A Process Based Stream Network Model for Predicting CO_2 Concentrations and Fluxes at High Resolution

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Abstract

Inland waters are an important component of the global carbon budget, emitting CO_2 to the atmosphere. However, our ability to predict carbon fluxes from stream systems remains uncertain as small scales of pCO_2 variability within streams (10^0-10^2 m), which makes efforts relying on monitoring data uncertain. We incorporate CO_2 input and output fluxes into a stream network advection-reaction model, representing the first process-based representation of stream CO_2 dynamics at watershed scales. This model includes groundwater (GW) CO_2 inputs, water column (WC), and benthic hyporheic zone (BHZ) respiration, downstream advection, and atmospheric exchange. We evaluate this model against existing statistical methods including upscaling and multiple linear regressions through comparisons to high-resolution stream pCO_2 data collected across the East River Watershed in the Colorado Rocky Mountains (USA). The stream network model accurately captures topography-driven pCO_2 variability and significantly outperforms multiple linear regressions for predicting pCO_2. Further, the model provides estimates of CO_2 contributions from internal versus external sources suggesting that streams transition from GW- to BHZ-dominated sources between 3rd and 4th Strahler orders, with GW, BHZ, and WC accounting for 49.3, 50.6, and 0.1% of CO_2 fluxes from the watershed, respectively. Lastly, stream network model CO_2 fluxes are 4-12x times smaller than upscaling technique predictions, largely due to inverse correlations between stream pCO_2 and atmosphere exchange velocities. Taken together, this stream network model improves our ability to predict stream CO_2 dynamics and efflux. Furthermore, future applications to regional and global scales may result in a significant downward revision of global flux estimates.

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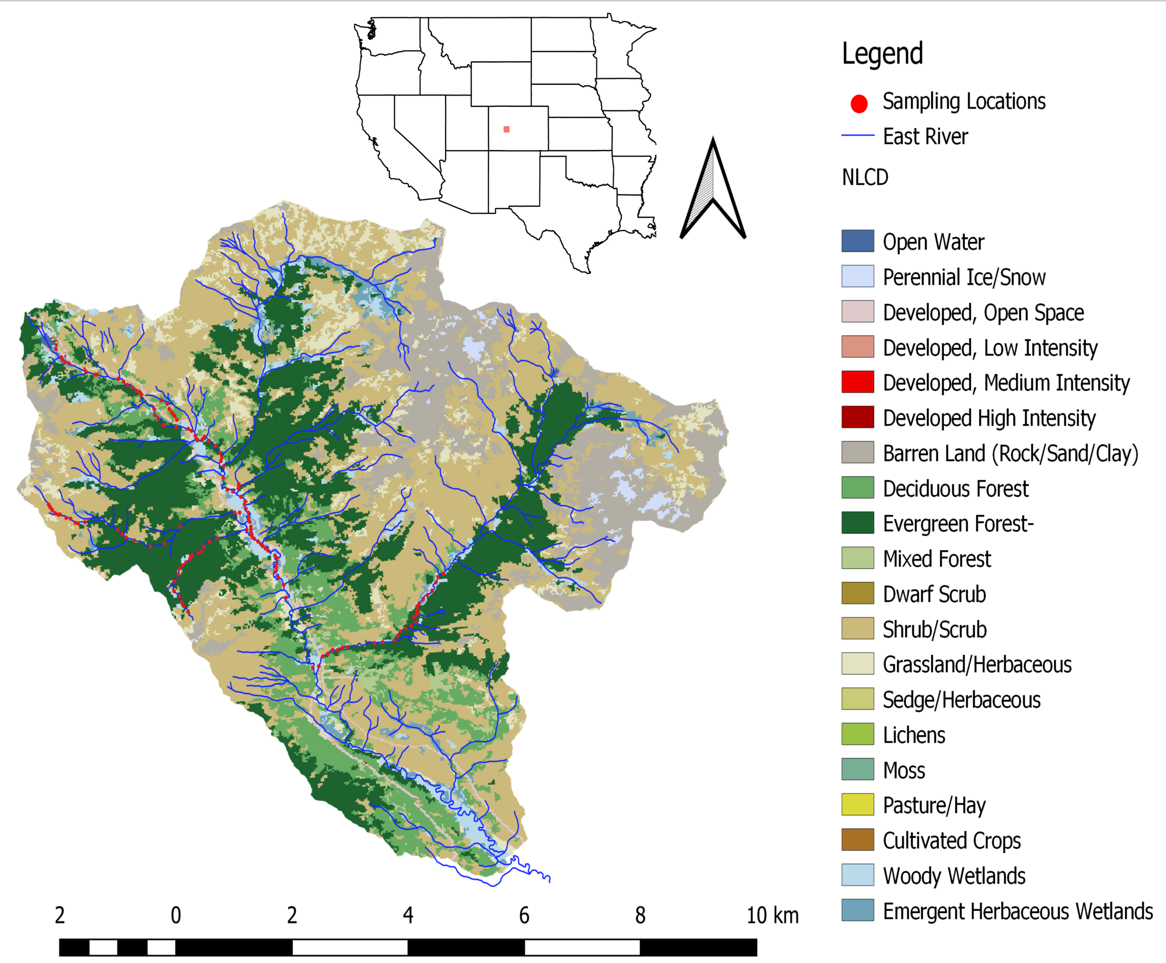
1. Background

The current estimate of atmospheric CO_2 fluxes from rivers and streams is uncertain ranging from 0.75 to 3.88 Pg C yr^{-1} (Drake et al 2018). This uncertainty is in part due to our inability to measure or predict CO_2 accurately at high resolution and across regions. Additionally current models used to upscale pCO_2 fluxes only provide the magnitude of estimated fluxes and little to no insight on the sources of the CO_2. We tested a process based stream network model to address these questions:

Can process-based models accurately predict pCO_2 at high-resolution?

Do process-based model offer new insights to the sources of CO_2?

2. East River Watershed, CO



We used the East River at the Rocky Mountain Biological Laboratory in Gothic Colorado (USA) as the test site for our CO_2 Stream Network Model.

The Watershed

- 87 km^2
- 2760-4123 m above sea level
- 1.2±0.26 m y^{-1}
- 1 ºC
- 1-5 Strahler order streams

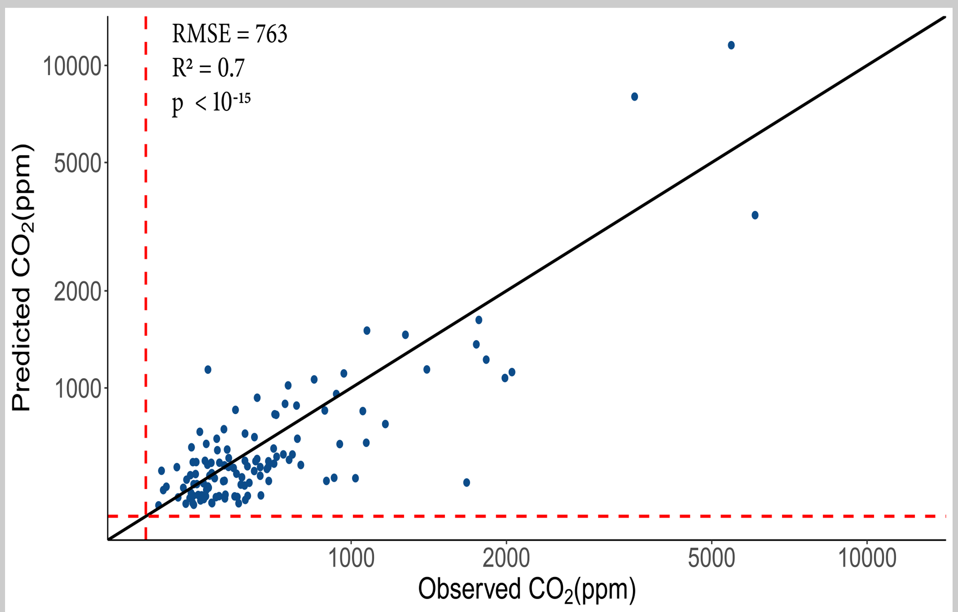
3. pCO_2 Model

$$\frac{dC}{dt} = -v\frac{dC}{dx} + \frac{1}{A}\frac{dQ}{dx}(C_{gw} - C) - k_{CO2}(C - C_{atm}) + k_{hz}(C_{hz} - C) + F_{wc}$$

Advection; Ground water input of CO_2; Losses from evasion; Benthic respiration; Water column respiration

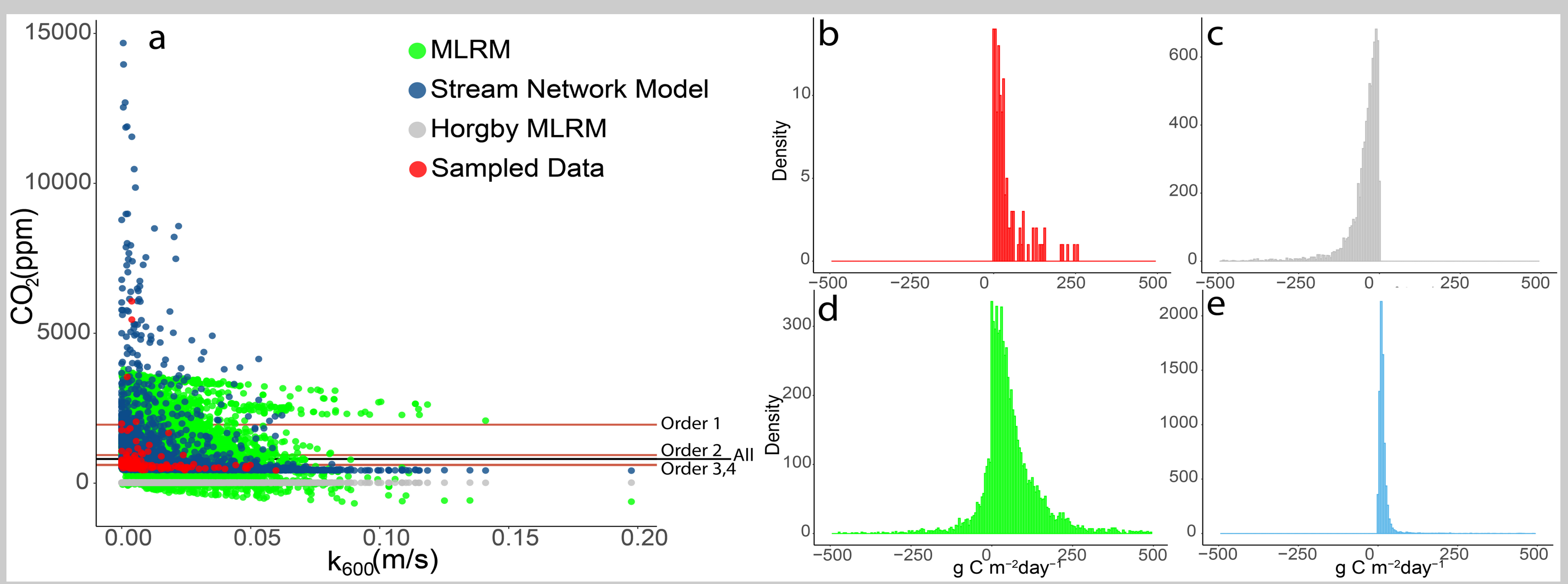
C: carbon (mol/L)
v: velocity (m/s)
A: stream cross-sectional area (m^2)
Q: discharge (m^3/s)
x: distance (m)
$*C_{gw}$: CO_2 in groundwater (mol/L)
C_{atm}: CO_2 at equilibrium with the atmosphere (mol/L)
$*C_{hz}$: hyporheic zone CO_2 (mol/L)
k_{hz}: hyporheic zone gas transfer velocity of CO_2 (m/s)
k_{CO2}: gas transfer velocity of CO_2 (m/s)
$*F_{wc}$: water column net respiration fluxes of $CO_{2(aq)}$ (mol/L/s)
* indicate free parameters

4. Validation & Results

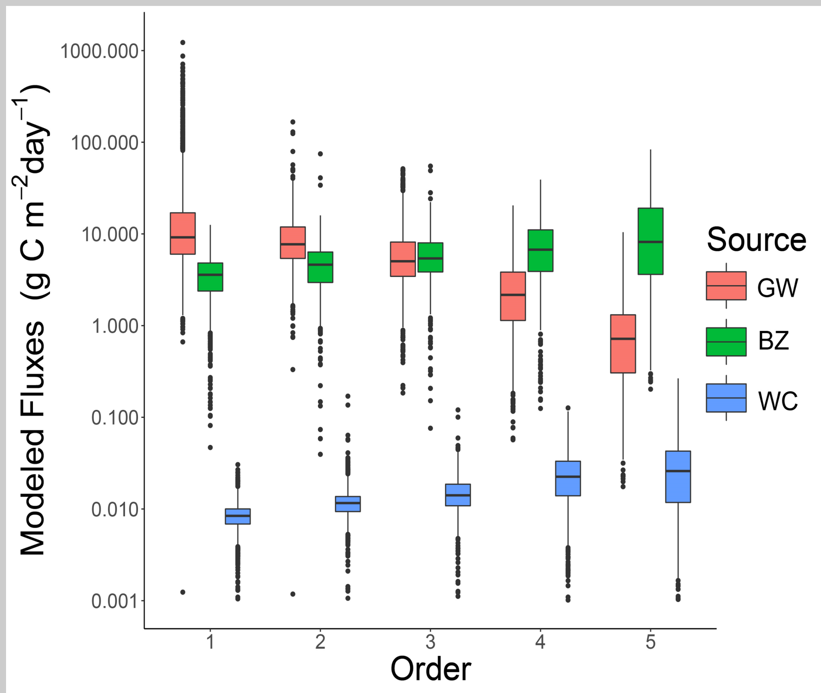


The Stream Network Model was validated using 121 sampled points across the East River. The validation samples include 1st to 5th Strahler order streams, with pCO_2 ranging from 423 to 6066, and a mean slope of 23°.

The Stream Network Model predicted pCO_2 is plotted on the Y axis with the measured pCO_2 on the X axis. The red dashed lines are atmospheric concentrations of CO_2 (400 ppm) and the black line is a 1:1 line.

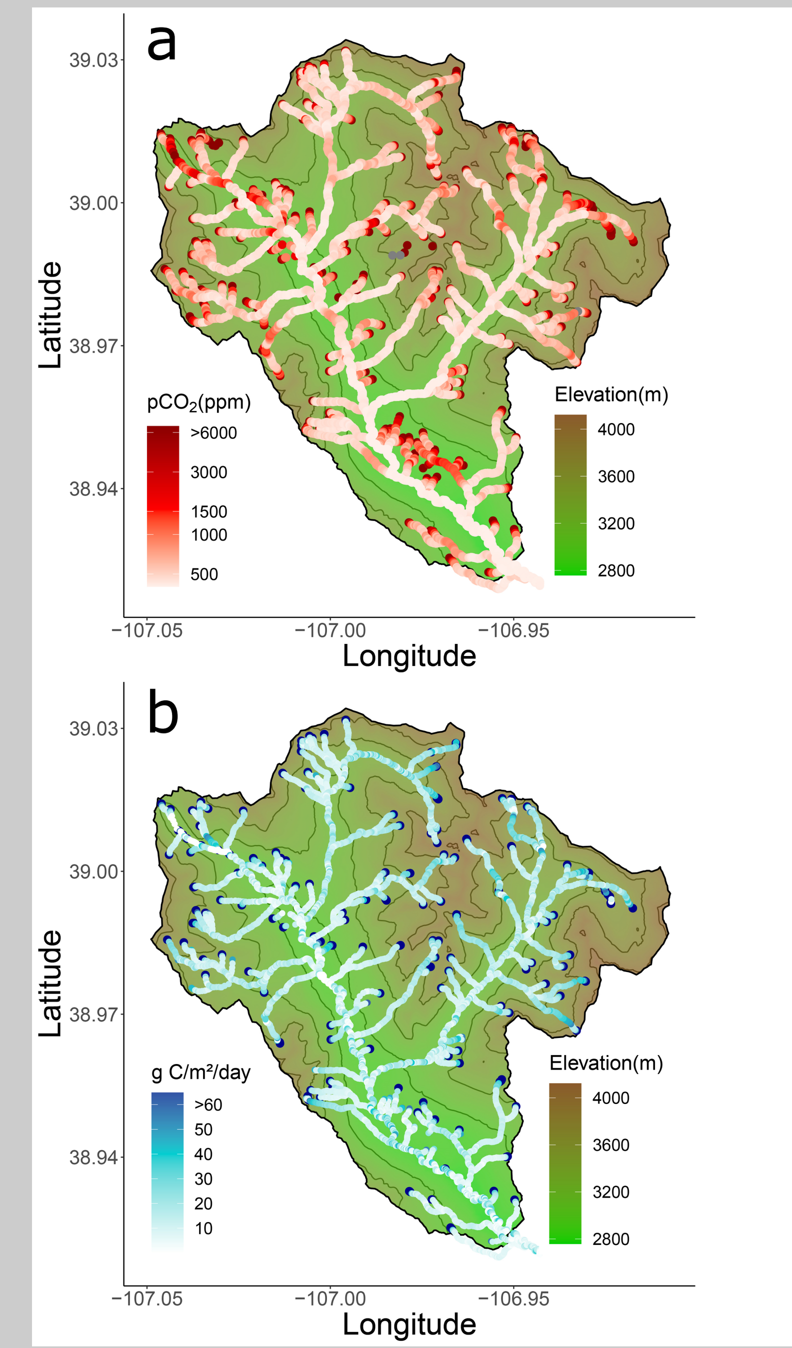


pCO_2 is often restricted by reaeration rates, as high k_{600} can rapidly equilibrium dissolved stream gases to atmospheric levels (Rocher-Ros et al., 2019). The stream network model was able to capture these patterns as seen in (a). Additionally, pCO_2 data is often right skewed as seen in the sampled data (b) which is reflected only in the Stream Network Model (e) and not in the multiple linear regression (MLRM) (d) or the Horgby mountain stream model (c) (Horgby et al., 2019).



In addition to pCO_2 predictions the Stream Network Model allows for a separation of CO_2 sources and therefor fluxes by groundwater (GW), benthic hyporheic zone respiration (BZ), and water column respiration (WC). With GW decreasing and respiration (BZ, WC) increasing as stream order increases agreeing with the findings of (Hotchkiss et al., 2015).

5. Discussion



The East River pCO_2 (ppm) in red (a) area normalized fluxes in blue (b)

- 18.2 g C m^{-2} day^{-1} mean predicted pCO_2 flux
- 3.9 Mg C day^{-1} total East River watershed flux
- First order reaches had the largest emissions totaling 1.2 Mg C day^{-1}
- 49.3% of CO_2 emitted is from groundwater
- 50.6% of CO_2 emitted is from benthic hyporheic respiration
- Water column respiration contributed 0.1%.

	pCO_2 range(ppm)	R^2	Fluxes Mg C/day	Sampled reach Fluxes Mg C/day
Sampled data	423 - 6066	-	-	0.16
Stream network Model	417 - 18000	0.7*	3.9	0.08
MLRM	-674 - 3795	0.21*	47.9	0.02
Horgby MLRM	12 - 32	0.27*	-16.1	-0.38
Upscaling by Mean pCO_2	806	-	16.9	0.39
Upscaling by Mean order pCO_2	603 - 1951	-	16.7	0.24

The predicted range of CO_2 and the R^2 with * denoting significance for each tested model. The Fluxes represent total predicted watershed C emissions whereas sample reach Fluxes represent C emissions of only the sampled points.

6. Conclusion

- **The process-based model outperformed statistical methods of predicting pCO_2 within the East River watershed.**
- **The stream network model provides estimates of external and internal CO_2 contributions, suggesting that benthic hyporheic exchange represents a significant portion of stream CO_2.**
- **Relationships between pCO_2 and atmosphere exchange velocities result in overestimates of CO_2 fluxes from statistical upscaling methods**

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