well as within the river channel as large, drowned wood and vegetation (Hinshaw & Wohl, 2021).

Much of the evidence remains focussed on above ground biomass and the first metre of soil (D'Elia et al., 2017). However, it is argued in Young et al., (2019) that recent carbon accumulation rates in surface peat can be misinterpreted in relation to carbon storage. It suggests that surface/topsoil peat measurements do not account for the future ability to be decomposed/lost in comparison to deeper long-term stores. This suggests that although there may be peat/organic matter present in topsoil this may not necessarily translate into long term carbon sequestration. A need for deeper sediment cores and paleoenvironmental analysis to present the natural state of UK rivers is identified across the literature (D'Elia et al., 2017; Quine et al., 2022), however, is not yet widely implemented, although the current Natural England led project to develop a national peat map is aiming to rectify this omission.

The quantification of carbon stored in floodplains and the potential for restoration to increase this remains poorly understood (Hinshaw & Wohl, 2021; Hofmann 2021). To be able to quantify carbon storage it requires understanding how much is buried (storage quantity), over what timescales (storage period) and what processes are associated with carbon burial and storage. These factors are addressed in this report to better understand carbon storage in UK floodplains and whether current restoration is effective at increasing this.

Human modifications

Carbon in rivers and floodplains is derived form a range of catchment and local sources. The carbon budget is a function of the mass of carbon input to a river/floodplain minus the mass lost through transport in the river and groundwater flows (DOC, POC, CPOC), respiration through biological activity, burning and minerogenic processes. Different areas of the river:floodplain system have different budgets either through their mass balances (less in more out, and vice versa) or processes that reduce or accelerate storage (e.g. higher water tables reducing aerobic respiration). Sequestration of carbon – the drawdown of atmospheric carbon into organic matter, and its net storage is dependent on the plant and animal communities involved and the rate of loss of that organic matter over time. Microbial processes that require oxygen break down plant and animal organic matter, producing methane and carbon dioxide as a by-product of respiration. Such microbial activity is found in floodplain soils and within riverbeds. Since both biological and chemical processes which release carbon into the atmosphere are regulated by oxygen and heat, processes that increase temperature (global warming, lack of shade resulting in direct insolation) or increase oxygen concentration of water (anaerobic digestion) or allow air contact with organic matter in floodplains and rivers, will increase rates of degassing and therefore C- emissions. Conversely, processes that increase net storage of carbon and reduce outgassing and are able to support this over long time periods can make a contribution to achieving net-zero emissions. Hydrologically connected, saturated floodplain zones and wetlands create the anoxic conditions that limit organic decay which means they have higher mass of soil organic carbon (Hinshaw & Wohl, 2021).

In their natural state, rivers are open systems through which carbon can move at different rates determined by the flux of water, extent, and type of storage. Critical processes include:

1. longitudinal (upstream to downstream), lateral (river to floodplain and return) and vertical (into and out of river bed and floodplain sediments) connectivity (Fryirs et al., 2007).
2. Maintenance of high water tables in floodplain soils
3. Diverse plant and animal communities with high rates of biomass production
4. Presence of ecosystem engineers that promote (1-3), for example large wood and associated logjams, beaver.
5. Stable rates of lateral movement by the river which promotes low rates of turnover and long-term storage of organic matter.
6. Cool water and air temperatures.

Human modifications to river floodplains systems have been extensive, long term and over the last 50 years, intensive (Brown et al., 2018). Centuries of modification have resulted in the disconnection of rivers from their floodplains and cut off their ability to store and process carbon (Brown et al., 2018; Lininger & Polvi, 2020). Whol et al., (2021) report that 50%–90% of European wetland ecosystems have been lost and more than 80% of the remaining floodplain wetlands significantly altered, resulting in lower rates of carbon sequestration and increased outgassing under warmer and more oxygen rich soil conditions.

These include draining of wetlands, channelisation and urbanisation, disconnection of rivers from floodplains, longitudinal disconnection from dams and weirs, mills, straightening affecting hydrodynamics, deforestation of riparian forest and vegetation, pollution from industry and agricultural practice. In addition, humans have extirpated ecosystem processes formerly driven by ecosystem engineers such as Beaver and larger herbivores (Aurochs wild cattle), and modified populations of others (e.g., salmon, sturgeon etc.). Land cover on floodplains has been progressively altered historically. Deforestation of floodplain forests has decreased standing available biomass in the floodplain (Lininger and Polvi, 2020). Agricultural expansion has modified the use of floodplains and increased the loss of heterogenous vegetation in floodplains. They have also been extensively built on. Furthermore, damming influences the longitudinal connectivity of the river system, affecting natural carbon cycling (Lininger & Polvi, 2020).

Disconnected rivers may accelerate CO_2 fluxes from floodplains due to drying of peat and organic material facilitating breakdown of organic material (Liu et al., 2017). Furthermore, this is leading to floodplains becoming oxidised through drops in water table levels, allowing the degradation of peat stored in the past and contributing to floodplains transitioning from carbon sinks to sources of emissions (Schiller et al., 2014). This also prevents the future formation of peat as modifications such as channelisation and the creation of embankments constrict the river. As chalk streams lack the energy for natural recovery, they will especially suffer from these extensive modifications (Barnsley et al., 2021) and are unable to reinstate processes that once stored carbon. Similarly, clearance of riparian woodlands and widening of river channels has increased instream temperatures and reduced the probability of logjam formation.

Some recent studies have suggested that artificial bank stabilisation and flood protection measures such as levees, may reduce carbon emissions by allowing faster delivery of carbon to oceans to be stored (Repasch, 2021; Shen et al., 2021). However, this does not account for carbon being emitted during riverine transport and the ability of carbon to be stored long term in floodplains for 100-1000 years (Wohl & Knox, 2022).

Human induced climate change affecting rainfall and groundwater recharge is contributing to the shrinking of perennial streams and extending of temporary watercourses (Westwood et al., 2006; Schiller et al., 2014). Furthermore, abstraction and drainage contribute to low flows and lowering of the water table creating periods of dry river in normally perennial reaches (Westwood et al., 2006; Keating, 1982). This has resulted in a reduced ability to transport organic material longitudinally through the river corridor and reduced the frequency of overbank flooding.

Carbon sources

For longer term organic carbon storage (floodplain peats and organic rich sediments) carbon sources vary, but typically are comprised of a combination of allochthonous catchment material, and autochthonous vegetation sources. In areas draining eroding peat landscapes, floodplain sediments can store eroded peat. Alderson et al., (2019) report storage of 3482-13460 tC in headwater floodplains draining eroding peatlands, accounting for 0.8-4.5% of Particulate Organic Carbon (POC) fluxes in the contemporary river system. This compares to 2% of POC stored in floodplains of the river Trent (Worall et al., 2012). They conclude that upland floodplains are dynamic components of the terrestrial carbon cycle where net carbon sequestration is controlled by biological and geomorphological processes. Restoration of eroding peat sources would reduce carbon inputs to floodplains; nevertheless, the potential to capture and store carbon in headwater floodplains would remain through processes of biomass growth (assuming vegetation was re-naturalised) and restoration of higher water tables.

Much upland blanket bog and ombrotophic mires are comprised of mosses, thus the eroded peats comprise moss plant remains which are then redeposited in river channel and floodplain environments. On floodplains, as the hydrological conditions change and nutrient levels vary, species switch to reed, sedge and brushwood (alder/willow) peats. Nutrient status, species composition and water table regime all determine (interactively) the specific plant communities and above vs below ground biomass that makes up the peat (Brown et al., 2018; Worall et al., 2012).

Since wetland species vary according to hydrology and nutrient status, it seems reasonable to expect the species and sedimentary composition of organic matter stored in floodplains to vary downstream and laterally across a hydrological gradient in a floodplain. Two different mechanisms of OC enrichment are important in floodplain soils the sedimentation of allocthonous OC rich material during flood events (Pinay et al., 1992) and the above average production of biomass within the floodplains (Graf-Rosenfellner et al., 2012). For example, chalk groundwater dominated catchments tend to have high instream and floodplain biodiversity and high productivity resulting from stable high water tables, stable thermal regimes and nutrient availability (Sear et al., 1999). In contrast to upland channels or alluvial dynamic rivers, bank erosion and thus erosion of former buried carbon tend to be low in groundwater dominated rivers, resulting in larger contributions of living biomass to the organic carbon load.

Fingerprinting of organic matter sources is an area of rapidly growing interest, utilising a range of techniques to quantify the organic geochemical characteristics of source organic carbon and using these to unmix the organic deposits in river beds (Collins et al., 2014). Table 1 summarises recent organic matter fingerprinting studies for a range of UK rivers.

River	**C- Store**	**Sources of Organic Matter (Carbon)**	**References**
Blackwater Runoff dominated Lowland river	Gravel bed	Instream decaying vegetation 39% Damaged road verges 28% septic tanks 21% farmyard manures/slurries 11%	Collins et al., (2013)
River Ithon Runoff dominated Upland river	Gravel bed	Instream decaying vegetation 41% Damaged road verges 11% septic tanks 4% farmyard manures/slurries 44%	Collins et al., (2014)
IRiver Lugg Runoff dominated Lowland river	Gravel bed	Instream decaying vegetation 52% Damaged road verges 15% septic tanks 4% farmyard manures/slurries 29%	Collins et al., (2014)
River Rede Runoff dominated Upland river	Gravel bed	Instream decaying vegetation 16% Damaged road verges 46%| septic tanks 10% farmyard manures/slurries 26%	Collins et al., (2014)
River Axe Runoff dominated Upland river	Gravel bed	Instream decaying vegetation 35% Damaged road verges 12%| septic tanks 4% farmyard manures/slurries 49%	Collins et al., 2017
River Yarty Runoff dominated Upland river	Gravel bed	Instream decaying vegetation 32% Damaged road verges 35%| septic tanks 6% farmyard manures/slurries 27%	Collins et al., 2017

River Arle Groundwater dominated	Gravel bed	Instream decaying vegetation 21% Damaged road verges 2%| septic tanks 2% farmyard manures/slurries 28% Watercress Farm 40% Fish Farm 7%	Zhang et al., (2017)
Tichbourne stream Groundwater dominated	Gravel bed	Instream decaying vegetation 26% Damaged road verges 6%| septic tanks 6% farmyard manures/slurries 26% Watercress Farm 36%	Zhang et al., (2017)
Candover Stream Groundwater dominated	Gravel bed	Instream decaying vegetation 15% Damaged road verges 2%| septic tanks 2% farmyard manures/slurries 74% Watercress Farm 7%	Zhang et al., (2017)
River Itchen Groundwater dominated	Gravel bed	Pasture sources 81% Arable sources 16% Instream sources 3%	Bateman (2012)

Table 1: Organic matter sources in the gravel beds of different UK river types.

In upland river systems dominated by livestock framing, organic matter in the riverbed is typically derived from instream vegetation and manure/slurry applications to the land surface. Septic tanks and eroding road verges typically account for less than 15% of the sources. These are in addition to carbon fluxes from eroding soils and direct leaf litter fall. In low gradient chalk groundwater rivers, this pattern is maintained, but additional OM sources occur including watercress and fish farms, though again these represent a minor component (Zhang et al., 2017). On the River Itchen, different source areas were targeted, but still identified the importance of pasture floodplain surfaces as the dominant OM sources (Bateman 2012). Pasture on floodplains and associated treatments of pasture using manure and slurry thus represent a key source of OM in riverbeds and highlight the connectivity between catchment and floodplain OM sources and the river network. Similarly, these studies illustrate the increasing role of human activity in the landscape as an agent for OM movement from land surfaces into river networks.

Wiltshire et al., (2022) argue that sediment fingerprinting alone fails to fully characterise the sources of organic carbon in riverbeds. They combined fingerprinting with a carbon loss model to show that the apparent high contribution of woodland organic matter sources to riverbed sediments really resulted from the direct inputs of leaves and twigs from the wooded riparian zone, and that without the buffering effect it provided, the dominant sediment source would be soil erosion from arable agriculture (Wiltshire et al., 2002).

Organic Carbon storage in Riverbeds

Organic matter is temporarily stored within the river channel network. These stores include channel bed surface, living and decaying vegetation stands, and within the channel bed sediments. Relative to the floodplain and riparian areas, river channels comprise smaller areas of the catchment surface (Riley et al., 2018), nevertheless they are an active part of the catchment organic matter and C-stores. Where the riverbed is permeable, suspended organic particles and dissolved organic material is transported into the bed where it accumulates and is processed by mineralogical and biological activity (Findlay, 1995; Hatch et al., 2010). Thus, riverbed sediments are an important area for concentrating both allochthonous and autochthonous organic matter (Trimmer et al., 2012).

The interactions between geomorphology and the water level variations in the river and surrounding landscape control the length, direction and hence network of subsurface flows through benthic and hyporheic sediments and influence the extent and rates of biogeochemical processing (Poole 2010; Trimmer et al., 2012). The contribution of the hyporheic zone to the biogeochemical budget of a river is thus governed by the balance between surface (fast) and subsurface (slow) flow and the intensity of the subsurface processes (Trimmer et al., 2012). Thus, channel complexity (pool-riffle-bars, large wood, vegetation, beaver dams etc) and benthic and bank permeability are important controls on residence times of surface and subsurface flows. Longer residence times tend to increase the chance for storage of organic carbon through physical and biogeochemical reactions, though some of these under increasing temperatures can also enhance oxidation and thus emissions (Hoffmann 2021).

The proportion of finer organic matter within riverbed gravels is highly variable (Sear et al., 2017). Table 2 provides indicative values from a range of UK rivers. Typically, chalk groundwater dominated rivers have fine sediments containing higher organic matter content than equivalent runoff dominated streams, reflecting the higher bed disturbance (flushing) of upland rivers, and the higher productivity and in-channel OM sources in lowland groundwater systems (Sear et al., 1999; Mondon et al., 2022). Nevertheless, Carbon contents vary and over time labile carbon is removed through oxidation (Sear et al., 2017), such that longer term OM content of fines stored in the riverbeds is lower. Values of benthic fine sediment Carbon are comparatively small reflecting this turnover and oxidation as well processing by benthic organisms. Carbon storage in lowland fine sediment rivers is likely to be higher due to the larger quantities of fines stored per unit area of bed (Naden et al., 2016). Similarly, presence of large wood and vegetation will increase storage in the riverbed in ponded regions upstream of logjams and among macrophyte beds in chalk rivers (Cotton et al., 2006). Thus, river type and complexity will determine the storage and overall contribution of riverbed sediments to river floodplain carbon budgets.

River	River Type	% OM in bed sediments	tC Ha^{-1}
Blackwater	Semi-Natural forest, Runoff dominated	3.7 (1.2)	0.0037
Arran	Upland pasture Runoff dominated	7.7 (6.9)	0.0369
Axe	Upland pasture Runoff dominated	30.8 (30.2)	0.0045
Esk	Upland pasture Runoff dominated	4.9 (3.7)	0.0009
Lugg	Upland pasture Runoff dominated	7.3 (0)	ND
Ithon	Upland pasture Runoff dominated	11 (0.)	0.0318
Rede	Upland pasture Runoff dominated	1.8 (1.4)	0.0004
Towy	Upland pasture Runoff dominated	3.4 (2.4)	0.0005
Itchen	Lowland Mixed farming Groundwater dominated chalk river	12.6 (2.2)	0.0104
Frome	Lowland Mixed farming Groundwater dominated chalk river	35.4 (19.5)	0.0118
Test	Lowland Mixed farming Groundwater dominated chalk river	20.0 (0)	0.0533
England & Wales	Riverbed surface fine sediment drapes (Naden et al., 2017)	16.4	0.25
England & Wales	Riverbed surface fine sediment drapes + 10cm depth river bed fines (Naden et al., 2017)	11.1	0.82

Table 2: Organic Matter composition of fine (<1mm) sediment within gravel riverbeds and Carbon storage scaled up to tonnes Carbon per Ha of river bed. Data from Sear et al., (2017) and for Arran and Blackwater Greig et al., (2005). England & Wales bed samples Naden et al., (2016).

A first order approximation of organic C storage in riverbeds can be estimated form the reported amounts in Table 2 and an estimate of the riverbed area of rivers and streams in the UK – the latter estimated as 1940 km^2 (194000 Ha). Using the mean value for riverbed surface drapes and bed sediment fines of 0.82 tC Ha^{-1} (Naden et al., 2016) generates an **estimate of c.159,000 tC stored in UK riverbeds.** This compares to Belgium streams with finer sandy/silt bed material that range from 0.016 – 0.73 Million tC (Swinnen et al., 2020). Modelling studies from small catchments in the USA estimated that 79% of terrestrial carbon inputs to riverbeds were outgassed as CO_2 and CH_4 (Qi et al., 2020) but the evidence from other river types is limited. Mobile riverbeds (those scoured during floods) are unlikely to store carbon in quantity or for long periods, as shown in table 2, and in total carbon budgets for river in Belgium where bed sediments accounted for less than 10% of total carbon stored in river floodplain systems (Swinnen et al., 2020).

Floodplain Sediment accumulation rates

Sediment accumulation on floodplains in the UK have been estimated using published data (Jones et al., 2015). To this database we have utilised additional relevant palaeoenvironmental measurements recorded in the 'Fields of Britannia' collated database (Rippon et al., 2015), and unpublished grey literature (e.g. unpublished archaeological reports). We converted the dated sequence into a measure of sediment accumulation rates (SAR in cm yr^{-1}). Strictly these are inorganic and organic rates of SAR calculated from the depth to dated deposit and age of the deposit in years. The results for the 433 data points are given in Figure 1.

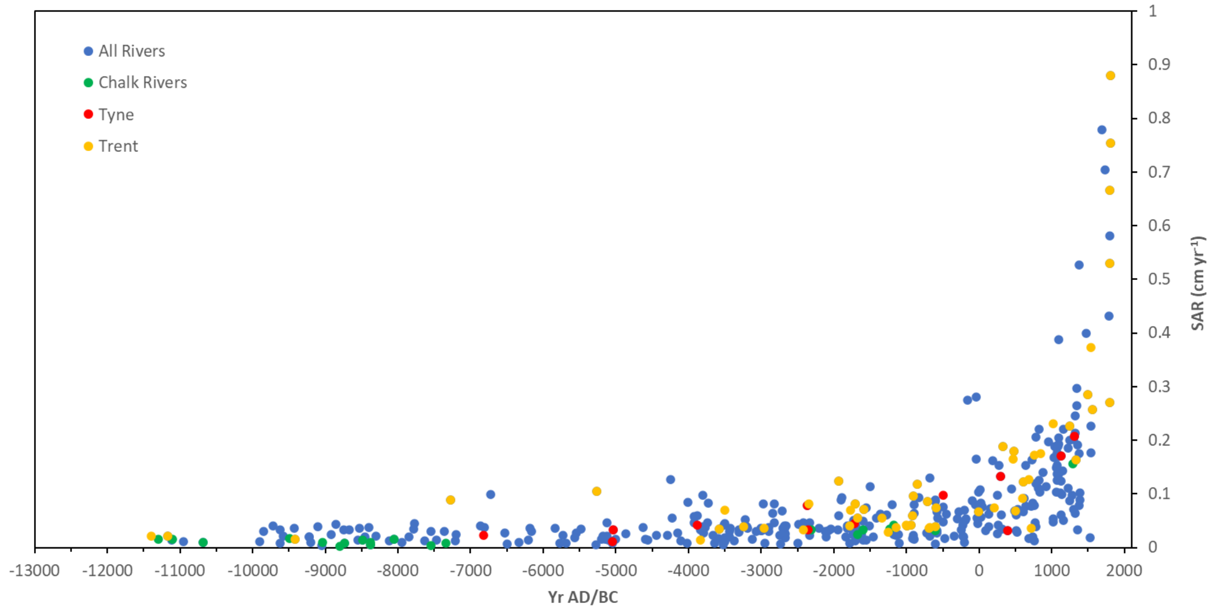


Figure 1: Floodplain sediment accumulation rates derived from dated floodplain sequences after Jones et al., 2016.

Rapid acceleration of SAR occurs following the intensification of agriculture post AD 1000 with the advent of extensive open field systems (Macklin et al., 2014). Recent agricultural intensification post AD 1700 reflects introduction of four-crop rotation and subsequent mechanisation of farming (Macklin et al., 2014). Chalk rivers have low rates of SAR as reflects their groundwater dominated flood hydrology (Sear et al., 1999). As others have noted there is a rapid increase in overbank deposition rates post intensification of agriculture (Brown et al., 2018; Hoffmann et al., 2021). Rates prior to human agricultural disturbance (c. 6000 yrs before present) average 0.03cm yr^{-1} ± 0.02 with the lowest rates occurring in chalk river systems (0.02± 0.01 cm yr^{-1}). Comparable rates post AD 1700 average 0.686 ± 0.271 cm yr^{-1} an almost 2500% increase over background levels. Much of the increase is attributable to increased soil erosion and sediment delivery to the floodplain following agricultural intensification (Jones et al., 2015). In turn this has resulted in simplification of river channel patterns through choking and infilling of multiple channels leading to single thread meandering patterns familiar in our contemporary landscape (Walter & Merritts 2012; Brown et al., 2018) and burial of organic rich deposits. A similar picture is evident in Europe with even higher rates of SAR reported in the larger river floodplains (Hoffmann et al 2021). The rates reported do not account for compaction and consolidation of sediments over time (effectively reducing SAR), nor do they account for loss of peats from centuries of drainage, oxidation and peat cutting -likely to be particularly effective in chalk river floodplains and lowland peri-estuarine floodplain systems.

In summary, the disturbance of the landscape by humans over the past 6000 years, and acceleration in the past 1000 years, has resulted in the burial of peat and organic materials in river floodplains. This alluviation has protected organic carbon stores that otherwise may have been released by drainage, reduced water table depths leading to oxidation, and the cutting of peat and ploughing up of floodplain surfaces.

Organic matter deposition rates on Temperate Floodplains

River-borne Organic Carbon (OC) is transformed under three conditions. First, under anaerobic conditions sediment microbial activity releases CO_2 into the atmosphere (Wohl et al., 2017; Brown et al., 2018). Secondly, carbon is transferred to the ocean in particulate or dissolved forms. Finally, carbon can be sunk in floodplains resulting in a long-term fixation within alluvial floodplain areas (Brown et al., 2018; Whol et al., 2022). Organo–mineral complexes developed during transient floodplain storage have been shown to help stabilize biospheric particulate organic carbon (POCbio), increasing the probability of long-term POCbio burial (Respach et al., 2021). Consequently, the preservation of organic matter reflects long-term carbon sequestration on floodplains and within channel storage (Macaire et al., 2005; Van Oost et al., 2012; Brown et al., 2018).

Respach et al., (2021) show from field and modelled data that sediment transit time and mineral protection (organo-metal complexes) are primary controls on the fate of fluvial POC during transit from source-to-sink. Lateral erosion into POC-rich floodplains can increase POC fluxes to downstream floodplains, thereby offsetting POC oxidation. Thus, Respach et al., (2021) conclude that rivers with high lateral channel mobility and organic rich floodplain sediments, can enhance CO_2 drawdown, while management practices that stabilize river channels and / or disconnect them from the floodplain, likely reduce the potential for CO_2 drawdown by reducing transit times (e.g. reduced storage in floodplains and in-channel sediments) and compensatory POC inputs from bank erosion.

Comparison between organic matter storage in floodplain sediments and organic matter deposition in contemporary sediments are not equivalent. Typically buried organic matter in floodplains have 40–80% organic matter (OM) content, compared with overbank silt clay deposits that have between 2–4% OM on average (Brown et al., 2018). In part this reflects the different sources of OM – in the floodplain these are typically comprised of *in-situ* biomass and over bank deposits, whereas contemporary over bank deposits comprise larger contributions from catchment and upstream in-channel sources due to land drainage and land use modifications. Nevertheless, rates of OM deposition on floodplains are an important measure of the input fluxes to floodplains, which thereafter may or may not be stored, in part depending on the balance between loss or preservation of Carbon post-deposition. Critically therefore, floodplains can switch between being net stores or net sources of atmospheric Carbon depending on local hydrological conditions and land cover (Whol et al., 2017; Brown et al., 2018).

As Table 3 below illustrates, species composition will influence organic matter accumulation rates on floodplains, with semi-natural deciduous wooded floodplains with strong channel:floodplain connectivity mediated by logjam dynamics and high water tables, accumulating Carbon more rapidly than pasture or intensive agricultural floodplain land use. Similarly, open reed and sedge fen deposits result in OM deposition rates c. 20 times higher than equivalent improved pasture floodplains. Of course, these are not net Carbon sequestration and do not account for oxidation, mineralisation and biological activity all of which contributes to emissions of carbon.

River/Floodplain Type	Organic matter deposition (t OM $ha^{-1}yr^{-1}$)	C deposition rates (tC ha^{-1} yr^{-1})	Source
Wet Woodland (Alder leaf input)	8 - 10	3.2-4.0	Ramade (2003)
Open Reed/Sedge fen	20	8	Ramade (2003)
Ancient wet woodland floodplain (New Forest)	10 – 60 (With logjams) 3 – 27 (No logjams)	6.4 – 24 1.2 – 10.8	Millington (2012) Jeffries et al., (2003) Sear et al., (2010)
Restored Ancient wet woodland (New Forest)	8 – 50 (With logjams) 4 – 24 (No logjams)	3.2 – 20 1.6 – 9.6	Millington (2012) Jeffries et al., (2003) Sear et al., (2010)
Improved Pasture Floodplain (UK)	0.7 – 1.1	0.3 – 0.4	Walling et al., (2008)
Improved pasture floodplain (Rhine, Germany)	0.05 – 1.17	0.02 – 0.47	Hoffman & Glatzel (2007)
Improved pasture floodplain	2 - 6	0.8 – 2.4	Suftin et al., (2016) Lüscher et al., (2004)

Table 3: Organic matter deposition rates in temperate floodplains based on field studies. Rates vary with land cover type and connectivity to the floodplain. C-content of OM assumes a value of 40% (Brown et al., 2018).

Evidence of longer-term OC deposition rates on UK floodplains has been derived from floodplain sediment cores dated using radionuclide inventory age modelling (Walling et al., 2006). Dating sediment cores in floodplains and measuring changing carbon content through these cores is widely used to inventory deposition rates over decadal to millennial timescales. Table 4 uses published sediment accumulation rates (Walling et al., 2006) and typical Organic Carbon contents of floodplain soil (Brown et al., 2018) to estimate the rate of Carbon deposition over the last 100 years on selected UK floodplains. Carbon accumulation rates vary considerably between floodplain sites, presumably controlled by local connectivity and upstream sediment supply. On average there is no difference between upland and lowland floodplains (both average c. 19.1 tC Ha^{-1} over the past 100 years), but there is more variability in lowland floodplain C accumulation rates, most likely reflecting increased embanking that would reduce overall deposition in this period (Sear et al., 2000). Carbon sequestration averages 0.19±0.11 tC ha^{-1} yr^{-1}.

River:Floodplain	Type	Deposition Rate (tC Ha^{-1})	Carbon deposition rate (tC Ha^{-1} yr^{-1})
Torridge	Upland runoff dominated	27.7	0.277
Taw	Upland runoff dominated	23.7	0.237
Start	Upland runoff dominated	20.1	0.201
Tone	Upland runoff dominated	22.1	0.221
Exe	Upland runoff dominated	17.8	0.178

Axe	Upland runoff dominated	20.1	0.201
Culm	Upland runoff dominated	13.8	0.138
Vyrnwy	Upland runoff dominated	8.3	0.083
Wye	Upland runoff dominated	5.9	0.059
Usk	Upland runoff dominated	34.8	0.348
Arun	Lowland runoff dominated	15.4	0.154
Medway	Lowland runoff dominated	5.9	0.059
Rother	Lowland runoff dominated	4.4	0.044
Dorset Stour	Lowland runoff dominated	1.6	0.016
Severn	Lowland runoff dominated	11	0.11
Severn	Lowland runoff dominated	48.3	0.483
Ouse	Lowland runoff dominated	37.6	0.376
Severn	Lowland runoff dominated	34	0.34
Adur	Lowland runoff dominated	20.1	0.201
Warwickshire Avon	Lowland runoff dominated	18.2	0.182
Thames	Lowland runoff dominated	20.1	0.201
Arun	Lowland runoff dominated	15.4	0.154
Bristol Avon	Lowland runoff dominated	15.4	0.154

Table 4: Carbon accumulation rates on UK floodplains (Walling et al., 2006), assuming C-content of deposits are c. 2-4% OM and of this 40% is organic Carbon (Brown et al., 2018). Annual rates of carbon sequestration in floodplain soils average 0.19±0.11 tC ha^{-1} yr^{-1} (over 100 years?)

Soil Organic Carbon estimates from Floodplains

Floodplain soil organic carbon (SOC) stocks reflect the balance between (i) rates of organic matter input from leaf litterfall on the floodplain and fluvial deposition, as well as dissolved carbon in surface and subsurface water fluxes into the floodplain; (ii) rates of carbon decomposition and soil respiration and release to the atmosphere; and (iii) floodplain sediment turnover (or residence) time that is constrained by lateral bank erosion rates and sediment transport (Whol and Knox 2022). Depth of water table in floodplain soils is important for preservation of anoxic conditions required or reducing organic matter breakdown.

Soil organic Carbon (SOC) in UK river floodplains can be estimated using a range of existing geospatial data. For this report, Peat soils identified in the Soil survey of England and Wales (2023) have been used to generate a dataset for floodplains in England by clipping the peat soil classification by the Environment Agency Floodzone2 Flood model layer (Defra 2023). The resulting geospatial data for floodplain peat soils (top 15cm of soil) totals 2,762 km^2 in England. Of this total, 16.8 % is accounted for by Chalk groundwater dominated river floodplains (Figure 2). The remaining 83.2% of floodplain peat soils in England are largely in floodplains formerly or currently controlled by marine influences that have created intertidal and freshwater ponded wetlands, (for example the Fens of East Anglia, Somerset and Humber Levels), and upland headwater rivers draining large areas of blanket peat such as the Pennines (Alderson et al., 2019).

Fig 2: Floodplain Floodzone2 in England (Left) and Floodplain Peat soils (right) recorded in the Soil Survey of England and Wales. 16.8% of peat floodplain soils (top 15cm) is found in chalk rivers.

An alternative source of data is the SOC inventory developed by BGS using quantified measures of SOC content for 252 sites under varying soil type and land cover (UK Soil Survey 2023). Using this data (Figure 3) it is possible to estimate the total carbon storage in floodzone2 defined floodplains in England. Clipping the SOC data with the Floodzone2 outline resulted in an estimated 14098 km^2 or 85.9% of total Floodzone2 area with values for SOC (Figure 3). Multiplying this area in Ha by the SOC in tC Ha^{-1} for each grid cell gives a total storage of **c76 x 10^6 ± 0.5 x 10^6** tonnes of carbon in the top 15cm of floodplain soils in England with an average SOC of **56.1±13.8 tC Ha^{-1}**. This is higher than the carbon content measured in floodplain soils over 100 years of accumulation (Table 5) which is to be expected both because of methodological differences, but also because SOC tends to decrease with depth (age) in floodplains (though see buried carbon estimates below and Hoffmann et al., 2013), however it is lower than values recorded in the wider literature (Suftin & Whol 2016 and Table 5). The overall values are of similar order of magnitude to catchment scale estimates for SOC stocks reported in the river:floodplain system of the South Platte river USA, where Whol & Knox (2022) estimate values for a 2916 km^2 floodplain of c. 41.8-42.7 x 10^6 tC Carbon.
An alternative approach to estimating carbon stored in floodplain soils is to use values reported in the literature for SOC (Whol & Knox, 2022). Table 5 provides updated values from the literature together with data collected for this study. Using the Floodplain area of England (1,409813 Ha) and the average value for temperate floodplain SOC reported in the literature (205 ± 323 tC Ha^{-1}) gives a total SOC storage of **289 ± 455 x 10^6 tC** stored in the floodplains of England. Quine et al., (2022) demonstrate that UK floodplain SOC vary with depositional environment with 0.9 x10^6 tC stored in areas with increased rates of deposition in the active channel belt, and 50.4 x10^6 tC in areas with decreased rates of deposition in more distal floodplain soils. This provides a total floodplain SOC in the UK river network of 51.3 x 10^6 tC which falls within the estimates made in this report. Tye et al., (2022) report

a first order assessment of OC stocks in Holocene alluvium in the UK as 48.5 x 10^6 tC.

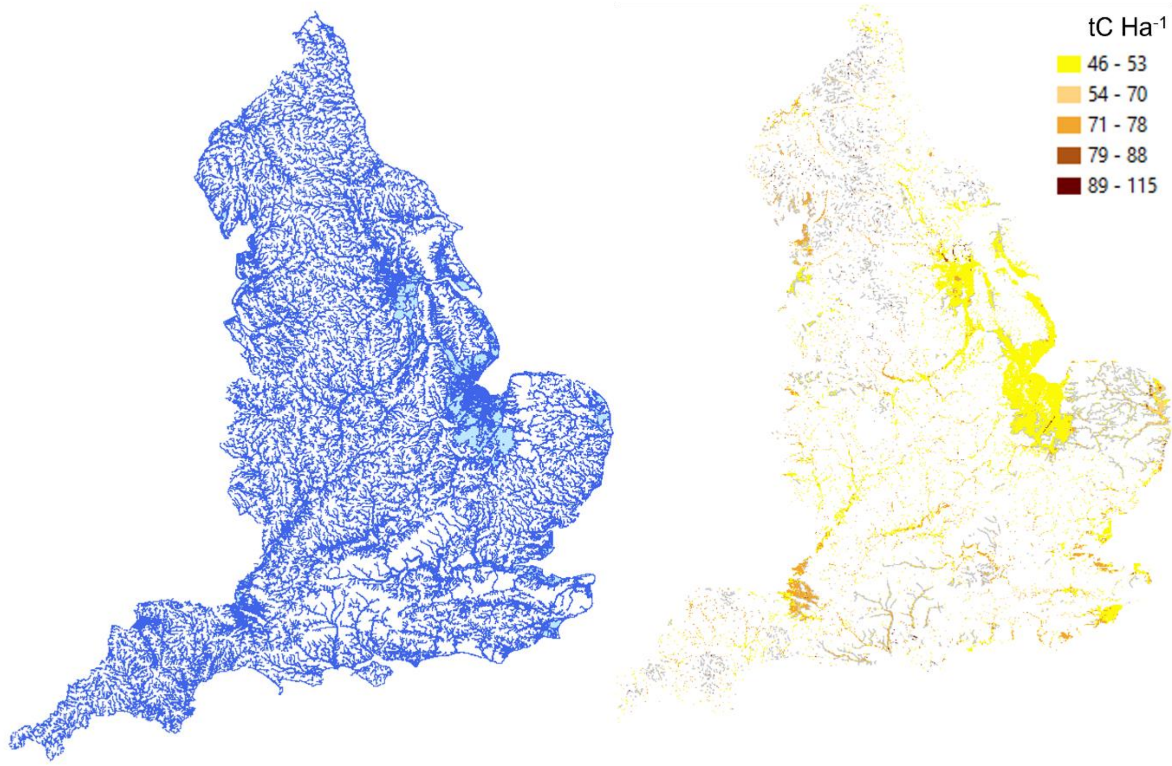


Fig 3: Floodplain Floodzone2 in England (Left) and Floodplain Soil Organic Carbon storage (tC Ha^{-1}in top 15cm) (right) recorded in UK Soil Survey Soil Carbon data (2023). Combined floodplain SOC amounts to 76 million tC in England alone.

Regardless of estimation, we conclude that for SOC alone, floodplains are a significant contribution to the carbon stock in England and Wales. Using the review of SOC recorded in the literature for temperate UK rivers and estimates made in this report, enables us to update the evidence more accurately in the House of Lords (UK Government 2022) and Gregg et al., (2021) Natural England reports (Figure 4). The revised estimates (without buried carbon) shows that floodplain SOC is a nationally important carbon store, potentially second only to fen and deep peat bogs, and larger than native woodland when in a restored condition. Whilst floodplain SOC is affected by upstream sources of organic matter, it is the biomass on floodplains together with the enabling conditions provided by restored / natural floodplain environments which create conditions for carbon accumulation and storage. To fully capture the C-storage in UK floodplains requires addition of other floodplain stocks including large dead wood, above ground biomass (AGB) and old buried Carbon in the form of Quaternary age peat and organic rich floodplain sediments.

Location	SOC carbon stock (tC Ha^{-1})	Reference
North St. Vrain Creek, Colorado, United States	60-1,013	Wohl et al., 2012
Lower Mississippi alluvial valley, United States	167	Hanberry et al., 2015
Danube River, Austria*	177 (42-354)	Graf-Rosenfellner et al., (2012)
Jalisco, Mexico	114	Jaramillo et al., 2003

Central Yukon River, Alaska, United States	152-402	Lininger et al., 2019
Congaree River, South Carolina, United States*	248-1118	Ricker and Lockaby, 2015
MF Snoqualmie River, Washington, United States	123-263	Scott and Wohl, 2020
Big Sandy River, Wyoming, United States	57-131	Scott and Wohl, 2020
Headwaters in s New England, United States*	117-400	Ricker et al., 2012
Rhine River, Germany*	538-671	Hoffman et al., 2007; Hoffman et al., 2009
Mid-Atlantic Piedmont streams, United States*	250-1350	Walter and Merritts, 2008
MF Flathead River, Montana, United States	7735	Appling, 2012
Cosumnes River, California, United States	83-182	D'Elia et al., 2017
Tallgrass prairie streams, United States	166-610	Wohl and Pfeiffer, 2018
Shortgrass prairie streams, United States	4-326	Wohl and Pfeiffer, 2018
Queensland, Australia	57-430	Adame et al., 2020
Dee River, Scotland, UK*	323 (34-1469)	Swinnen et al., 2020
Rocky Mountain National Park, Colorado, United States	50.5-595.7	Sutfin et al., 2021
Deep Creek, Oregon, United States	391-521	Hinshaw and Wohl, 2021
South Fork McKenzie River, Oregon, United States	177-348	Hinshaw and Wohl, 2022
River Ashop, Peak District, UK*	203-783	Alderson et al., 2019
River Culm, Devon, UK	147 ± 29	Quine et al., 2022
South Platte River, Colorado, United States	63-279	Wohl and Knox, 2022
UK River Floodplains*	56.1 ± 13.8	This Study
UK River Floodplains*	19.1 (1.6 – 48.3)	Walling et al., (2006)
River Nar, UK Restored reach*	11	This study
River Cole, UK Restored*	3	This study
New Forest, UK Floodplains*	76	Pogue 2016

Table 5. Soil Organic Carbon storage in published literature from around the world. Values with * were used to estimate an average for UK temperate floodplains. Updated after Suftin & Whol (2016). References in Suftin & Whol (2016).

Long term storage and sequestration of Carbon in floodplains

Buried carbon is emerging as a widespread and potentially large component of the carbon budget of river:floodplain systems (Lininger et al., 2017; Swinnen et al., 2020). Values for buried carbon (peat, OM rich sediments) in the literature are consistently high but variable 55-3925 tC ha^{-1}, with contributions to total Holocene carbon storage reported to be between 45.2 and 75.0% in 4 Belgium streams (Swinnen et al., 2020). However, few estimates exist for UK river:floodplain systems. To estimate the amount of buried carbon in floodplains we used the extensive BGS Borehole datasets and clipped these using the Floodzone2 flood inundation layer. We then randomly sampled 105 boreholes from across Great Britain, and allocated each to a catchment classification upland, middle and lower reaches of the river (Figure 5). At each borehole we identified presence of peat and organic rich layers and recorded their burial depth and thickness in relation to total depth of alluvium. In addition, we sampled upland, middle and lower reaches of three river systems, the Tyne (a large gravel bed runoff river typical of upland catchments), the Trent, (a large gravel bed runoff river with extensive lowland floodplain) and the River Avon (a large gravel bed groundwater river with extensive lowland floodplains). At each borehole we again identified the presence of peat and organic rich layers and recorded their burial depth, thickness of each peat/organic rich layers and proportion of total alluvium depth that was organic rich sediments.

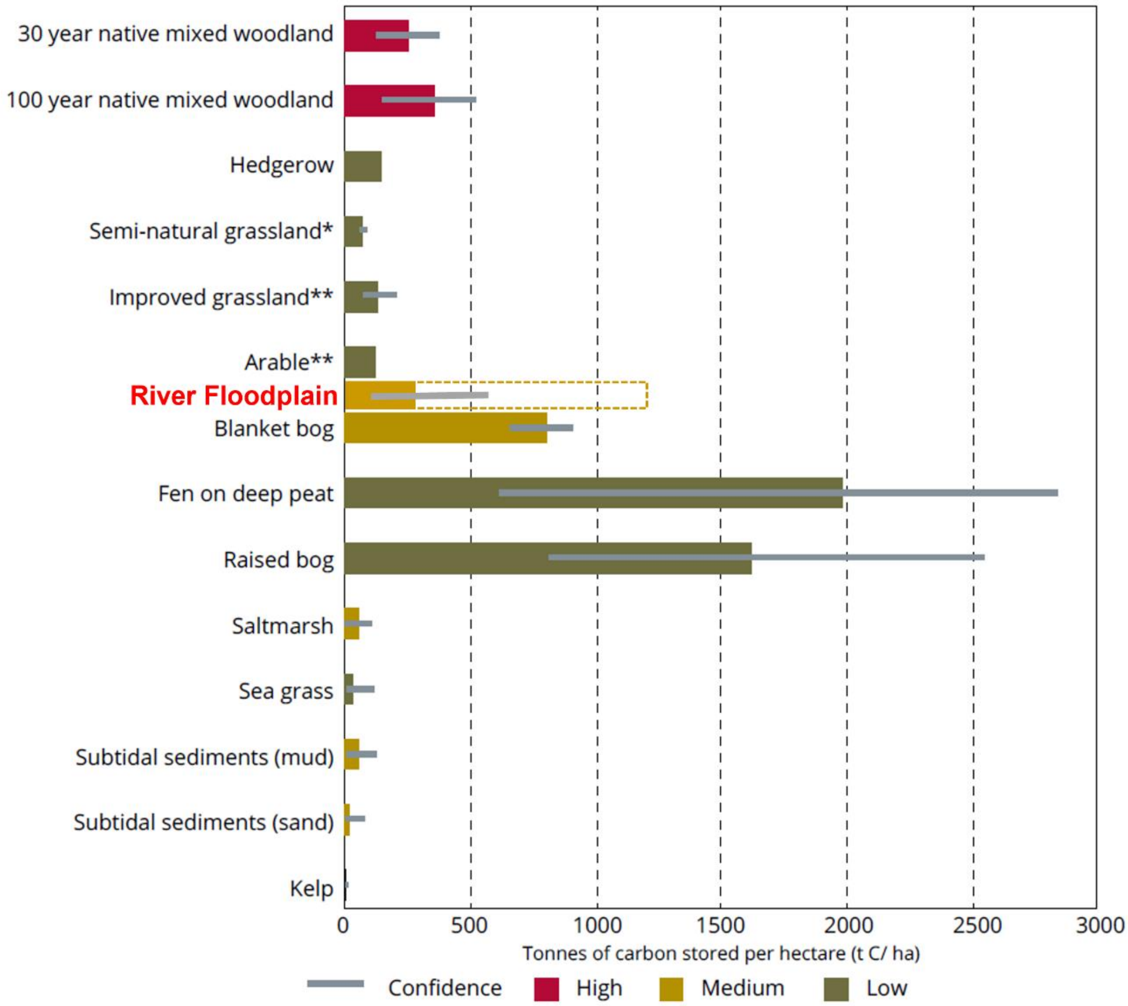


Fig 4: Soil Organic Carbon stored in a range of UK Habitats updated to show estimates for temperate floodplain estimates from around the world and updated values reported in this study. Estimates use different soil depths. Values are based on disturbed floodplains not natural and are thus an underestimate. Pecked line shows the increased range in values when natural floodplains are included. Buried Carbon not included. Note that floodplains are not the equivalent as the Habitat classifications used by Natural England in Gregg et al., (2021). Thus, floodplains contain mosaics of the different habitats in Figure 4.

For the random 105 samples we calculated catchment area at each point, and floodplain area for a 1km reach centred on the borehole. Total alluvium depths were used to calculate a total floodplain volume for a 1km reach centred on each borehole and using the proportion of total alluvium depth recorded as organic rich sediments (peat, organic rich silts and sand) we estimated total volume of buried organic rich sediment per km (Figure 6).

Figure 6 shows how floodplain area (a) Carbon storage (b) and organic sediment burial depth (c) scale approximately with increasing catchment area. As catchments increase in size, the size of the floodplain typically scales with increasing runoff with exceptions where local geological controls narrow floodplains in their lower reaches, floodplain sedimentary deposits also tend to thicken, and the quantity of organic matter storage increases. Burial depths of organic matter in the floodplains increase but at a lower rate (Fig 6c).

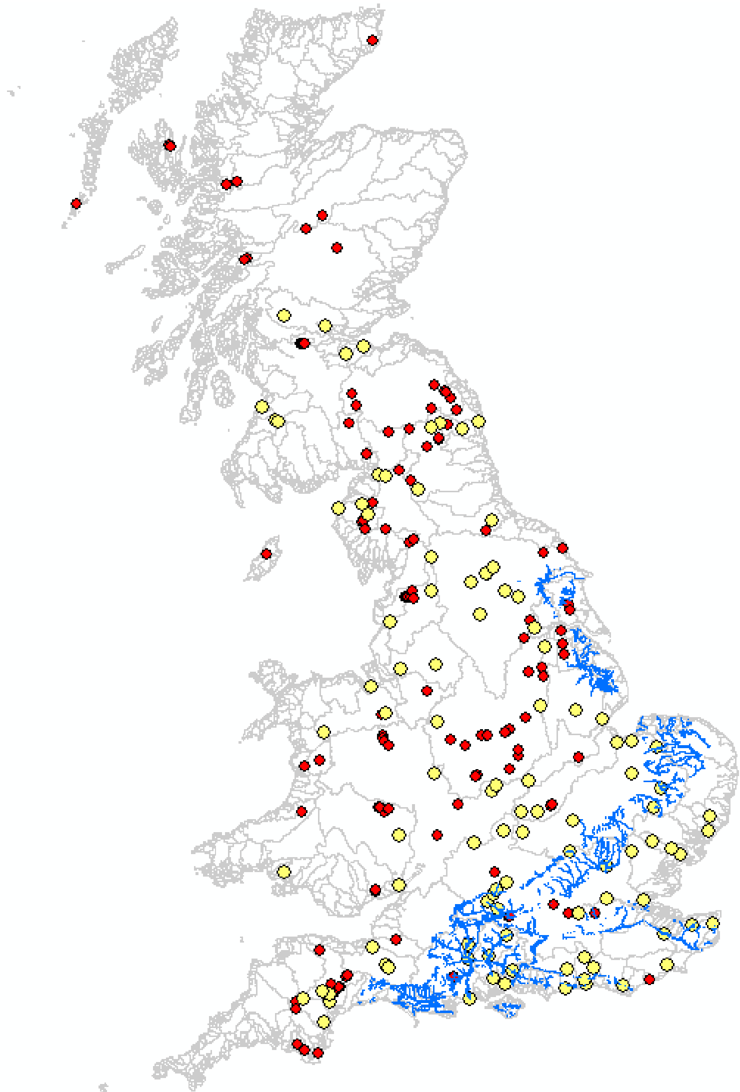


Figure 5: Location of BGS boreholes (Red) and dated sediment sequences derived form the literature (Yellow). Catchment boundaries (grey) and chalk river network (blue) are also shown.

Since C-storage in floodplains depends on maintenance of anoxic conditions, the depth of burial is important as these determine the sensitivity to water table fluctuations – shallower deposits are at greater risk (Swinnen et al., 2020). Burial depths increase with catchment area, and chalk catchments tend to have shallow peat layers, that are at risk from oxidation due to water table lowering. Beerten and Letern (2015) report floodplain water table lowering of 0.5-2m since 19th century as a result of drainage. Assuming a 1m drop in water table this would expose a further 16.2% of buried peat deposits, which is similar the ranges (12.5-50.4%) reported by Swinnen et al., (2020) for a 1.5m drop in floodplain water table elevation.

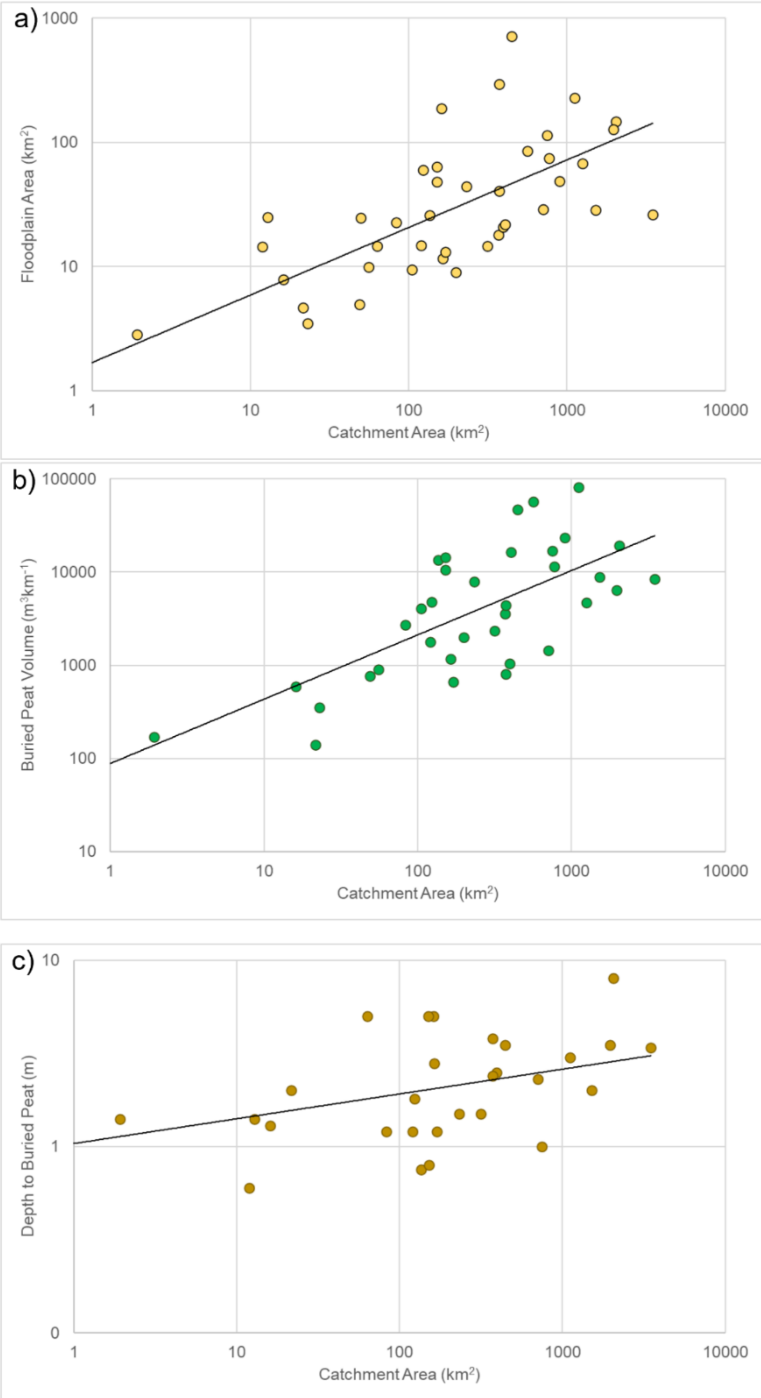


Figure 6: Scaling of a) floodplain area; b) buried organic matter carbon storage and; c) burial depth with catchment size. Note log:log axes demonstrate high variability in values.

As a first order approximation we can scale carbon storage by Strahler stream order and estimate buried organic Carbon storage. Thus, we further classified these data into upland, middle and lower reaches of each river system based on Strahler stream order (Table 6) from which we derived an average and standard deviation of all boreholes, based estimates of OM volume per stream order class (Table 6). Organic rich sediment volumes are converted into tonnes of Carbon using the assumption of a 52% C-content for peats (Lindsay 2010) and a dry bulk density of 0.4 tm^{-3} (JNCC 2011).

River network position	Proportion of Boreholes with OM	Stream Order	River Length (km)	Burial depth of Organic rich sediments (m)	Carbon storage (tC km^{-2})
Upland (10)	0.51	1-2	126338	1.37±0.45	1931 ± 910
Middle (18)	0.78	3-5	40931	2.41±1.44	4173 ± 4110
Lowland (9)	0.66	6-7	4788	3.98±2.32	4680 ± 3064

Table 6: Summary values of buried C-storage for different regions of river networks. The mass of buried carbon in floodplains increases downstream and deposits are buried deeper.

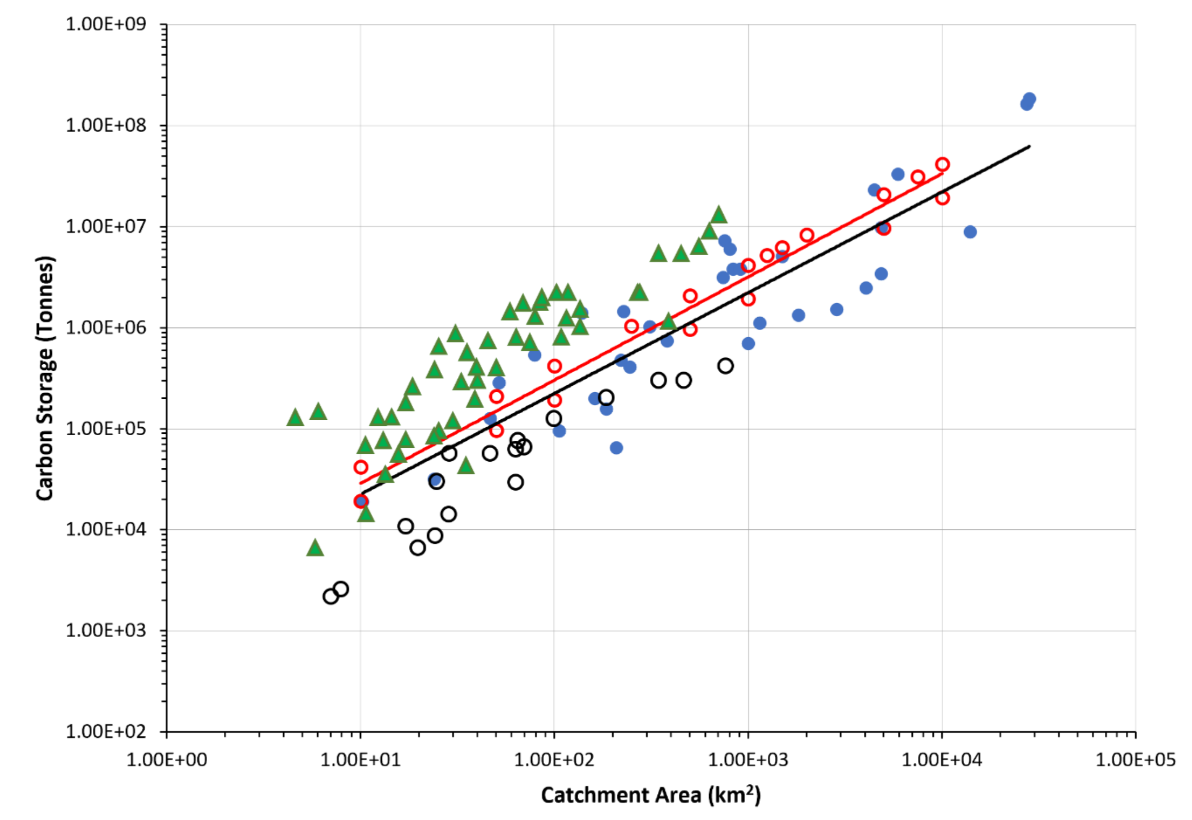


Figure 7: Relationship between river catchment area and total organic carbon stored in floodplain sediments. Blue symbols after Hoffman et al., (2013) for central European lowland floodplains. Red symbols are estimates based on buried carbon stocks in UK floodplains. White Symbols are for River Dee, Scotland, from Swinnen et al., (2019). Green Symbols are Belguim rivers draining sand and clay catchments (Swinnen et al., 2020).

Hoffmann et al., (2013) derived a relationship between river catchment area and tonnes of carbon stored in floodplain sediments for lowland central European catchments (Figure 7). Iteratively applying the values derived above yields a close approximation to the Hoffman et al., (2013) relationship (Figure 7) in which the value of carbon stored per km^2 is closest to 1931 tC for lower order streams but overall is 2737 km^{-2} tC. Based on the floodplain areas of England and Wales (16,000km^2) and England (14,098 km^2) and relationships between catchment areas and buried organic carbon defined above for the UK, gives a **first order approximation of buried floodplain carbon of c.43-31 x 10^6 tC and c.39 - 27 x 10^6 tC** respectively. In comparison, Hoffmann et al., (2013) estimate a Floodplain sediment carbon stock of 1.2 billion tC for lowland central European Rhine floodplain (excluding the Alpine Rhine), while Swinnen et al., (2019) report 0.72 x 10^6 tC for the 663 km^2 catchment of the River Dee Scotland, whilst Swinnen et al., (2020) estimate values of 1.7 – 6.8 x 10^6 tC from sandy peaty and clay peat organic rich floodplain soils for river catchments ranging from 89-774 km^2 in Belgium. The lower values for the River Dee are considered to reflect net removal and deposition of coarser sandy gravels with lower OC content by glacial activity (Swinnen et al., 2019).

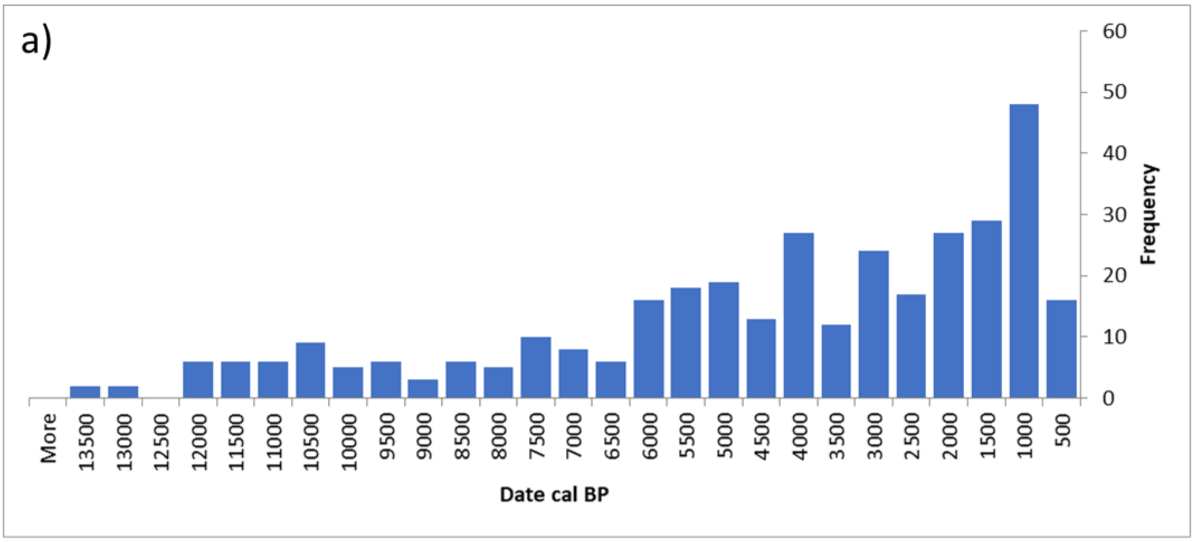
Adding the buried carbon estimates above to the SOC estimates (top 15 cm) give values of **between c.119 x 10^6 – 107 x 10^6 tC floodplain sediment Carbon stocks in England**, with a higher estimate of 332 x 10^6 – 320 x 10^6tC based on literature values for SOC.

We conclude that buried organic rich sediments and peat are a substantial store of old carbon in the floodplains of England and provide comparable values to European temperate floodplain sediment stores, indeed Hoffmann et al., (2013) make the point that these stocks are larger than woodland equivalents.

Age of buried floodplain peat

A constraint in the BGS Borehole data is the lack of dated sequences. This precludes any estimate of Carbon accumulation, or any sense of the longevity of storage in floodplain sediment sequences. To address this shortfall, we assembled the dated floodplain sequences available from the literature and summarised in Macklin et al., (2016) and related metadata base (Jones et al., (2015). We augmented this database using collated published palaeoenvironmental sequences and unpublished grey literature derived for the “Fields of Britannia” project (Rippon et al., 2015) and more recent dated sequences. We checked the locations against the BGS boreholes but found no acceptable (<25m) spatial coincidence.

Buried floodplain peat and sediments with high organic matter content illustrate the potential longevity of carbon stored under alluvium in floodplains in England and Wales (Figure 8a). Most dated sequence are over 1000 years old, with an average of c. 4000 years extending back beyond the Holocene (c. >10,000 yrs). Burial depth of organic matter layers in floodplains of England and Wales vary according to alluviation history but tend to be >1m. Chalk catchments and those in the peri-estuarine reaches of lowland rivers have peat or organic matter rich sediments closer to the surface (<0.5m). Peat deposits in chalk catchments are both nearer the surface of the floodplains and are far older than other floodplain sequences of comparable depth.



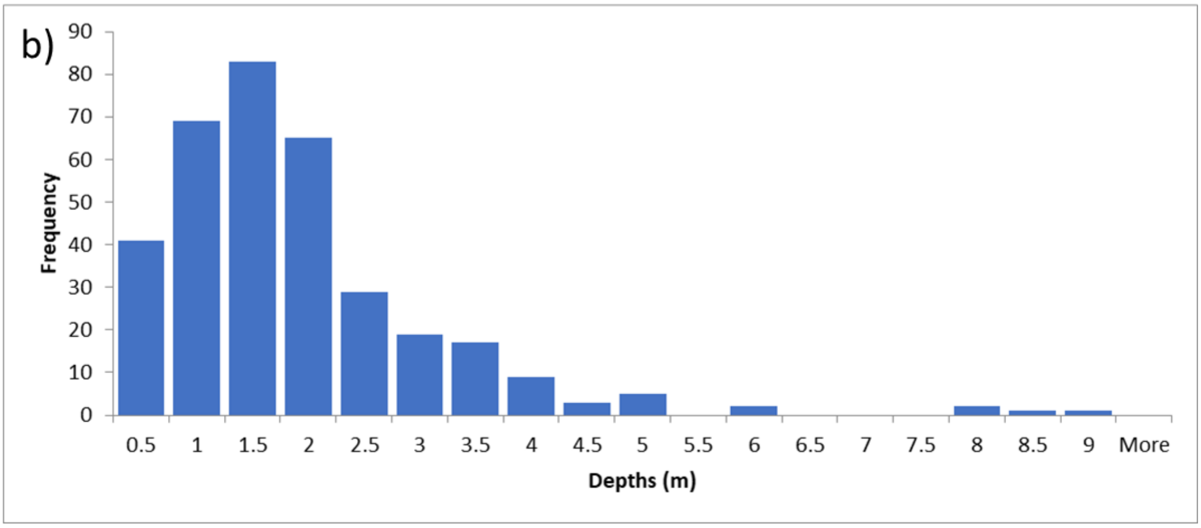


Figure 8: Frequency of a) dates from buried organic matter deposits in floodplains in England and Wales after Macklin et al., (2016), and b) burial depths of organic matter deposits (Rippon et al., 2015; BGS boreholes, Macklin et al., 2016).

Chalk river floodplains are among the most organic rich sediment sequences, storing organic carbon in the form of peat over multiple millennia (mean age 8182 ± 4057 yrs cal. BP; mean burial depth 1.15m ± 0.51m) compared with upland (3804 ± 3084 yrs cal. BP; mean burial depth 1.49m ± 1.08m) and middle (4410 ± 3339 yrs cal. BP; mean burial depth 1.81 ± 1.19m) reaches of river systems in the UK. Relatively small burial depths reflect the limited sediment yield of these catchments combined with groundwater modulated flood hydrology that reduces the frequency of overbank flooding (Barnsley et al., 2022). Floodplains of chalk streams naturally have high and stable groundwater tables and high productivity, resulting in ideal conditions for the development of wetland fen, pool and Carr habitats – evidenced by marl formation and extensive sedge and brushwood peat deposits. Shallow burial depths and older carbon make chalk floodplains highly sensitive to warming temperatures and falling water tables, that can result in oxidation and release of old carbon into the atmosphere. Conversely, restoration of chalk river floodplain creates conditions for rapid and long-lasting carbon storage.

Estimates of Large Wood C-storage in River and Floodplains

In natural river floodplain systems large wood (>0.1m diameter, >1m length wood referred to as LW here on in) is recruited to both river and floodplain surfaces by senescence, disease, windthrow and channel migration (Sear et al., 2010; Whol et al., 2021)). Floodplain woodlands and wooded riparian zones adjacent to the channel are sources of LW in rivers. Similarly, floodplain LW can be a source of wood to the channel as channels migrate, erode banks, and transport wood from the floodplain. LW on floodplains can influence floodplain inundation and sedimentation patterns by increasing hydraulic resistance during overbank flow (Jeffries et al., 2003; Sear et al., 2010), and can influence channel planform and lateral migration rates (Lininger et al., 2017). Transport of large wood from upstream, and from slopes coupled to the river system add to the accumulation within the river network. Storage of large wood in river floodplain systems depends on rates of breakdown of wood through biophysical processes. In rapidly accreting systems, large wood can be buried and stored in floodplain sediments. Re-exposure occurs because of floodplain stripping during large floods and channel migration. Residence time of large wood in river networks is also a function of wood trapping into accumulations – logjams or lografts. Increased wood loading tends to reduce wood travel distances and thus presents a feedback loop by which large wood can accumulate in the river (Oswald and Wohl 2008). Similarly, mobility of fallen large wood on floodplain is likely to be reduced by the density of other trees, and large wood on the floodplain. Carbon content of LW in undisturbed temperate floodplains average 23 ± 20.4 tC Ha^{-1} Lininger et al (2017). Globally, dead LW can be 10–20% of the above-ground biomass of forests, resulting in a stock estimated at 36–72 Pg C (1 Pg =1 Gigaton; Cornwell et al., 2009; Lininger et al., 2017).

Estimates of large wood storage in river systems are given in Table 7 below which is an update on Hinshaw and Whol (2021). Estimates range considerably according to density, age and species of trees, but also the size of wood relative to channel width (e.g. Dixon & Sear 2014).

Location	Organic carbon stock ($tC\ Ha^{-1}$)	Reference
North St. Vrain Creek, Colorado, United States	166–2,743	Wohl et al., 2012
Central Yukon River, Alaska, United States	2–11	Lininger et al., 2017
Congaree River, South Carolina, United States	26-44	Wohl 2011
Quebec, Canada	57	Naiman et al., 1987
Central Chile	23-158	Comiti et al., 2008
SF Calawah River, Washington, United States	67-230	Scott and Wohl 2020
Tierra del Fuego, Argentina	30	Comiti et al., 2008
Danube River, Austria	5-40	Cierjacks et al., 2010
Jalisco, Mexico	13-23	Jaramillo et al., 2003
Rocky Mountain National Park, Colorado, United States	0.6-61.7	Sutfin et al., 2021
Deep Creek, Oregon, United States	1-21	Hinshaw and Wohl 2021
South Fork McKenzie River, Oregon, United States	39-136	Hinshaw and Wohl 2022
West Creek, Colorado, United States	678.6	Lininger et al., 2021
River Nar Restoration	31	This study
Coleshill Restoration	633	This Study

Table 7: Large wood carbon loadings after Hinshaw & Whol (2021), updated with results from the current report. Large wood on floodplains and in river systems in UK are much lower or non-existent

due to centuries of land cover management and clearance. References found in Hinshaw & Whol (2021).

Estimates of Above ground biomass in Rivers and Floodplains

The contribution to Carbon stocks from above ground biomass (BGB) depends on the vegetation species, structure and age or successional stage. Suftin et al., (2016) report estimates of carbon storage in ABG on river floodplains ranging from 7 tC ha^{-1} to 360 tC ha^{-1}. The highest values tend to be in riparian forests and the lowest in herbaceous meadows or willow scrub. Collectively, Hanberry et al., (2015) estimate values for biomass carbon stocks in forested floodplains in the Missouri river valley as 5 x 10^{6} tC, compared to historical pre-clearance values of 234 x 10^{6} tC. In mature forests on flood plains of the Danube River in Austria Carbon stocks range between 160 to 280 tC ha^{-1} whereas younger, replanted trees contained significantly lower levels c.35 tC ha^{-1} (Cierjacks et al., 2010). In herbaceous flood plain meadows AGB carbon stocks are much lower (21.5 tC ha^{-1}) due to the lower biomass of managed grasslands (Suftin et al., 2016). Shupe et al., (2021) show how age and density of woodland influences C-stocks in oak dominated deciduous floodplain woodland reporting estimates of 50.2 ± 10.8 SE tC ha^{-1} for young plantations, 140.6 ± 11.6 SE tC ha^{-1} for old dense forests, and 180.4 ± 26.6 SE tC ha^{-1} for old sparse forests on the Elbe floodplain.

Pogue (2017) reports variations in AGB for floodplain alluvial forests and other land covers in the New Forest National Park (Figure 9; Table 8). Floodplain type (forested, carr/bog and lawn) controls the vegetation communities and thus the quantity of carbon stored in AGB. Trees and SOC contribute the largest to overall floodplain C-stores. When added together, AGB dominated the total stock across the Forest with grazed lawns contributing the smallest AGB.

Land Cover Type	Non-Tree vege (tC ha^{-1})	Litter (tC ha^{-1})	Trees (tC ha^{-1})	SOC (tC ha^{-1})	% ABG Total New Forest C (tC)
Riverine woodland	0.16	1.96	116.3	75.6	61.2
Bog woodland/Carr	0.24	0.28	116.3	93.7	55.5
Ancient Woodland	0.14	3.34	229.3	66.15	77.9
Lawn Floodplain	0.53	-	-	76.1	0.7

Table 8: Empirical measures of ABG biomass C storage for floodplain vegetation and Ancient and Ornamental forest in the New Forest preambulation after Pogue (2017).

Summary Carbon stocks in River:Floodplain systems

Total carbon stock estimates for temperate and where possible UK river floodplains are given in Table 9, these demonstrate wide variability and high dependence on land cover. Presence of trees and old growth trees substantially increases AGB and large dead wood contributions to carbon stocks. River bed stocks are small reflecting their high turnover and largely gravel bedded stream systems in England and Wales. Values for lower gradient sandy-silt river beds are likely to be considerably higher.

Carbon Stock	Total (tC Ha^{-1})
River bed	0.01 - 0.82
Large dead wood	0.6-633
AGB	0.5 - 360
SOC	19.1-421
Buried Carbon	10.1 – 3925

Table 9: Summary first order approximation of carbon stocks in temperate UK river:floodplains. Buried carbon stocks are highly variable according to presence and thickness of peat deposits. Above ground biomass (AGB) and SOC values are highly dependent on land cover. Large dead wood is based on published values from temperate river floodplain systems.

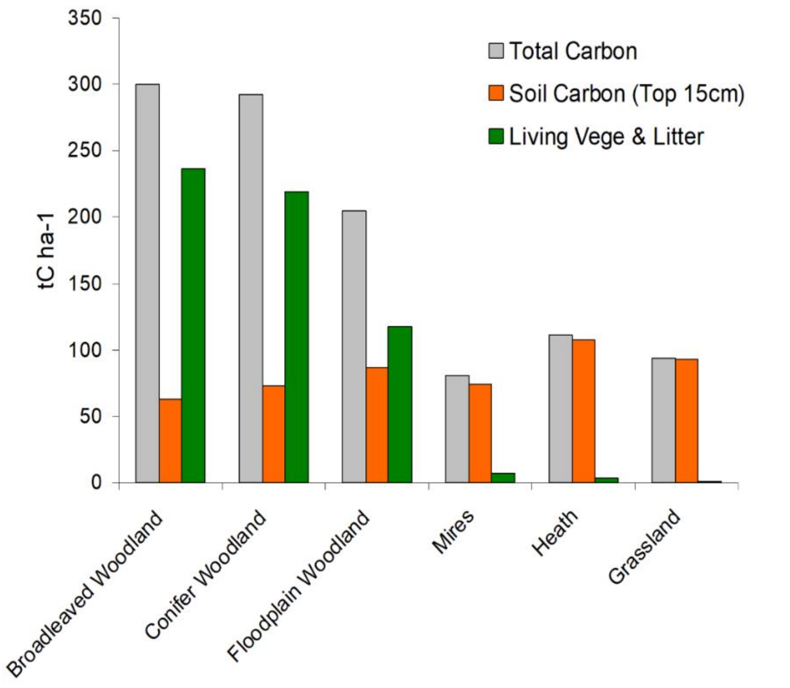


Figure 9: Carbon stores in the New Forest National Park by land cover type after Pogue (2017). Note the dominance of AGB in woodlands in comparison to SOC dominance in other land cover types. Alluvial floodplain Forests have the third largest total Carbon store per unit area, yet their contribution to the landscape carbon stock is ultimately controlled by floodplain area.

The largest contribution to Carbon stocks come from floodplain soils and alluvium, those with extensive, deep buried peats and organic rich sediments (Swinnen et al., 2020; Hoffmann et al., 2013). Buried carbon is likely to be a major unaccounted stock of old carbon in UK floodplains and reflects storage under natural or low intensity agricultural landscapes and natural river:floodplains prior to drainage and disconnection. The high values for these older buried floodplain peat soils, contrasts with the relatively low values for more recent SOC in England floodplain soils as has been noted across developed landscapes (Hofmann 2021). Natural floodplain SOC levels reported in the wider literature from temperate systems including the UK have values more than 10 times those seen under intensive agriculture (Table 5). Thus, the buried C-stock provides a guide as to the potential scale of uplift in C-storage and sequestration possible through restoration of river:floodplain systems.

Processes supporting C storage in Rivers and Floodplains and conceptual model

To utilise the ecosystem services of Carbon sequestration derived from river: floodplains systems, it is important to understand the processes by which Carbon is stored over longer periods of time. This enables better design of nature-based river and floodplain restoration. Floodplains have been described as 'fast in slow out' sediment systems, in which rates of sediment deposition and accumulation (decades – centuries) are relatively fast but output via lateral erosion of riverbanks and floodplain stripping are comparatively slow (centuries to millennia). The result is long term (centuries-millennia) storage of sediment together with associated macronutrients and geochemicals (Trimble 2010; Feeney et al., 2020). Rates of floodplain turnover (the time taken to completely remove former sediment stores) vary according to the rate of lateral migration and in the case of organic carbon, rates of oxidation and removal by biological respiration. River systems with low rates of lateral migration (e.g. chalk rivers) have longer term and deeper storage of sediments relative to more dynamic systems. Further controls on floodplain storage volumes are set by the size of valley floor available (geological controls of artificial confinement by embankments), the frequency of overbank inundation by flooding (determined by climate and catchment characteristics and connectivity to the floodplain) and the sediment load of the upstream catchment (set by land use, topography and soil type). Thus, river floodplain systems with low rates of lateral erosion, high sediment loads and high frequency of inundation in broad valley settings will store larger quantities of sediments over relatively short timescales – typical of intermediate river network settings or lowland floodplain rivers. Conversely, river:floodplain systems with high rates of erosion, frequent inundation, and low sediment loads within a narrow valley setting are likely to result in fast and short turnover times and relatively low storage volumes. Such settings describe steep headwater valleys within montane areas. Swinnen et al (2020) demonstrate how these floodplain types are linked to carbon storage in an upland glaciated river in Scotland.

Changes in climate and more recently changes in floodplain land cover and channel:floodplain connectivity will result in different sequences of floodplain sediment storage and channel activity over time. Moreover, the tendency for rivers to reoccupy former channel courses tends to increase turnover times as some areas of a floodplain are less likely to be eroded in the long term (Feeney et al., 2020), although these low lying palaeochannels are hotspots for Carbon sequestration (Quine et al., 2022).

Biological processes interact with geomorphic processes to generate highly diverse sediment deposits and channel :floodplain geomorphology. Vegetation growth and recruitment of large wood into river channels and on floodplains results in increased rates of sedimentation through the feedback between flow resistance and sediment transport (e.g. Sear et al., 2010 example in New Forest Floodplains). Riparian vegetation can reduce lateral erosion rates, thus increasing the turnover time of floodplain sediment stores. Moreover, channel patterns tend to simplify in the presence of vegetation from multi-channel dynamic braided systems to single thread or stable multichannel anastomosed systems. Other species such as bank burrowing invertebrates and mammals further modify the river channel system through enhanced bank erosion (reducing turnover times). The life history traits of Beaver promote strong river floodplain connectivity and rapid accumulation of sediment and C-storage, generating over time transformation of floodplains into beaver meadows with large buried carbon stocks (Brazier et al., 2021; Puttock et al., 2017).

Whol et al., (2017) and Whol (2021) have summarised the research on key processes supporting OC storage in floodplains (Figure 10). These correspond with pre-human natural river:floodplain rivers, and as such provides a template for restoration projects aimed at increasing carbon sequestration on floodplains whilst delivering further benefits including Natural Flood Management and Biodiversity gain.

As revealed in this study, buried carbon is an important store, and represents three key processes – first the accumulation of organic matter during periods of wetter, cooler climate when swamp and wet woodland habitats were common on floodplains. Secondly, the burial of these deposits by inorganic alluvium resulting from soil erosion due to intensive agricultural activity. Third, the stabilising of river channels by vegetation and more cohesive inorganic sediments that reduced net loss of carbon from bank erosion and lateral channel movement.

The extent of carbon storage in floodplains varies spatially and over time due to fluctuating water tables and active floodplain erosion. In higher energy systems, however migration of the river channel(s) in particular channel avulsion and cutoffs, are key processes for the formation of palaeochannel depressions into which organic rich sediments can accumulate. Cierjacks et al., (2011) demonstrate for the Danube floodplain that highly dynamic sites are characterised by low tree cover, high stem numbers and formation of shallow soil horizons. More stable sites have larger older and denser tree cover and are characterised by deeper larger sediment horizons with high C Stocks. Thus, floodplain dynamics also control AGB and longer term rates of C-sequestration.

Stable multichannel systems (anastomosing) with logjams and high water tables generate ideal conditions for rapid sustained organic matter accumulation, and should be a focus for restoration activity (Quine et al., 2022). In upland and middle order reaches of rivers, climatic and land use changes can drive incision of rivers into their floodplains particularly during phases of increased flood frequency (Macklin et al., 1992). This in turn can result in falling water tables in floodplains and thus risk oxidation of buried carbon stocks, and higher rats of lateral erosion and thus loss of buried carbon stocks.

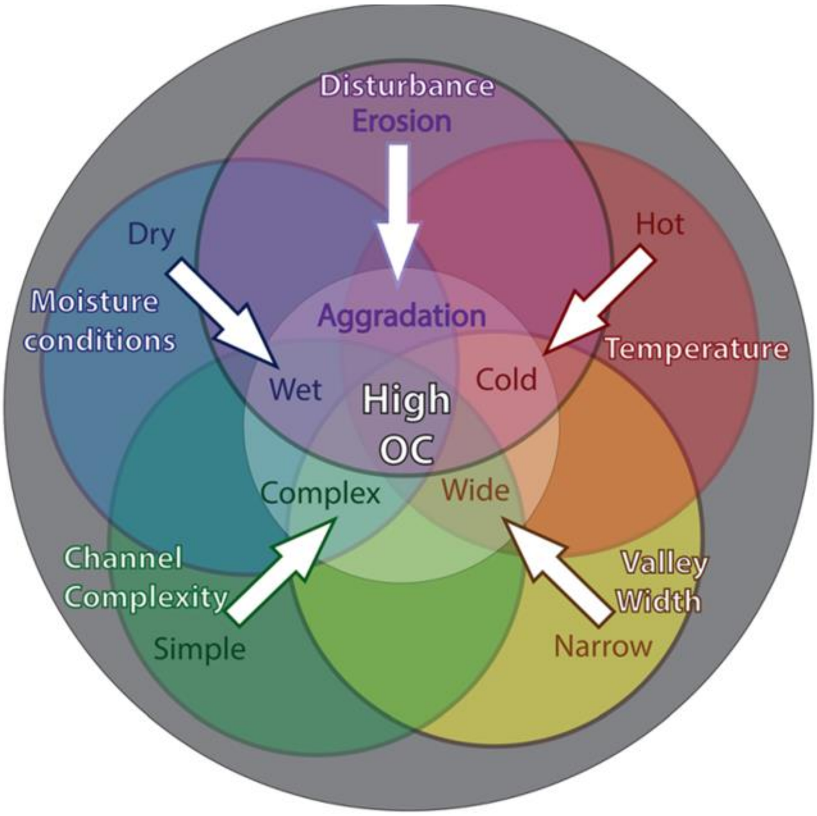


Figure 10: Processes required to optimise OC storage in river:floodplain systems (Hinshaw & Whol 2021). Climate, hydrology, geomorphology and biology combine to generate optimal (or sub-optimal conditions) for C-storage in floodplains. What is clear, is that stable, disconnected rivers with limited complexity of form and supressed ecological activity such as characterise much of the UK river network, is not conducive to C-storage, moreover they are less resilient to future climate change.

River restoration

River restoration that involves reconnecting the floodplain to the river channel and restoring complexity provides the opportunity to protect as well as increase current carbon stocks (Hinshaw & Wohl, 2021). As floodplain restoration is increasingly being considered alongside channel restoration, there is increasing potential for restoration to deliver long term carbon storage (Wohl et al., 2021). However, there remains barriers to implementation of restoration in practice. Quantification of carbon storage is important in the valuation of carbon sequestration as an ecosystem service to enable restoration to become integrated into policy (Gifford 2020).

Restoration of the lateral connectivity and the reinstation of natural complex floodplain processes is important in bringing back these services (Hinshaw & Wohl 2021; Wohl & Knox 2022). Much of the literature agrees that the most valuable way of restoring floodplain environments for carbon storage is by reconnecting the river to the floodplain and allowing it to become inundated (Wohl et al., 2021; Hinshaw & Wohl 2021; Quine et al., 2022). This is because wet floodplains create anoxic conditions that prevent microbial decomposition of organic matter (Nahlik & Fennessy 2016; Wohl et al., 2021) and so disproportionately store more carbon (Tangen & Bansal 2020). However, this is a simplified idea that will not necessarily apply to all river types.

River restoration efforts include large wood addition to the river as well as replanting of trees in the riparian zone (Dybala et al., 2019; Lininger et al., 2021). This can act as an addition of another carbon store as well as influencing other processes such as overbank flooding increasing floodplain carbon storage and sedimentation rates (Lininger et al., 2021). Log jams can promote formation of multiple channels and complexity and smaller channel log jams can lead to abandonment of secondary channels and infilling of organic material (Sear er al., 2010; Lininger et al., 2021). Large wood can interact directly with particulate organic matter by creating depositional sites for particulate organic, which can also influence hydraulic influence the porosity of large wood (Lininger et al., 2021). Large wood can be added in channel by human activity as part of restoration process, but also transported from trees in the riparian zone particularly during flood events (Zischg et al., 2018; Lininger et al., 2021). Floodplain large wood is likely to have a longer residence time particularly within areas that are highly productive but with reduced decay rates (Wohl et al., 2018; Galia et al., 2020; Lininger et al., 2021).

Evidence for the effectiveness of River:Floodplain Restoration actions and C-storage

Floodplains cover over c. 1.6 million hectares in England and Wales but just 0.19% is occupied by species-rich floodplain grassland, and 0.54% by alluvial forest and bog woodland. Moreover, 42% of floodplains are no longer connected to the river system and do not contain land-use types typical of a fully functioning river floodplain (Heritage & Entwhistle 2017). Recognition of the value of floodplains has driven a new emphasis on approaches to restore their functionality and reconnection.

Approaches to the restoration of river:floodplain systems are changing, with increasing emphasis on multiple benefits and reconnection of floodplains (Whol et al., 2021). One of the benefits suggested is increased storage and sequestration of carbon both in-channel via increased contributions by large wood, and through enhanced overbank carbon deposition and storage on floodplains. Restoration is increasingly subsumed within the broader term Nature Based Solutions, but this is to miss the important distinction that River and floodplain restoration has been evolving since its inception in the later 1980s and early 1990s (Whol et al., 2021). Despite these interests and as a result of a general failure to monitor the performance of restoration projects, there is relatively little evidence specifically relating to carbon storage. What evidence exists supports theoretically and empirically that reconnection of floodplains and the reestablishment of their natural vegetation communities can result in increased storage or Carbon relatively to current conditions (Hinshaw & Whol 2021). For example, Swinnen et al., (2020) point out that increasing water table elevations in carbon rich floodplains is an effective method for protecting existing buried C-stores and increasing rates of carbon sequestration. D'Elia et al., (2017) demonstrated that within 10 years of reconnecting the floodplain on the Cosumnes river, that restoration of floodplains can increase C-sequestration to pre-disturbance levels. Hinshaw and Whol (2021) assessed the effectiveness of two floodplain restoration projects in the US montane environment and developed conceptual models for large wood and Soil Organic Carbon accumulation. The two cases show statistically significant increases in large wood carbon storage, SOC and total C-stored per ha between the degraded state and the treatment reaches (Table 11), with values for the latter an order of magnitude larger than equivalent examples in the UK. River management strategies focused on hydrologically reconnecting channels and floodplains are the most effective way to enhance carbon storage and sequestration (e.g., Hanberry et al., 2015; Whol & Knox 2022).

Dybala et al., (2019) have modelled the increase in Carbon resulting from reestablishment of riparian forests, including that within 20-30 years post restoration C-storage increases by 100%, with a 200% increase in a century (Figure 11). Dixon et al., (2018) show through numerical modelling of riparian forest growth, that there is a lag of 20–40 years between the establishment of a new forest stand and the delivery of stable in-channel deadwood, and that the volume of dead wood varies with forest species composition – mixed deciduous woodlands being most effective. This research points to the need for resource managers to be aware that Natural Capital benefits, including NFM are unlikely to be realised during this initial phase of forest growth without additional management intervention, for example, using engineered logjams (Dixon et al., 2018).

Increased wood loadings can result in detectable changes in physical habitat and ecological processes over shorter timescales if introduced to degraded rivers. Pess et al., (2023) report an increase in wood loading and channel-spanning logjams, which contributed to deeper and more frequent pools, a reduction in particle size, increases in sediment storage, reduced stream width, vegetation re-establishment in the riparian zone, and increased development and maintenance of floodplain channels after 23 years of restoring channel wood loading.

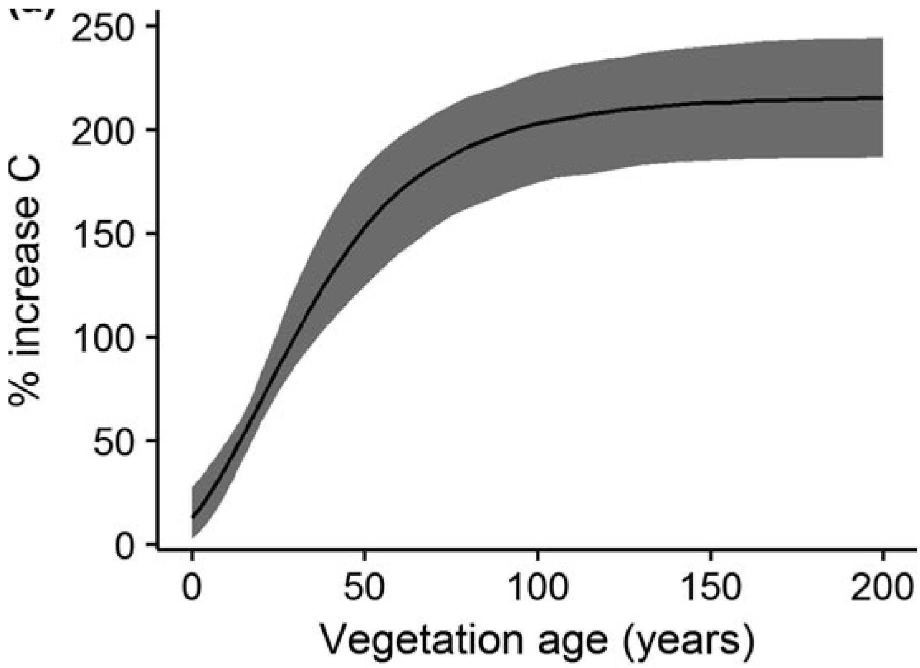


Figure 11: Percentage increase in Carbon stock relative to baseline for recovering riparian forests. These values are modelled and reflect the restoration scenario whereby riparian forests are allowed to regenerate. Values suggest restoration of riparian forests in cool wet temperate environments will have a benefit for C-storage relative to current land cover (Dybala et al., 2018).

Site	Large Wood (tC Ha^{-1})	Total SOC (tC Ha^{-1})	Source
River Nar Norfolk			
Untreated	0	71.7	This study
Treatment	11.4	140.0	

Coleshill Oxfordshire Untreated Treatment	 0 633	 80.4 98.5	 This study
Deep Creek USA Untreated Treatment	 21 7	 437 528	 Hinshaw & Whol (2021)
South Fork McKenzie Untreated Treatment	 39 136	 225 500	 Hinshaw & Whol (2021)
Consummes River, USA Untreated Treatment	 - -	 34 42	 D'Elia et al., (2017)

Table 11: Comparison of treated (restored) and untreated river:floodplain Carbon storage. Note this does not include buried carbon. Hinshaw & Whol (2021) sites report only large wood and SOC, with the latter estimated over 1m depth.

To extend the evidence base for the UK, we report preliminary assessments of Carbon storage from two lowland UK river and floodplain restoration projects. The two sites targeted were chosen for their contrasting geology and longevity of treatment. The river Nar floodplain restoration project was undertaken between 7-5 years prior to measurement. The site is a floodplain one corresponding to an untreated grazing floodplain and channelised river state, and the other a restored channel and conservation managed floodplain. The sites are located in Norfolk on the River Nar SSSI and is a chalk groundwater dominated river with a surficial geology of glacial fluvial sands. Floodplain soils are organic rich peats with some inorganic topsoils. Floodplain and channels were modified by humans over the past 1000 years or more. The second site is located on the River Restoration Project demonstration site at Coleshill on the Oxfordshire:Wiltshire border. The river Cole is a south bank headwater tributary of the Thames and drains a mixed geology catchment underlain by chalk but capped with London clay and outcrops of Corralian Rag limestone. Soils in the floodplain have high clay content and runoff is influenced by the urban headwaters draining Swindon. The River Cole at Coleshill was restored under an EU-LIFE project in 1994-95, and involved in its downstream section, re-meandering, bed level raising, and the cutting of a two-stage inset floodplain (Sear et al., 1998; Kronvang et al., 1998). The site has been left to develop naturally, whilst retaining intensive arable farming on the broader floodplain and pasture on the opposite floodplain banks.

The methodology for quantifying Carbon storage followed that of Pogue (2017) and involves two steps; first identification of landcover types including the riparian and river channel as well as floodplain, and an estimate of large wood loading following standard methods (Hinshaw & Whol 2021). The second step was to generate random quadrat (5 per land cover) in ARCMAP10.8 and at each 0.5m2 quadrat sample the Carbon in soil (top 10cm), litter, ground vegetation, above ground vegetation, trees/shrubs (Pogue 2017). In the river, all vegetation in a quadrat was cut and returned to the laboratory for measurement and Loss on Ignition (LOI). At each quadrat, samples of soil and other Carbon stores were taken within the quadrat, bagged and returned to the cold store until processing for wet and dry weight and Loss on ignition at 550°C (Pogue 2017). Adjustments for Carbon content were based on standard estimates of 40% Carbon per organic matter content derived from LOI. Large wood volume was measured over 100m in each channel, and scale dup to the total channel length. Quadrat data were scaled up using the area of each representative land cover. Total carbon inventory was the sum of the different Carbon stores, scaled by area to provide a standard tC Ha^{-1}. Thus, for each land cover type and channel, we estimated an average and standard deviation based on the quadrat data. For woodland we utilised the point-centre-quarter method of sampling trees and then estimated tree mass using standard allometric methods for relevant tree species (Willow, Oak, Alder e.g. Bludjea et al., 2012) with wood volumes converted to mass using appropriate wood density values. Organic Carbon mass was estimated using appropriate conversion factors from the literature (ibid.

Summary data from these two sites are given in Figures 12 and 13 and in Table 11 for the spatially averaged total carbon storage. Total storage at the two sites is estimated at 963± 199 tC (treated) vs 218±120 tC (untreated) at Coleshill, and 248±117 tC (treated) vs 76±36 tC (untreated) for the river Nar. In both cases spatially averaged total C-storage is 50% (Nar) and 161% (Coleshill) higher post restoration. In both cases the restored river:floodplains were estimated to have higher rates of SOC storage compared with untreated sites. For the River Nar, this amounted to a 95.3% increase in SOC relative to untreated, and at the Coleshill a 20.5% increase. These compare well with the values of 21% and 122% increase in SOC post restoration reported by Hinshaw & Whol (2021).

For the river Nar, restoration treatment increased the Carbon stored in rough grass, woodland and large wood in the river relative to untreated. The untreated Carbon stores were less diverse and dominated by grazed grassland, channel riparian zone and in-channel vegetation (Figure 12). In the river Cole, growth of trees and high instream storage of large wood dominated the restored reach carbon storage whilst reducing the plant material stored in the river channel compared to the untreated reach. River biomass is an important Carbon store in untreated channelised rivers with no riparian tree shade; restoration reduces this, largely through shading (Cole) and species differences (Nar).

Figure 12: Summary Carbon storage for restored and un-restored reaches of the river Nar, chalk stream and floodplain, Norfolk, UK. All data normalised by area to give comparable site average in tonnes of Carbon storage per Hectare. Restored river:floodplain stores more than a comparable pre-restoration river floodplain. Age of restoration c.7-5 yrs.

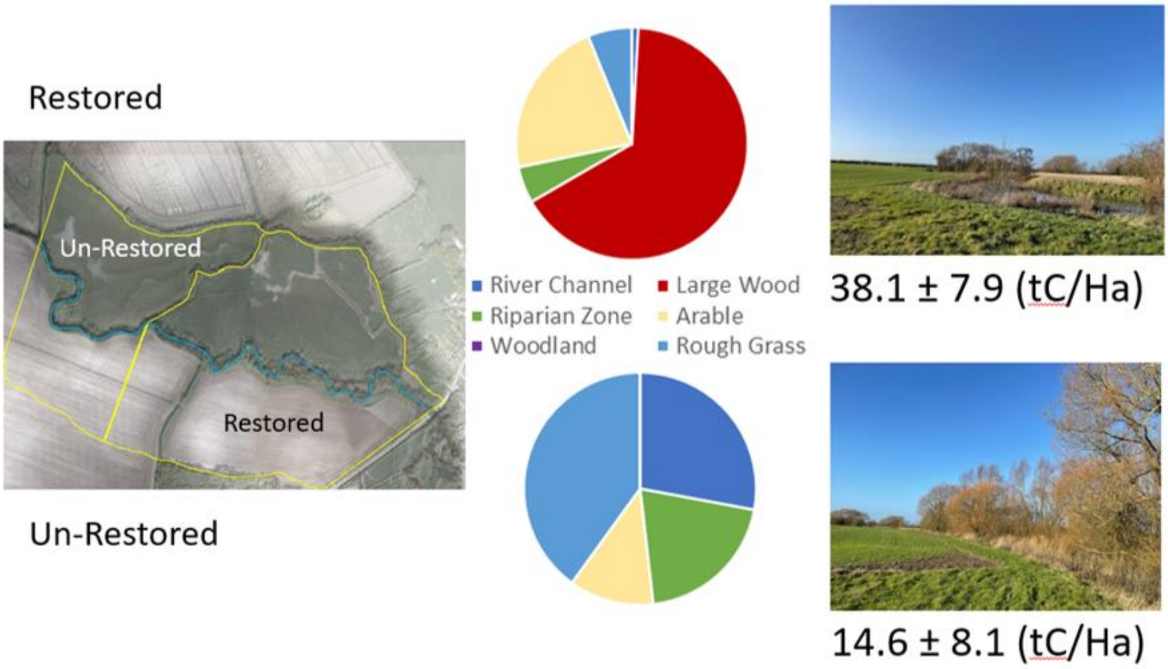


Figure 13: Summary Carbon storage for the restored and un-restored reaches of the river Cole clay / chalk geology stream and floodplain, Oxfordshire/Wiltshire, UK. All data normalised by area to give comparable tonnes of Carbon storage per Hectare. Restored river: floodplain stores more than twice the comparable pre-restoration river floodplain. Site is the River Restoration Project Demonstration Project (Kronvang et al.,1998). Age of restoration 27 yrs.

Large wood loadings show an increase post restoration in 3 out of 4 sites post restoration. In the Coleshill site, this represents natural growth and recruitment over the 27-year time since restoration, whilst the river Nar site represents the addition of within river large wood structures.

In summary, restoration has a detectable and large increase in SOC and large wood carbon storage within 25 years of construction, resulting from large wood and accumulation of plant matter under wetter floodplain conditions. Feedback between logjam formation due to increased wood recruitment to the channel and ageing woodland resulting in larger trees, will likely result in positive feedback as floodplain water levels and connectivity increase, generating conditions suited to preservation of organic matter and swamp peat formation. As Quine et al., (2022) conclude, "*while these types of wetlands can have emissions of CO_2 and Ch_4, the large carbon stocks in these systems suggests naturally functioning wetlands will act as a sink of carbon*".

Summary

- Carbon storage in river:floodplains is quantitatively substantial, comparable to other fens and swamps and in natural state are typically larger than deciduous woodlands and other land cover types.
- Estimates for buried carbon in the floodplains of England and Wales approximate c. **43-31 x 10^{6} tC** and are in line with other estimates for temperate European and UK river catchments.
- Estimates for SOC in the floodplains of England approximate **c.76 x 10^{6} ± 0.5 x 10^{6} tC** and literature based SOC estimates of **289 ± 455 x 10^{6} tC**.
- Combined buried plus SOC generate an estimate of total sediment C-stocks for English floodplains of between **c.119 x 10^{6} – 107 x 10^{6} tC** with a higher estimate of **332 x 10^{6} – 320 x 10^{6}tC** based on literature values for SOC.
- Organic carbon buried in floodplain is old and is indicative of the longer term (centennial-millennial) storage of carbon (largely organic) in river floodplain systems.
- Buried carbon is currently unaccounted for in national inventories of Carbon and yet this study indicates that it is more substantial than Soil Organic Carbon (SOC).
- Large wood carbon stocks where present, represent a further substantial carbon store, although unless buried and protected from oxidation and biological action, are relatively short lived (decades to centennial).
- Carbon deposited into river beds represents a smaller pool of carbon and in many instances where river beds are turned over by flooding, are short lived (days-years).
- **Chalk streams and adjacent floodplains are a very important long-term store** of carbon, but are sensitive to reductions in floodplain water tables resulting from drainage and / or increasing air temperatures.
- Evidence exists for the effectiveness of river:floodplain restoration but all of it to date shows rapid (<25yr) and substantial (>50%) increases in Carbon stocks relative to untreated scenarios.
- **Rivers and floodplains are a substantial UK carbon stock with the potential to increase through restoration and change in land management regime to promote wetland, wet woodland and higher water tables though reconnection and management of higher water tables.**

Recommendations

This report represents an initial review of data pertaining to C-stock and accumulation in river:floodplain systems. It has highlighted the potential of different sources of information notably BGS borehole records and paleoenvironmental data sets to extend our understanding of local to national carbon stocks. Future research should focus on a lager sampling of the BGS borehole data for floodplains, with a specific emphasis on classifying these data by stream order, and floodplain type. Additional information on organic matter content of borehole logs where these exist could be used to augment the estimation of carbon stock. Statistical modelling of this data alongside other contextual information is recommended to derive models like the BGS SOC data layers (see Tye et al., 2022).
The relative absence of dates on buried peats needs to be addressed more systematically, using geospatial data analysis and sampling to derive better estimates of the age of buried carbon stocks. Ideally this would include dates bracketing the main buried peat deposits to enable rats of C-accumulation to be estimated.
C-flux and net C-sequestration data is sparse for both in-channel and floodplain surfaces. Further research is required to estimate the loss of Carbon from different river:floodplain systems sampled geographically to capture the different river:floodplain types and land cover (See Swinnen et al., 2019). This review has not made use of remotely sensed data. Remote sensing is widely used to estimate AGB, and surface C-emissions (Qi et al., 2020). Currently, use of RS for estimation of Carbon stocks and emissions form river:floodplain systems is poor relative to other land covers (peat, forest) and marine environments (Qi et al., 2020). Campbell et al (2022) make the point that *"Local estimates rely on* in situ *samples to estimate site-level carbon budgets. The gap between these scales will increasingly rely on earth observation. System-specific estimates are often extrapolated from limited* in

situ *data, but remote sensing can capture spatial variability, quantify uncertainty, and improve carbon estimates*." Methods for estimating buried carbon alongside other stocks in floodplains may be possible and alongside other measures for AGB and SOC plus emissions, will need to be developed in order to quantify and reduce uncertainty in estimating their contribution of Net-Zero and UK Carbon budgets.

River and floodplain restoration projects are poorly monitored. Given their potential contribution to attaining Net Zero targets along with other benefits for nature conservation, water management and biodiversity, there needs to be better monitoring to capture their carbon emissions and sequestration, ideally over longer timescales. A typological approach to classifying restoration projects would optimise data capture and usefulness. Methods such as those reported in this study suggest such data can be captured in two-three days plus 1 days laboratory work.

This report was initiated in response to earlier reviews on C-storge and sequestration potential of nature-based solutions and natural processes (Gregg et al., 2021). At the time these reports had relatively limited evidence (Environment Agency 2021) or lacked explicit links between habitats (e.g. fens, bogs, wetland grassland etc.) and river:floodplain systems. Since these reviews had influenced policy on the role of nature in supporting Net zero (House of Lords Science & Technology Select Committee report, 2022), this report has sought to explicitly highlight the importance of river:floodplain systems in supporting national net zero ambitions. The evidence presented in this report builds a strong case for a wider recognition of rivers and floodplains as carbon stores and loci of carbon sequestration through increased above-ground biomass relative to agricultural use, and long-term preservation of organic carbon due to wetter soil conditions found in restored and natural floodplains. Government policy for Biodiversity Net Gain (Understanding Biodiversity Net Gain 2023) and Water Policy (Water improvement Plan 2023), alongside the Environmental Improvement Plan (2023) highlight the importance of river restoration as a nature-based solution to the biodiversity crisis and flooding challenges moving forward. **This report confirms that when reconnected to their floodplains restored rivers and more natural river:floodplains also perform important contributions towards net zero**.

References

Alderson, D.M., Evans, M.G., Rothwell, J.J. et al. (2 more authors) (2019) Geomorphological controls on fluvial carbon storage in headwater peatlands. Earth Surface Processes and Landforms, 44 (9). pp. 1675-1693. ISSN 0197-9337.

Aufdenkampe, A.K., Mayorga, E., Raymond, P.A., Melack, J.M., Doney, S.C., Alin, S.R., Aalto, R.E., Yoo, K., (2011). Riverine coupling of biogeochemical cycles between land, oceans, and atmosphere. Front. Ecol. Environ. 9, 53–60. https://doi.org/10.1890/100014.

Barnsley, I., Spake, R., Sheffield, J., Leyland, J., Sykes, T., & Sear, D., (2021). Exploring the capability of natural flood management approaches in groundwater-dominated chalk streams. Water (Switzerland), 13(16).

Bateman S.L. (2012) Sources and impacts of inorganic and organic fine sediment in salmonid spawning gravels in chalk rivers, Unpublished PhD thesis, School of Geography, university of Southampton, 323pp. https://eprints.soton.ac.uk/349382/1/Thesis.pdf

Beerten, K., Leterme, B., (2015). Palaeohydrological reconstruction (1500–2000AD) of a drift sand landscape using pedogeomorphological and historical data (Campine area,NE Belgium). Catena 135, 208–218. https://doi.org/10.1016/j.catena.2015.07.022.

Blujdea, V.N.B., Pilli, R., Dutca, I., Ciuvat, L., & Abrudan,I.V. (2012) Allometric biomass equations for young broadleaved trees in plantations in Romania, Forest Ecology and Management,264,172-184, ISSN 0378-1127, https://doi.org/10.1016/j.foreco.2011.09.042 .

Brown, A.G., Lespez, L., Sear, D.A., Macaire, J.J., Houben, P., Klimek, K., Brazier, R.E., Van Oost, K. and Pears, B., (2018). Natural vs anthropogenic streams in Europe: History, ecology and implications for restoration, river-rewilding and riverine ecosystem services. Earth-Science Reviews, 180, pp.185-205.

Campbell, A.D., Fatoyinbo, T., Charles, S.P., Bourgeau-Chavez, L.L., Goes, J., Gomes, H., Halabisky, M., Holmquist, J., Lohrenz, S., Mitchell, C. and Moskal, L.M., 2022. A review of carbon monitoring in wet carbon systems using remote sensing. Environmental Research Letters, 17(2), p.025009.
DOI 10.1088/1748-9326/ac4d4d

Brazier et al., 2021 Brazier, R.E., Puttock, A., Graham, H.A., Auster, R.E., Davies, K.H. and Brown, C.M., 2021. Beaver: Nature's ecosystem engineers. Wiley Interdisciplinary Reviews: Water, 8(1), p.e1494.Cierjacks, A., Kleinschmit, B., Babinsky, M., Kleinschroth, F., Markert, A., Menzel, M.,Ziechmann, U., Schiller, T., Graf, M., Lang, F., 2010. Carbon stocks of soil and vegetation on Danubian floodplains. J. Plant Nutr. Soil Sci. 173, 644–653. https://doi.org/10.1002/jpln.200900209.

Cierjacks, A., Kleinschmit, B., Kowarik, I., Graf, M. and Lang, F. (2011), Organic matter distribution in floodplains can be predicted using spatial and vegetation structure data. River Res. Applic., 27: 1048-1057. https://doi.org/10.1002/rra.1409

Collins, AL, Zhang, Y, McMillan, S, et al. 2017 Sediment-associated organic matter sources and sediment oxygen demand in a Special Area of Conservation (SAC): a case study of the River Axe, UK. River Res Applic. 33: 1539– 1552. https://doi.org/10.1002/rra.3175

Collins, A.L. L.J. Williams, Y.S. Zhang, M. Marius, J.A.J. Dungait, D.J. Smallman, E.R. Dixon, A. Stringfellow, D.A. Sear, J.I. Jones, P.S. Naden, (2014) Sources of sediment-bound organic matter infiltrating spawning gravels during the incubation and emergence life stages of salmonids, Agriculture, Ecosystems & Environment,196,76-93, https://doi.org/10.1016/j.agee.2014.06.018

Collins, A.L. L.J. Williams, Y.S. Zhang, M. Marius, J.A.J. Dungait, D.J. Smallman, E.R. Dixon, A. Stringfellow, D.A. Sear, J.I. Jones, P.S. Naden, (2013) Catchment source contributions to the sediment-bound organic matter degrading salmonid spawning gravels in a lowland river, southern England, Science of The Total Environment, Volumes 456–457, 181-195, https://doi.org/10.1016/j.scitotenv.2013.03.093.

Cornwell W.K., Cornelissen J.H.C., Allison S.D., Bauhus J., Eggleton P., Preston C.M., Scarff F., Weedon J.T., Wirth C., Zanne A.E. (2009). Plant traits and wood fates across the globe: rotted, burned, or consumed? Global Change Biology 15: 2431– 2449. DOI:10.1111/j.1365-2486.2009.01916.x.

Cotton, J.A.,Wharton, G., Bass, J.A.B., Heppell, C.M., Wotton, R.S. (2006) The effects of seasonal changes to in-stream vegetation cover on patterns of flow and accumulation of sediment, Geomorphology,77; 320-334, https://doi.org/10.1016/j.geomorph.2006.01.010

Defra (2023) (Floodzone2 layer) https://www.data.gov.uk/dataset/cf494c44-05cd-4060-a029-35937970c9c6/flood-map-for-planning-rivers-and-sea-flood-zone-2, accessed March 2023.

D'Elia, A.H., Liles, G.C., Viers, J.H. and Smart, D.R., 2017. Deep carbon storage potential of buried floodplain soils. Scientific reports. 7(1), pp.1-7.

Dixon, S.J. and Sear, D.A., 2014. The influence of geomorphology on large wood dynamics in a low gradient headwater stream. Water Resources Research, 50(12), pp.9194-9210.

Dixon, S.J., Sear, D.A. and Nislow, K.H. (2018), A conceptual model of riparian forest restoration for natural flood management. Water and Environment Journal, 33: 329-341. https://doi.org/10.1111/wej.12425

Dybala KE, Matzek V, Gardali T,Seavy NE. 2019 Carbon sequestration in riparian forests: A global synthesis and meta-analysis. Glob Change Biol. 25:57–67. https://doi.org/10.1111/gcb.14475.

Environment Agency (2021) Achieving net zero: A review of the evidence behind potential carbon offsetting approaches, Report FRS19212, 172p.

European Environment Agency., 2019. Floodplains: a natural system to preserve and restore (Publication No. 24/2019). EEA, Luxembourg.

Feeney, C.J., Chiverrell, R.C., Smith, H.G., Hooke, J.M., & Cooper, J.R. (2020). Modelling the decadal dynamics of reach-scale river channel evolution and floodplain turnover in CAESAR-Lisflood, Earth Surf. Process. Landforms 45, 1273–1291 DOI: 10.1002/esp.4804

Findlay, S. (1995). Importance of surface–subsurface exchange in stream ecosystems: the hyporheic zone. Limnol Oceanogr, 40; 159-164.

Floodplain Meadows Partnership, (2018). Soil carbon stocks in UK grasslands. A brief summary of the literature. Milton Keynes, Floodplain Meadows Partnership.

Fryirs, K. A., Brierley, G. J., Preston, N. J., and Kasai, M. (2007). Buffers, barriers and blankets: the (dis)connectivity of catchment-scale sediment cascades. Catena 70, 49–67. doi: 10.1016/j.catena.2006.07.007

Galia, T., Macurová, T., Vardakas, L., Škarpich, V., Matušková, T., & Kalogianni, E. (2020). Drivers of variability in large wood loads along the fluvial continuum of a Mediterranean intermittent river. Earth Surface Processes and Landforms, 45(9), 2048–2062.

Gifford, L., 2020. “You can’t value what you can’t measure”: a critical look at forest carbon accounting. Climatic Change, 161(2), pp.291-306.

Graf-Rosenfellner, M., Cierjacks A., Zehetner, F., Mentler, A., Kleinschmit, B., and Lang, F. (2012) Distribution and stabilization of organic carbon in Danubian floodplain soils, World Congress of Soil Science, Soil Solutions for a Changing World 1 – 6 August 2010, Brisbane, Australia. file:///C:/Users/ds5/Downloads/Distribution_and_stabilization_of_organic_carbon_i.pdf

Gregg, R., Elias,J.L., Alonso, I., Crosher, I.E., Muto, P., & Morecroft, M.D. (2021) Carbon storage and sequestration by habitat: a review of the evidence (second edition) Natural England Research Report NERR094. Natural England, York. http://publications.naturalengland.org.uk/publication/1412347

Greig S.M., Sear, P.A. and Carling, P.A. (2007) A field-based assessment of oxygen supply to incubating Atlantic salmon embryos. Hydrological Processes, 21, 22, 3087 – 3100.

Hanberry, B.B., Kabrick, J.M., & He, H.S. (2015) Potential tree and soil carbon storage in a major historical floodplain forest with disrupted ecological function, Perspectives in Plant Ecology, Evolution and Systematics,17, 1, 17-23, https://doi.org/10.1016/j.ppees.2014.12.002 .

Hatch, C.E., Fisher, C.T., Ruehl, C.R., & Stemler, G. (2010). Spatial and temporal variations in streambed hydraulic conductivity quantified with time-series thermal methods. J Hydrol, 389; 276-288.

Heritage, G. & Entwistle, NS. (2017). The impact of floodplain degradation on flooding in the UK. E-proceedings of the 37th IAHR World Congress. August 13–18, 2017, Kuala Lumpur, Malaysia.

Hinshaw, S. & Wohl, E., (2021). Quantitatively estimating carbon sequestration potential in soil and large wood in the context of river restoration. Front. Earth Sci, 9, p.708895.

Hoffman, T.O. & Glatzel, S., (2007) A carbon storage perspective on alluvial sediment storage in the Rhine catchment. Geophysical Research Abstracts, 9, Hoffmann, T., Schlummer, M., Notebaert, B., Verstraeten, G., and Korup, O. (2013), Carbon burial in soil sediments from Holocene agricultural erosion, Central Europe, Global Biogeochem. Cycles, 27, 828– 835, doi:10.1002/gbc.20071.

Hoffmann, T.O., (2021) Carbon Sequestration on Floodplains, in: Shroder, J.F. (Ed) 'Treatise on Geomorphology' (Second Edition), Academic Press, 458-477, ISBN 9780128182352, https://doi.org/10.1016/B978-0-12-818234-5.00069-9.

House of Lords Science & Technology Select Committee report (2022) Nature-based solutions: rhetoric or reality? The potential contribution of nature-based solutions to net zero in the UK, https://committees.parliament.uk/work/1294/naturebased-solutions-for-climate-change/publications/

Jeffries, R., Darby, S.E. & Sear, D.A. (2003) The influence of vegetation and organic debris on floodplain sediment dynamics: a case study of a low-energy stream in the New Forest, Hampshire., Geomorphology, 51, 61-80.

Joint Nature Conservation Committee (2011). Towards an assessment of the state of UK Peatlands, JNCC report No. 445.

Jones, A.F., Macklin, M.G. and Benito, G. (2015) Meta-analysis of Holocene fluvial sedimentary archives: a methodological primer, Catena 130, 3-12.

Keating, T., 1982. A Lumped Parameter Model of a Chalk Aquifer-Stream System in Hampshire, United Kingdom. Groundwater, 20(4), pp.430-436.

Kronvang, B.Svendsen, B., Brookes, A., Fisher, K., Moller, B., Ottosen, O., Newson, M.D., & Sear, D.A. 1998. Restoration of the Rivers Brede, Cole & Skerne: Joint Danish & British EU-LIFE Demonstration Project III - Channel morphology, hydrodynamics and transport of sediments and nutrients. Aquatic Conservation, 8, 1, 209 - 222.

Lindsay, R. (2010) Peatbogs and Carbon: A critical synthesis to inform policy development in oceanic peat bog conservation and restoration in the context of climate change. Environmental Research Group, University of East London.

Lininger, K.B, Whol, E., Sutfin, N.A. & Rose, J.R. (2017) Floodplain downed wood volumes: a comparison across three biomes. Earth Surf. Process. Landforms 42, 1248–1261 DOI: 10.1002/esp.4072

Lininger, K.B. and Polvi, L.E., (2020). Evaluating floodplain organic carbon across a gradient of human alteration in the boreal zone. Geomorphology, 370, p.107390.

Lüscher, A., Daepp, M., Blum, H., Hartwig, E., & Nösberger, J. (2004) Fertile temperate grassland under elevated atmospheric CO2 - role of feed-back mechanisms and availability of growth resources Eur. J. Agron., 21 (2004), pp. 379-398

Macaire, J-J., Di-Giovanni, C., & Hinschberger, F. (2005) Relations entre production organique et apports terrigènes dans les sediments fluviatiles holocènes: observations et interpretations hétérodoxus. Comptes Rendus des Geosciences, 337; 735-744.

Macklin, M.G., Rumsby, B.T. and Heap, T., 1992. Flood alluviation and entrenchment: Holocene valley-floor development and transformation in the British uplands. Geological Society of America Bulletin, 104(6), pp.631-643.

Macklin, M.G., Lewin, J., and Jones, A.F. (2016) Anthropogenic alluvium: An evidence-based meta-analysis for the UK Holocene, Anthropocene, 6; 26-38, ISSN 2213-3054, https://doi.org/10.1016/j.ancene.2014.03.003 .

Millington CE. 2007. The Geomorphological Dynamics of a Restored Forested Floodplain, PhD Thesis. University of Southampton; 328 pp.

Mondon, B., Sear, D.A., Collins, A.L., Shaw, P.J. and Sykes, T. (2022) 'The scope for a system-based approach to determine fine sediment targets for chalk streams', CATENA, 206, pp. 105541.

Naden, P.S., Murphy, J.F., Old, G.H., Newman, J., Scarlett, P., Harman, M., Duerdoth, C.P., Hawczak, A., Pretty, J.L., Arnold, A., Laizé, C., Hornby, D.D., Collins, A.L., Sear, D.A. and Jones, J.I. (2016) 'Understanding the controls on deposited fine sediment in the streams of agricultural catchments', Science of The Total Environment, 547, pp. 366-381.

Nahlik, A., & Fennessy, M. (2016) Carbon storage in US wetlands. Nat Commun 7, 13835. https://doi.org/10.1038/ncomms13835.

Oswald, E. B., and Wohl, E. (2008). Wood-mediated Geomorphic Effects of a Jökulhlaup in the Wind River Mountains, Wyoming. Geomorphology 100, 549–562. doi:10.1016/j.geomorph.2008.02.002

Pess, G.R., McHenry, M.L., Liermann, M.C., Hanson, K.M., and Beechie,T.J. (2023) How does over two decades of active wood reintroduction result in changes to stream channel features and aquatic habitats of a forested river system? Earth Surface Processes and Landforms 48 (4); 817-829

Pinay G, Fabre A, Vervier P, Gazelle F (1992) Control of C, N, P distribution of riparian forests. Landscape Ecology 6, 121-132.

Pogue, S. J., (2017). Resilience management in social-ecological systems: Developing a new evolutionary approach. A case study- The New Forest National Park. PhD thesis. University of Southampton.

Poole, G.C. (2010). Stream hydrogeomorphology as a physical science basis for advances in stream ecology. J N Am Benthol Soc;29:12–25.

Puttock, A., Graham, H.A., Cunliffe, A.M., Elliott, M. and Brazier, R.E., (2017). Eurasian beaver activity increases water storage, attenuates flow and mitigates diffuse pollution from intensively-managed grasslands. Science of the total environment, 576, pp.430-443.

Qi, J., Zhang, X., Lee, S. et al. (2020) Modelling sediment diagenesis processes on riverbed to better quantify aquatic carbon fluxes and stocks in a small watershed of the Mid-Atlantic region. Carbon Balance Manage **15**, 13. https://doi.org/10.1186/s13021-020-00148-1

Quine, T. A., Cressey, E. L., Dungait, J. A. J., De Baets, S., Meersmans, J., Jones, M. W., & Nicholas, A. P. (2022). Geomorphically mediated carbon dynamics of floodplain soils and implications for net effect of carbon erosion. Hydrological Processes, 36(9), e14657. https://doi.org/10.1002/hyp.14657

Ramade F. (2003) Eléménts d'ecologie Dunod, Paris.

Repasch, M., 2021. Unexpected consequences of river engineering on the carbon cycle. AGU Advances, 2(1), p.e2021AV000402.

Ricker, M.C., Lockaby, B.G. (2015) Soil Organic Carbon Stocks in a Large Eutrophic Floodplain Forest of the Southeastern Atlantic Coastal Plain, USA. Wetlands **35**, 291–301. https://doi.org/10.1007/s13157-014-0618-y

Riley, W. et al., (2018) Small Water Bodies in Great Britain and Ireland: Ecosystem function, human-generated degradation, and options for restorative action. Science of the Total Environment, 645: 1598-1616.

Rippon, S., Smart, C. and Pears, B. 2015 'The Fields of Britannia: Continuity and Change in the Late Roman and Early Medieval Landscape' Oxford University Press.

Rutter, J., and Sasse, T. (2022). Net zero: agenda 2022. Institute for government. Available at: https://www.instituteforgovernment.org.uk/sites/default/files/publications/net-zero-agenda-2022.pdf Accessed: 14/10/2022.

Schiller, D.V., Marcé, R., Obrador, B., Gómez-Gener, L., Casas-Ruiz, J.P., Acuña, V. and Koschorreck, M., 2014. Carbon dioxide emissions from dry watercourses. Inland waters, 4(4), pp.377-382.

Sear, D.A., Briggs, A. & Brookes, A., (1998) A preliminary analysis of the morphological adjustment within and downstream of a lowland river subject to river restoration. Aquatic Conservation, 8; 167 - 184.

Sear, D.A., Armitage, P.D. and Dawson, F.H. (1999) 'Groundwater dominated rivers', Hydrological Processes, 13(3), pp. 255-276.

Sear, D.A., Wilcock, D., Robinson, M.R. & Fisher, K.R., (2000) Channel modifications and impacts, in: Acreman, M., ed., The Changing Hydrology of the UK, Routledge; 55 - 81.

Sear, D. A., Millington, C. E., Kitts, D. R., & Jeffries, R. (2010). Logjam controls on channel: Floodplain interactions in wooded catchments and their role in the formation of multi-channel patterns. Geomorphology, 116(3–4), 305–319.

Sear D.A., Pattison I., Collins .AL., Smallman D.J., Jones J.I., Naden P.S. (2017). The magnitude and significance of sediment oxygen demand in gravel spawning beds for the incubation of salmonid embryos. River Res Applic. 2017;1–13. https://doi.org/10.1002/rra.3212

Shupe, H.A.; Hartmann, T.; Scholz, M.; Jensen, K.; Ludewig, K. (2021) Carbon Stocks of Hardwood Floodplain Forests along the Middle Elbe: The Influence of Forest Age, Structure, Species, and Hydrological Conditions. Water, 13, 670. https://doi.org/10.3390/w13050670

Swinnen,W., Broothaerts, N., Hoevers,R. & Verstraeten G. (2020) Anthropogenic legacy effects control sediment and organic carbon storage in temperate river floodplains, CATENA,195, https://doi.org/10.1016/j.catena.2020.104897.

Swinnen, W., Daniëls, T., Maurer, E., Broothaerts, N., and Verstraeten, G. (2019) Geomorphic controls on floodplain sediment and soil organic carbon storage in a Scottish mountain river. Earth Surf. Process. Landforms, 45: 207– 223. https://doi.org/10.1002/esp.4729.

Shen, Z., Rosenheim, B. E., Törnqvist, T. E., & Lang, A. (2021). Engineered continental-scale rivers can drive changes in the carbon cycle. *AGU Advances*, 2, e2020AV000273. https://doi.org/10.1029/2020AV000273

Tangen, B.A. & Bansal,S. (2020) Soil organic carbon stocks and sequestration rates of inland, freshwater wetlands: Sources of variability and uncertainty, Science of The Total Environment, 749, 141444, ISSN 0048-9697, https://doi.org/10.1016/j.scitotenv.2020.141444.

Trimble, S.W., 2010. Streams, valleys and floodplains in the sediment cascade. Sediment Cascades: An Integrated Approach. 307–343.

Trimmer, M., Grey, J., Heppell, C.M., Hildrew, A.G., Lansdown, K., Stahl, H., YvonDurocher, G., (2012). River bed carbon and nitrogen cycling: state of play and some new directions. Sci. Total Environ. 434, 143–158. https://doi.org/10.1016/ j.scitotenv.2011.10.074.

Tye, A.M., Evans, D.L., Lee, J.R. and Robinson, D.A. (2022) The role of post UK-LGM erosion processes in the long-term storage of buried organic C across Great Britain – A 'first order' assessment, Earth-Science Reviews, 232, 104126, ISSN 0012-8252, https://doi.org/10.1016/j.earscirev.2022.104126.

UK Government (2023) Plan for Water. https://www.gov.uk/government/publications/plan-for-water-our-integrated-plan-for-delivering-clean-and-plentiful-water/plan-for-water-our-integrated-plan-for-delivering-clean-and-plentiful-water

UK Government (2023) understanding Biodiversity Net Gain. https://www.gov.uk/government/collections/biodiversity-net-gain

UK Government (2023) Environmental Improvement Plan. https://www.gov.uk/government/publications/environmental-improvement-plan

UK Soil Observatory (2023) Soil Organic Carbon data accessed March 20230 https://mapapps2.bgs.ac.uk/ukso/home.html

Van Oost, K., Verstraeten, G., Doetterl, S., Notebaert, B., Wiaux, F., Broothaerts, N., Six,J., (2012). Legacy of human-induced C erosion and burial on soil-atmosphere C exchange.Proc. Natl. Acad. Sci. 109, 19492–19497. https://doi.org/10.1073/pnas.1211162109

Walling, D.E, Fang, D., Nicholas, A., Sweet, R., Rowan, J., Duck, R., & Werritty, A. (2006). River flood plains as carbon sinks. IAHS Publication; 306, 460.

Walter, R.C., Merritts, D.J., (2012). Natural streams and the legacy of water-powered mills. Science (80-.). 319, 299–304. https://doi.org/10.1126/science.1151716.

Wohl, E., (2021). An integrative conceptualization of floodplain storage. Reviews of Geophysics, 59(2).

Wohl, E., Castro, J., Cluer, B., Merritts, D., Powers, P., Staab, B., & Thorne, C. (2021). Rediscovering, re-evaluating, and restoring lost river wetland corridors. Frontiers in Earth Science, 9, 511. https://doi.org/10.3389/feart.2021.653623

Wohl, E., Hall Jr, R.O., Lininger, K.B., Sutfin, N.A. and Walters, D.M., (2017). Carbon dynamics of river corridors and the effects of human alterations. Ecological Monographs, 87(3), pp.379-409.

Wohl, E. and Knox, R.L., (2022). A first-order approximation of floodplain soil organic carbon stocks in a river network: The South Platte River, Colorado, USA as a case study. Science of The Total Environment, p.158507.

Worrall, F. and others. 2020. The dissolved organic carbon flux from the UK – A new Bayesian approach to flux calculation. Journal of Hydrology, 590: 125511.

Westwood, C. G., Teeuw, R. M., Wade, P. M., Holmes, N. T. H., & Guyard, P. (2006). Influences of environmental conditions on macrophyte communities in drought-affected headwater streams. River Research and Applications, 22, 703–726. https://doi.org/10.1002/ rra.934

Wiltshire, C., Glendell, M., Waine, T.W. *et al.* (2022). Assessing the source and delivery processes of organic carbon within a mixed land use catchment using a combined *n*-alkane and carbon loss modelling approach. *J Soils Sediments* 22, 1629–1642.

Young, D.M., Baird, A.J., Charman, D.J. *et al.* (2019). Misinterpreting carbon accumulation rates in records from near-surface peat. *Sci Rep* **9**, 17939. https://doi.org/10.1038/s41598-019-53879-8

Zhang, Y, Collins, AL, McMillan, S, et al. (2017) Fingerprinting source contributions to bed sediment-associated organic matter in the headwater subcatchments of the River Itchen SAC, Hampshire, UK. River Res Applic. 33: 1515– 1526. https://doi.org/10.1002/rra.3172

Zischg, A. P., Galatioto, N., Deplazes, S., Weingartner, R., & Mazzorana, B. (2018). Modelling spatiotemporal dynamics of large wood recruitment, transport, and deposition at the river reach scale during extreme floods. Water, 10(9), 1134.