A Process-based Stream Network Model for Predicting CO_2 Concentrations and Fluxes

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Abstract

Inland waters are recognized as a significant source of CO_2 to the atmosphere; however, the global magnitude of this flux remains uncertain. In particular, CO_2 concentrations and fluxes in stream systems are extremely variable at scales of 10's to 100's of meters, complicating monitoring and prediction efforts. Thus, models of pCO_2 that capture these scales of spatial variability are necessary for the accurate prediction and monitoring of stream CO_2 fluxes. Despite a strong conceptual framework for the hydrologic processes that control stream CO_2, predictive models to date have been empirical, based on Strahler stream order and regressions between observed pCO_2 and landscape variables. We hypothesize that models incorporating well-described hydrologic processes may lead to new insights into the magnitude of various CO_2 sources and improve predictions. Here, we develop and apply a process-based stream network model of CO_2 based on NHDplus flowlines and driven by groundwater inputs, hyporheic exchange, water-column metabolism, advective transport, and atmospheric exchange. Model output is compared with 151 measurements of pCO_2 (424 - 9718 ppm) collected in August, 2019 across the upper East River watershed in Gothic, CO, a mountainous, high-elevation headwaters system within the Colorado River basin. We find that modeled pCO_2 captures observed spatial patterns and predicts measured values with a RMSE of ~250 ppm and R^2 of 0.47 ($p<10^{-15}$). Additionally, our process-based model performs significantly better than a multiple linear regression model between observations and a geomorphic variables (r^2=0.35, $p<10^{-7}$). Estimates from an optimized stream network model give additional insight into CO_2 sources, suggesting that groundwater accounts for 70-80% of evasion fluxes, hyporheic processes for 20-30%, and water-column metabolism for ~1% across the East River watershed. The ability of our model to predict pCO_2 at the spatial scales of variability may provide an important next step in estimating global CO_2 fluxes, and future research will test the predictive power of process-based models at regional and global scales.

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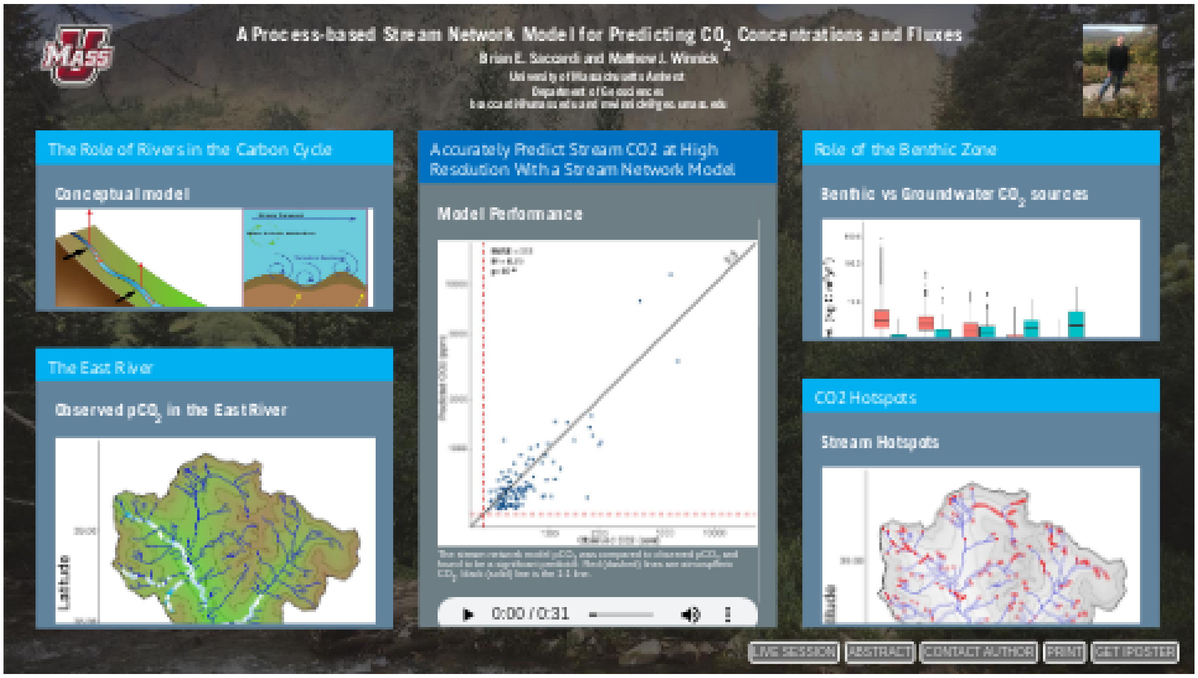

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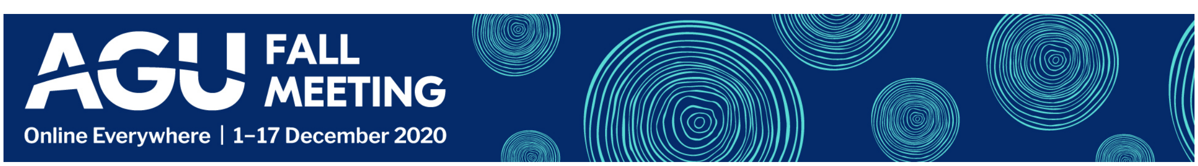
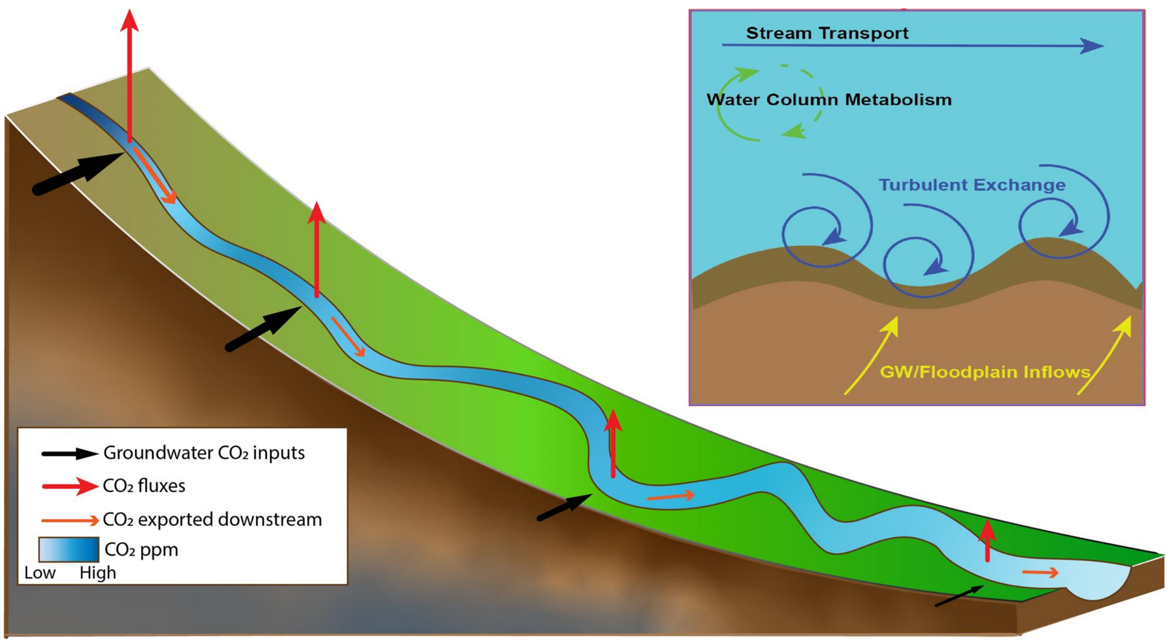


THE ROLE OF RIVERS IN THE CARBON CYCLE

Conceptual model



Conceptual model of CO_2 in river networks symbol sizes represent the magnitude of fluxes. Groundwater contributions of CO_2 (black arrow) being larger in headwaters and steadily decrease as discharge (Q) increases (Hotchkiss et al., 2015). Internally produced CO_2 (inset) remains relatively consent becoming a greater portion of CO_2 in larger rivers. the concentration of CO_2 (blue scale) decreases in steep sections or with reduced inputs.

Background

- Inland waters release CO_2 to the atmosphere (Cole et al., 2007).
- Rivers and streams make up 70% of the CO_2 emitted from inland waters (Raymond et al., 2013).
- Headwaters are hotspots contributing roughly 30% of the 3.88 Pg of C/yr emit into the atmosphere by rivers and streams (Drake et al., 2018).

Stream network model

$$\frac{dC}{dt} = \overbrace{-v\frac{dC}{dx}}^{\text{Advection}} + \underbrace{\frac{1}{A}\frac{dQ}{dx}(C_{gw} - C)}_{\text{Ground water input of } CO_2} \overbrace{- k_{CO2}(C - C_{atm})}^{\text{Losses from evasion}} + \underbrace{k_{hz}(C_{hz} - C)}_{\text{Benthic respiration}} + \overbrace{F_{wc}}^{\text{Water column respiration}}$$

Inputs

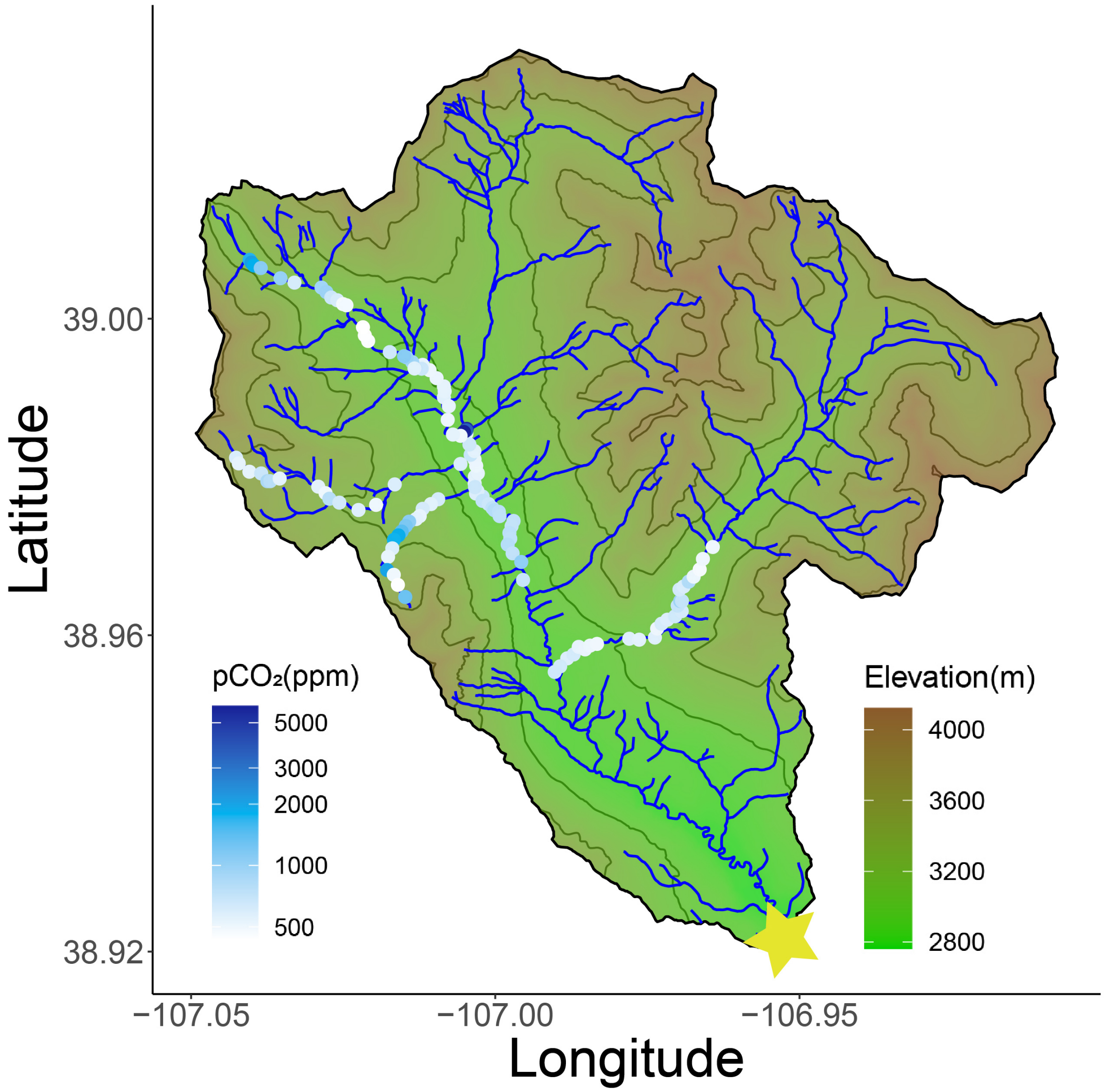
- C: carbon (mol/L)
- v: velocity (m/s)
- A: stream cross-sectional area (m^2)

- Q: discharge (m^3/s)
- x: distance (m)
- *C_{gw}: CO_2 in groundwater (mol/L)
- C_{atm}: CO_2 at equilibrated with the atmosphere (mol/L)
- *C_{hz}: hyporheic zone CO_2 (mol/L)
- k_{hz}: hyporheic zone gas transfer velocity of CO_2 (m/day)
- k_{CO2}: gas transfer velocity of CO_2 (m/day)
- Fwc: water column net respiration fluxes of $CO_{2(aq)}$ (mol/L/s)

* indicated free parameters

THE EAST RIVER

Observed pCO_2 in the East River



The East River watershed, sampled points pCO_2 are shown in red, elevation is shown in green and the stream network delineated at the star is blue.

Site

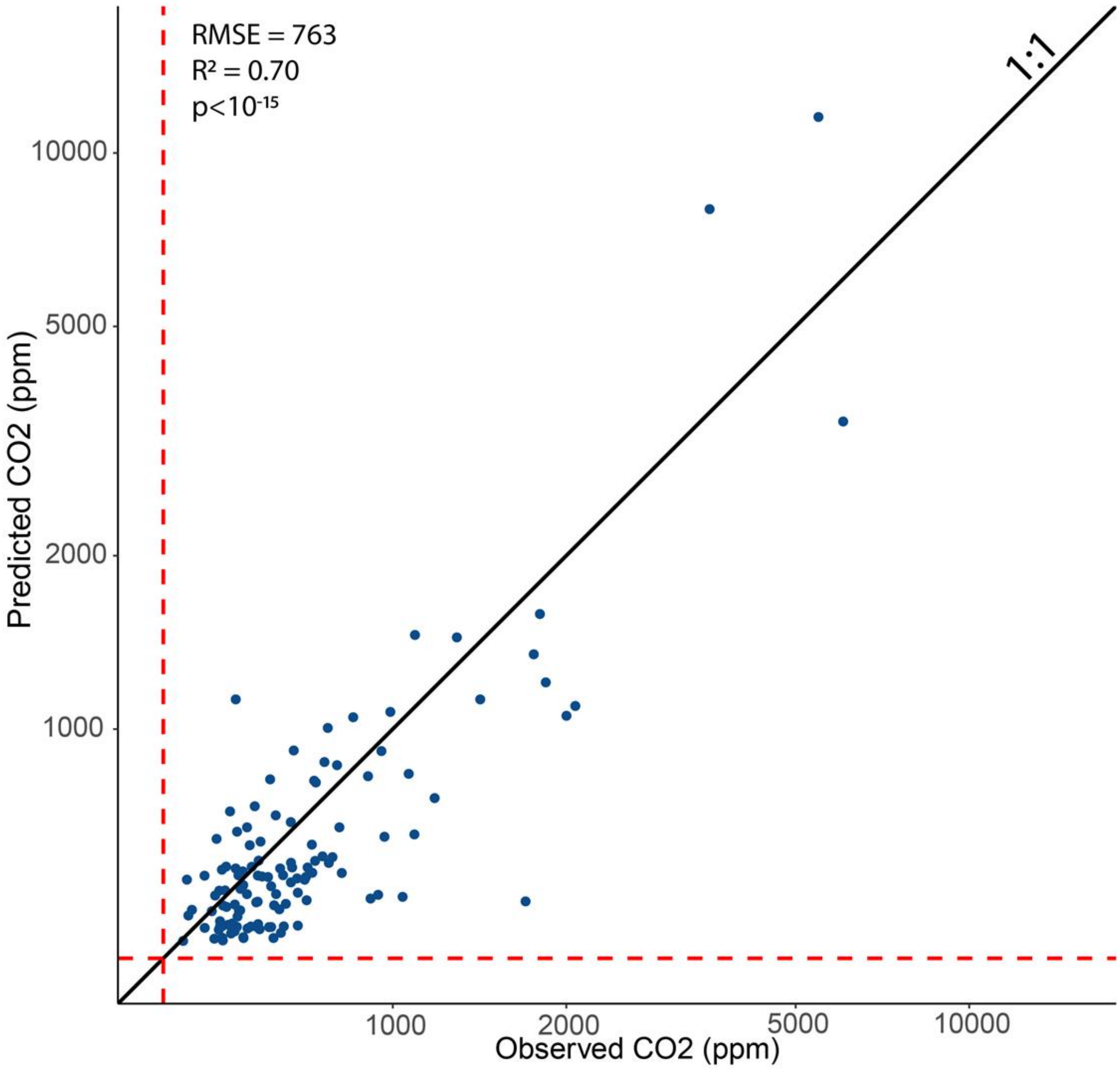
East River, Rocky Mountain Biological Laboratory, Gothic Colorado (USA).

The watershed

- 87 km^2 (delineated at the star)
- 1-5 Strahler order streams
- 2,760 to 4,123 m above sea level
- Average precipitation 1.23+0.26 m y^{-1}
- The annual average temperature is 1ºC

ACCURATELY PREDICT STREAM CO2 AT HIGH RESOLUTION WITH A STREAM NETWORK MODEL

Model Performance



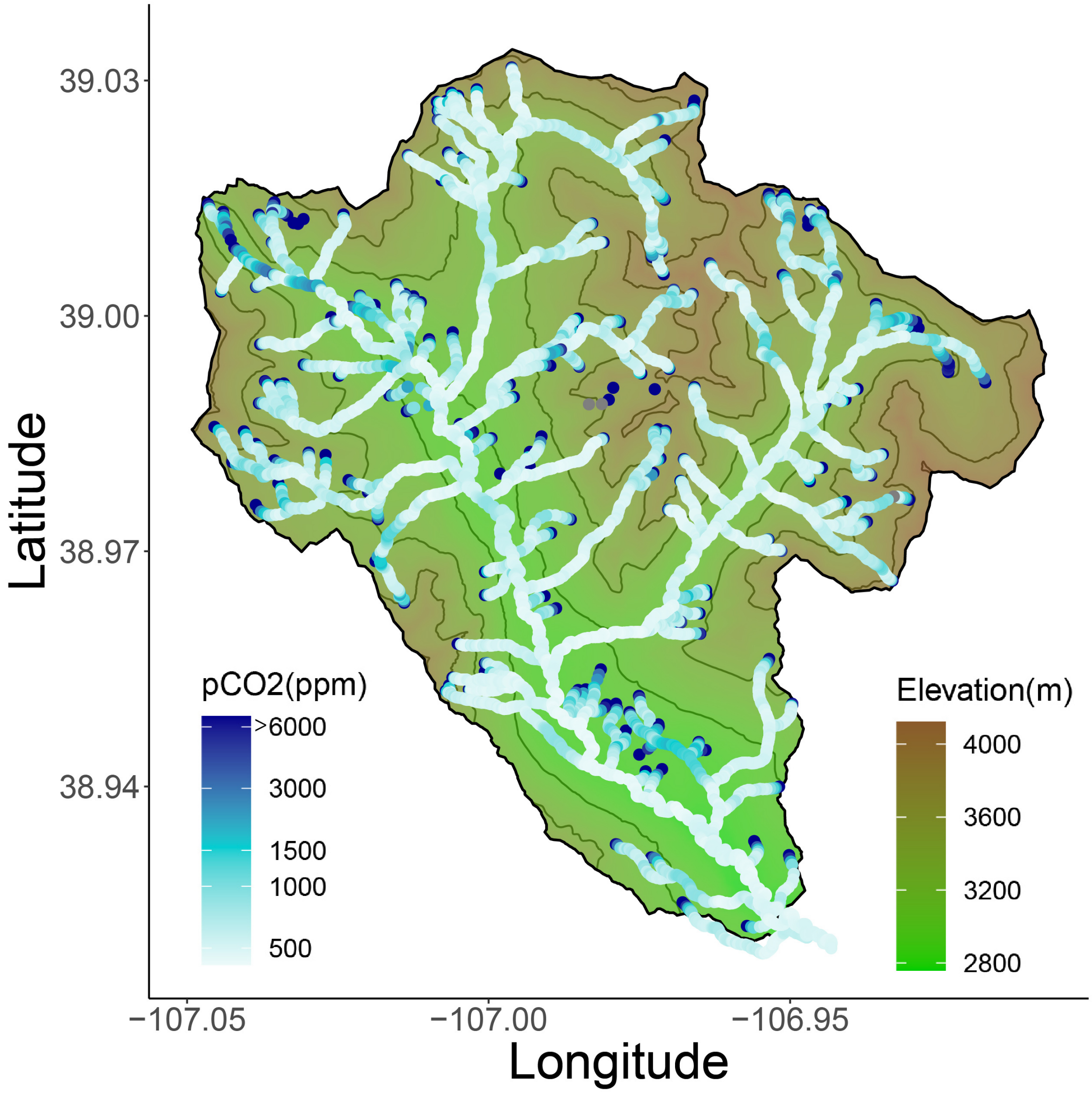
The stream network model pCO_2 was compared to observed pCO_2 and found to be a significant predictor. Red (dashed) lines are atmospheric CO_2, black (solid) line is the 1:1 line.

Problem Statment

Currently, statistical methods and multiple linear regressions are the most common methods of upscale CO_2. Therefore, this work represents the first proses based model to predict CO_2 and fluxes at watershed scales.

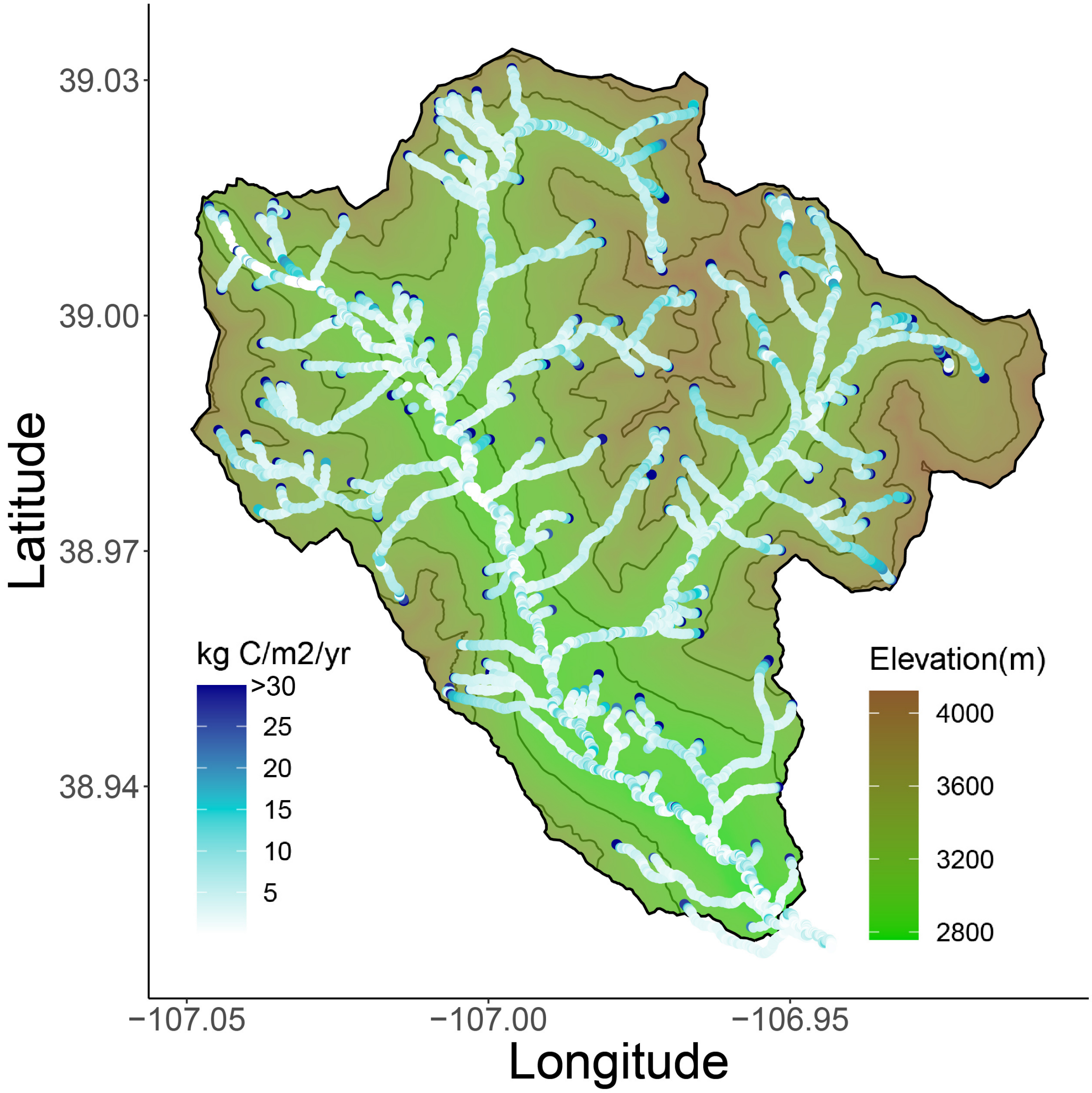
Model	R^2	RMSE	P	pCO_2 range(ppm)	Fluxes Gg C/yr
Stream network Model	0.70	763	$<10^{-15}$	416 - 18000	1.3
NPP Multiple linear regression	0.30	521	$<10^{-15}$	52 - 3315	11.7
Horgby mountain stream regression	0.27	1106	$<10^{-12}$	12 - 32	-5.9

Modeled pCO_2



As sampling CO_2 is not feasible at regional scales a stream network model provides pCO_2 at the spatial resolutions and accuracy required to predict fluxes (<100m). The model predicts a mean pCO_2 across the East River of 1087 ppm.

Modeled CO_2 Fluxes



Area normalized fluxes of CO_2 (blue) across the east river.

Model Uses

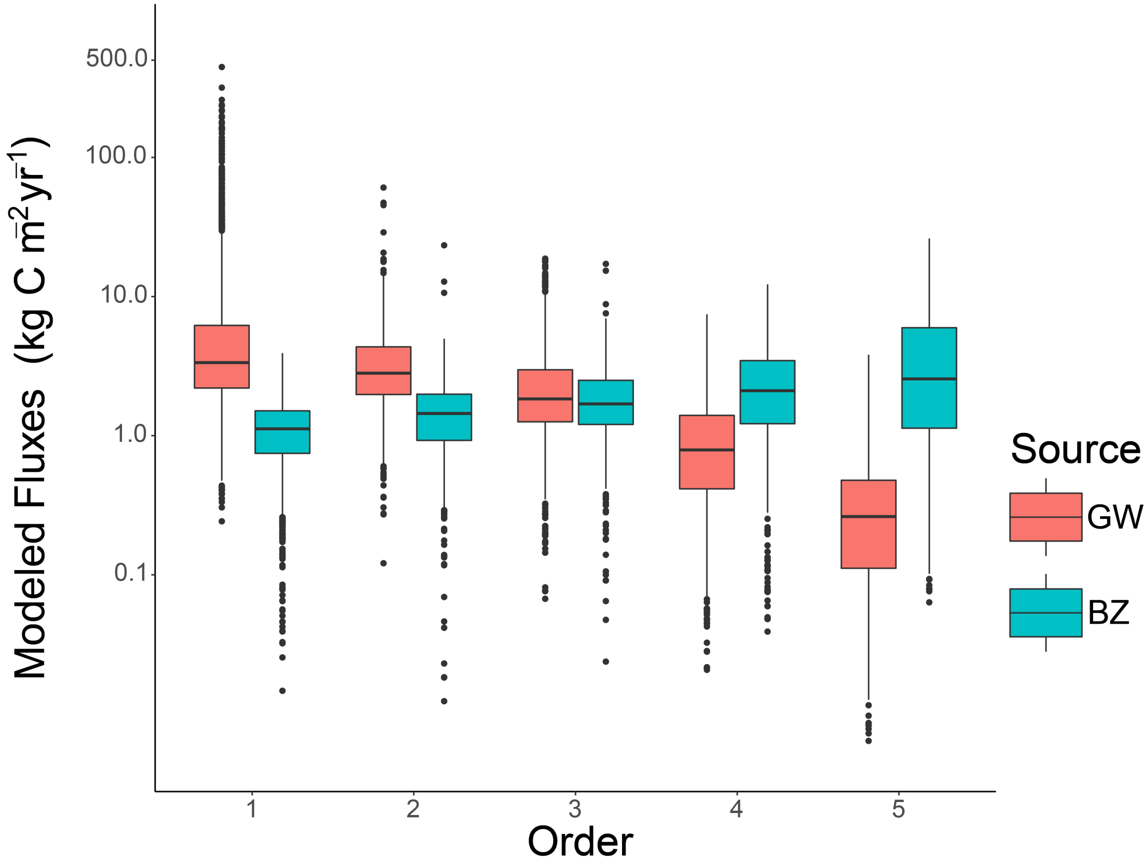
- Predicting pCO_2 and fluxes at regional scales with DEM and stream network data.
- Identify locations of transport or source limitation, for field studies.
- Identify hotspots across the landscape.
- Predict the importance of internal vs external production through stream order.

Conclusion

This work has achieved a stream network model capable of predicting pCO_2 and fluxes across river networks that can be used to test the current understanding of CO_2 processing in rivers.

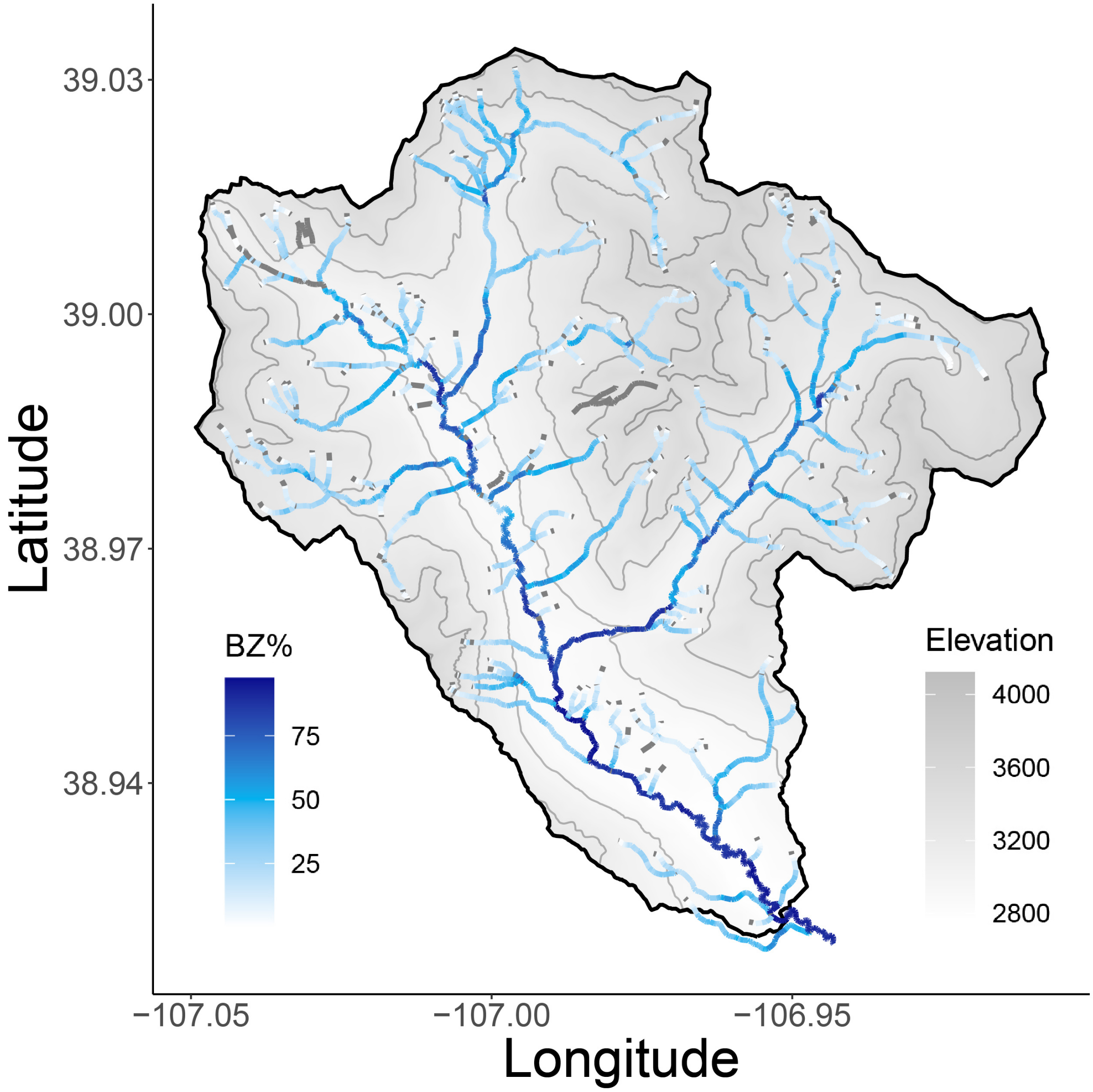
ROLE OF THE BENTHIC ZONE

Benthic vs Groundwater CO_2 sources



CO2 sources by order with groundwater inputs on the left in red and benthic respiration on the right in blue. 86 points that are included in the analysis are not shown as they are < 0.005.

Benthic CO_2 Patterns within East River



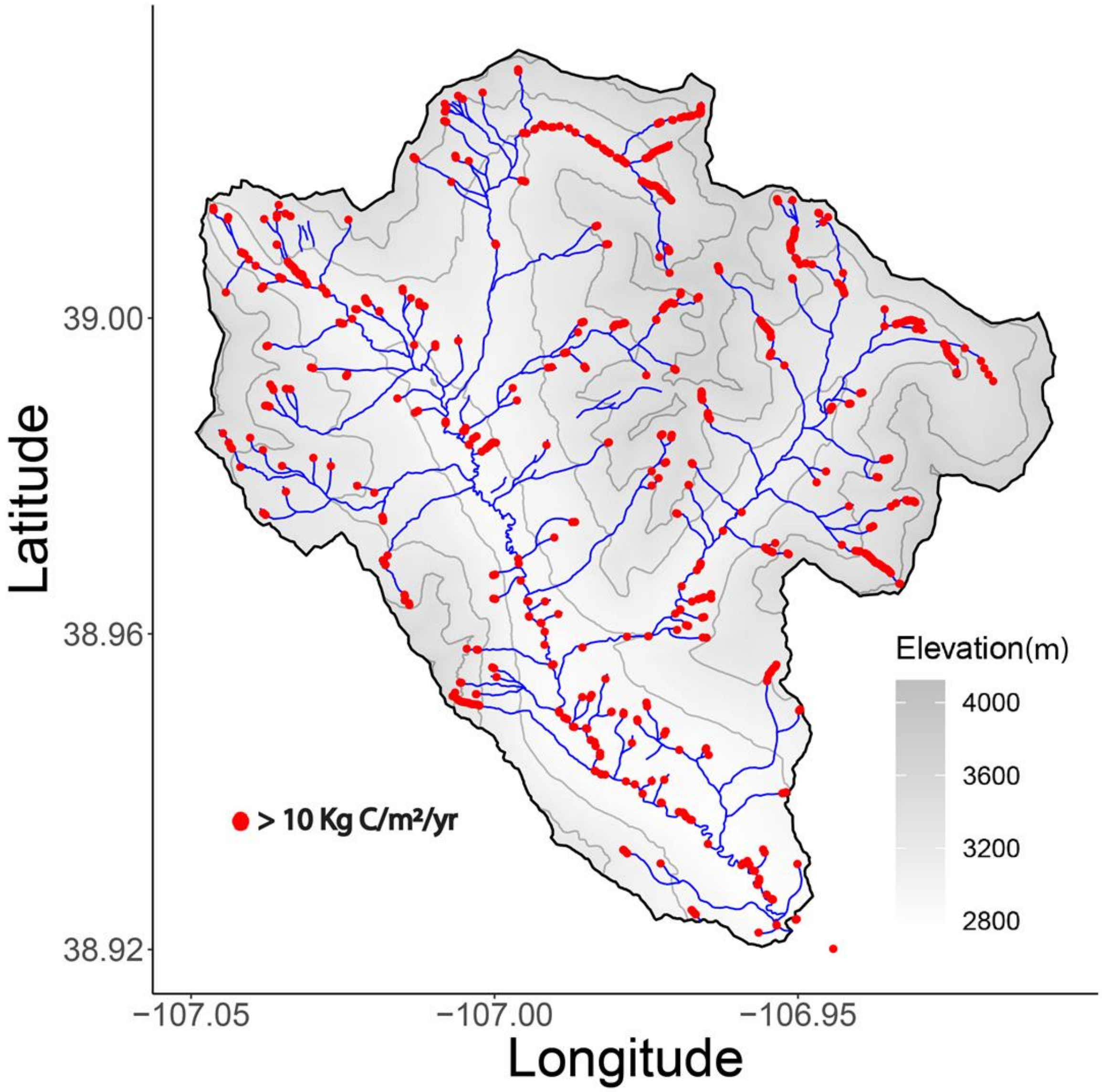
Percent benthic respiration shown in blue with headwaters having less benthic respiration derived CO_2 (lighter blue) than the East river mainstem (dark blue).

Conclusions

- Benthic respiration dominated sections exist in lower-order streams.
- Groundwater CO_2 fluxes decrease significantly with order.
  - Supports the patterns predicted in Hotchkiss et al. 2015 however the magnitude of benthic contribution is larger.
- Benthic CO_2 fluxes increased marginally with order.

CO2 HOTSPOTS

Stream Hotspots



hotspots defined as locations emitting more than 10 kg C/m^2/yr are shown in red with the east river shown in blue.

First-order Stream Hotspots

- The largest fluxes are found at points of stream emergence
- ~77% of hotspots are in first-order streams

Hotspots by order

- 17% of first-order streams by length are hotspots
- 4% of second-order streams by length are hotspots
- 6% of third-order streams by length are hotspots
- 4% of fourth-order streams by length are hotspots
- 9% of fifth-order streams by length are hotspots

Conclusions

- ~11% of the east river by length are CO_2 hotspots (>10 kg C/m^2/yr)

- Hotspots are predominantly found in first-order streams however large rivers may represent a smaller but significant source of hotspots.

ABSTRACT

Inland waters are recognized as a significant source of CO_2 to the atmosphere; however, the global magnitude of this flux remains uncertain. In particular, CO_2 concentrations and fluxes in stream systems are extremely variable at scales of 10's to 100's of meters, complicating monitoring and prediction efforts. Thus, models of pCO_2 that capture these scales of spatial variability are necessary for the accurate prediction and monitoring of stream CO_2 fluxes. Despite a strong conceptual framework for the hydrologic processes that control stream CO_2, predictive models to date have been empirical, based on Strahler stream order and regressions between observed pCO_2 and landscape variables. We hypothesize that models incorporating well-described hydrologic processes may lead to new insights into the magnitude of various CO_2 sources and improve predictions. Here, we develop and apply a process-based stream network model of CO_2 based on NHDplus flowlines and driven by groundwater inputs, hyporheic exchange, water-column metabolism, advective transport, and atmospheric exchange. Model output is compared with 151 measurements of pCO_2 (424 - 9718 ppm) collected in August, 2019 across the upper East River watershed in Gothic, CO, a mountainous, high-elevation headwaters system within the Colorado River basin. We find that modeled pCO_2 captures observed spatial patterns and predicts measured values with a RMSE of ~250 ppm and R^2 of 0.47 ($p<10^{-15}$). Additionally, our process-based model performs significantly better than a multiple linear regression model between observations and a geomorphic variables ($r^2=0.35$, $p<10^{-7}$). Estimates from an optimized stream network model give additional insight into CO_2 sources, suggesting that groundwater accounts for 70-80% of evasion fluxes, hyporheic processes for 20-30%, and water-column metabolism for ~1% across the East River watershed. The ability of our model to predict pCO_2 at the spatial scales of variability may provide an important next step in estimating global CO_2 fluxes, and future research will test the predictive power of process-based models at regional and global scales.