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Disentangling the effects of discharge and temperature on CO_2 production in the hyporheic zone of an alpine stream

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Gravel bars (GBs) represent sections of the streambed which are increasingly exposed to the atmosphere with decreasing discharge, and represent a direct interface between the "streambed" and atmosphere. These and other in-stream structures promote hyporheic exchange – inducing the downwelling of streamwater into the streambed where it mixes with groundwater, re-emerging over time periods ranging from seconds to days. Here, we investigated CO_2 concentration and fluxes across a GB within an Alpine cold water stream –Oberer Seebach (OSB), Austria over 3 seasonal flows (summer, autumn, winter). Utilizing high resolution topographic and water level data, in combination with measured physiochemical data, we developed steady state, variably saturated groundwater flow models for each of the three discharge scenarios using the multi-component reactive transport modelling program MIN3P, to elucidate the sources and potential drivers of CO_2 production and release from the OSB GB. Measured hydraulic heads (23 locations along the GB) over 3 different seasonal discharges corresponded closely to that of the model (NSE = 0.68 – 0.87 across seasons). Measured average GB CO_2 concentration was significantly higher (1.18 – 1.76 times) than that of streamwater across all seasons, identifying the GB as a source of CO_2 to the atmosphere. The majority of CO_2 within the sub-surface water (44 – 121%) could be explained by streamwater CO_2 concentrations, with increasing streamwater contributions from summer through autumn to winter (highest contribution), and spatially decreasing from the head toward the tail (lowest contribution) of the GB. Supported by the reactive transport groundwater model, these results suggest that CO_2 concentration increases along the downwelled flowpath from the head toward the tail of the GB, and that seasonal factors (temperature, discharge, dissolved organic matter (DOM) quantity and composition) likely affect CO_2 production within stream subsurface. Furthermore, the model results show that in the saturated parts below the OSB GB large amounts of CO_2 are produced, which is lost to the groundwater. Model residuals (range: -26% to 52% of observed CO_2 concentration) as the unexplained CO_2 production, were negatively related to the degree of humification of DOM, with increasingly higher degrees of humification across the GB from summer to winter, suggesting that higher CO_2 concentrations were the result of fresher and more bioavailable DOM (as characterized by absorbance and fluorescence measurements). Together our results show that the stream sub-surface is a key source of CO_2 and that GBs play a role in the production and partial release of this CO_2 to the atmosphere varying across seasons and discharges. Therefore, the effect of the OSB GB in terms of the carbon cycling and CO_2 outgassing likely occurs not only on the reach scale (direct outgassing of CO_2 from the GB), but also on the catchment scale, where downwelled streamwater under predominantly losing conditions lost to the GW system may upwell some distance downstream within the same or adjoining sub-catchments.