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RESEARCH/REVIEW ARTICLE

Summer CO₂ evasion from streams and rivers in the Kolyma River basin, north-east Siberia

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Keywords

Arctic streams and rivers; CO₂ evasion; inland water surface area; Kolyma River; pCO₂; Siberia.

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Abstract

Inland water systems are generally supersaturated in carbon dioxide (CO₂) and are increasingly recognized as playing an important role in the global carbon cycle. The Arctic may be particularly important in this respect, given the abundance of inland waters and carbon contained in Arctic soils; however, a lack of trace gas measurements from small streams in the Arctic currently limits this understanding. We investigated the spatial variability of CO₂ evasion during the summer low-flow period from streams and rivers in the northern portion of the Kolyma River basin in north-eastern Siberia. To this end, partial pressure of carbon dioxide (*p*CO₂) and gas exchange velocities (*k*) were measured at a diverse set of streams and rivers to calculate CO₂ evasion fluxes. We combined these CO₂ evasion estimates with satellite remote sensing and geographic information system techniques to calculate total areal CO₂ emissions. Our results show that small streams are substantial sources of atmospheric CO₂ owing to high *p*CO₂ and *k*, despite being a small portion of total inland water surface area. In contrast, large rivers were generally near equilibrium with atmospheric CO₂. Extrapolating our findings across the Panteleikha–Ambolikha sub-watersheds demonstrated that small streams play a major role in CO₂ evasion, accounting for 86% of the total summer CO₂ emissions from inland waters within these two sub-watersheds. Further expansion of these regional CO₂ emission estimates across time and space will be critical to accurately quantify and understand the role of Arctic streams and rivers in the global carbon budget.

Inland waters are active components of the global carbon (C) cycle storing terrestrially derived C in sediments, transporting large quantities of C from land to the ocean and acting as important regions of C processing and sources of carbon dioxide (CO₂) and methane (CH₄) to the atmosphere. Inland water systems are routinely supersaturated with CO₂ and CH₄ and subsequent C fluxes make them critical components to global atmospheric CO₂ and CH₄ budgets (Kling et al. 1991; Cole et al. 2007; Battin et al. 2009; Aufdenkampe et al. 2011). Headwater streams, comprising a majority of stream length within a given watershed (Bishop et al. 2008), are hotspots of CO₂

concentrations because they interact closely with terrestrial soils and sediment-bound microbes (Hope et al. 2004; Rasera et al. 2008; Teodoru et al. 2009; Davidson et al. 2010; Koprivnjak et al. 2010; Wallin et al. 2010; Butman & Raymond 2011; Benstead & Leigh 2012). Furthermore, headwater streams act as regions of rapid mineralization, processing C exported from terrestrial ecosystems to adjacent rivers and lakes and therefore inclusion of headwater streams is fundamental for accurately quantifying regional CO₂ emissions (Öquist et al. 2009). However, small streams are generally under-represented in global atmospheric CO₂ emission estimates owing to a lack of

spatial and temporal flux measurements and unquantified areal coverage (Cole et al. 2007; Bishop et al. 2008; Melack 2011; Benstead & Leigh 2012).

CO₂ evasion to the atmosphere from surface waters is jointly controlled by the partial pressure of carbon dioxide ($p\text{CO}_2$) and the gas exchange velocity (k) of CO₂ at the water–atmosphere interface. Terrestrially derived C greatly influences riverine $p\text{CO}_2$, entering either as dissolved inorganic carbon (DIC) directly in the form of CO₂ from soil respiration, decomposition and weathering of bedrock minerals, or as dissolved organic carbon (DOC) from allochthonous organic C that can subsequently be respired within the stream (Butman & Raymond 2011 and references within). In addition, autochthonous organic C produced in the stream (e.g., emergent macrophytes) reduces $p\text{CO}_2$ via photosynthesis and increases $p\text{CO}_2$ via respiration. As organic C is transported downstream, microbial respiration and phototransformation may alter the lability of C, potentially affecting its degradability (Aufdenkampe et al. 2011; Mann et al. 2012). Furthermore, across a river network the DOC (Laudon et al. 2011) and DIC (Tank et al. 2012) entering inland waters can vary seasonally as the hydrograph transitions from spring freshet to late summer flow conditions (Neff et al. 2006; Holmes et al. 2008; Holmes et al. 2012).

Rapid CO₂ evasion has been found to occur in headwater streams (Öquist et al. 2009) as high water turbulence increases the exchange ability of CO₂ at the water–atmosphere interface (Raymond et al. 2012). As streams become wider and deeper, gas exchange velocities become increasingly influenced by wind-driven processes, rather than turbulent flow processes (Alin et al. 2011). Gas exchange velocities can therefore vary spatially within a watershed (Alin et al. 2011; Raymond et al. 2012), owing to differences in sub-watershed climate, land cover and morphology. Consequently, CO₂ evasion in permafrost-dominated rivers likely varies spatially and seasonally across river networks, yet to this point has not been systematically quantified across these important landscapes.

Past studies focused on inland water CO₂ evasion have been conducted in tropical regions of the Amazon (Richey et al. 2002; Rasera et al. 2008; Davidson et al. 2010), temperate regions (Hope et al. 2001; Jones et al. 2003; Butman & Raymond 2011), boreal regions (Kelly et al. 2001; Teodoru et al. 2009; Koprivnjak et al. 2010; Wallin et al. 2010), and the Alaskan Arctic (Kling et al. 1991; Cole et al. 1994); however, CO₂ evasion from lotic systems in the Siberian Arctic has not yet been reported. Arctic landscapes are critical for understanding global CO₂ emissions from inland water surfaces as permafrost occupies about 22% of the exposed land surface in the

Northern Hemisphere (Zhang et al. 1999), which if thawed will likely release an old and potentially labile source of C to streams (Frey & McClelland 2009). Permafrost, storing large quantities of long-sequestered soil C (Zimov et al. 2006), plays a unique role in the hydrologic pathways of terrestrially derived C entering inland waters by minimizing percolation into deep soils (Frey et al. 2007). In permafrost-dominated regions, terrestrially derived C enters streams via surface and shallow surface pathways with minimal ground water flow, even during summer periods.

This study focuses upon CO₂ evasion from headwater (order 1–3) streams to the Kolyma River main stem, exploring the spatial variability in riverine $p\text{CO}_2$ and gas exchange velocities during summer low-flow conditions. Additionally, DOC concentration and five-day biological oxygen demand (BOD) were measured to help interpret spatial patterns in $p\text{CO}_2$. The objectives of this study were to: (a) determine $p\text{CO}_2$ concentrations for individual streams and rivers in a permafrost-dominated riverine system within the northern Kolyma River basin during the summer low-flow period; (b) understand the spatial variability of CO₂ evasion fluxes from streams and rivers across this region; and (c) estimate total CO₂ emission from sub-watersheds as a whole within the northern Kolyma River basin (requiring the areal coverage of streams and rivers to be quantified). To address these objectives, field-based measurements of summer $p\text{CO}_2$ and gas exchange velocities were combined with geographic information system (GIS) and remote sensing techniques to extrapolate summer CO₂ flux estimates across a bounded study area in the northern Kolyma River basin region, as well as two sub-watersheds within the region (the Panteleikha–Ambolikha river watershed).

Data and methods

Study site

The Kolyma River basin in north-east Siberia is the largest Arctic watershed (ca. 650 000 km²) completely underlain by continuous permafrost. The major soils in this region, known as yedoma, store vast amounts of sequestered organic C and nutrients, characterized by Pleistocene-aged, ca. 10–90 m thick icy loess deposits containing ca. 3–5% organic C (Zimov et al. 2006). The soils are comprised of a shallow organic top layer (ca. 5–7 cm) underlain by permafrost, with active layer thicknesses that range from ca. 50 to 90 cm. The bedrock in this region retains a relatively large proportion of basalts compared to other large Arctic watersheds and therefore carbonate (ca. 78–85%) and silicate (ca. 22–42%) weathering both contribute to the inorganic C pool

in the region (Tank et al. 2012). The diverse forest–tundra vegetation and mountain–floodplain landscape (Semiletov 1999) combined with strong continental climate of warm summers (mean ca. 12°C), cold winters (mean ca. –35°C) and low annual precipitation (mean ca. 185 mm yr^{–1}; Welp et al. 2005) promote seasonally variable river discharge. Annual discharge in the Kolyma River (mean ca. 132 km³) follows a seasonal hydrological pattern typical of Arctic rivers, with a sharp rise and fall in discharge during the spring freshet and consistently low winter discharge (Holmes et al. 2012).

Sampling pCO₂ during summer low flow

From 11 July to 14 August 2010, during summer low-flow conditions, a survey spanning ca. 260 km of the northern region of the Kolyma River was conducted to examine biogeochemical properties among a diverse set of river locations and tributaries. A total of 29 different sites were sampled (10 stream, 11 river, and eight Kolyma main stem locations), 14 of which were sampled two or more times (total $n = 56$; Fig. 1). For the purpose of this study, “streams” were defined where total reach length was <10 km and “rivers” were defined where total reach length was >10 km. Reach length refers to the length from a stream or river source (headwater streams from lake/wetland source and higher order streams from the confluence of the connecting water body upstream) to the outlet (defined as the point of confluence into another water body). At each location, pH, temperature, dissolved oxygen (DO) saturation and specific conductivity were measured using a Pro Plus multiparameter instrument (YSI, Yellow Springs, OH, USA) at a depth of ca. 0.5 m (Table 1). In shallow streams, less than 0.5 m in depth, measurements were taken approximately midway below the surface and the bottom. Water samples for DOC and pCO₂ were collected in dark bottles without headspace to minimize degassing. Upon returning from the field, DOC samples were filtered through precombusted 0.7-μm GF/F glass fibre filters (Whatman, Kent, UK) directly into acid-washed, precombusted glass vials and acidified with HCl to a pH of <2, following the protocol used by Mann et al. (2012). Samples were refrigerated in the dark until measurement (within one week of collection) at the Northeast Science Station (Cherskiy, Russia) via high-temperature combustion using a TOC-V organic carbon analyzer combined with nitrogen detection unit (TNM-1) (Shimadzu Scientific Instruments, Columbia, MD, USA) (0.5 μg L^{–1} detection limit). DOC was calculated as the mean of ca. 3–5 injections with a coefficient of variance always <2%. Samples for alkalinity analyses were filtered through 0.45-μm Sterivex-HV filters (Millipore,

Watford, UK) and were analysed within one day of collection. Total alkalinity was determined using a digital titrator (Hach, Loveland, CO, USA) using the Gran function plot method in an alkalinity calculator (<http://or.water.ursgs.gov/alk/>). Carbonate alkalinity was calculated by correcting for organic anion contributions to total alkalinity, using measured DOC and pH (Thurman 1985). Briefly, organic anion contributions were calculated as the percent fulvic DOC dissociated in water, assuming that 90% of the measured DOC was fulvic. pCO₂ was then calculated from carbonate alkalinity, pH, water temperature and temperature-adjusted dissociation constants for carbonic acid (K_1 and K_2 ; Millero 2010) and water (K_w ; Millero 1979).

The following equation utilized for determining pCO₂ was adapted from Stumm & Morgan (1981):

$$p\text{CO}_2 = \frac{\left(\frac{(\text{Alk} - [\text{OH}^-] + [\text{H}^+])}{(\alpha_1 + 2\alpha_2)} \right) (\alpha_0)}{K_0} \quad (1)$$

where pCO₂ (in units of microatmospheres [μatm]) does not directly refer to the concentration of free CO₂ in water but rather—applying Henry’s Law of gas constant (K_0)—suggests that the concentration of a dissolved gas is proportional to its pressure in the gas phase. K_0 , expressed in mol L^{–1} atm refers to a litre of solution at the temperature of the measurement (Weiss 1974). Carbonate species relation equations ($\alpha_0 = \text{H}_2\text{CO}_3$, $\alpha_1 = \text{HCO}_3^-$, $\alpha_2 = \text{CO}_3^{2-}$), referenced from Stumm & Morgan (1981), account for the activity of each individual carbonate species. At select locations—streams ($n = 8$), rivers ($n = 10$), main stem ($n = 4$)—60-mL HDPE bottles were slowly filled with water to be analysed in the laboratory for BOD. BOD was calculated as the difference in DO concentration (mg L^{–1}) before and after five-day incubations of unfiltered waters in the dark at room temperature (20°C).

Finally, discharge data for the Kolyma River at Kolymskoye were obtained from the ArcticRIMS database and adjusted to reflect discharge of the Kolyma River at Cherskiy, located about 160-km downstream of the Kolymskoye gauging station (e.g., Holmes et al. 2012). Daily discharge data (Fig. 2) for the Kolyma River were used to assist in understanding summer low-flow hydrology and potential influences on biogeochemistry within this region.

Gas exchange velocity (k) measurements

CO₂ flux estimates require an understanding of k , which varies as a function of physical and environmental

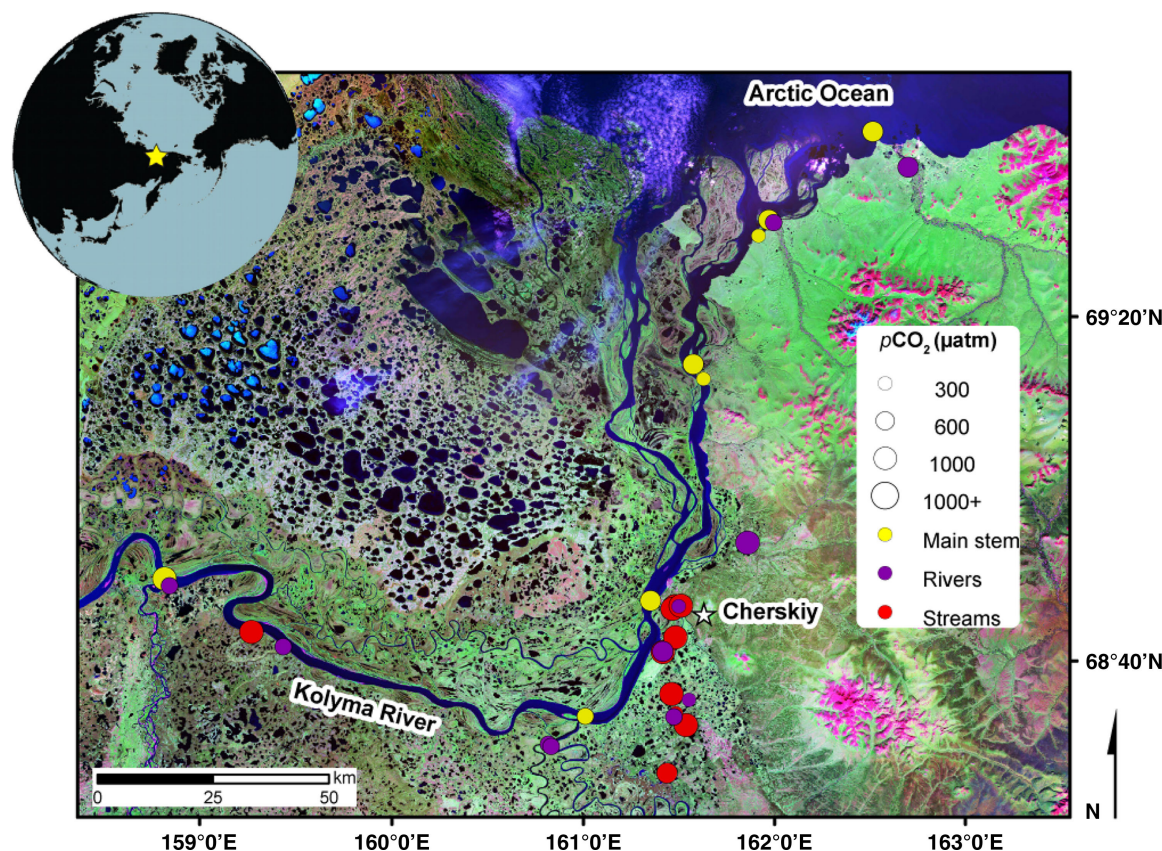


Fig. 1 Field sample locations from 11 July to 14 August 2010. A total of 29 different sites were sampled (10 stream, 11 river and eight main stem locations), 14 of which were sampled two or more times (total $n = 56$) spanning ca. 260 km along the Kolyma River main stem. Aquatic system types are colour coded, and streams and rivers were defined where reach length was <10 km and >10 km, respectively. Average $p\text{CO}_2$ for each site is represented by varying circle size.

characteristics of the system (Alin et al. 2011). Several recent studies have utilized values for k from the literature without empirical field validation (e.g., Teodoru et al. 2009; Humborg et al. 2010), yet direct measurements of k allow for more accurate CO₂ evasion estimates (Wallin et al. 2011). One such field approach utilizing floating chambers offers a highly localized measurement of k . The chamber method has been criticized for potentially reducing wind shear, causing mass boundary layer perturbations, or disturbing the air–water interphase, yet there is no consensus about whether fluxes measured by chambers yield values consistent with other methods (Alin et al. 2011) or overestimates compared to other methods (Vachon et al. 2010). However, due to the remote region of our study, floating chambers offered a relatively robust approach for directly measuring k for a diverse set of stream and rivers.

During the summer of 2011, we measured the evasion of $p\text{CO}_2$ across the air–water interface to assess k values across streams ($n = 8$), rivers ($n = 8$) and the Kolyma main stem ($n = 3$). We traced the accumulation of CO₂ in

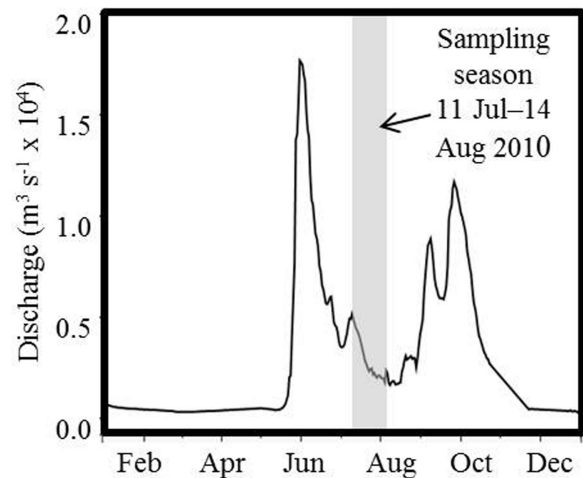
a circular, plastic chamber with a fixed headspace. The chamber (30 cm above water level) was allowed to float freely along streams or alongside a boat to minimize interference from water turbulence. The concentration of CO₂ was continually monitored using a closed air circuit and air-pump flowing through a GM70 portable infrared gas analyser system (Vaisala, Vantaa, Finland). Values of k were calculated from the slope of the linear regression of $p\text{CO}_2$ over a 15-min deployment time (with r^2 values typically greater than 0.98). Values of k were then calculated in units of cm hr^{-1} . To compare gas transfer velocity values among sites and aid in comparison with other studies, k values were normalized to a temperature of 20°C using a Schmidt number of 600, that is, k_{600} (e.g., Alin et al. 2011).

CO₂ evasion flux calculations

To calculate CO₂ evasion fluxes ($\text{g C m}^{-2} \text{d}^{-1}$), the rate that CO₂ degasses from surface waters to the atmosphere, the following equation was utilized:

Table 1 Summary description of physical and biogeochemical characteristics of streams (<10 km reach length) and rivers (>10 km reach length) sampled in the northern Kolyma River basin during summer low-flow conditions.

| Inland water type | Range | Physical characteristics ^a | | | | | Biogeochemical characteristics | | | | | | |
|---|-------|---------------------------------------|------------------|-----------|-----------|--------------------------------------|--------------------------------|--------------------------|--|------|--|---|--------------------------------------|
| | | Watershed (km ²) | Reach length (m) | Width (m) | Slope (°) | k ^b (cm h ⁻¹) | Temp (°C) | DO ^c (% sat.) | Cond ^d (μS cm ⁻¹) | pH | DOC ^e (mg L ⁻¹) | Alk ^f (μeq L ⁻¹) | pCO ₂ ^g (μatm) |
| Streams (n = 21) Reach length < 10 000 m | Min | 0.03 | 152 | 1 | 0.2 | 3 | 4.5 | 33 | 110 | 6.44 | 5.0 | 0.28 | 274 |
| | Max | 17 | 5403 | 19 | 6.5 | 55 | 19.0 | 114 | 41 | 7.82 | 21.6 | 1.36 | 9402 |
| | Mean | 5 | 2051 | 7 | 3.1 | 21 | 13.1 | 73 | 67 | 7.04 | 13.8 | 0.63 | 3336 |
| Rivers (n = 21) Reach length > 10 000 m | Min | 59 | 19 389 | 23 | 0.9 | 5 | 11.5 | 22 | 92 | 6.92 | 2.0 | 0.09 | 5 |
| | Max | 115 166 | 815 447 | 400 | 6.5 | 37 | 20.5 | 119 | 21 | 9.13 | 11.5 | 0.69 | 1010 |
| | Mean | 23 115 | 222 284 | 158 | 2.1 | 16 | 16.0 | 89 | 50 | 7.69 | 5.5 | 0.27 | 412 |
| Kolyma River (n = 14) | Min | 424 505 | 2 024 530 | 1.6 | 1.6 | 8 | 11.8 | 88 | 129 | 7.47 | 3.2 | 0.39 | 123 |
| | Max | 664 119 | 2 319 608 | 1.8 | 1.8 | 28 | 20.1 | 106 | 66 | 8.22 | 5.3 | 0.81 | 1079 |
| | Mean | 630 029 | 2 232 463 | 1.7 | 1.7 | 17 | 16.1 | 94 | 88 | 7.75 | 4.4 | 0.56 | 613 |

^aSample size (n) only includes individual watershed once; streams (n = 19), rivers (n = 11), main stem (n = 8).^bBased on samples collected during summer 2011; streams (n = 8), rivers (n = 9), main stem (n = 3).^cDissolved oxygen.^dConductivity.^eDissolved organic carbon.^fAlkalinity.^gPartial pressure of carbon dioxide.**Fig. 2** Daily discharge of the Kolyma River (adjusted to Cherskiy, Russia, ca. 160 km downstream of the gauging station at Kolymskoye) for 2010. The grey box indicates the sampling season of this study (11 July–14 August 2010), representing summer low-flow conditions.

$$\text{Evaporation flux}_{(\text{CO}_2)} = k \cdot k_h (p\text{CO}_{2 \text{ water}} - p\text{CO}_{2 \text{ air}}), \quad (2)$$

where average k values were used for streams, rivers and the Kolyma main stem (21.2 cm hr⁻¹, 16.2 cm hr⁻¹, 16.7 cm hr⁻¹, respectively); k_h (Henry's constant) corrects for temperature (Weiss 1974); $(p\text{CO}_{2 \text{ water}} - p\text{CO}_{2 \text{ air}})$ accounts for the difference between concentrations in the water and in the air; and $p\text{CO}_{2 \text{ air}}$ (the atmospheric CO₂ concentration) was set to 389.3 ppm, the average global 2010 atmospheric CO₂ concentration during the sampling period (11 July–15 August) (Tans & Keeling undated).

Areal CO₂ emission calculations

To obtain estimates of areal CO₂ emissions (g C d⁻¹) from inland surface waters, CO₂ evasion fluxes (Eqn. 2) were multiplied by surface water area estimates. Regional estimates of CO₂ emission from inland water bodies rely as much on estimates of inland surface water area as on the CO₂ evasion per unit area of surface water (Aufdenkampe et al. 2011), emphasizing the importance of accurately quantifying surface water area. Owing to the expansive and remote nature of north-east Siberia, GIS techniques and satellite remote sensing offer powerful and practical tools to determine surface water area, providing a means to extrapolate $p\text{CO}_2$ field measurements beyond field-based sampling sites alone and allowing for areal CO₂ emissions to be calculated.

To determine areal CO₂ emissions, both CO₂ evasion fluxes from non-sampled stream and river surface areas needed to be estimated. Since the Kolyma River network comprises a few large rivers and a vast amount of small

streams and rivers, four different data sets were utilized to represent the varying spatial scales of our field-based sampling sites (Fig. 3, Table 2). Satellite imagery was acquired during summer, allowing surface area conditions to be accurately determined during typical low-flow conditions. All satellite imagery was geometrically corrected and georeferenced to UTM zone 57N. Watershed area and Kolyma main stem surface area were manually digitized from orthorectified Landsat Thematic Mapper mosaics. A threshold classification technique was applied to Phased Array type L-band Synthetic Aperture Radar (PALSAR) and GeoEye imagery to determine surface areas for rivers and larger streams (i.e., streams that were

detectable in this imagery). Imagery was reclassified as water and non-water based on empirically determined pixel value histograms (e.g., Smith & Alsdorf 1998). However, the smallest streams sampled in this study were not readily apparent in GeoEye imagery owing to such conditions as thickly vegetated overstories. A digital elevation model (DEM) can provide a more detailed picture of smaller channels that are often undetectable by traditional mapping techniques (Benstead & Leigh 2012). As such, through topographic modelling of stream networks (with the use of Hydrological Extension in ESRI® ArcGIS™ v. 10.0 software), Advanced Spaceborne Thermal Emission and Reflection Radar DEM data allowed for

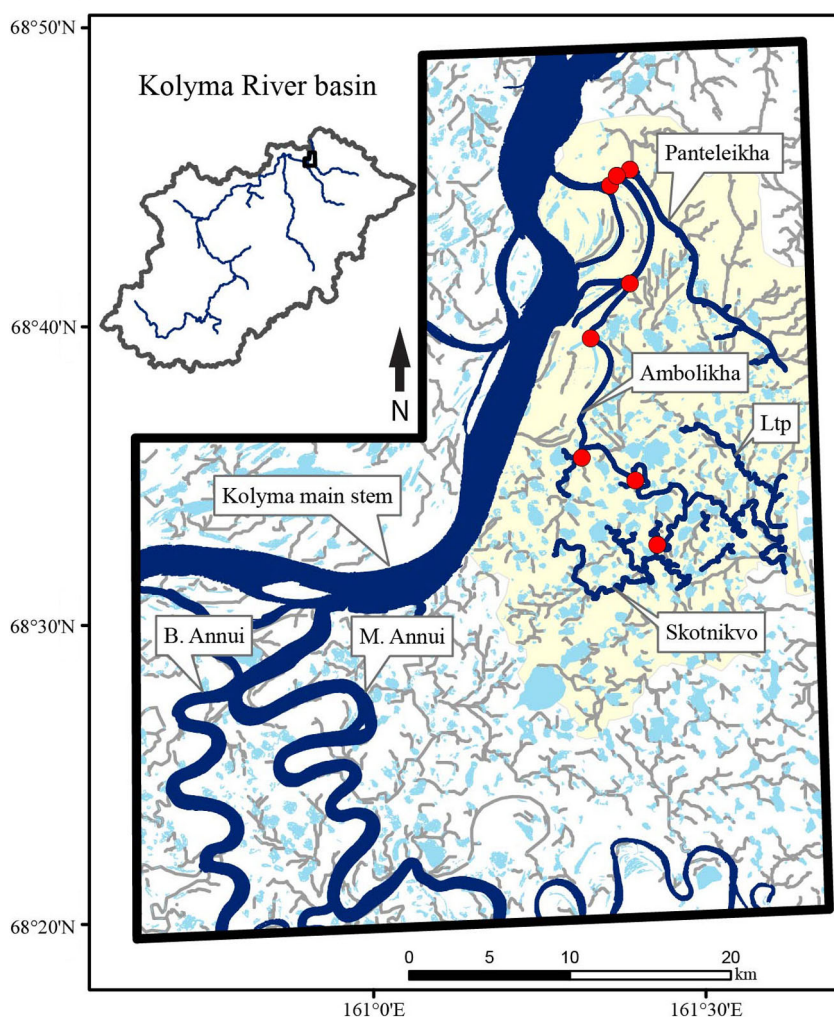


Fig. 3 Bounded study area of the lower Kolyma River basin (black box). Areal coverage of surface water for a subset of sampled rivers and streams in the Kolyma River basin determined using four different types of satellite remotely sensed imagery (Table 2). Dark blue determined from pixel value histogram reclassification and light grey predicted from the ArcGIS™ Hydrological Extension (Table 3). Light yellow area represents the portion of the Panteleikha–Ambolikha watershed covered by GeoEye imagery (30% of the total watershed areas; Table 4). Red dots denote sampled stream locations. Lakes (light blue) were included for clarity.

Table 2 Summary of satellite imagery used to determine water surface area within the bounded study area.

| Data set | Acquisition date | Spatial resolution | Spatial coverage of study area | Availability |
|---|------------------|--------------------|---------------------------------------|--|
| Orthorectified Landsat Thematic Mapper Mosaic | N/A | 14.25 m | Kolyma River main stem | National Aeronautical and Space Administration Applied Science and Technology Project Office http://zulu.ssc.nasa.gov/mrsid/ |
| Phased Array type L-band Synthetic Aperture Radar (PALSAR) | 30 July 2010 | 12.755 m | Large rivers (M. and B. Annui) | Alaska Satellite Facility http://www.asf.alaska.edu/ |
| GeoEye (Panchromatic) | 13 August 2009 | 0.48 m | Small rivers ^a and streams | GeoEye http://geofuse.geoeye.com/maps/Map.aspx |
| Advanced Spaceborne Thermal Emission and Reflection Radar Digital Elevation Model | N/A | 15 m | Length of small streams (order 1–3) | Earth Observing System Data and Information System. 2009. https://wist.echo.nasa.gov/api/ |

^aSmall rivers were those that PALSAR had difficulty characterizing because of their smaller size but instead could be identified in GeoEye.

the smallest streams (order 1–3; not identified with the GeoEye imagery) to be represented (at stream lengths >200 m). Stream surface area was determined by multiplying stream length (an output of Hydrological Extension) and width (determined from an empirical relationship), where the following empirical relationship with length provided the best prediction of stream width: (width = 0.0018 [length]; $r^2 = 0.91$, $n = 12$, $p < 0.001$). The sample size ($n = 12$) in this relationship represented the eight streams and four rivers whose total length and width (orthogonal distance across the inundated area) was determined from the PALSAR and GeoEye imagery acquired during summer low-flow conditions.

CO₂ evasion fluxes were then estimated from non-sampled streams in the riverine network using an empirically derived relationship to predict $p\text{CO}_2$ for non-sampled streams from field-based $p\text{CO}_2$ and averaged k (calculated as 21.2 cm hr^{-1}) for streams. The empirical relationship with stream width ($p\text{CO}_2 = 3739.2e^{-0.118[\text{width}]}$, $r^2 = 0.63$, $n = 8$) provided the best relationship for predicting $p\text{CO}_2$. This relationship only includes stream samples ($n = 8$)—and excludes river samples—for two reasons: (1) $p\text{CO}_2$ in streams are highly variable compared to river samples; and (2) non-sampled streams were of lengths (<10 km) and widths (<20 m) most comparable to the range of our sampled streams.

Using the relationships determined above, areal CO₂ emission was then determined within a bounded study area (e.g., Teodoru et al. 2009), defined by the available remotely sensed imagery of the northern Kolyma River basin (Fig. 3). Next, values were extrapolated to a watershed boundary providing a more meaningful and systematic approach to upscaling. An extrapolation to the entire Kolyma River basin would require an increased number of watersheds represented in the southern and mid-Kolyma River basin at much lower latitudes; there-

fore, logistical and analytical constraints limited extrapolation to sub-watersheds in the northern region of Kolyma River only. The Panteleikha–Ambolikha watershed was selected for this analysis because they were highly sampled within our study area, including eight streams, two rivers, and the Ambolikha and Panteleikha main stems. Landsat imagery covers 100% of these two watersheds; however, fine resolution GeoEye imagery only covers 30% of the two watersheds. As such, the total length of the Panteleikha River was manually determined and the average width was applied to obtain the total Panteleikha main stem surface area. For all other rivers and streams in the two watersheds, the proportion of total stream and river surface area in the known 30% area of watershed was applied to the total area of the watershed.

Results

Spatial patterns of CO₂ evasion during summer low flow

Physical and biogeochemical characteristics among riverine system types exhibited wide variability (Table 1); streams had the lowest pH (mean 7.04 ± 0.38), whereas rivers (mean 7.69 ± 0.60) had slightly higher pH values than the main stem (mean 7.75 ± 0.21). Sampling sites had low, yet variable, alkalinity (ranging from ca. 0.09 to $1.36 \mu\text{eq L}^{-1}$), with extremely low values recorded in rivers (mean ca. $0.21 \mu\text{eq L}^{-1}$). Overall, streams were consistently supersaturated in CO₂ (excess partial pressure of carbon dioxide [$E_p\text{CO}_2$] $2948 \mu\text{atm}$), while rivers ($E_p\text{CO}_2$ $24 \mu\text{atm}$) and the Kolyma main stem were slightly supersaturated in CO₂ ($E_p\text{CO}_2$ $225 \mu\text{atm}$). $p\text{CO}_2$ was high in streams (mean $3336 \pm 2737 \mu\text{atm}$) compared to rivers (mean $412 \pm 250 \mu\text{atm}$) and the Kolyma main stem (mean $613 \pm 315 \mu\text{atm}$; Fig. 4a). Values of k were

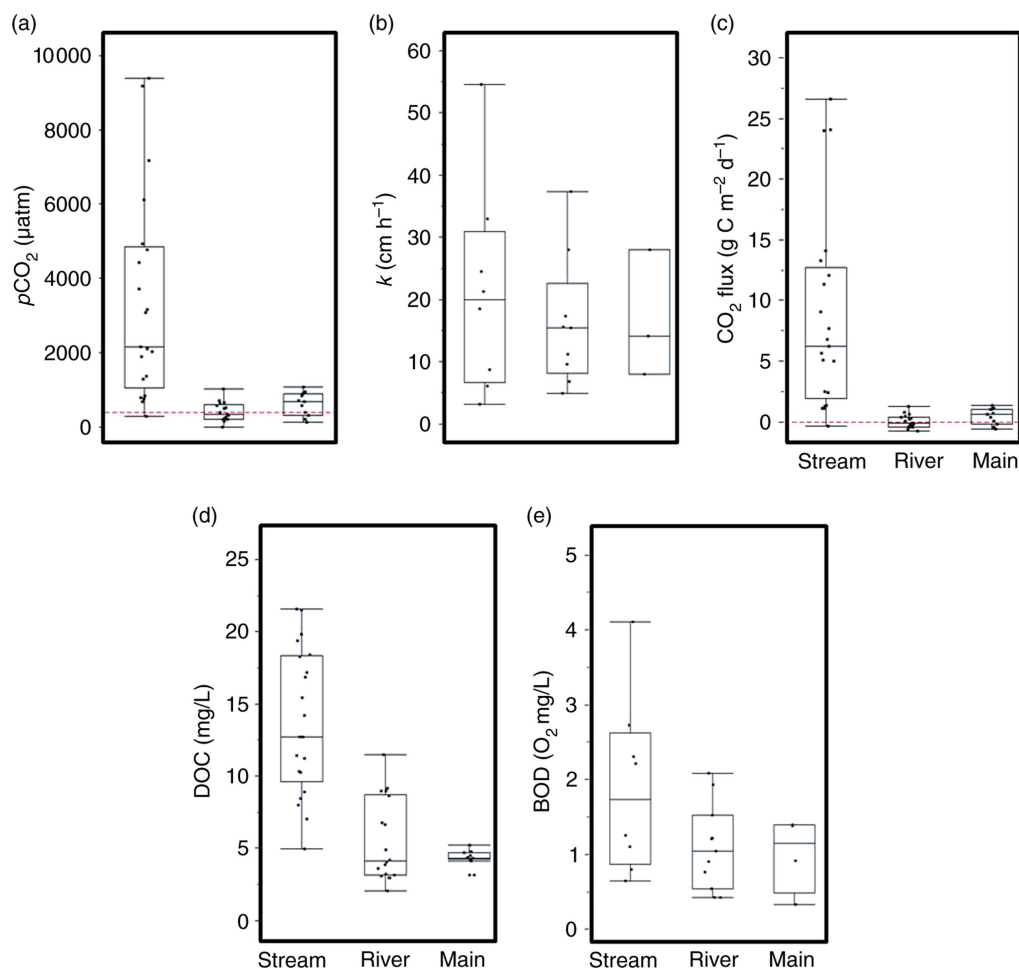


Fig. 4 Comparison of (a) $p\text{CO}_2$ (μatm), (b) k (cm hr^{-1}), (c) CO_2 flux ($\text{g C m}^{-2} \text{d}^{-1}$), (d) dissolved organic carbon (DOC, in mg L^{-1}) and (e) biological oxygen demand (BOD, in mg L^{-1}) among streams (<10 km reach length), rivers (>10 km reach length) and the Kolyma main stem. Box plots show range, quartiles and median. The red dashed line in (a) represents $389.3 \mu\text{atm}$, the mean 2010 atmospheric CO_2 concentration during the sampling period (11 July–14 August 2010) and the red dashed line in (c) represents CO_2 in equilibrium with the atmosphere (values above the line indicate a CO_2 source and values below the line indicate a CO_2 sink). Average k for streams, rivers and Kolyma main stem (21.2 cm hr^{-1} , 16.2 cm hr^{-1} , 16.7 cm hr^{-1} , respectively) were used to calculate CO_2 flux.

variable among streams (mean $21.2 \pm 16.8 \text{ cm hr}^{-1}$), rivers (mean $16.2 \pm 10.5 \text{ cm hr}^{-1}$) and the Kolyma main stem (mean $16.7 \pm 10.3 \text{ cm hr}^{-1}$; Fig. 4b). CO_2 evasion fluxes followed a similar pattern to $p\text{CO}_2$ and k , with highly variable fluxes from streams (mean $8.6 \pm 8.0 \text{ g C m}^{-2} \text{d}^{-1}$) compared to rivers (mean $0.007 \pm 0.5 \text{ g C m}^{-2} \text{d}^{-1}$) and the Kolyma main stem (mean $0.5 \pm 0.7 \text{ g C m}^{-2} \text{d}^{-1}$; Fig. 4c). DOC concentration and variability decreased along the fluvial path from streams (mean $13.8 \pm 5.0 \text{ mg L}^{-1}$) to rivers (mean $5.5 \pm 2.9 \text{ mg L}^{-1}$) to the main stem (mean $4.4 \pm 0.5 \text{ mg L}^{-1}$; Fig. 4d). Mean BOD rates declined moving from streams (mean $1.9 \pm 1.2 \text{ mg L}^{-1}$), rivers (mean $1.1 \pm 0.6 \text{ mg L}^{-1}$) and the Kolyma main stem (mean $1.0 \pm 0.5 \text{ mg L}^{-1}$; Fig. 4e).

To address hydrologic and watershed processes within the stream category, streams were separated depending upon source material loading categories: (a) yedoma streams (draining upland high C-content yedoma soils); (b) floodplain streams (draining low-lying terrestrial vegetation and Holocene soils) and (c) connecting streams (linking a confluence of lakes and wetlands). Yedoma streams were typically long (mean $3562 \pm 1903 \text{ m}$ length) and narrow (mean $2.0 \pm 1.4 \text{ m}$ width); floodplain streams were usually more narrow (mean $2.0 \pm 0.0 \text{ m}$ width) within small watersheds (mean $0.5 \pm 0.8 \text{ km}^2$ watershed area); and connecting streams were relatively long (mean $2156 \pm 2190 \text{ m}$ length) and wide (mean $14.0 \pm 4.5 \text{ m}$ width). Yedoma streams typically contained

highest DOC concentrations (mean 18.0 ± 2.5 mg L⁻¹), yet floodplain streams had highest $p\text{CO}_2$ (mean 4661 ± 2990 μatm). In contrast, connecting streams had the lowest DOC concentrations (mean 8.0 ± 0.4 mg L⁻¹) and $p\text{CO}_2$ (mean 775 ± 1192 μatm).

Areal CO₂ emission estimates

Areal CO₂ emission was calculated within a bounded study area, defined by the available remotely sensed imagery of the northern Kolyma River basin (Fig. 3; Table 3). The drainage network within the defined study area covers a total of 9.3% of the defined study area (1871 km²), composed of 1034 streams (order 1–3), four small rivers (Skotnikvo, Ambolikha, Panteleikha, Ltp), two large tributary rivers (Bolshoi Annui and Malinki Annui) and the Kolyma River main stem, representing 0.2, 0.3, 1.6 and 7.2% of the defined study area, respectively. Streams (order 1–3) comprise a majority of stream length but contribute only a small fraction of total inland water surface area (ca. 2.4%). To calculate areal CO₂ emission, k values averaged for each system type (Table 1) were used. The areal CO₂ emission for the summer low-flow period from the combined stream–river–main stem network within the bounded study area was ca. 75.5×10^6 g C d⁻¹, ca. 38.3% of which was emitted by streams, ca. 0.4% by small rivers and ca. 61.3% by the Kolyma River main stem alone. In contrast, large rivers on average acted as a weak CO₂ sink, reducing the areal emission of CO₂ by ca. 2.0%.

To broadly investigate the fractional CO₂ contribution from inland waters in the Kolyma River basin from a watershed perspective (as opposed to an arbitrary

bounded study region, as above), values from the northern Kolyma River defined study zone (Fig. 3) were additionally scaled to the Panteleikha–Ambolikha watershed (Table 4). These estimates suggest that during summer low-flow, ca. 20.4×10^6 g C d⁻¹ is emitted as CO₂ to the atmosphere from streams and rivers in the watershed (with streams emitting ca. 17.7×10^6 g C d⁻¹ and rivers—excluding the Panteleikha—emitting ca. 2.7×10^6 g C d⁻¹). However, total CO₂ emission from the watershed is reduced to ca. 11.9×10^6 g C d⁻¹ when incorporating the Panteleikha (as this river acted as a sink, decreasing CO₂ evasion by ca. 8.5×10^6 g C d⁻¹). Therefore, of the CO₂ emitted to the atmosphere, streams accounted for 86%, rivers accounted for 10% and the Ambolikha main stem accounted for 4%. The Panteleikha River (during our period of observation) reduced the total estimated CO₂ evasion by 42%.

Discussion

Spatial patterns of CO₂ evasion

Streams measured in this study were consistently supersaturated in CO₂, suggesting they act as net sources of CO₂ to the atmosphere during the summer low-flow period. Larger rivers (including the Kolyma River main stem) contained relatively low CO₂, yet occasionally were supersaturated in CO₂, resulting in these water bodies acting as weak net sources and periodically weak net sinks of atmospheric CO₂. The observed gradient and magnitude of directional processing from small streams to large tributaries is consistent with findings in other

Table 3 Estimates of areal CO₂ evasion fluxes from surface waters of the northern Kolyma River bounded study area (black box in Fig. 3) during summer low-flow conditions.

| Inland water type | Surface water area (km ²) | Surface water area (%) | Total study area (%) | Average $p\text{CO}_2^a$ (μatm) | CO ₂ evasion flux (g C m ⁻² d ⁻¹) | Total areal CO ₂ emission (10 ⁶ g C d ⁻¹) | Fractional CO ₂ contribution (%) |
|--------------------------------------|---------------------------------------|------------------------|----------------------|--|---|---|---|
| Streams ($n=1034$) | 4.2 | 2.4 | 0.2 | 2860 | 7.00 | 29.5 | 38.3 |
| Order 1 ($n=686$) | 1.6 | | | 3137 | 7.78 | 12.1 | |
| Order 2 ($n=256$) | 1.5 | | | 2886 | 7.07 | 10.6 | |
| Order 3 ($n=92$) | 1.1 | | | 2556 | 6.14 | 6.7 | |
| Small rivers ($n=4$) | 5.6 | 3.2 | 0.3 | 378 | −0.001 | 0.3 | 0.4 |
| Ltp | 0.3 | | | 264 | −0.27 | −0.1 | |
| Skotnikvo | 0.9 | | | 397 | 0.02 | 0.01 | |
| Panteleikha | 2.4 | | | 145 | −0.50 | −1.2 | |
| Ambolikha | 2.0 | | | 707 | 0.75 | 1.5 | |
| Large rivers ($n=2$) | 29.0 | 16.7 | 1.6 | 388 | −0.005 | −1.5 | −2.0 |
| Bolshoi A. | 9.8 | | | 461 | 0.14 | 1.4 | |
| Malinki A. | 19.2 | | | 316 | −0.15 | −2.9 | |
| Kolyma main stem ($n=1$) | 134.8 | 77.7 | 7.2 | 547 | 0.35 | 47.2 | 61.3 |
| Bounded area (1871 km ²) | 173.1 | 100 | 9.3 | 1049 | 2.1 | 75.5 | 98 |

^aPartial pressure of carbon dioxide.

Table 4 From a watershed perspective, estimates of CO₂ evasion fluxes were scaled up to the Ambolikh-Panteleikha watershed during summer low-flow conditions.

| Inland water type | Surface water area (km ²) | Surface water area (%) | Watershed area (%) | Average pCO ₂ (µatm) ^d | CO ₂ evasion flux (g C m ⁻² d ⁻¹) | Total area CO ₂ emission (10 ⁶ g C d ⁻¹) ^e | Fractional CO ₂ contribution (%) |
|--|---------------------------------------|------------------------|--------------------|--|---|---|---|
| Streams (order 1–3) | 2.4 ^a | 8.7 | 0.13 | 2883 | 7.2 | 17.7 | 86.4 |
| Rivers (order 4–5) | 6.9 ^a | 24.9 | 0.37 | 456 | 0.3 | 1.9 | 9.5 |
| Ambolikh River | 1.1 ^b | 4.1 | 0.06 | 707 | 0.8 | 0.8 | 4.1 |
| Panteleikha River | 17.3 ^c | 62.3 | 0.93 | 145 | −0.5 | −8.5 | −41.7 |
| Panteleikha–Ambolikh watershed (1849 km ²) | 27.7 | 100 | 1.49 | 1048 | 1.9 | 11.9 | 58.3 |

^aThe proportion of total in known 30% of watershed (yellow area in Fig. 3) was applied to the total watershed.^bDetermined by reclassification of GeoEye imagery.^cLength manually measured using Orthorectified Landsat Thematic Mapper mosaic imagery and multiplied by average width.^dAverage partial pressure of carbon dioxide (pCO₂) from samples collected; streams (n=8), rivers (n=3), Ambolikh (n=1), Panteleikha (n=4).^ePositive value indicates CO₂ emitted to the atmosphere and negative value indicates CO₂ absorbed by water surfaces.

regions (Teodoru et al. 2009; Koprivnjak et al. 2010; Butman & Raymond 2011). Since small streams are tightly connected to the landscape, they receive and process terrestrially derived organic C (e.g., Vannote et al. 1980). In a study conducted by Öquist et al. (2009), 90% of DIC originating from soil was released to the atmosphere as CO₂ within 200 m of the water entering the stream, suggesting subsurface inflow of DIC is rapidly evaded from streams. Arctic streams may also function as hotspots for CO₂ evasion which is particularly important to understand as permafrost C is likely to be initially mobilized into smaller headwater streams. Additionally, factors including increased photochemical degradation and residence times as well as increased autochthonous production, flocculation and sedimentation may result in lower rates of CO₂ accumulation in larger rivers. We may therefore expect downstream river CO₂ budgets to be influenced more by in-stream processes (e.g., microbial productivity), whereas smaller stream CO₂ patterns to be primarily driven by catchment characteristics and stream morphology.

Variability in stream pCO₂ (ranging from 274 to 9402 µatm) and *k* (ranging from 3.2 to 54.6 cm h⁻¹), resulted in consistently high and variable CO₂ evasion rates (ranging from −0.33 to 20.56 g C m⁻² d⁻¹). In a study by Alin et al. (2011) sensitivity analysis showed that *k* was particularly sensitive to changes in stream depth and water velocity, which may account for the variability in *k* observed here. Measured *k*₆₀₀ values in this study are comparable to floating chamber values reported in the literature with average values of 24.6, 17.6, and 18.0 cm h⁻¹ for streams, rivers and main stem, respectively (e.g., Vachon et al. 2010). Furthermore, Laudon et al. (2011) found that in heterogeneous catchments, the C quantity entering stream waters was regulated by a combined effect of hydrological mechanisms and the proportion of major landscape characteristics. In the northern region of the Kolyma River basin, floodplain streams on average had the highest pCO₂, whereas yedoma streams on average had the highest DOC concentrations. Furthermore, connecting streams had pCO₂ an order of magnitude lower than floodplain and yedoma streams, as lakes and wetlands draining into the stream likely process organic C before entry. It is therefore likely the lability of organic C sourced to the streams in this region differed: young C leached from floodplain vegetation throughout the growing season is generally comprised by low molecular weight, hydrophilic compounds that are rapidly biodegradable compared to more aromatic, higher molecular weight permafrost soils (e.g., Wickland et al. 2007).

Only half of the rivers in this region were super-saturated in CO₂ ($p\text{CO}_2$ averaged 412 ± 250 μatm), suggesting that rivers in this region were near equilibrium with respect to atmospheric CO₂ during the summer low-flow period. Similar respiration and production rates may partially explain these observations of low $p\text{CO}_2$. Measurements of BOD were consistent, suggesting low, yet continuous metabolism of organic C and the generation of CO₂. The general reduction in BOD from streams to rivers is also consistent with the preferential utilization of a more labile C fraction in smaller headwaters. In addition, rivers sampled in the Kolyma River basin are meandering, relatively shallow and therefore potentially conducive to in situ primary production during this time of the year. Significant phytoplankton growth was observed in the Panteleikha River during our study period, resulting $p\text{CO}_2$ declining from 219 to 5 μatm . Although rivers were found to act as both a net source and a net sink of atmospheric CO₂ during summer low-flow, this may vary seasonally when light availability and hydrologic conditions change.

Our study could not differentiate the source of CO₂ production between surface and subsurface terrestrial flow paths and in situ metabolism; however, a continuous flow of C is likely being sourced to the river network via surface or subsurface flow. We therefore hypothesize that surface and subsurface flow of terrestrial organic C supported the majority of CO₂ production. During low-flow conditions, the stable surface water volume and floodplain–river connectivity is typically reduced (Battin et al. 2008), resulting in consistent subsurface flow with sporadic floodplain–river surface flow during high precipitation events. Mann et al. (2012) found evidence in the Kolyma River main stem to suggest that dominant flow paths shifted over the year from the organic surface layer during spring freshet to flow through deeper soil horizons (i.e., yedoma soils rich in organic C) via deepening of the active layer during summer. Respiration of terrestrially derived organic matter is actively occurring across fluvial paths in the Kolyma River network, as DOC and BOD had a similar decrease from headwater streams to larger rivers during the summer low-flow period. Humborg et al. (2010) found DIC increased downstream within Swedish watersheds, suggesting groundwater can regulate a continuous inflow of CO₂ within a river network. However, the Kolyma River basin has been suggested to have relatively low annual flow-weighted DIC concentrations compared to other major Arctic rivers, of which 72% is bicarbonate or carbonate (i.e., not present as CO₂; Tank et al. 2012). Rather, high DOC flux and resulting high riverine DOC concentrations in Eurasian watersheds (Holmes et al.

2012) and high inputs of particulate organic matter from coastal erosion across the Siberian coast (Vonk et al. 2012) likely contribute substantially to the source of CO₂ production in the Kolyma River basin.

Areal CO₂ emission

Area-specific CO₂ evasion fluxes from streams were an order of magnitude greater than the Kolyma main stem, but the total CO₂ emission from these sub-categories was on the same order of magnitude given that the surface area of the Kolyma main stem covers about 32 times that of streams (within our bounded study area). Conversely, streams occupy a relatively small proportion of the total study area (ca. 0.2%), yet act as hotspots for CO₂ evasion due to typically high $p\text{CO}_2$ and k values.

Although current studies have begun to measure stream $p\text{CO}_2$ at regional scales, few studies have attempted to quantify gas exchange velocities and surface areas of small streams at regional scales. Unlike larger rivers and lakes, narrow and densely vegetated streams are difficult to detect in satellite imagery (Benstead & Leigh 2012) and upscaling current gas exchange at small spatial scales is problematic due to the variation between streams and larger water bodies (Raymond et al. 2012). Even with the use of GeoEye imagery, currently the highest spatial resolution imagery publicly available for this region (ca. 0.41–1.65 m), the smallest streams measured in situ were not detected. Therefore, estimates of stream surface area, inclusion of under-represented streams (using physical characteristics as a proxy), and directly measured k unique to streams allowed for improved spatially extrapolated field-based observations. In this study, stream width had the best predictive power ($r^2 = 0.66$) for our observed $p\text{CO}_2$. $p\text{CO}_2$ was negatively exponentially related to width, whereas $p\text{CO}_2$ in streams declined with an increase in width. This is an expected relationship, as past studies (e.g., Hope et al. 2001) have also found $p\text{CO}_2$ to decline along the stream gradient.

CO₂ evasion flux estimates from this study were compared to other regions (Table 5) to assess the overall relative importance of summer CO₂ emissions from the Kolyma River basin. It is important to note that comparisons among regions should be interpreted with caution as land cover, hydrologic processes, and sampling techniques may differ between studies. From these first-order comparisons, however, it is evident that CO₂ evasion from inland waters in the northern Kolyma River basin are comparable to inland water systems typical of Northern Hemisphere regions (temperate, boreal and Alaskan Arctic). We suggest that, driven by large contributions from small streams, the Kolyma River basin could be an

Table 5 A summary of CO₂ evasion fluxes from published studies of streams, rivers and main stem locations across different geographic regions in the Northern Hemisphere. Evasion estimates were adapted from the literature to be expressed as a loss of grams of C per m² of water surface area per day. The selection includes studies for which daily evasion estimates were available (or could be readily calculated) for summer (June–August). CO₂ evasion fluxes are recorded as a range and/or a mean of samples.

| Region | Watershed | CO ₂ evasion flux (g C m ⁻² d ⁻¹) | | | Reference |
|-----------|-----------------------------------|---|-----------------------|-----------------------|-----------------------|
| | | Streams | Rivers | Main stem | |
| Siberia | Kolyma River, Russia ^a | –0.33 to 26.56 8.59 | –0.77 to 1.27 0.01 | –0.62 to 1.36 0.46 | This study |
| Arctic | North Slope, Alaska | – | 0.02 to 0.15 0.09 | – | Kling et al. (1991) |
| Boreal | Eastman River, Canada | 3.12 | 0.39 | 0.19 | Teodoru et al. (2009) |
| Temperate | Brocky Burn, Scotland | 0.26 to 45.88 – | – | – | Hope et al. (2001) |

^aCalculated from all field-based samples; see Table 1.

important contributor to global inland water CO₂ emission. However, to provide this broad conclusion, annual flux estimates from the entire Kolyma River basin are required. Our findings may provide a predictive conceptual model that could be used in similar locations in the Arctic with fluvial systems underlain by permafrost.

To provide a broad estimate of the importance of C contributions from the Kolyma River basin at a watershed scale, results from the northern Kolyma River bounded study area (Fig. 3) were further scaled to the Panteleikha–Ambolikha watershed (Table 4). Extrapolating across the Panteleikha–Ambolikha watershed, our estimates suggest streams play a major role in CO₂ emission during summer low-flow, providing 86% of the total ca. 20.4×10^6 g C d⁻¹ estimated for the combined watershed (whereas the Ambolikha main stem and rivers accounted for the remaining 14%). The Panteleikha River acted as a net CO₂ sink (-8.5×10^6 g C d⁻¹) reducing the total watershed CO₂ emission to ca. 11.9×10^6 g C d⁻¹. Across the watershed, rivers (order 4–5) covered about three times more surface area than streams (order 1–3), yet streams emit about nine times more CO₂ per day compared to rivers. This broad GIS-based estimate of CO₂ emission from fluvial environments within the Panteleikha–Ambolikha watershed provides valuable insights into the fractional CO₂ contribution across the whole Kolyma River basin. These results suggest that although streams cover a small proportion of total inland water surface area, their fractional atmospheric CO₂ emission is substantial. In contrast, rivers have a larger surface water area and are close to equilibrium with atmospheric CO₂, contributing much less to overall watershed CO₂ emission during the summer low-flow period.

Future implications

In this study, we were able to approximate the three terms needed to estimate areal CO₂ emission: $p\text{CO}_2$, k , and water surface area. Our CO₂ emission estimates capture a diverse stream and river network in the northern region of the Kolyma River basin; however, regional diversity, seasonality, and lake measurements were not captured in this study. Current findings in boreal regions suggest CO₂ evasion from streams is highest during the summer (Koprivnjak et al. 2010). However, CO₂ evasion from large rivers and the Kolyma River main stem may be highest during the spring flood pulse when floodplains and rivers are connected and young fresh C is exported (Mann et al. 2012). To prevent overestimating annual CO₂ emission from streams and underestimating annual CO₂ emission from rivers, only CO₂ evasion fluxes during summer low-flow conditions were utilized in this study. Future studies need to consider how to incorporate additional seasons to arrive at accurate annual evasion. In addition, we neglected to address the role of lakes in this study. Lakes have the potential to significantly influence regional C evasion budgets within the Kolyma River basin, as they cover about 10% of the entire watershed area (Welp et al. 2005). Utilizing empirically-measured gas exchange velocities for a set of streams and rivers in the Kolyma River basin provided a basis for producing regionally representative values that improved the accuracy of CO₂ emission estimates. Applying generalized gas transfer velocities from the literature has been found to produce an error of up to 100% in CO₂ evasion fluxes (Wallin et al. 2011). Furthermore, overestimations caused by floating chambers is not consistent and is dependent on the turbulence regime, with a strong bias found in calm, low turbulent

(wind speed $<1\text{--}2\text{ m s}^{-1}$) environments (Vachon et al. 2010). Based on the overestimation ratio outlined in Vachon et al. (2010), our samples, with an average wind speed of ca. 3 m s^{-1} in rivers and an average current of ca. 15 cm s^{-1} in streams, have a mean overestimation ratio of 1.58 ± 0.34 . Finally, this study used the best available remotely sensed imagery during the summer low-flow period to estimate stream and river surface areas, but as new technology and satellite imagery become available, these estimates should be refined and should also include estimates of lake surface area.

Quantification of the net emission of CO₂ from freshwater ecosystems is necessary on a global scale (Cole et al. 2007), with particular regional emphasis placed on high-latitude ecosystems susceptible to C loss via permafrost thaw (Battin et al. 2009). This study provides a starting point for estimating regional CO₂ emission by incorporating spatial variability of $p\text{CO}_2$ and k during summer low flow from streams to rivers and representing total areal coverage of understudied headwater streams in the Kolyma River basin. The results of this study suggest hydrological flow paths and terrestrial derived C sources are key determinants of the observed spatial variability in stream CO₂ evasion, while in situ aquatic ecosystem processes likely play more of a role in river and main stem CO₂ evasion. A more detailed characterization of C cycling in the Kolyma River basin is needed to better quantify watershed-wide CO₂ emissions and more fully understand the mechanisms that deliver and generate CO₂ in the water column and subsequent atmospheric evasion. CO₂ evasion from water surfaces within the Kolyma River basin will depend on the environmental response of the surrounding permafrost-dominated landscape, requiring a sustained watershed-level analysis of the annual transport and processing of C as it moves with water from terrestrial uplands to the Arctic Ocean. Similar efforts are required in diverse Arctic regions to best quantify CO₂ emissions from the entire Arctic Ocean watershed and accurately assess the overall contribution of Arctic inland waters to the global C budget.

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