A conceptual carbon budget for an icy riverine corridor

Suzanne P. Anderson, Cole Cochran, Robert S. Anderson, Marisa Repasch,
Josie Arcuri & Irina Overeem

*Institute of Arctic and Alpine Research, University of Colorado, Boulder,
Colorado, United States*

ABSTRACT

The contribution of river corridors to the global carbon budget exceeds their small areal footprint, yet our understanding of fluvial carbon dynamics is incomplete, particularly in periglacial settings. Frequent disturbance and lateral fluxes are key attributes of carbon budgets in riparian corridors. Climate change affects the pace and style of fluvial and biogeochemical processes in periglacial settings. The effects of these can be assessed with a carbon budget, a statement of all fluxes in and out of a control volume, which we outline for a river corridor.

We are generating data from a field campaign of the carbon stock in select river corridor segments of the Canning River, Alaska. This gravel-bedded river drains continuous permafrost from glaciated headwaters in the Brooks Range to its delta in the Beaufort Sea. Fluvial erosion and deposition generate distinct, mappable geomorphic surfaces in the river corridor that accumulate carbon over time. Carbon stocks on surfaces are summed across the river corridor to compute the total carbon stock. Characterizing the depth of alluvium is a poorly constrained component of the carbon stock. Lateral bank erosion hews away geomorphic surfaces, while sediment deposition buries carbon and generates new surfaces. Deposition of uprooted willows or turf mats augment the carbon stock and can jump-start plant succession. All fluxes in the carbon budget are sensitive to warming and arctic hydrologic intensification. Analyzing how these fluxes may change and affect the carbon stock in icy river corridors will advance our understanding of their contribution to the global carbon budget.

1 INTRODUCTION

Permafrost regions hold a large reservoir of organic carbon (Tarnocai et al. 2009; Hugelius et al. 2014) that has accumulated over thousands of years and is vulnerable to decomposition upon thaw (Schuur et al. 2015; McGuire et al. 2018). Although warming raises permafrost temperatures, increases active layer depths, changes hydrology, and instigates abrupt thaw features (Meredith et al. 2019), the implications of these physical processes for carbon cycling in a fluvial system are unclear. The most recent IPCC Assessment Report places low confidence on knowledge of decadal trends in carbon fluxes between permafrost regions and the atmosphere (Canadell et al. 2021), due to sparse observations and incomplete process models. Fluvial systems are one component of land surfaces that are not well represented in global carbon budgets (e.g., Friedlingstein et al. 2022), and are understudied in permafrost regions (Wrona et al., 2016). Nevertheless, there is growing understanding that significant carbon processing occurs in rivers, lakes, and coastal oceans (Regnier et al. 2013, 2022).

The carbon stock in periglacial river corridors is particularly dynamic and vulnerable to effects of climate warming. The stock of carbon in Arctic fluvial systems is large: Hugelius et al. (2014) estimate that the deltas of 12 major Arctic rivers store 91 Pg of carbon in frozen sediment layers below 3 m depth. The deep carbon reservoirs in these 12 deltas alone contain one-tenth of the total soil organic carbon in northern polar permafrost regions, despite the surveyed deltas occupying less than 1% of the area of permafrost soils and not including other significant occurrences of deltas or upstream river corridors in the Arctic (Hugelius et al. 2014). Data are limited on the volume (particularly the depth of deposits) and carbon content of alluvium (Hugelius et al. 2014).

Warming is increasing productivity across the tundra biome. From 1980–2010, tundra vegetation increased in height and shrubs became more abundant (Elmendorf et al. 2012). Shrub and tree expansions are linked to particular geomorphic settings, especially those subject to disturbance such as fluvial corridors (Tape et al. 2012; Frost and Epstein 2014). Even without treating differences across geomorphic settings, warming-induced increased vegetation productivity was found to offset carbon emissions from permafrost in the modeling scenarios explored by McGuire et al. (2018).

Finally, the physical effects of climate change on rivers are large. Extreme warming in the Arctic is driving hydrologic intensification, which increases freshwater fluxes (Stuefer et al. 2017; Lafrenière and Lamoureux 2019). Discharge in large rivers has risen by 0.22% per year across the Arctic over the last three decades (Feng et al. 2021). Decreasing snow cover and snow cover duration (Meredith et al. 2019) are leading to an earlier spring freshet in some areas (Zheng et al. 2019; Feng et al. 2021) and earlier river ice breakup (Cooley and Pavelsky 2016). Changes in precipitation, evapotranspiration, snowmelt, and active layer depth affect runoff generation in dissimilar ways and have resulted in an increase in interannual variability in river discharge (Stuefer et al. 2017). Together, these shifts in hydrologic intensity are expected to produce profound impacts on ecological systems (Wrona et al. 2016) that may significantly impact the carbon budget of river corridors.

The large carbon stock, rapid increases in productivity, and changes in fluvial processes make it difficult to predict the trend in carbon fluxes in river corridors under changing climate regimes. Developing a carbon budget that addresses these processes can help evaluate the significance of river corridors in regional carbon budgets.

1.1 Riverine Landscapes

The riverine landscape is the area occupied by the river corridor. Larger than the channel itself, it encompasses the terrain created by a river and its sediment load (e.g., Ward et al. 2002; Wymore et al. 2023). A primary component of a river corridor is the floodplain, which is the flat area adjacent to the channel constructed by the river under the present climate and is frequently subject to overflow (Leopold and Dunne 1978). The floodplain, in other words, is part of the present hydroclimatic conditions and undergoes recurrent disturbance (Nanson and Croke 1992). Terraces are floodplain surfaces that are rarely inundated, due to channel entrenchment or migration. As such, river corridors comprise a mosaic of surfaces distinguished by varying frequency of fluvial inundation and disturbance (Wolman and Leopold 1957) and states of plant succession (Bliss and Cantlon 1957). These variations produce a range of environments that support diverse ecological communities (Naiman and Décamps 1997: Hauer et al. 2016). On Alaska's Arctic coastal plain for example, the Canning River corridor (Figure 1) includes sparsely vegetated gravel bars, transitory aufeis, and fully vegetated terraces. The interplay between vegetation growth (modulated by proximity to water) and flow disturbance governs both the distribution of biomass within the river corridor and the evolution of channel morphology (Gurnell et al. 2012). Our goal in this paper is to outline a carbon budget for a river corridor under rapidly changing periglacial conditions, with a focus on the interactions of physical processes and storage of organic carbon within the system.

2 Previous Work on Riverine C Budgets

Cole et al. (2007) first suggested that rivers play an active and significant role in the carbon cycle at global or regional scales, rather than serving as passive pipes that transmit carbon from terrestrial ecosystems to the sea. In their analysis, aquatic systems are both net sources of gaseous carbon to the atmosphere and net accumulators of stored organic matter because they receive inputs of organic carbon from surrounding terrestrial ecosystems. This situation contrasts with terrestrial environments, where gross primary production (GPP) is the main pathway to introduce carbon into the system (aside from minor abiotic sources like weathering). In the terrestrial ecosystem, fluxes to the atmosphere, storage, and exports cannot collectively exceed GPP. Cole et al. (2007) compiled a global freshwater aquatic ecosystem carbon budget to show that carbon fluxes to gaseous carbon efflux, storage, and export (all losses to the aquatic ecosystem) require large carbon inputs (both GPP and organic carbon from the land); carbon inputs into freshwater systems exceed the global export of carbon to the ocean by at least a factor of two. The carbon "subsidy" from terrestrial landscapes supports aquatic ecosystems as simultaneous C sources and sinks.

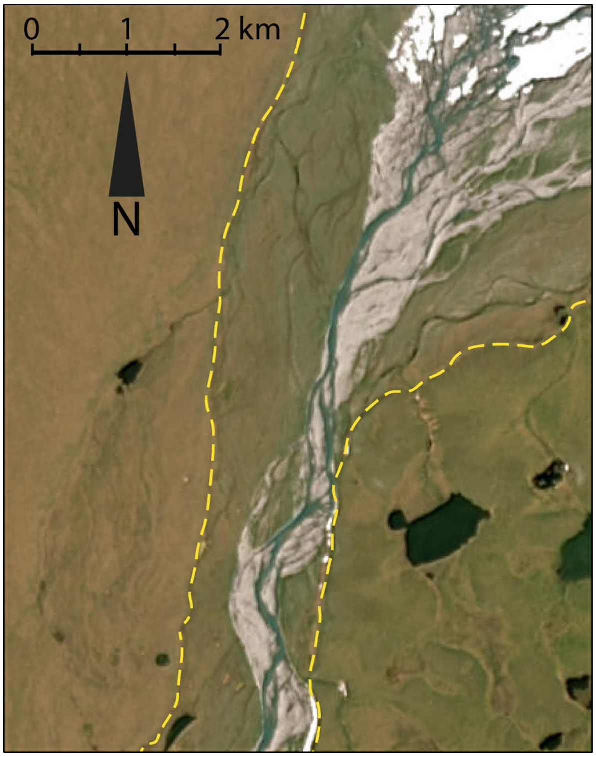

Figure 1. The Canning River in northern Alaska illustrates the heterogeneity in carbon stocks and surface age across an active river corridor in contrast with the surrounding tundra. The river corridor between the dashed yellow lines spans a shifting mosaic of vegetation communities in different stages of growth and whose carbon stock has been augmented and/or depleted by fluvial processes. The example here includes gravel bars, vegetated channels, vegetated terraces, and bodies of aufeis. (Landsat image.)

The land-ocean aquatic continuum (LOAC) model of Regnier et al. (2013) builds a more detailed carbon budget for inland waters. Like the Cole et al. (2007) mass budget, carbon fluxes to the inland waters section (rivers, lakes, and reservoirs) of the LOAC (Figure 2) are bracketed by the total C delivered into inland waters from surrounding terrain ($C_{tot,in,}$) and the total C delivered out to estuaries ($C_{tot,out}$). The difference between these is balanced by fluxes arising from processes within the inland waters system: net primary production within the aquatic ecosystem (GPP-plant respiration), C_{NPP}; gases released by respiration and decomposition of organic matter, C_{CO2} and C_{CH4}; dissolved inorganic carbon from weathering, $C_{inorg,w}$; rock-derived petrogenic carbon, $C_{petro,}$ (Hilton and West 2020); and organic carbon burial C_{sed}. The fluxes at the top of the box (C_{NPP}, C_{CO2}, and C_{CH4}) reflect plant growth, decay, and microbial activity within the inland waters system. The fluxes at the bottom of the box ($C_{inorg,w}$, C_{petro}, and C_{sed}) arise from physical and (in the case of weathering) chemical interactions with sediments and bedrock. Because this is a budget, all fluxes sum to 0.

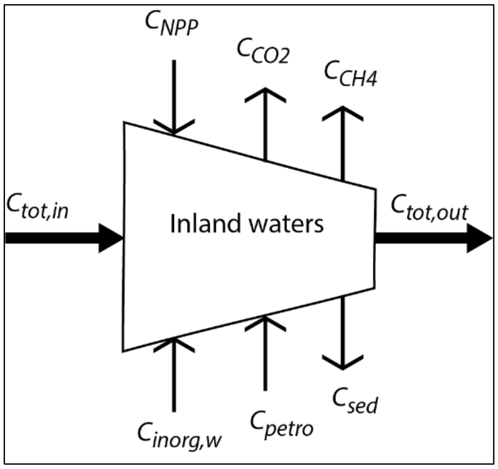

Figure 2. C budget of inland waters (modified from Regnier et al. 2013, inspired by Cole et al. 2007). The trapezoid mirrors the funneling of input ($C_{tot,in}$) from the surrounding watershed to the aquatic system. Fluxes across the top of the box are direct exchanges with the atmosphere, fluxes at the bottom of the box arise from groundwater ($C_{inorg,w}$) and production or deposition of sediment. C inputs from the terrestrial landscape ($C_{tot,in}$) generally exceed fluvial exports to the sea ($C_{tot,out}$).

Several conceptual carbon models address processes unique to fluvial systems. Wohl et al. (2017) treat the active river channel and surrounding riparian area as separate linked systems. In twin mass balance equations, fluvial erosion and deposition are implicitly included in organic carbon mass flux terms into and out of each system. Lininger and Wohl (2019) elaborate that in permafrost regions these fluxes are affected by the ratio of “erosive force to erosional resistance”. Sutfin et al. (2016) conclude that organic carbon retention in river systems is optimized by cool, wet conditions and wide river corridors with complex channel forms.

3 TAILORING A CARBON BUDGET FOR AN ICY RIVERINE CORRIDOR

The Icy Landscapes project addresses fluvial processes and their carbon budget implications in a riverine corridor in continuous permafrost terrain (Anderson et al. 2022). This report outlines how the data we are generating will inform a riverine corridor carbon budget.

Our field site is the Canning River in northern Alaska (Figure 3), which drains a catchment area of 7,142 km^2 and flows ~200 km through continuous permafrost from glaciated headwaters in the Brooks Range to its delta in the Beaufort Sea. Its multi-thread channel is gravel-bedded and flows in a river corridor that tends to widen from ~0.5 km in the mountains to ~1.5 km in the foothills and widens further in the delta on the coastal plain. The vegetation in the watershed ranges from prostrate shrub tundra in the mountains to graminoid tundra in the foothills to sedge wetlands in the delta (Raynolds and Walker, 2022), but the river corridor as distinct from the surrounding landscape is dominated by willow shrub communities (Schickhoff et al. 2002; Bockheim et al. 2003).

Our study focuses on a few sites along the channel (Figure 3), each representing different hydrologic and ecological environments within the watershed. At each site, we define a control volume that spans the breadth of the river corridor and extends downstream one to several kilometers. In these sites, we have collected samples to characterize organic carbon stocks and constrain deposit ages within the river corridor segment, and we have made spot measurements of river sediment and solute fluxes (Repasch et al. 2024). Data from these samples are still being generated. We complement these data with studies of fluvial erosion processes (Arcuri et al. 2022).

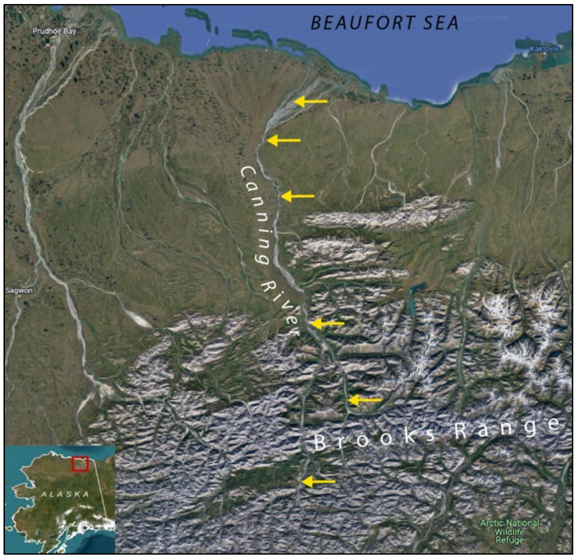

Figure 3. Riverine corridors cross the continuous permafrost terrain of the North Slope of Alaska. Yellow arrows show sites on the Canning River where we have sampled to assess the carbon stock. Inset shows location in Alaska. (Landsat image)

Although the carbon budgets outlined thus far (see Figure 2) focus on carbon fluxes, in campaign-style field work it is more practical to collect data on carbon stock. Figure 4 shows an adaptation of the carbon budget to analyze the carbon stock (S_{Ctot}) in a river corridor segment. The fluxes from weathering processes ($C_{inorg,w}$ and C_{petro}) are now included in the fluvial flows in and out ($C_{tot,in}$ and $C_{tot,out}$). Bicarbonate from weathering reactions ($C_{inorg,w}$) and recalcitrant carbon from rock organic carbon (C_{petro}) both tend to pass through the channel system unchanged and the fluxes are small relative to those of organic matter (Regnier et al. 2013). The remaining fluxes (C_{NPP}, C_{CO2}, C_{CH4}, and C_{sed}) directly affect the standing carbon stock. The challenge is to discover how these fluxes are changing and may affect the carbon stock. To do so, we next consider how to compute the C stock across the heterogeneous river corridor, the accumulation of organic carbon on a fluvial surface, and the fluvial processes that both create and destroy floodplain surfaces.

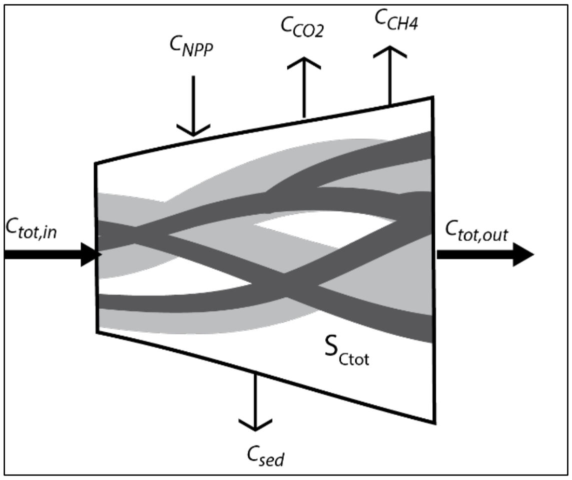

Figure 4. Carbon budget refined to analyze carbon stocks (S_{Ctot}) in a braided river corridor segment. River corridors often widen downstream, as suggested with the widening trapezoid shape. Dark gray lines represent channels within the river corridor. Light gray and white areas represent different age geomorphic surfaces on which carbon stocks differ due to the time-integrated effects of C_{NPP}, C_{CO2}, C_{CH4}, and C_{sed}. The fluxes $C_{inorg,w}$ and C_{petro} are now included in $C_{tot,in}$ and $C_{tot,out}$.

3.1 Geomorphic Surfaces

Fluvial erosion and deposition processes regularly create, modify, and destroy landforms that comprise the river corridor, producing a heterogeneous landscape of abandoned channels, meander scrolls, bars, islands, and terraces (Figure 4; see also Figure 1). These geomorphic surfaces can be mapped from aerial imagery (Wellstein et al. 2003), surveys of vegetation communities (e.g., Kalliola and Puhakka 1988), or detailed stratigraphic study (Mann et al. 1995). Pioneer vegetation species establish on newly exposed surfaces and succession proceeds until a sufficiently large flood removes or buries the community. Although disturbance is a defining characteristic of river corridors, some surfaces remain stable for decades or more. Cross-cutting relationships, vegetation stages, and age-dating techniques can be used to identify a chronosequence of geomorphic surfaces that span a range of development.

3.2 Carbon Stock

The carbon stock (S_{Ctot}) on a geomorphic surface is the total of soil organic matter, above ground biomass, and below ground biomass (roots), integrated over the depth of the deposit. Soil organic matter generally forms the largest part of the total carbon stock, particularly in arctic soils where decomposition rates are low. The carbon stock on a fluvial geomorphic surface reflects inputs from plant growth (C_{NPP}), losses from microbial respiration (C_{CO2}) and methanogenesis (C_{CH4}), and the net fluvial deposition and erosion of organic matter (C_{sed}).

Growing plant communities can sequester carbon rapidly (Cole et al. 2007). Primary succession on alluvial surfaces on Alaska's North Slope progresses from pioneering herbaceous species, through a succession of shrub (predominantly willow) species, and, if undisturbed, ultimately to a wet tundra meadow community (Bliss and Cantlon 1957; Bliss and Peterson 1992). These changes are associated with an increase in soil organic matter and in permafrost, a decrease in active layer thickness. Among arctic vegetation types, riparian willow shrubs have the highest productivity (Shaver and Chapin 1991), suggesting that there is an increase in the input flux, C_{NPP}, on riparian surfaces with surface age up through the shrub stages. The efflux of carbon from a surface due to microbial respiration, C_{CO2}, should increase along with the carbon stock, assuming a fixed rate of microbial respiration per unit mass of organic matter. The net effect of these time-varying fluxes is expected to produce an asymptotic increase in the carbon stock on an undisturbed fluvial geomorphic surface (i.e., $C_{sed} = 0$) over time (Figure 5 top). The development of carbon stock on a surface may be punctuated by flood events that deposit organic matter, producing a step increase in the stock, or remove organic matter, producing a step decrease. These processes are not included in the idealized scenario shown in Figure 5, but their occurrence is seen in truncated soil profiles and buried organic layers in floodplain deposits (e.g., Mann et al. 1995).

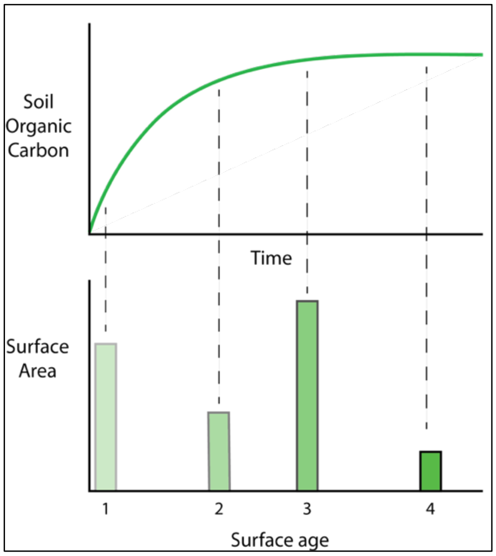

Figure 5. (Top) Hypothetical accumulation of soil organic carbon (SOC) over time on an undisturbed geomorphic surface. (Bottom) Areas (A_i) of four surfaces, numbered 1–4, of different ages that might be used in Equation 1 to compute total carbon stock in a reach (S_{Ctot}).

The carbon stock for a reach of a river corridor (e.g., Figure 4) must account for the mosaic of different surface areas and states of vegetation succession and organic matter accumulation. The total carbon stock in a reach, S_{Ctot}, is therefore computed as the sum of the carbon stocks on all geomorphic surfaces:

$$S_{Ctot} = \Sigma A_i SOC_i \qquad [1]$$

where A_i is the area and SOC_i is the carbon stock of the ith geomorphic surface (Figure 5).

An unknown in measuring the carbon stock on a geomorphic surface is the depth over which to integrate. The depths of arctic alluvial deposits are poorly constrained (Hugelius et al. 2014). Alluvium of North Slope rivers probably ranges from 5–8 m in depth and increases to 15–20 m in deltaic areas (Carter et al. 1986). The gravel and sand-dominated deposits are poor candidates for auger or core sampling.

3.3 Dynamics of Periglacial River Corridors

Channel migration, gravel bar formation, bank incision, and overbank deposition are among the fluvial processes that create and destroy alluvial geomorphic surfaces. Collectively these processes control the areas of geomorphic surfaces (A_i in Equation 1) on which plants grow and soil organic matter accumulates (SOC_i; Ward et al. 2002). Therefore, understanding fluvial processes and rates and their control are important for predicting future carbon budget changes. We consider three aspects of fluvial processes in floodplain ecosystems under warming whose effects need to be incorporated into a carbon budget analysis: channel erosion rates, changing hydrology, and vegetation feedbacks.

3.3.1 Channel erosion

A recent analysis of riverbank erosion found that, on average, permafrost riverbank erosion rates are nine times lower than non-permafrost rivers (Rowland et al. 2023). They conclude that permafrost limits bank erosion and infer that bank erosion rates will increase as warming degrades permafrost. A second study of Arctic rivers by Ielpi et al. (2023), however, showed declining channel lateral migration rates since 1970. They suggest that the northward-advance of shrubs and deepening of their root systems under warming conditions strengthens riverbanks and limit bank erosion. Both studies focus on lateral bank erosion and channel migration, processes that reduce the areas of geomorphic surfaces (A_i) adjoining an active channel.

Floodplains are also affected by vertical accretion by sediment deposition in bars, overbank deposits, and channel fills, processes that act as episodic C_{sed} flux events. Douglas et al. (2021) found that particulate organic carbon (POC) deposition at least partially offsets current bank erosion rates. Non-organic sediment deposition also plays a role by burying peat, wood, and leaves, common components of arctic floodplain stratigraphy (Carter et al. 1986; Mann et al. 1995). The deposits that entomb organic carbon, also serve as new surfaces (A_i) on which vegetation growth and soil organic matter accumulation restarts.

As climate warms, the question arises whether periglacial river systems will undergo net aggradation or net incision. Early Holocene warming apparently triggered an increase influx of sediment into fluvial systems from thawing hillslopes, which drove aggradation in floodplains on the North Slope (Mann et al. 2010). That history suggests that a full understanding of likely carbon budget trajectories for arctic river systems is connected to processes that deliver sediment from hillslopes.

3.3.2 Hydrologic change

Rivers like the Canning in continuous permafrost are subject to arctic hydrologic intensification effects that may influence bank erosion and overbank flows. Stream gauge data on the Canning River are limited, but data on the nearby Kuparuk River are probably representative of the region. The Kuparuk has shown an increase in discharge of 35% since the 1970s, an earlier arrival of the spring freshet, and rising river water temperatures (Zheng et al. 2019). The mechanisms of ice breakup during the freshet and their impacts on flooding and erosion are difficult to observe, particularly where extensive aufeis fields develop (Overeem et al. 2023). If the freshet arrives before riverbanks have thawed substantially, lateral bank erosion might be reduced. This effect would be countered, however, by warming river waters. Ice-cemented banks in the Canning River are most prominent along the edges of the river corridor in the delta region. We measured river water temperatures of 11–17 °C in July of 2022 and 2023, which suggests that the summer flows are capable of considerable thermal erosion in reaches with ice cemented banks. Observations and measurements during the challenging conditions of the spring freshet are needed to understand these competing processes and how they are changing.

Another hydrologic change is a possible increase in frequency and severity of convective storms (e.g., Poujol et al. 2020). The potential impact of these events is illustrated by observations of Repasch et al. (2024). During convective storms in 2022 and 2023 on the Canning River the discharge roughly doubled, suspended sediment flux increased 30-fold, and particulate organic carbon flux increased 90-fold. It will take more work to determine the source and fate of the sediments mobilized in such events. At the same time, increasing active layer depths may increase subsurface water storage capacity on hillslopes and limit storm runoff peaks as warming continues, an effect that would reduce storm erosion.

3.3.3 Vegetation feedbacks

Throughout the tundra biome, increased temperatures are causing an increase in plant canopy height and abundance of shrubs (Elmendorf et al. 2012). In the Canning and other north-flowing rivers on the North Slope, the riparian vegetation canopy height is greatest in the Brooks Range foothills and decreases downstream with increasing latitude. Riparian willows interact with flood waters in more ways than simply providing bank strength (Gurnell et al. 2012). Bank scour (and probably ice jam breakup) can erode well-established willow clumps from banks during floods and redeposit (i.e., strand) them on gravel bars downstream. Cursory observations along the Canning River suggests that sharp outer bends in channels are prone to this type of scour, and that willow clump deposition is most likely on the upstream edge of the next gravel bar. Even so, we observed willow clumps (several meters in length) rolling down the channel in the coastal plain, far from obvious erosional sources. Deposited willow clumps can re-sprout and form a living anchor for a growing bar. Alternatively, the willow does not survive, but adds to the carbon stock of the surface on which it is deposited. In both cases, deposited willow clumps form obstacles that interact with water flow and sediment deposition, in some places inciting scour and in other places supporting deposition. These complex interactions are not unique to periglacial systems (Gurnell et al. 2012). The habitat expansion and rapid growth of shrubs are introducing new vegetation-channel dynamics to arctic river corridors.

While willow shrubs are important players in channel dynamics in the upper reaches of the Canning River, graminoid and wet sedge tundra dominate the vegetation in the coastal plain. In these areas, the active layer is often a strongly rooted turf mat, and the bank is peat rich. The river can incise into this vegetation community and mobilize the carbon stock it contains. Our summertime observations show that these banks erode by fluvial thermal undercutting, followed by cantilevered block collapse (Arcuri et al. 2022), mirroring the erosion of coastal bluffs along the Beaufort Sea (e.g., Barnhart et al. 2014). Blocks of strongly rooted turf are typically < 1 m thick (typically 10s of cm, essentially the active layer where roots thrive), and several meters in breadth. Often, the turf block does not cleanly break at the surface, but instead drapes over the riverbank, armoring it for some period. The blocks that break free may lie stranded on the channel edge close to the bank from which it fell or may be trundled some distance downstream. Like willow clumps, turf blocks are deposited on the upstream edges of bars and can either re-sprout or not. On one gravel bar we surveyed > 100 turf blocks with dimensions of ~0.3 m x 1 m x 1 m in an area < 200 m^2. The blocks serve as an important addition to the carbon stock and can initiate plant growth on barren bars. Understanding these contributions to the carbon budget deserves more study.

4 SUMMARY

We have reviewed aquatic system carbon budgets with an eye toward understanding the role of riverine corridors on carbon exchange with the atmosphere in a changing climate. River corridors characteristically contain a mosaic of surfaces shaped by fluvial inundation and disturbance and colonized by successional plant communities. It is therefore practical to assess the carbon stock on multiple geomorphic surfaces and deduce the impacts of changing processes and their rates on that stock. An understudied component of the carbon stock is the depth of alluvium within river corridors. Every flux that affects carbon stocks is likely to be impacted by climate warming, from plant growth rate to microbial degradation, to the size of floods and their timing relative to timing of bank thawing. Organic matter deposition on the floodplain, in the form of large willow clumps or intact turf blocks, has received little attention yet appears to play important roles that have yet to be elucidated.

5 ACKNOWLEDGEMENTS

The Icy Landscapes project is funded by NSF 2001225; MR supported by NSF OPP Post-Doctoral Fellowship. We thank Sue Aikens (Kavik River Camp), Cyn Merrow and Kyle Milne (Arctic Wild), Justin Hill and Faustine Bernadac (Polar Field Services), and Scott (Alpine Air). We thank J. Koch and two reviewers for their input.

6 REFERENCES

Arcuri, J., Overeem, I., Repasch, M.N., Anderson, S.P., Anderson, R.S., and Koch, J. 2022. ‘Permafrost riverbanks shaped by thaw-dependent fluvial erosion’, in *American Geophysical Union Fall Meeting*. Chicago, Illinois, United States: 12–16 December, 2022.

Anderson, S.P., Repasch, M.N., Overeem, I., Arcuri, J., Anderson, R.S., and Koch, J. 2022. ‘Icy riverine landscapes: mobilization and fate of carbon-rich sediment in a periglacial braided river corridor’, in *American Geophysical Union Fall Meeting*. Chicago, Illinois, United States: 12–16 December, 2022.

Barnhart, K.R., Anderson, R.S., Overeem, I., Wobus, C., Clow, G.D. and Urban, F.E. 2014. ‘Modeling erosion of ice-rich permafrost bluffs along the Alaskan Beaufort Sea coast’, *Journal of Geophysical Research - Earth Surface* 119(5), pp. 1155–1179, doi:10.1002/2013JF002845.

Bliss, L.C. and Cantlon, J.E. 1957. ‘Succession on river alluvium in northern Alaska’, *The American Midland Naturalist* 58(2), pp. 452–469. Available at: https://www.jstor.org/stable/2422628/.

Bliss, L.C. and Peterson, K.M. 1992. ‘Plant succession, competition, and the physiological constraints of species in the Arctic’, in F.S. Chapin III, R.L. Jefferies, J.F. Reynolds, G.R. Shaver, J. Svoboda, and E.W. Chu (eds.), *Arctic Ecosystems in a Changing Climate: An Ecophysiological Perspective*. San Diego, California, United States: Academic Press, pp. 111–136.

Bockheim, J.G., O’Brien, J.D., Munroe, J.S., and Hinkel, K.M. 2003. ‘Factors affecting the distribution of *Populus balsamifera* on the North Slope of Alaska, U.S.A’, *Arctic, Antarctic, and Alpine Research* 35 (3), pp. 331–340. doi:10.1657/1523-0430

Canadell, J. G., Monteiro, P. M. S., Costa, M. H., Cotrim da Cunha, L., Cox, P. M., Eliseev, A. V., et al. 2021. ‘Global carbon and other biogeochemical cycles and feedback’, in V. Masson-Delmotte, et al. (eds.), *Climate Change 2021: The Physical Science Basis, Contribution of Working Group I to the Sixth Assessment Report of the IPCC*. Cambridge, United Kingdom and New York, New York, United States: Cambridge University Press, pp. 673–816, doi:10.1017/9781009157896.007.

Carter, L.D., Ferrians, O.J., Jr., and Galloway, J.P. 1986. ‘Engineering-geologic maps of northern Alaska coastal plain and foothills of the Arctic National Wildlife Refuge’, *United States Geological Survey* Open-File Report 86–334.

Raynolds, M. and Walker, D. 2022. *Raster Circumpolar Arctic Vegetation Map*. Mendeley Data, version 2. doi:10.17632/c4xj5rv6kv.2.

Cole, J.J., Prairie, Y.T., Caraco, N.F., McDowell, W.H., Tranvik, L.J., Striegl, R.G., Duarte, C.M., Korelainen, P., Downing, J.A., Middelburg, J.J., and Melack, J. 2007. ‘Plumbing the global carbon cycle: Integrating inland waters in the terrestrial carbon budget’, *Ecosystems* 10, pp. 171–184. doi:10.1007/s10021-006-9013-8.

Cooley, S.W. and Pavelsky, T.M. 2016. ‘Spatial and temporal patterns in Arctic river ice breakup revealed by automated ice detection from MODIS imagery’, *Remote Sensing of Environment* 175, pp. 310–322. doi:10.1016/j.rse.2016.01.004

Douglas, M.M., Li, G.K., Fischer, W.W., Rowland, J.C., Kemeny, P.C., West, A.J., Schwenk, J., Piliouras, A.P., Chadwick, A.J., and Lamb, M.P. 2021. ‘Organic carbon burial by river meandering partially offsets bank erosion carbon fluxes in a discontinuous permafrost floodplain’, *Earth Surface Dynamics* 10, pp. 421–435. doi:10.5194/esurf-10-421-2022

Elmendorf, S.C., Henry, G.H.R., Hollister, R.D., et al. 2012. ‘Plot-scale evidence of tundra vegetation change and links to recent summer warming’, *Nature Climate Change* 2, pp. 453–457. doi:10.1038/nclimate1465.

Feng, D., Gleason, C.J., Lin, P., Yang, X., Pan, M., and Ishitsuka, Y. 2021. ‘Recent changes to Arctic river discharge’, *Nature Communications* 12, 6917. doi:10.1038/s41467-021-27228-1

Friedlingstein, P. et al. 2022. ‘Global carbon budget 2022’, *Earth System Science Data* 14, pp. 4811–4900. doi:10.5194/essd-14-4811-2022.

Frost, G.V. and Epstein, H.E. 2014. ‘Tall shrub and tree expansion in Siberian tundra ecotones since the 1960s’, *Global Change Biology* 20, pp. 1264–1277. doi:10.1111/gcb.12406.

Gurnell, A.M., Bertoldi, W., and Corenblit, D. 2012. ‘Changing river channels: The roles of hydrological processes, plants and pioneer fluvial landforms in humid temperate, mixed load, gravel bed rivers’, *Earth-Science Reviews* 111, pp. 129–141. doi:10.1016/j.earscirev.2011.11.005.

Hauer, F.R., Locke, H., Dreitz, V.J., Hebblewhite, M., Lowe, W.H., Muhlfeld, C.C., Nelson, C.R., Proctor, M.F., and Rood, S.B. 2016. ‘Gravel-bed floodplains are the ecological nexus of glaciated mountain landscapes’, *Science Advances* 2, e1600026. doi:10.1126/sciadv.1600026.

Hilton, R.G. and West, A.J. 2020. ‘Mountains, erosion and the carbon cycle’, *Nature Reviews - Earth and Environment* 1, pp. 284–299. doi:10.1038/s43017-020-0058-6.

Hugelius, G., Strauss, J., Zubrzycki, S., Harden, J.W., Schuur, E.A.G., Ping, C.-L., Schirrmeister, L., Grosse, G., Michaelson, G.J., Koven, C.D., O’Donnell, J.A., Elberling, B., Mishra, U., Camill, P., Yu, Z., Palmtag, J., and Kuhry, P. 2014. ‘Estimated stocks of circumpolar permafrost carbon with quantified uncertainty ranges and identified data gaps’, *Biogeosciences* 11, pp. 6573–6593. doi:10.5194/bg-11-6573-2014.

Ielpi, A., Lapôtre, M.G.A., Finotello, A., and Roy-Léveillée, P. 2023. ‘Large sinuous rivers are slowing down in a warming Arctic’, *Nature Climate Change* 13, pp. 375–381. doi:10.1038/s41558-023-01620-9.

Kalliola, R. and Puhakka, M. 1988. ‘River dynamics and vegetation mosaicism: A case study of the River Kamajohka, northernmost Finland’, *Journal of Biogeography* 15, pp. 703–719. Available at: https://www.jstor.org/stable/2845334.

Lafrenière, M.J. and Lamoureux, S.F. 2019. ‘Effects of changing permafrost conditions on hydrological processes and fluvial fluxes’, *Earth-Science Reviews* 191, pp. 212–223. doi:10.1016/j.earscirev.2019.02.018.

Leopold, L.B. and Dunne, T. 1978. *Water in Environmental Planning.* San Francisco, California, United States: W.H. Freeman and Co.

Lininger, K.B. and Wohl, E. 2019. ‘Floodplain dynamics in North American permafrost regions under a warming climate and implications for organic carbon stocks: A review and synthesis’, *Earth-Science Reviews* 193, pp. 24–44.

Mann, D.H., Fastie, C.L., Rowland, E.L., and Bigelow, N.H. 1995. ‘Spruce succession, disturbance, and geomorphology on the Tanana River floodplain, Alaska’, *Écoscience* 2(2), pp. 184–199. Available at: https://www.jstor.org/stable/42900819.

Mann, D.H., Groves, P., Reanier, R.E., and Kunz, M.L. 2010. ‘Floodplains, permafrost, cottonwood trees, and peat: What happened the last time climate warmed suddenly in arctic Alaska?’, *Quaternary Science Reviews* 29, pp. 3812–3830. doi:10.1016/j.quascirev.2010.09.002

McGuire, A.D., Lawrence, D.M., Koven, C., Clein, J.S., Burke, E., Chen, G., et al. 2018. ‘Dependence of the evolution of carbon dynamics in the northern permafrost region on the trajectory of climate change’, *PNAS* 115(15), pp. 3882–3887, doi:10.1073/pnas.1719903115.

Meredith, M., Sommerkorn, M., Cassotta, S., Derksen, C., Ekaykin, A., Hollowed, A., Kofinas, G., et al. 2019. ‘Polar Regions’, in H.-O. Pörtner, et al. (eds.), *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate*. Cambridge, United Kingdom and New York, New York, United States: Cambridge University Press, pp. 203–320. doi:/10.1017/9781009157964.005.

Naiman, R.J. and Décamps, H. 1997. ‘The ecology of interfaces: Riparian zones’, *Annual Review of Ecological Systems* 28, pp. 621–658, doi:10.1146/annurev.ecolsys.28.1.621.

Nanson, G.C. and Croke, J.C. 1992. ‘A genetic classification of floodplains’, *Geomorphology* 4, pp. 459–486.

Overeem, I., Arcuri, J., Repasch, M., Anderson, R.S., Anderson, S.P., Urban, F., Koch, J., Vachon, R., and Cochran, C. 2023. ‘Thermal state controls coupling discharge and sediment transport in Arctic rivers’, in *AGU23—Wide. Open. Science*. San Francisco, California, United States: 11–15 December, 2023.

Poujol, B., Prein, A.F., and Newman, A.J. 2020. ‘Kilometer-scale modeling projects a tripling of Alaskan convective storms in future climate’, *Climate Dynamics* 55 (11–12), pp. 3543–3564. doi:10.1007/s00382-020-05466-1.

Regnier, P., et al. 2013. ‘Anthropogenic perturbation of the carbon fluxes from land to ocean’, *Nature Geoscience* 6, pp. 597–607. doi:10.1038/NGEO1830.

Regnier, P., Resplandy, L, Najjar, R.G., and Ciais, P. 2022. ‘The land-to-ocean loops of the global carbon cycle’, *Nature* 603, pp. 401–410. doi:10.1038/s41586-021-04339-9.

Repasch, M., Arcuri, J., Overeem, I., Anderson, S.P., Anderson, R.S., and Koch, J.C. 2024. ‘Impacts of convective storms on runoff, erosion, and carbon export in a continuous permafrost landscape’, in *ICOP 2024 12th International Conference on Permafrost*. Whitehorse, Yukon, Canada: 16–20 June, 2024.

Rowland, J.C., Schwenk, J.P., Shelef, E., Muss, J., Ahrens, D., Stauffer, S., et al. 2023. ‘Scale-dependent influence of permafrost on riverbank erosion rates’, *Journal of Geophysical Research-Earth Surface* 12, e2023JF007101. doi:10.1029/2023JF007101.

Schickhoff, U., Walker, M.D., and Walker, D.A. 2002. ‘Riparian willow communities on the Arctic Slope of Alaska and their environmental relationships: A classification and ordination analysis’, *Phytocoenologia* 32(2), pp. 145–204. doi:10.1127/0340-269X/2002/0032-0145.

Schuur, E.A.G., McGuire, A.D., Schädel, C., Grosse, G., Harden, J.W., Hayes, D.J., et al.. 2015. ‘Climate change and the permafrost feedback’, *Nature* 520, pp. 171–179. doi:10.1038/nature14338

Shaver, G.R. and Chapin, F.S. 1991. ‘Production: biomass relationships and element cycling in contrasting Arctic vegetation types’, *Ecological Monographs* 61(1), pp. 1–31. doi:10.2307/1942997.

Stuefer, S.L. Arp, C.D., Kane, D.L., and Liljedahl, A.K. 2017. ‘Recent extreme runoff observations from coastal arctic watersheds in Alaska’, *Water Resources Research* 53, pp. 9145–9163. doi:10.1002/2017WR020567

Sutfin, N.A., Wohl, E., and Dwire, K.A. 2016. ‘Banking carbon: a review of organic carbon storage and physical factors influencing retention in floodplains and riparian ecosystems’, *Earth Surface Processes and Landforms* 41, pp. 38–60. doi:10.1002/esp.3857.

Tarnocai, C., Canadell, J.G., Schuur, E.A.G., Kuhry, P., Mazhitova, G., and Zimov, S. 2009. ‘Soil organic carbon pools in the northern circumpolar permafrost region’, *Global Biogeochemical Cycles* 23, GB2023. doi:10.1029/2008GB003327

Tape, K.D., Hallinger, M., Welker, J.M., and Ruess, R.W. 2012. ‘Landscape heterogeneity of shrub expansion in Arctic Alaska’, *Ecosystems* 15, pp. 711–724. doi:10.1007/s10021-012-9540-4.

Ward, J.V., Tockner, K., Arscott, D.B., and Claret, C. 2002. ‘Riverine landscape diversity’, *Freshwater Biology* 47, pp. 517–539. doi:10.1046/j.1365-2427.2002.0893.x.

Wellstein, C., Uehlinger, U., and Zah, R. 2003. ‘Terrestrial floodplain vegetation’, in J.V. Ward and U. Uehlinger (eds.), *Ecology of a Glacial Flood Plain*. Dordrecht, Netherlands: Springer Science+Business Media.

Wohl, E., Hall, R.O, Jr., Lininger, K.B., Sutfin, N.A., and Walters, D.M. 2017. ‘Carbon dynamics of river corridors and the effects of human alteration’, *Ecological Monographs* 87, pp. 379–409. doi:10.1002/ecm.1261/full

Wolman, M.G. and Leopold, L.B. 1957. ‘River flood plains: Some observations on their formation’, *US Geological Survey* Professional Paper 282-C. US Government Printing Office, Washington, D.C., United States, 28 p.

Wrona, F.J., Johansson, M., Culp, J.M., Jenkins, A., Mård, J., Myers-Smith, I.H., Prowse, T.D., Vincent, W.F., and Wookey, P.A. 2016. ‘Transitions in Arctic ecosystems: Ecological implications of a changing hydrologic regime’, *Journal of Geophysical Research: Biogeosciences* 121, pp. 650–674. doi:10.1002/2015JG003133

Wymore, A.S., Ward, A.S., Wohl, E., and Harvey, J.W. 2023. ‘Viewing river corridors through the lens of critical zone science’, *Frontiers in Water* 5, 1147561. doi:10.3389/frwa.2023.1147561

Zheng, L., Overeem, I., Wang, K., and Clow, G.D. 2019. ‘Changing Arctic river dynamics caused localized permafrost thaw’, *Journal of Geophysical Research-Earth Surface* 124. doi:10.1029/2019JF005060.