Research Brief

Carbon dioxide emissions from dry watercourses

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Abstract

Temporary watercourses that naturally cease to flow and run dry comprise a notable fraction of the world's river networks, yet estimates of global carbon dioxide (CO_2) emissions from watercourses do not consider emissions from these systems when they are dry. Using data from a sampling campaign in a Mediterranean river during the summer drought period, we demonstrate that the CO_2 efflux from dry watercourses can be substantial, comparable to that from adjacent terrestrial soils and higher than from running or stagnant waters. With an up-scaling approach, we show that including emissions from dry watercourses could increase the estimate of CO_2 emissions from watercourses in our study region by 0.6–15%. Moreover, our results tentatively illustrate that emissions from dry watercourses could be especially important in arid regions, increasing the estimate of global CO_2 emissions from watercourses by 0.4–9%. Albeit relatively small, the contribution of dry watercourses could help to constrain the highly uncertain magnitude of the land carbon sink. We foresee that in many areas of the world, the expected increase in the extent of temporary watercourses associated with future global change will increase the relevance of CO_2 emissions from dry watercourses.

Key words: carbon dioxide, carbon emissions, CO_2, dry streams, ephemeral streams, intermittent streams, temporary streams

Introduction

Watercourses have the ability to process carbon during downstream transport, thereby emitting significant amounts of carbon dioxide (CO_2) to the atmosphere (Cole et al. 2007, Battin et al. 2009). Temporary watercourses that naturally cease to flow and run dry comprise a notable fraction of the world's river networks (Larned et al. 2010, Raymond et al. 2013, Acuña et al. 2014). Yet, current estimates of global CO_2 emissions from watercourses (Tranvik et al. 2009, Aufdenkampe et al. 2011, Raymond et al. 2013) do not consider emissions from these systems when they are dry, probably because they are perceived to be inactive and outside the domain of inland waters.

Temporary watercourses may only be "aquatic" during certain periods of the year and can be dry most of the time. Our understanding of the biogeochemical processes that occur during this dry phase is limited (Larned et al. 2010, Steward et al. 2012), yet recent studies have shown that biofilms process organic carbon in dry watercourses (Zoppini and Marxsen 2011, Timoner et al. 2012), and that CO_2 can be released from these dry systems (Gallo et al. 2013). Emissions of CO_2 from dry watercourses should not be considered terrestrial emissions because the carbon processed in dry watercourses has either already left terrestrial ecosystems and entered the river network or has been produced within the river network. In addition, the sediments from dry watercourses and the terrestrial soils are different environments in terms of physical structure and biogeochemical dynamics (McIntyre et al. 2009, Larned et al. 2010, Steward et al. 2012). Thus, not considering CO_2 emissions from dry watercourses may overlook the role of a fundamental component of river networks in the carbon balance of inland waters.

Here, we used data from a sampling campaign in a Mediterranean river during the summer drought to explore

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the relevance of CO_2 emissions from dry watercourses compared to those from other aquatic and terrestrial environments. In addition, we used an up-scaling approach to examine the potential contribution of dry watercourses to CO_2 emissions from watercourses in our study region and on a global scale. We discuss the possible implications of our results for the assessment of the land carbon sink.

Methods

We measured the CO_2 efflux from the different environments typically found along a ~40 km section of a Mediterranean river (River Fluvià, northeast Spain) during the summer drought period (Sep 2013). Sampled environments included running water reaches, stagnant water stored in weirs and dams, and sediments from temporary running water reaches that had run dry a few weeks before. Running and stagnant waters were found along the whole section, whereas dry watercourses were found exclusively in the upper part of the section. The locations of the sites that were farthest upstream and farthest downstream were 42°07′24″N; 2°26′50″E and 42°11′12″N; 2°45′42″E, respectively. The catchment of the latter site was dominated by forests (84%), with relatively small proportions of agricultural land (14%) and urban land (3%). At each site we measured the CO_2 efflux with a floating or soil chamber coupled to a Fourier-transform-infrared (FTIR) spectrometer (Gasmet 4010, Finland). To compare our CO_2 effluxes from river environments with those from the terrestrial environment, we compiled 42 soil respiration measurements from the Mediterranean biome obtained from a global soil respiration database (Bond-Lamberty and Thomson 2012).

We estimated the percentage contribution of dry watercourses to the total effective area of all watercourses in each COastal Segmentation and related CATchments (COSCAT) region (Meybeck et al. 2006) using data provided by Raymond et al. (2013). The effective area of the dry watercourses was estimated by combining the percentage length of temporary streams with the number of dry days obtained from correlation analyses between hydrological and climatic variables (Raymond et al. 2013). The total effective area of all watercourses was estimated using hydraulic equations (Raymond et al. 2013).

To estimate the annual CO_2 emissions from dry watercourses in each COSCAT region, we multiplied the effective area occupied by dry watercourses in each COSCAT region by the median CO_2 efflux measured in our dry watercourses. To determine the percentage contribution of dry watercourses to the total emission of CO_2 from all watercourses in each COSCAT region, we combined our estimated emissions from dry watercourses with those from flowing watercourses calculated by Raymond et al. (2013). We estimated the global annual emissions from dry watercourses by summing the values from all COSCAT regions. In addition, we estimated the global percentage contribution of dry watercourses to the total CO_2 emissions from watercourses by combining our up-scaled global annual emissions from dry watercourses with those from flowing watercourses reported by Raymond et al. (2013).

We acknowledge that figures obtained in this way should be viewed with caution because the up-scaling was based on limited data on dry watercourse emissions. Our intention, however, was not to provide a definitive, unbiased estimate of dry watercourse emissions, but, in a first approach, to attempt to obtain an estimate of their magnitude. We also report emissions using the minimum and maximum CO_2 efflux from dry watercourses found in the compiled dataset (our study and Gallo et al. 2013) to highlight the large uncertainty that results from the scarcity of data on the efflux of CO_2 from dry watercourses.

Results

At our study sites, the CO_2 efflux from dry watercourses (median 212 mmol m^{-2} d^{-1}; range 36–455 mmol m^{-2} d^{-1}) was highly variable but comparable to the CO_2 efflux from the compiled dataset of Mediterranean soils (median 188 mmol m^{-2} d^{-1}; range 44–371 mmol m^{-2} d^{-1}) and significantly higher than the CO_2 efflux from running waters (median 79 mmol m^{-2} d^{-1}; range 41–96 mmol m^{-2} d^{-1}) and stagnant waters (median 24 mmol m^{-2} d^{-1}; range 22–41 mmol m^{-2} d^{-1}; Fig. 1).

The percentage contribution of dry watercourses to the total effective area of all watercourses in each COSCAT region was highly variable, with values ranging from 0 to 73% (Fig. 2). In COSCAT region 418, which included our sampling sites, dry watercourses accounted for 15% (352 km^2) of the total effective area of all watercourses

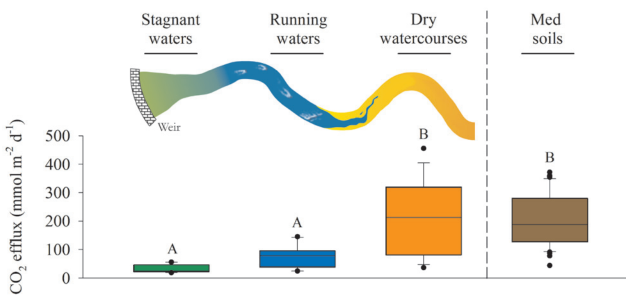

Fig 1. CO_2 efflux measured from stagnant waters (n = 13), running waters (n = 12), and dry watercourses (n = 17) found along a ~40 km section of a Mediterranean river (River Fluvià, northeastern Iberian Peninsula) during the summer drought period (Sep 2013) and from soils in the Mediterranean biome (n = 42; data from Bond-Lamberty and Thompson 2012). Box plots display the 10th, 25th, 50th, 75th, and 90th percentiles, and individual outliers. Environment had a significant effect on CO_2 efflux (Kruskal–Wallis test, $P < 0.001$); capital letters group environments following a pairwise Dunn's test ($P < 0.05$).

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(2432 km^2). Globally, dry watercourses accounted for at least half of the total effective area of all watercourses in 16% of the COSCAT regions, and for at least one-third in 44% of the regions. The relevance of dry watercourses was highest in arid regions around 30°N and 30°S (Fig. 2). Unexpectedly, the relevance of dry watercourses was also high in some boreal COSCAT regions, which may reflect the limitations of the empirical approach used to evaluate the areal extent of dry watercourses (PA Raymond, Yale University, February 2014, pers. comm.).

In the COSCAT region 418, our up-scaling approach provided a median[min-max] CO_2 emission value from dry watercourses of 0.3[0.2–0.7] Tg yr^{-1} C, which represents an increase of 7.0[0.6–15]% with respect to the most recent estimate of total CO_2 emissions from watercourses in this region (4.7 Tg yr^{-1} C; Raymond et al. 2013). Furthermore, our up-scaling approach provided a global CO_2 emission value from dry watercourses of 0.08[0.01–0.17] Pg yr^{-1} C, which represents an increase of 4.4[0.4–9]% with respect to the most recent global estimate for CO_2 emissions from watercourses (1.8 Pg yr^{-1} C; Raymond et al. 2013). Interestingly, by comparing our up-scaled emissions with those estimated by Raymond et al. (2013), we found that emissions from dry watercourses could account for at least half of the CO2 emissions from all watercourses in 23[0.4–48]% of the COSCAT regions of the world, and for at least one-third in 37[0.9–54]% of the regions (Fig. 3).

Discussion

Our results from a sampling campaign in a Mediterranean river during the summer drought demonstrate that dry watercourses are not inert in terms of CO_2 exchange with the atmosphere, and that CO_2 efflux from these environments can be substantial and highly heterogeneous in space. These results are in line with studies in wetlands, where increases in CO_2 emissions after drying have been widely reported (Moore and Knowles 1989, Freeman et al. 1993, Fenner and Freeman 2011). Moreover, our CO_2 efflux from dry watercourses was generally slightly above values found by Gallo et al. (2013) for dry desert streams in the North American Southwest (range 19–65 mmol m^{-2} d^{-1}), in what to our knowledge is the only previous study reporting CO_2 emissions from dry watercourses. This result suggests that, similar to soils, there may be significant regional differences in CO_2 emissions from dry watercourses. Note that our sampling campaign in a single river section covered a wider range of CO_2 emissions than the most complete dataset for respiration in Mediterranean soils. In soils, the CO_2 efflux is generally higher in warmer and wetter regions than in colder and drier regions (Yiqi and Zhou 2010). The sensitivity of CO_2 emissions from dry watercourses to environmental conditions (e.g., temperature, humidity, organic matter content, and substrate type) could not be assessed with the available data, however, indicating that further studies should be conducted on this topic.

The similar CO_2 emissions from dry watercourses and soils do not necessarily imply that these environments are functionally equivalent in terms of carbon dynamics. Sediments from dry watercourses and terrestrial soils diverge strongly in their physical structure and exhibit fundamental differences in carbon supply, storage, processing, and lateral transport (McIntyre et al. 2009, Larned et al. 2010, Steward et al. 2012). Thus, it cannot be assumed that CO_2 emissions from these environments have the same sensitivity to environmental factors. Most important, carbon processed in dry watercourses has either already left terrestrial ecosystems and entered the river network or has been produced within the river network. Thus, considering dry watercourses as terrestrial soils, when they should be considered an integral part of river networks, is conceptually problematic and may lead to an incorrect understanding of carbon processing in inland waters, especially in arid regions.

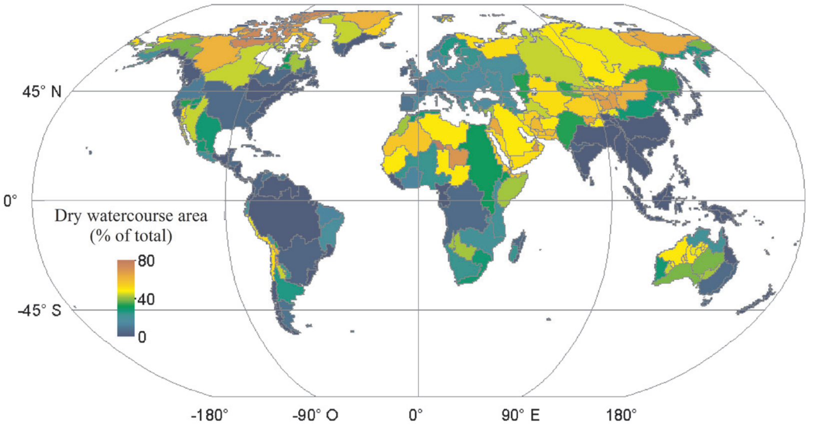

Fig 2. Estimated percentage contribution of dry watercourses to the total effective area of all watercourses in each COSCAT region. The areal contribution of dry watercourses was estimated after Raymond et al. (2013).

The estimates of the percentage contribution of dry watercourses to the total effective area of dry watercourses in our study region and worldwide agree with other regional estimates showing that stream drying is widespread in many areas of the world (Larned et al. 2010, Acuña et al. 2014). This result suggests a high potential contribution of dry watercourses to CO_2 emissions from the world's river networks. The up-scaling to our study region (COSCAT 418) indicates that including emissions from dry watercourses could increase the estimate of CO_2 emissions from watercourses by 0.6–15%. At the global scale, the up-scaling approach shows that emissions from dry watercourses could be especially important in arid regions around 30°N and 30°S, increasing the estimate of

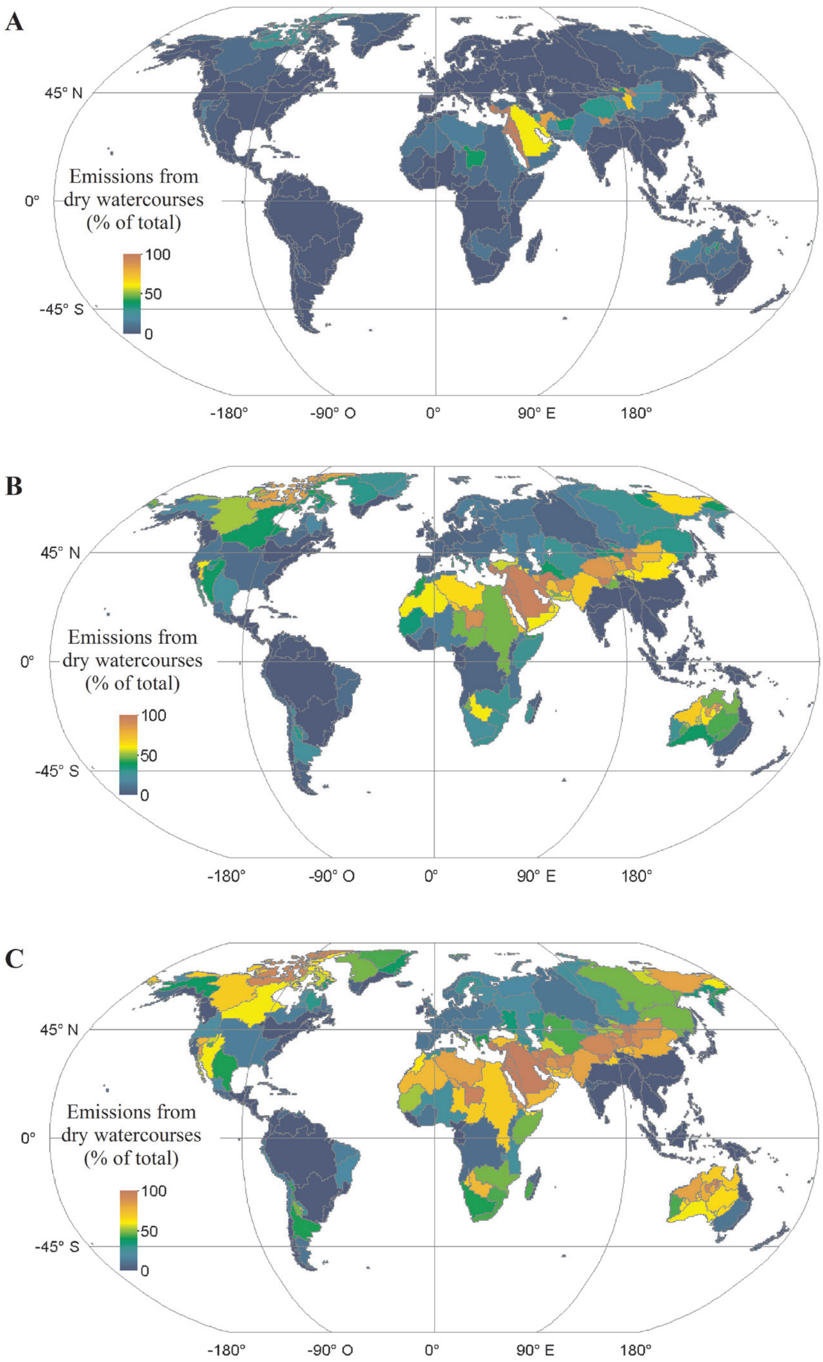

Fig. 3. Estimated percentage contribution of dry watercourses to the total emission of CO_2 from all watercourses in each COSCAT region. We built 3 scenarios using the minimum (panel A), median (panel B), and maximum (panel C) CO_2 efflux from dry watercourses reported in the literature (Gallo et al. 2013) and in this study (see Fig. 1).

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global CO_2 emissions from watercourses by 0.4–9%. Overall, our results indicate that taking into account CO_2 emissions from dry watercourses may have only a small effect on the estimate of global CO_2 emissions from inland waters. Yet, our results also indicate that the efflux of CO_2 from dry watercourses may substantially contribute to, and even dominate, the CO_2 balance of watercourses in arid regions worldwide.

We acknowledge that our results represent only a first rough estimate of the role of the dry phase of temporary watercourses on CO_2 emissions from river networks. Our up-scaling approach was based on measurements of CO_2 efflux from dry watercourses from only 2 sites: a section of an Iberian Mediterranean river (this study) and a few desert streams of the North American Southwest (Gallo et al. 2013). Despite these studies covering a wide range of CO_2 efflux values, they may be representative of only some of the COSCAT regions of the world. The large differences in the results from our up-scaling approach using the minimum and maximum CO_2 efflux values show the need for further studies covering wider geographical scales to constrain these estimates. Previous studies in streams (Gallo et al. 2013) and wetlands (Fenner and Freeman 2011) have shown that CO_2 emissions during the dry phase can be temporarily highly dynamic, however, especially during precipitation events. Thus, by not considering such "hot moments" of CO_2 emission, we may have underestimated the gaseous efflux from dry watercourses. Last but not least, although the approach of Raymond et al. (2013) used in our study allowed us to approximate the areal extent of dry watercourses on regional and global scales, it most likely failed to capture some important parts of the river network, such as first-order ephemeral streams (Benstead and Leigh 2012). Thus, considering all uncertainties, our results are probably a conservative estimate of the significance of dry watercourses for CO_2 emissions from inland waters.

Emissions of CO_2 from inland waters have attracted the attention of researchers because of their potential impact on current estimates of the land anthropogenic carbon sink (Regnier et al. 2013). Our estimate for total CO_2 emissions from dry watercourses was only 3.2[0.4–6.8]% of the current estimate for the land sink (2.5 Pg yr^{-1} C; Ciais et al. 2013). The same percentage for a region containing vast arid and semiarid areas like Australia, however, almost doubles to 7.0[0.7–15.7]% (for an estimated sink of 0.04 Pg yr^{-1} C; Haverd et al. 2013), suggesting that the role of dry watercourses on the continental carbon cycle may be quantifiable in dry areas of the world.

A fundamental question that arises from our study is how to incorporate emissions from dry watercourses into global and regional carbon assessments of the land carbon sink. This is relatively easy when using residual global calculations (e.g., Regnier et al. 2013) or bottom-up approaches based on inventories (e.g., Tupek et al. 2010) because in these methods the rest of the carbon fluxes included in the calculations can be considered unaffected by emissions from inland waters (including emissions from dry watercourses). In comparison, atmospheric CO_2 inversion models (Ciais et al. 2011) and global terrestrial ecosystem models (Piao et al. 2013) that use carbon fluxes obtained with eddy-covariance towers may integrate the signal from inland waters into that of the surrounding terrestrial landscapes. In such situations we cannot add emissions from dry watercourses to existing estimates without a substantial risk of double accounting. The reverse situation, however, may also imply that some conclusions regarding the role played by vegetation and soils in the land sink are biased because of the confounding effect of inland water emissions if these are not taken into account in the calibration of terrestrial ecosystem models.

The magnitude of the emissions reported here suggests that estimates of the land sink or the current parameterization of vegetation/soil models are not severely affected by the omission of dry watercourses alone; however, recent research on the land carbon sink suggests that to disentangle its exact nature and to reduce the high uncertainty around its magnitude we need to better understand all processes that may play a significant role, even if this role is small (Ciais et al. 2013). Recent findings firmly support the idea that carbon processing in inland waters is one of the missed processes that need to be incorporated into land carbon sink estimates to constrain their uncertainty (Regnier et al. 2013). This study suggests dry watercourses be considered as an integral biogeochemical element of inland waters.

In conclusion, available evidence suggests that the contribution of the dry phase of temporary watercourses to CO_2 emissions from inland waters must not be ignored and should be further investigated. This is especially important if we consider that the expected increase in the spatial and temporal extent of temporary watercourses that will result from global change (Palmer et al. 2008) will further increase the relevance of dry watercourses for global CO_2 emissions from inland waters in many areas of the world.

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