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¡Cuba! River Water Chemistry Reveals Rapid Chemical Weathering, the Echo of Uplift, and the Promise of More Sustainable Agriculture

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ABSTRACT

For the first time in more than half a century, a joint Cuban/American science team has worked together to quantify the impacts of chemical weathering and sustainable agriculture on river water quality in Cuba—the largest and most populous Caribbean island. Such data are critical as the world strives to meet sustainable development goals and for understanding rates of landscape change in the tropics, an understudied region. To characterize the landscape, we collected and analyzed water samples from 25 rivers in central Cuba where upstream land use varies from forested to agricultural.

Cuban river waters bear the fingerprint of the diverse rock types underlying the island, and many carry exceptionally high dissolved loads. Chemical denudation rates are mostly among the top 25% globally and are similar to those measured in other Caribbean islands. High rates of solute export and the distinct composition of the waters in specific basins suggest flow paths that bring river source waters into contact with fresh, weatherable rock—unusual in a warm, wet, tropical climate where weathering should extend deep below the surface. Tectonically driven uplift likely maintains the supply of weatherable material, leading to channel incision and, thus, to the exposure of bedrock in many river channels.

Despite centuries of agriculture, the impact on these rivers' biogeochemistry is limited. Although river water in many central Cuban rivers has high levels of *E. coli* bacteria, likely sourced from livestock,

concentrations of dissolved nitrogen are far lower than other areas where intensive agriculture is practiced, such as the Mississippi River Basin. This suggests the benefits of Cuba's shift to conservation agriculture after 1990 and provides a model for more sustainable agriculture worldwide.

INTRODUCTION

The Republic of Cuba (Fig. 1) has more than 11 million inhabitants, but there has been little collaboration between U.S. and Cuban scientists for more than half a century although only 160 km separates the two countries (Feder, 2018). River biogeochemistry data, which are sparse in tropical regions, are needed to guide sustainable development in Cuba and, by example, in other tropical and island nations.

Here, we present and interpret extensive new data characterizing river waters in

central Cuba, the result of a bi-national, collaborative field campaign. Biogeochemical analyses allow us to address fundamental geologic questions, such as the pace of chemical weathering in the tropics, as well as applied environmental questions related to the quality of river water and human impacts on a landscape where small-scale, sustainable farming has replaced substantial swaths of industrial agriculture (The Guardian, 2017).

BACKGROUND AND METHODS

Cuba's wet, warm tropical landscape is dominated by mountains (up to 1917 m above sea level [asl] in the east, 500–700 m asl elsewhere) running parallel to the north and south coasts (Fig. 1). Mainly forested uplands descend into farmed rolling plains and mangrove-lined, low-lying coastal estuaries. The climate is summer-wet and

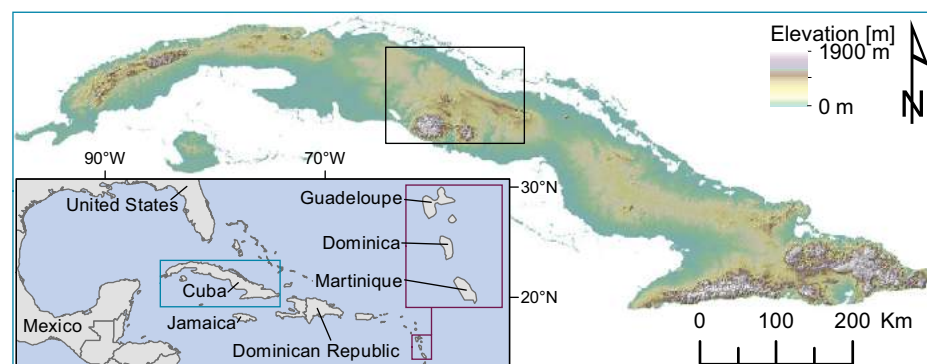


Figure 1. Cuba with elevation as color ramp. Black outline is area mapped in Figure 3. Inset shows location of Cuba in relation to North America.

winter-dry with precipitation delivered both by trade-wind showers and by larger tropical storms.

The diverse geology of Cuba reflects its tectonic setting at the boundary of the North America and Caribbean plates. Central Cuban basement lithologies include accreted igneous rocks, sediments (clastic, carbonate, and evaporite) formed along passive margins, obducted ophiolite, and island arc rocks (Iturralde-Vinent et al., 2016). This basement is unconformably overlain by slightly deformed, younger marine and terrestrial sedimentary rocks (Iturralde-Vinent, 1994). Where river water has interacted with these diverse rocks, surface water chemistries should reflect the composition of underlying rock units.

Agriculture has been practiced in Cuba for centuries. Indigenous people cultivated cassava, yucca, and maize (Coscolluela, 1946). Spanish colonization from 1492 brought slaves, large-scale sugar agriculture, and cattle farming (Zepeda, 2003). Following Cuba's independence from Spain in 1898, sugar production in Cuba quadrupled under U.S. influence (Whitbeck, 1922). When Cuba allied with the Soviet Union in 1959, industrialization of the sugar industry to increase yields and exports became a central goal (Pérez-López, 1989). By the 1980s, Cuba boasted the most mechanized agricultural sector in Latin America (Febles-González et al., 2011); however, the collapse of the Soviet Union in 1991 catalyzed Cuban adoption of reduced tillage, organic soil amendments, the use of cover crops, and the replacement of fuel-hungry tractors with domesticated draft animals, including horses and oxen (Gersper et al., 1993).

Surface water biogeochemical monitoring in central Cuba has focused mainly on reservoirs. In central Cuba, water chemistry data (1986–2005) from four reservoirs, representing two river systems and four basins with varied geology (Betancourt et al., 2012) showed that the primary control on major ion concentration is rock weathering upstream; there was no statistically significant difference in water chemistry between dry and rainy seasons in three of the four basins.

In August 2018 (the wet season), we collected water samples from 25 river basins in central Cuba. We selected these sites to encompass a range of land uses, underlying upstream rock types, discharges, and basin

sizes, while avoiding rivers that had major dams (Figs. 2 and 3N). See the GSA Data Repository¹ for detailed methods. Our analysis assumes that the concentration of cations and anions we measured are representative of annual average values (Godsey et al., 2009).

RESULTS

River water samples from central Cuba contain high concentrations of dissolved material (Figs. 3 and 4). Conductivity and total dissolved load were high (130–1380 $\mu\text{S}/\text{cm}$ and 117 to over 780 mg/L, respectively, Tables S1 and S2 [see footnote 1]); stream water, except that sampled from forested catchments, was turbid. Sample pH was near neutral to slightly alkaline with high values of bicarbonate alkalinity (65–400 mg/L). As, Ba, Cr, Mn, Ni, Sr, and U were present in some or all of the Cuban river waters we analyzed, in all cases at levels below drinking water standards (Table S3 [see footnote 1]). Dissolved oxygen measured in the field ranged from 59% to 145% (average 97%). Using basin-specific precipitation (Fig. 3), along with run-off estimates (Beck et al., 2015, 2017) and total dissolved solids (TDS) from each Cuban water sample, we estimate chemical weathering rates between 42 and 302 t $\text{km}^{-2} \text{y}^{-1}$ with a mean of $161 \pm 66 \text{ t km}^{-2} \text{y}^{-1}$.

Dissolved organic carbon (DOC) was highly variable, ranging from <1 mg/L to 9 mg/L (Table S4 [see footnote 1]). Total dissolved nitrogen (TDN) ranged from <0.1–1.5 mg/L (mean = 0.76 mg/L); on average 60% was present as nitrate (range 24%–93%). Nitrate values measured in the field and then in the lab several weeks later are well correlated. Nitrite was present in all samples, averaging 1.2 mg/L (0.37 mg/L of N). DOC/TDN ratios also vary widely, from 1.3 to 14.8. Anion concentrations decreased in the order $\text{HCO}_3^- > \text{Cl}^- > \text{SO}_4^{2-} > \text{NO}_3^- > \text{HPO}_4^{2-} > \text{NO}_2^- > \text{Br}^- > \text{F}^-$.

The anion orthophosphate (as P) was measured both in the field (0.1–0.8 mg/L) and lab (0.4–0.5 mg/L); field and lab analyses were positively correlated. Cations decreased on average in the order $\text{Ca} > \text{Na} > \text{Mg} > \text{Si} > \text{K}$.

E. coli bacteria were found in all samples, and most samples (20/24) contained enough bacteria to be deemed unsafe for recreational use according to World Health Organization criteria (Most Probable Number (MPN) > 127/100 ml). Genetic microbial source trac-

ing in two samples with MPN/100ml >1000 (CU-107 and 110) did not identify any human-sourced bacteria; rather, the bacteria in sample CU-110 were identified as being of unguilate origin, and no specific source could be determined for bacteria in CU-107.

There are numerous correlations between anions and cations in our river water samples (Table S5 [see footnote 1]). Na and Cl are positively correlated ($p < 0.01$) as well as Na and HCO_3^- , F, SO_4^{2-} , NO_2^- , K, Ca, Br, Ti, As, Rb, Sr, Ba, and U ($p < 0.05$, all positive, Fig. 4). These elements are also correlated to one another positively and significantly. In addition, Mg is positively correlated to SiO_2 , V, Cr, and Ni ($p < 0.05$). NO_2^- is positively correlated with conductivity.

Four of the 25 samples (CU-120, -121, -122, and -132), all collected in the northwestern part of the field area, are geochemically distinct (Figs. 3, 4, and 5). These samples have the highest or nearly highest Cl, SO_4^{2-} , Br, NO_2^- , and Na concentrations, field conductivity, and TDS (Fig. 4, red symbols) in the sample set. These are four of only five samples to contain low but measurable As (1.0–1.4 ppb). They plot in a distinct zone of the Piper diagram (Fig. 5) and also have higher Rb, Sr, Ba, and U concentrations (1.8–4.3 ppb) than other Cuban river water samples. Three of the four samples contain >115 mg/L Ca and high concentrations of Na, Cl, and SO_4^{2-} . These four samples were collected near one another and drain the same bedrock map unit (post-Eocene marine sediment). One (CU-122) drains mostly wetland while the others drain dominantly agricultural catchments.

DISCUSSION/INTERPRETATION

Bedrock Controls Central Cuban River Water Chemistry

In central Cuba, river water composition and TDS covary with rock types (Figs. 3 and 4D) suggesting a close connection between river water chemistry and underlying rock units. For example, high concentrations of Ca, Mg, and alkalinity in most samples are consistent with the mapped presence of carbonate rocks in most sampled drainage basins (Fig. 3). Distinct anion, cation, and trace metal compositions of rivers draining four (CU-120, -121, -122, -132) watersheds in the NW quadrant of our field area and underlain by marine sediments (French and Schenk, 2004) suggest dissolution of evap-

¹GSA Data Repository item 2020097, data tables and extended methods, is available online at <https://www.geosociety.org/datarepository/2020>.

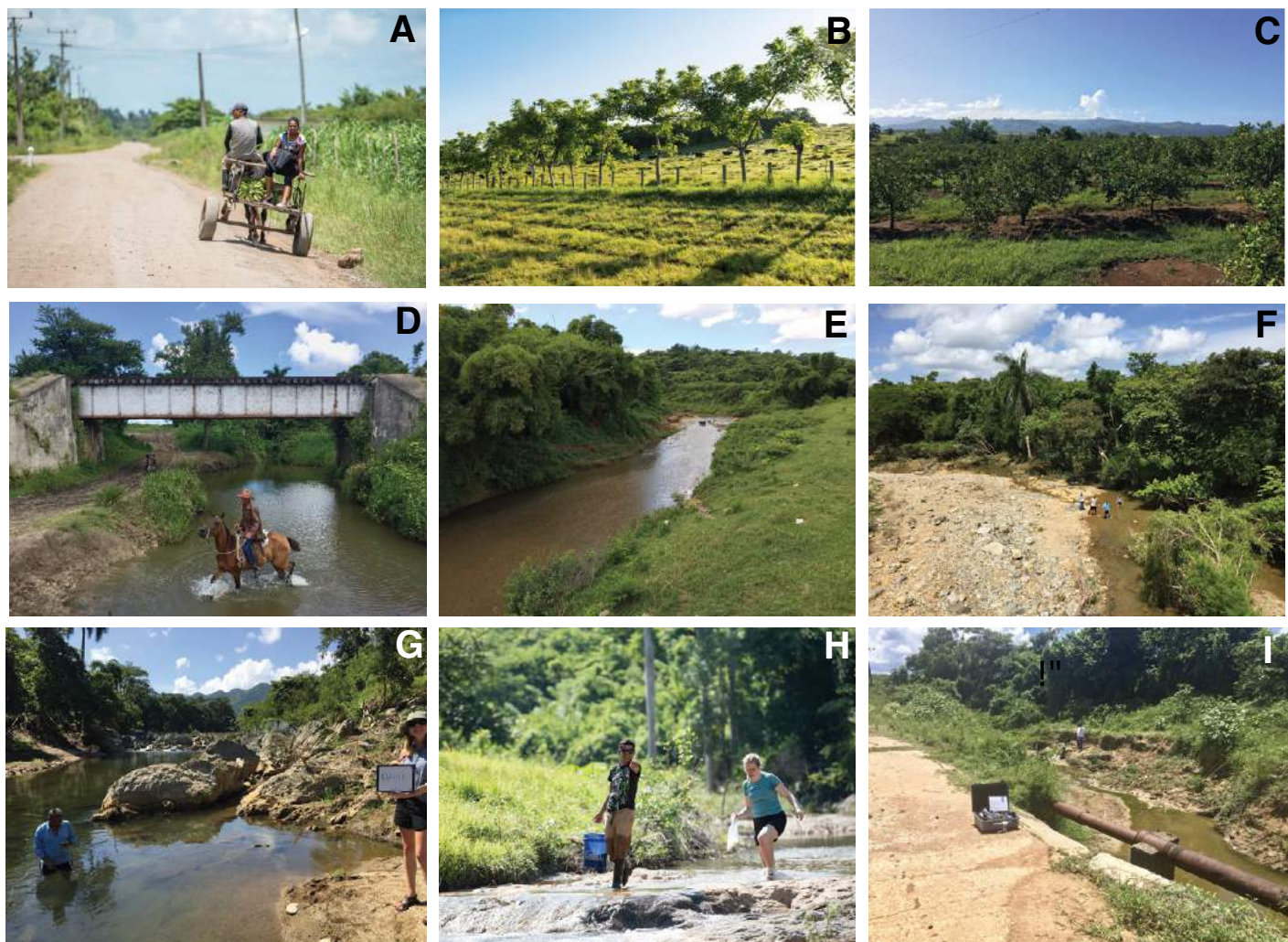


Figure 2. Common Cuban landscapes and example sample sites. (A) Sugarcane and dirt roads are common on the island. (B) Cattle grazing on cleared fields. (C) Citrus groves on slopes in southern field area. (D) Horses were frequently in rivers, CU-132. (E) Plane-bed sand and gravel channel with cows in the river, CU-101. (F) Large point bar flooded during Hurricane Alberto showing dynamic range of river flows over time, CU-114. (G) Boulder/bedrock channel during conductivity measurement, CU-115. (H) Bedrock channel, CU-114. (I) Low flow sample site in incised channel, CU-122. Locations identified by letter in Figure 3N.

orite deposits including those that contain nitrite (Figs. 3, 4, and 5).

The relationship between water chemistry and bedrock type in central Cuba suggests the presence of fresh, weatherable mineral surfaces along flow paths carrying subsurface flow to Cuban rivers. This inference is supported by comparison of Cuban river water chemistry with that from Martinique, Guadeloupe, and Dominica (Rad et al., 2013). The latter three islands are underlain primarily by andesite, and their surface water contains more Si and K and less Ca and Mg than Cuban rivers (Fig. 6A). The higher concentration of most other anions and cations in Cuban waters as compared to waters from volcanic Caribbean islands reflects the influence of readily soluble carbonate and evaporite rocks in Cuba. Although average TDS for waters from

Cuba exceeds that on other, e.g., volcanic, Caribbean islands (Fig. 6A), chemical denudation rates estimated from central Cuban river water samples are similar to other Caribbean islands (Fig. 6B) because mean annual precipitation and thus runoff in Cuba is lower. All Caribbean chemical denudation rates are high when compared to global data (Larsen et al., 2014).

Field observations of incised, bedrock-floored river channels and the chemical data that mandate extensive water/rock interaction similar to that on tectonically active, volcanic Caribbean islands suggest ongoing bedrock uplift in central Cuba rather than tectonic stability and the development of a deep tropical weathering mantle. Raised marine terraces along southern and eastern Cuba (Muhs et al., 2017) are consistent with such uplift, which, along

with tectonically induced rock fracturing, is likely responsible for the continued supply of fresh, easily weatherable rock, and thus high chemical weathering rates.

Human Activities and Water Quality

High TDS in central Cuban river water as a result of bedrock chemical weathering is not hazardous but could limit some uses. About 20% of samples we collected have TDS and Na levels above the taste threshold. High TDS samples may cause CaCO_3 scaling on pipes, household cooking implements, and industrial equipment; scaling could be a health benefit if lead remains in the water distribution system. High levels of DOC (up to 9 mg/L) in central Cuban river water suggest a potential risk of trihalomethane formation during chlorination (Engelage et al., 2009), which is the most

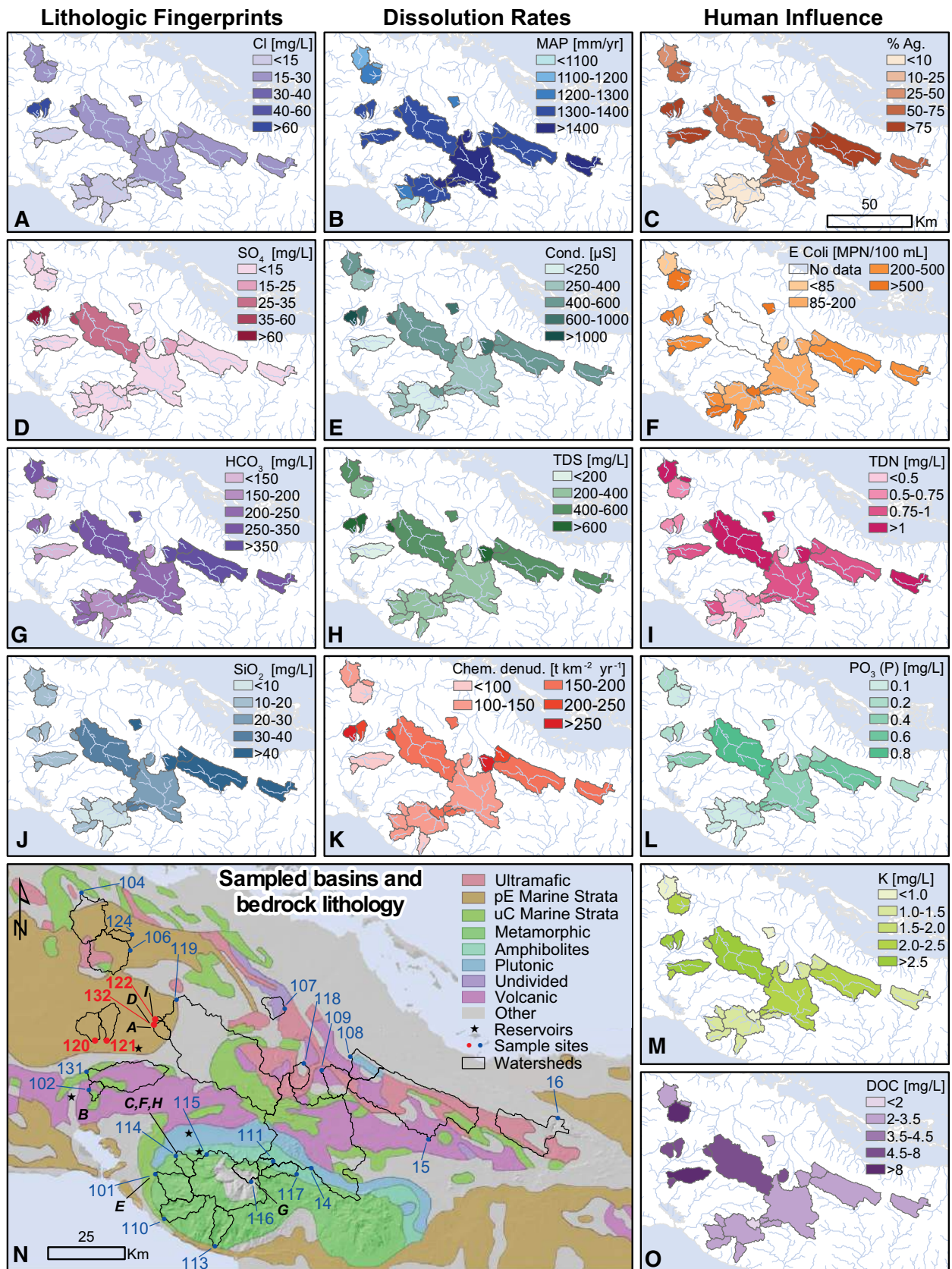


Figure 3. Results of river water biogeochemical analyses plotted for 25 sampled basins. (A) Chloride. (B) Mean annual precipitation. (C) Percent agricultural land use. (D) Sulfate. (E) Conductivity. (F) *E. coli*. (G) Bicarbonate. (H) Total dissolved solids. (I) Total dissolved nitrogen. (J) Silica. (K) Chemical denudation rate. (L) Orthophosphate as phosphorus. (M) Potassium. (N) Sampled basins overlain on generalized geological map (French and Schenk, 2004). Letters show location of photos in Figure 2. Four basins (CU-120, -121, -122, and -132 labeled with red text and points) have distinct water chemistry. Dots represent sample sites. Stars shows reservoir water samples (Betancourt et al., 2012). (O) Dissolved organic carbon.

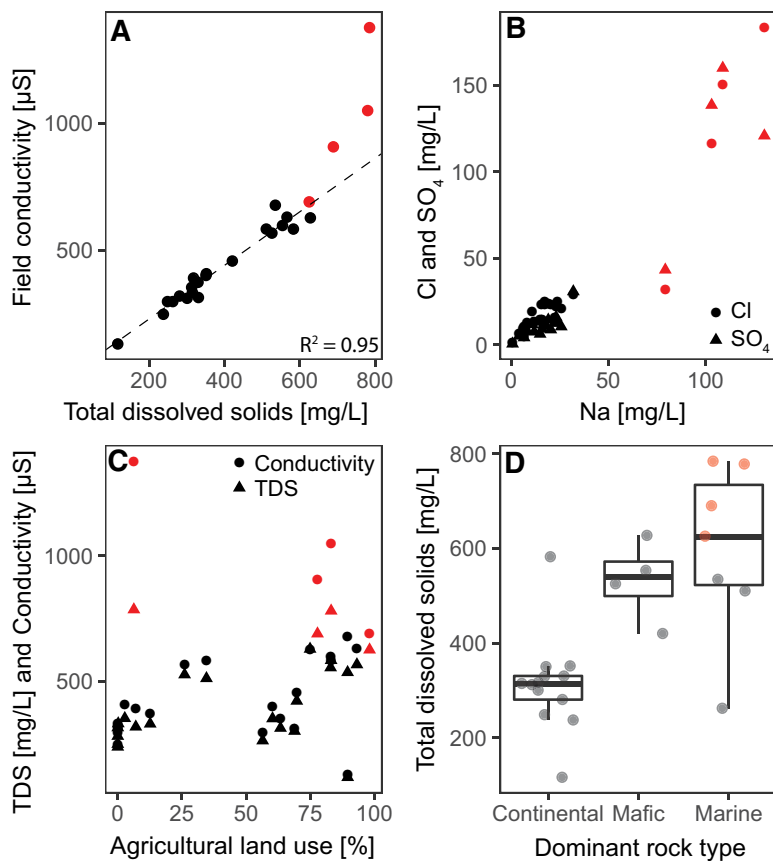


Figure 4. Rock type influences river water chemistry. Red symbols indicate basins with distinct water chemistry highlighted in Figures 3 and 5. (A) Total dissolved solids (TDS) and field conductivity are well correlated. (B) Positive correlation of Na with SO_4 and Cl suggests evaporite source of these solutes. (C) No correlation between percent basin area used for agriculture and total dissolved solids or conductivity. (D) Basins underlain by marine and mafic rocks have higher river water TDS.

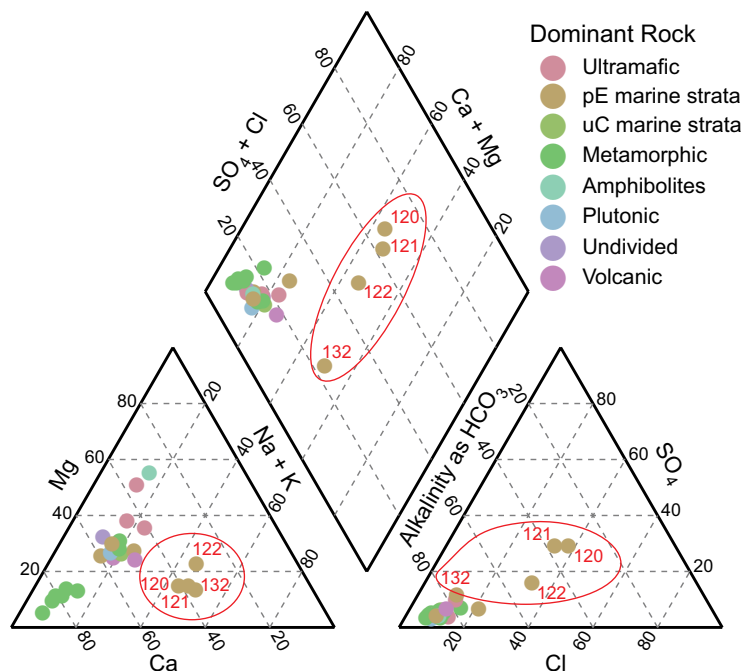


Figure 5. Piper diagram of all data color-coded by mapped lithology (Fig. 3) (French and Schenk, 2004). Numbered samples are those with distinct water chemistry influenced by evaporite rocks.

frequently used water treatment technique in Cuba (Cueto and De Leon, 2010).

Bacterial contamination of river water in central Cuba is consistent with the nearly ubiquitous presence of livestock on the landscape, perhaps because animals have in part replaced fossil-fuel-powered transportation and farm equipment (Fig. 3). We do not know the source of the detected *E. coli*; however, the ungulate match in one of two samples we tested is consistent with numerous cows we observed walking in and around rivers as well as extensive pastures near and upstream of many sampling sites.

High levels of *E. coli* are found in rivers around the world. Data from other Caribbean islands, including Martinique, Trinidad, and Puerto Rico, show similarly high *E. coli* levels in river, spring, and coastal waters (Bachoon et al., 2010; Pommepuy et al., 2000; Wampler and Sisson, 2011). *E. coli* levels above health advisory levels are routinely measured in Vermont river water, a similarly agricultural state with more than a quarter million cows, only half the stocking density per area of Cuba (Riera, 1994). Although pigs and chickens were common in central Cuba, we did not see them near rivers, which may explain why tests for fecal matter from these animals were negative as were those for human fecal bacteria.

Central Cuban river waters provide evidence that agriculture need not overload rivers, and thus reservoirs and coastal zones, with nutrients. N and P are present in Cuban river waters, but at lower concentrations than in the United States, where agriculture is intensive and fertilizer use is heavy (Fig. 6). Total dissolved nitrogen in central Cuban river water is <50% of the Mississippi River average and <25% of peak Mississippi River concentrations (Fig. 6C). Cuban waters have only slightly more TDN than less agricultural Caribbean volcanic islands (Rad et al., 2013).

The history of fertilizer use over time is telling (Fig. 6D). Cuban fertilizer use peaked in 1978 and then declined, whereas fertilizer use in the United States rose after 1961 and has remained high, more than twice the area-normalized value as Cuba. Sustainable agricultural initiatives, implemented in Cuba after the end of Soviet assistance, have resulted in less fertilizer use and better river water quality (Fig. 6). The result is far less downstream transport and loading of nutrients into coastal waters, nutrients that can have a profound and negative effect, including the presence of anoxic, marine dead zones (Obenour et al., 2013).

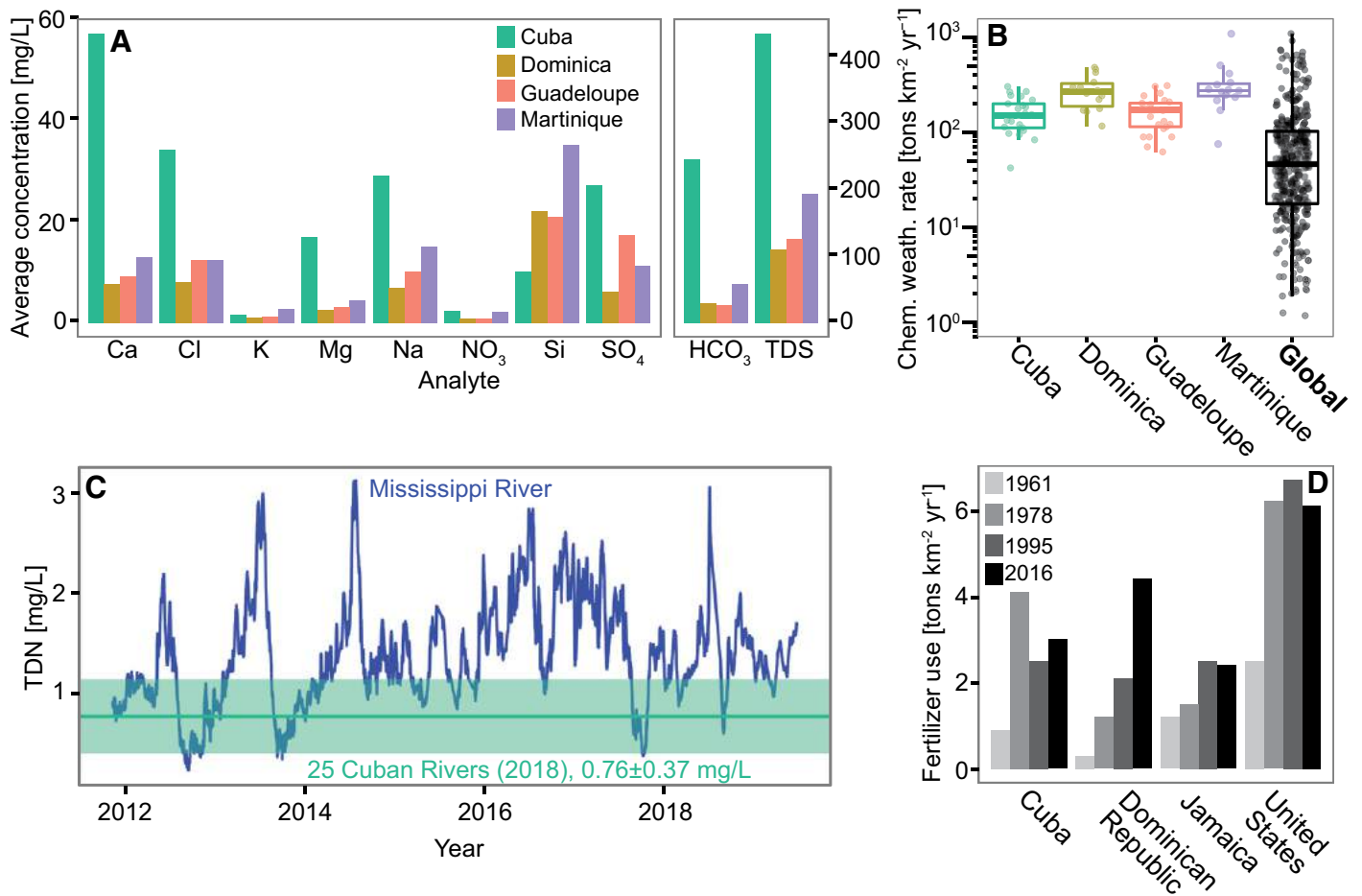


Figure 6. Cuban river water data in context. (A) Cuban waters contain greater dissolved concentrations for most elements or ions than other Caribbean islands (Rad et al., 2013). (B) Chemical weathering rates (cations, anions, and Si) in rivers sampled in central Cuba, Dominica, Guadeloupe, and Martinique (Rad et al., 2013) are high and similar (cf. global from Larsen et al. [2014]; $n = 299$). Note log scale. Median is middle line, the 25th and 75th percentiles are the edges, and whiskers extend to include all samples within 1.5 times the range of the box. (C) Total dissolved nitrogen (TDN) for Mississippi River at Baton Rouge (water.usgs.gov) compared to central Cuban rivers (this paper). (D) Cuban fertilizer use (P, K, N) normalized by arable land area is stable and less than other nations. Data from <https://data.worldbank.org/indicator/>, Rawlins et al. (1998), and <https://www.epa.gov/roe/>.

IMPLICATIONS

Our data provide a comprehensive snapshot of the chemistry of water moving through rivers in central Cuba. From these data, we calculate high rates of rock weathering and landscape-scale denudation and thus infer the presence of flow paths through fresh rock or regolith supplying water to rivers we sampled—perhaps in response to tectonic uplift. Cuba’s transition toward sustainable agriculture (and its reduced use of fertilizer per acre of crop land) results in much lower river-water nutrient concentrations in central Cuban rivers than in the Mississippi River—a model for other agricultural economies. Additional management strategies to reduce manure and sediment loads to rivers (such as fencing to keep cattle off river banks) could further and rapidly improve central Cuban river water quality. Reducing sediment and manure loads will have economic benefits, because rivers eventually discharge into the coastal zone

where suspended sediment, and bacteria from agricultural activity, impact water quality and clarity on coral reefs and beaches frequented by tourists (Rawlins et al., 1998), a source of income to Cuba (Duffy and Kline, 2018).

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