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Of Small Streams and Great Lakes: Integrating Tributaries to Understand the Ecology and Biogeochemistry of Lake Superior

Amy M. Marcarelli, Ashley A. Coble, Karl M. Meingast, Evan S. Kane, Colin N. Brooks, Ishi Buffam, Sarah A. Green, Casey J Huckins, David Toczydlowski, and Robert Stottlemyer

Research Impact Statement: Interactions between Lake Superior and its tributaries are frequently ignored, and understanding the Lake Superior ecosystem requires a nuanced consideration of these interactions in time and space.

ABSTRACT: Lake Superior receives inputs from approximately 2,800 tributaries that provide nutrients and dissolved organic matter (DOM) to the nearshore zone of this oligotrophic lake. Here, we review the magnitude and timing of tributary export and plume formation in Lake Superior, how these patterns and interactions may shift with global change, and how emerging technologies can be used to better characterize tributary–lake linkages. Peak tributary export occurs during snowmelt-driven spring freshets, with additional pulses during rain-driven storms. Instream processing and transformation of nitrogen, phosphorus, and dissolved organic carbon (DOC) can be rapid but varies seasonally in magnitude. Tributary plumes with elevated DOC concentration, higher turbidity, and distinct DOM character can be detected in the nearshore during times of high runoff, but plumes can be quickly transported and diluted by in-lake currents and mixing. Understanding the variability in size and load of these tributary plumes, how they are transported within the lake, and how long they persist may be best addressed with environmental sensors and remote sensing using autonomous and unmanned vehicles. The connections between Lake Superior and its tributaries are vulnerable to climate change, and understanding and predicting future changes to these valuable freshwater resources will require a nuanced and detailed consideration of tributary inputs and interactions in time and space.

(KEYWORDS: aquatic ecology; biogeochemistry; lakes; Great Lakes; watersheds; stream–lake interactions; streams; nutrients; dissolved organic carbon; dissolved organic matter.)

INTRODUCTION

The thousands of small tributaries that feed the Great Lakes have been overlooked as drivers of nearshore ecosystems and whole-lake budgets. The Great Lakes contain 21% of the world's surface freshwater (Sterner et al. 2017), yet their drainage areas are small relative to other lakes with similar surface areas and volumes (catchment area to lake area ratio of 1.55–3.4 for the Great Lakes compared to 6.0 average for the world's five other largest lakes and >100 for most tributaries; Kalff 2002; Cotner et al. 2004). As a result, the amount of water that falls into the Great Lakes directly as precipitation is equal to or larger than the runoff from the watershed — for

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Department of Biological Sciences (Marcarelli, Huckins, Toczydlowski, Stottlemyer), School of Forest Resources and Environmental Science (Meingast, Kane), and Department of Chemistry (Green), Michigan Technological University, Houghton, Michigan, USA; National Council for Air and Stream Improvement, Inc. (Coble), Corvallis, Oregon, USA; Michigan Tech Research Institute (Brooks), Michigan Technological University, Ann Arbor, Michigan, USA; and Department of Biological Sciences (Buffam), University of Cincinnati, Cincinnati, Ohio, USA (Correspondence to Marcarelli: ammarcar@mtu.edu).

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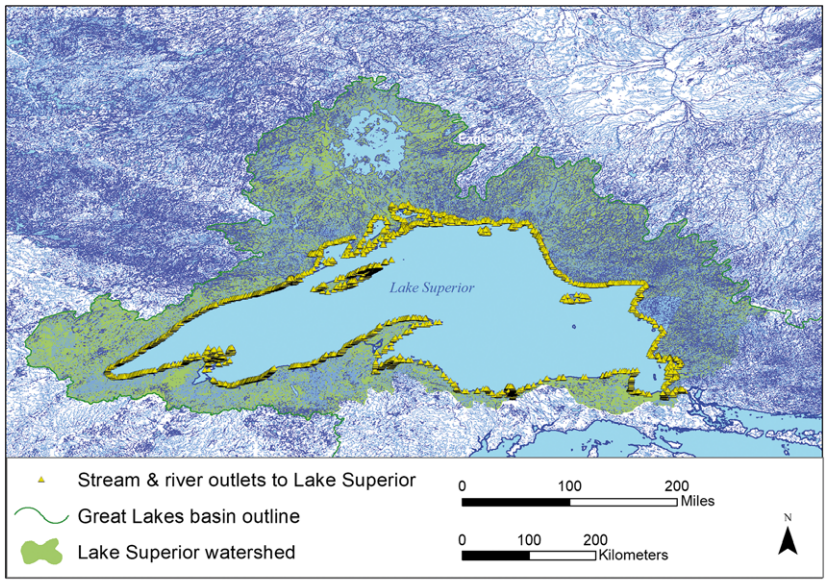
example, 5,400 m^3/s is delivered as watershed runoff cumulatively across the Great Lakes basin vs. 6,300 m^3/s in precipitation inputs directly into the lakes (excluding water flow from upstream Great Lakes, e.g., from Erie to Ontario, etc.; Botts and Krushelnicki 1995). The importance of contributing watersheds and terrestrial sources of material can be overlooked in these systems where water inputs are dominated by precipitation. Yet across the Great Lakes, nearshore to offshore gradients have been documented for concentrations of dissolved and particulate nutrients (Makarewicz, Lewis, Pennuto, et al. 2012; Marko et al. 2013; Larson et al. 2016), characteristics of dissolved organic matter (DOM) (Stephens and Minor 2010; Larson et al. 2014; Dila and Biddanda 2015), rates of microbial activity and photosynthesis (Lohrenz et al. 2004; Dila and Biddanda 2015), and abundance of organisms (Yurista et al. 2009; Auer et al. 2013). These gradients are established through the influence of a few large tributaries or the cumulative impact of many small tributaries (Yurista and Kelly 2009; Makarewicz, Lewis, Boyer, et al. 2012; Minor et al. 2014). Moreover, these patterns are particularly strong and persistent in Lake Superior (Yurista et al. 2011), which has historically had the lowest rates of in-lake productivity and felt the least cumulative anthropogenic disturbance of all of the Great Lakes (Evans et al. 2011; Allan et al. 2013; Bunnell et al. 2014).

Lake Superior's approximately 2,800 small to large tributaries (Figure 1) provide inputs of nutrients (e.g., carbon [C], nitrogen [N], phosphorus [P], silica, iron, and other trace metals) that support the productivity of nearshore microbes (Biddanda and Cotner 2002; Yurista et al. 2011; Larson et al. 2013; Kruger et al. 2016), but large uncertainties exist in their net contributions. When considered at the scale of annual whole-lake budgets, tributaries provide a proportional amount of N relative to their water inputs (38%–48% of N influx relative to 40% of water influx; Urban 2009a). In contrast, tributary inputs amount to 5%–37% of the known organic C inputs and 2%–8% of P inputs (Urban et al. 2005; Urban 2009a, b). The wide range of these estimates result from uncertainties in magnitude and variation of inputs (e.g., atmospheric deposition, shoreline erosion, photosynthesis) and outputs (e.g., burial, respiration, denitrification; Urban et al. 2005; Urban 2009a; Bennington et al. 2012). Moreover, tributary inputs are estimated based on quite limited monitoring data — for example, P loading into Lake Superior was extrapolated from measurements of seven tributaries that were used to model export from 18 tributaries with drainage areas >325 km^2 (Robertson 1997; Urban 2009a). Although tributaries of this size comprise a majority of the area of the Lake Superior watershed, most tributaries have drainage areas smaller than 5 km^2, and river mouths of small and large tributaries are located in close proximity all around the Lake Superior watershed (Figure 1). These small and large tributaries all combine to influence coastal conditions and nearshore habitats, and deposit nutrients and organic carbon at punctuated intervals and distinct locations in the nearshore zone, each with its own composition and rhythm of delivery.

The composition of nutrients exported from different tributaries varies according to watershed characteristics and changes as materials travel from terrestrial sources through soil, tributaries, and within the lake. Spatial variation in nutrient and DOM loading among tributaries results from differences in topography, underlying geology, and land/forest cover, particularly widely distributed wetlands (Burtner et al. 2011; Yurista et al. 2011; Larson et al. 2014). Fluxes from watersheds into streams also vary seasonally, as changes on the terrestrial landscape like snowpack development and forest transpiration modify the magnitude of water flow, flushing different pools of nutrients and DOM (Frost et al. 2009; Wilson et al. 2013; Raymond et al. 2016). Physical (adsorption/coagulation), chemical/photochemical, and biological processing transform and modify nutrient loads, as well as remineralize DOM and change its reactivity and biodegradability (Peterson et al. 2001; Cole et al. 2007; Massicotte et al. 2017). Many of these modifications occur within the dynamic environments of small tributaries (Bernhardt et al. 2005), which may process and retain nutrients differently than larger rivers.

Inputs of nutrients, sediment, and DOM from tributaries form plumes that create local hotspots and heterogeneity in biogeochemical and ecological processes in the nearshore region of Lake Superior and the other Great Lakes. The existence of such riverine plumes in Lake Superior has been recognized at the largest tributaries and during high discharge events (e.g., Churchill et al. 2003; Budd 2004; Minor et al. 2014; Trochta et al. 2015), but much uncertainty remains about the size, duration, and ecological consequences of riverine plumes across the full span of tributary sizes in Lake Superior and the other Great Lakes. Sampling of tributaries and their nearshore plumes has been limited, especially in winter, by the large number of sites and their poor accessibility. Moreover, satellite-based remote sensing of tributary inputs is hindered by the small extent of their plumes, frequent cloud cover (Schwab et al. 1999), bottom interference in nearshore regions, and optically complex waters (Shuchman et al. 2013). Yet, understanding the timing and locations of these delivery plumes is critical to tracking the delivery and fate of nutrients and carbon to Lake Superior,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Stream & river outlets to Lake Superior
Great Lakes basin outline
Lake Superior watershed
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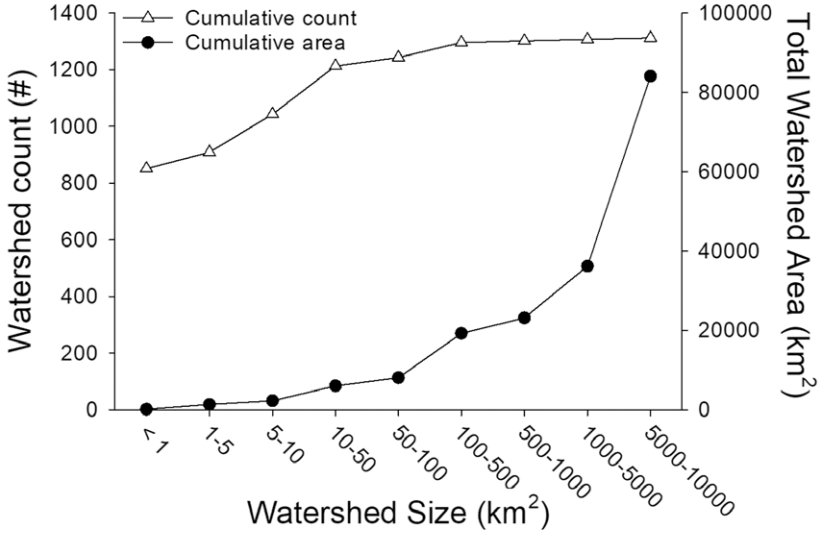
Cumulative count
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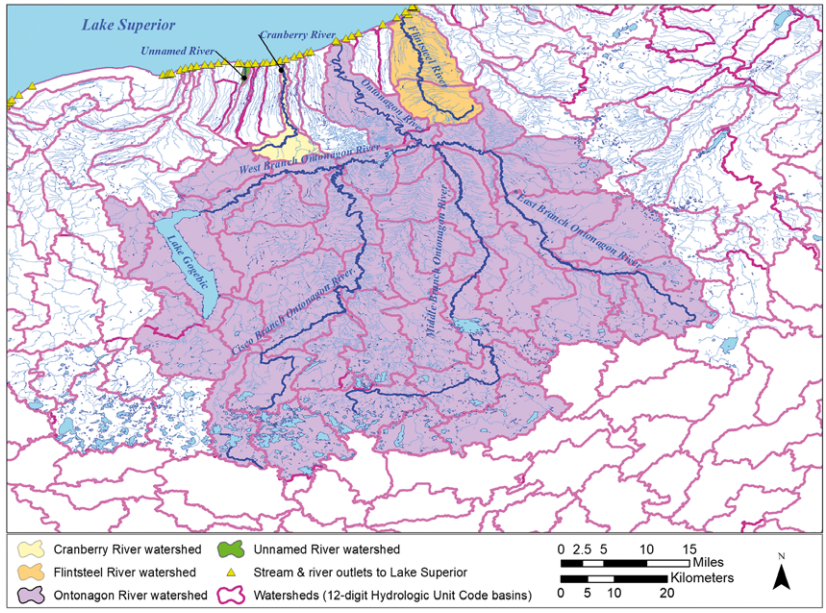
Lake Superior
Cranberry River
Unnamed River
Flintsteel River
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West Branch Ontonagon River
East Branch Ontonagon River
Middle Branch Ontonagon River
Lake Gogebic
Cranberry River watershed
Flintsteel River watershed
Ontonagon River watershed
Unnamed River watershed
Stream & river outlets to Lake Superior
Watersheds (12-digit Hydrologic Unit Code basins)
0 2.5 5 10 15 Miles
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FIGURE 1. (top) About 2,800 tributaries enter Lake Superior; tributary mouths indicated by yellow triangles. Tributaries for the United States (U.S.) were identified from National Hydrography Dataset High Resolution and tributaries for Canada were identified from Ontario Hydro Network. (center) Tributary drainage areas range in size from <1 km^2 to thousands of km^2 in size, as demonstrated through analysis of U.S. tributaries National Hydrography "Plus" dataset (https://www.epa.gov/waterdata/nhdplus-national-hydrography-dataset-plus). Although most tributaries to Lake Superior are 5 km or less in drainage area, the five largest watersheds make up >75% of the drainage area in the U.S. (bottom) Small and large tributaries are distributed around the watershed, with moderate size tributaries (e.g., Cranberry River, 51 km^2; Firesteel River, 166 km^2) next to very large drainages (e.g., Ontonagon River, 3,583 km^2). On this figure pink outlines represent 12-digit hydrologic unit code (HUC) basins; note that some of these HUC basins integrate across multiple small tributaries that feed into Lake Superior (>1 yellow triangle per HUC basin intersection with Lake Superior shoreline). An example of one of these small watersheds (3.2 km^2) is outlined in green to the left of the Cranberry River watershed. Each of these small and large tributaries may have distinct timing and composition of material export controlled by their size, location, and watershed characteristics.

especially in a changing climate. Emerging technologies and novel monitoring approaches are providing enhanced opportunities to observe and quantify these inputs.

In this paper, we explore the temporal and spatial variation in tributary inputs of DOM, N, and P and discuss their fate in Lake Superior. We addressed three specific questions:

1. When and what do tributaries export into Lake Superior, and can we characterize their nearshore plumes?
2. How may patterns of tributary–Lake Superior interactions shift with global change?
3. How can emerging technologies be used to address unknowns in the study of interactions between Lake Superior and its tributaries?

Our goal was to assess these questions by integrating existing literature with new data to highlight what we currently do and do not know, and to describe approaches for addressing gaps in our understanding of these linkages and their consequences.

WHEN AND WHAT DO TRIBUTARIES EXPORT INTO LAKE SUPERIOR?

The spring freshet typically generates the vast majority of annual DOM and nutrient exports from Lake Superior tributaries across streams of all orders and watershed areas. For example, Calumet Watershed (1.7 km^2), Salmon-Trout River (127 km^2), and Ontonagon River (3,400 km^2) exported 43%–63% of their annual dissolved organic carbon (DOC) load during the spring snowmelt freshet for the period of July 2013–June 2014 (Coble, Marcarelli, Kane, Stottlemyer, et al. 2016). To explore whether these patterns of export varied among years, we estimated monthly loads of DOC and nitrate from 25-year records of discharge and nutrient concentrations from Calumet Watershed (Stottlemyer and Toczydlowski 2006). Loads of DOC and nitrate always exhibit their highest peaks during spring runoff, which corresponds to the maximum discharge period each year (Figure 2) (Stottlemyer and Toczydlowski 2006). Nevertheless, storm events in summer or fall produced secondary peaks that could export 20%–80% as much as the spring runoff peaks in some years (Figure 2). The timing and magnitude of these peaks of delivery of materials to the lake is determined by the amount, composition, and timing of materials delivered into the tributary as well as by processing within the stream during transit. The fate of exported materials in Lake Superior depends on the conditions in the lake, which will differ dramatically during the spring freshet vs. during summer storms. Moreover, spring freshets are synchronized across watersheds within a region and therefore combine to contribute large inputs into Lake Superior, while spring storms are much more localized, influencing a much smaller area of the lake via pulses of export.

Small streams have high rates of uptake and retention for limiting nutrients, particularly N and P (Peterson et al. 2001; Hoellein et al. 2007). Nutrient enrichment experiments suggest that N and P limit periphyton production independently or in co-limitation in Lake Superior tributaries (Wold and Hershey 1999; Marcarelli, unpublished data), while P alone is the primary limiting nutrient for algal and bacterial production in the open water of Lake Superior (Lohrenz et al. 2004; Sterner et al. 2004; Urban 2009a). N retention can be high in Lake Superior tributaries, where ammonium can be cycled up to 50 times before being exported (Coble, Marcarelli, Kane, and Huckins 2016), and denitrification can permanently remove approximately 30% of nitrate produced via nitrification (Bellinger et al. 2014). Indeed, nitrate concentrations in many tributaries are lower than concentrations in the surface water of Lake Superior, which are high for an oligotrophic lake (300–350 μg N/L; Table S1; Finlay et al. 2007; McDonald et al. 2010). As such, tributary plumes may actually dilute nearshore N concentrations. In contrast, phosphate

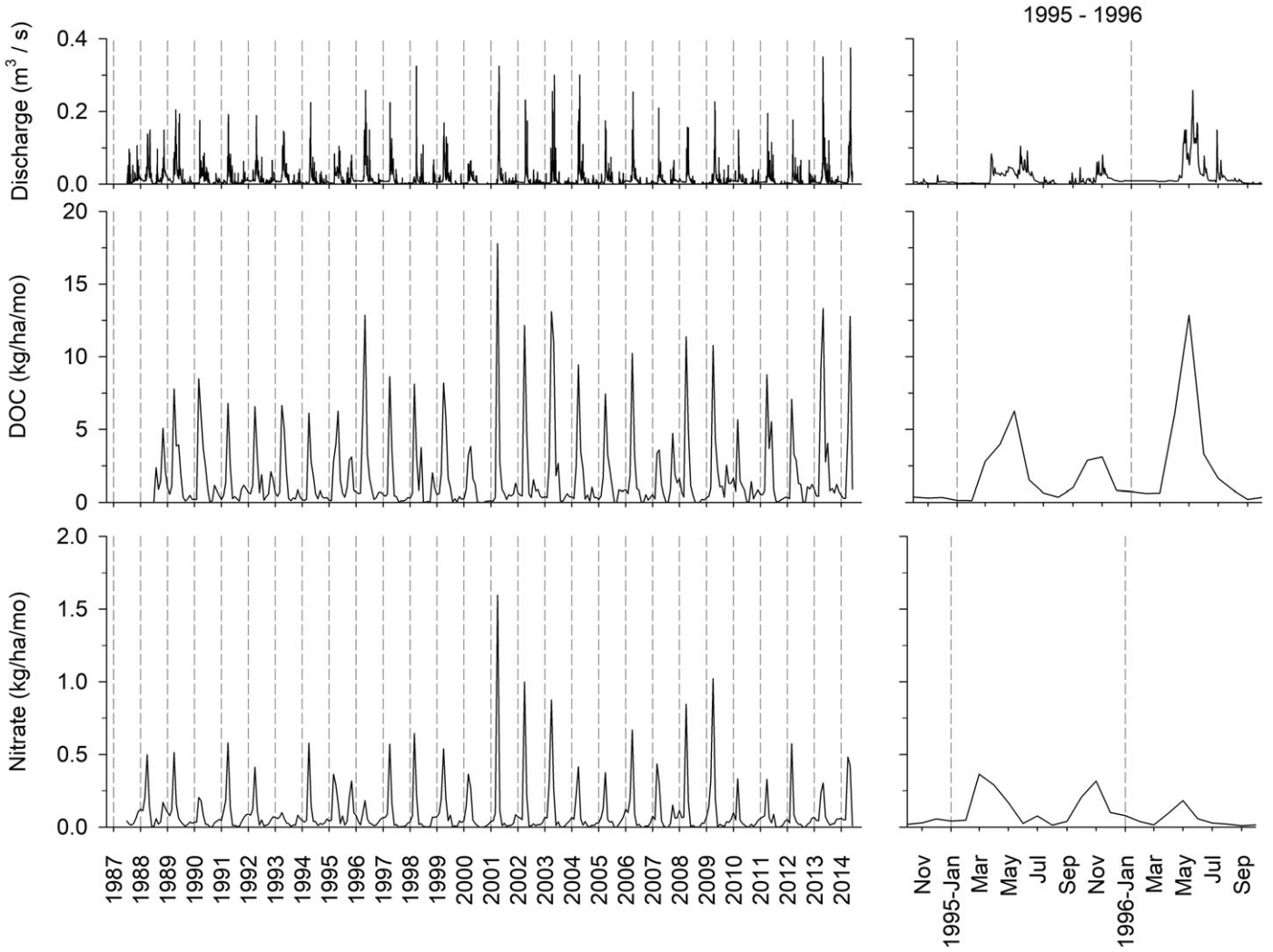

FIGURE 2. Time series of monthly yields from Calumet Watershed for dissolved organic carbon (DOC) and nitrate. The left column shows the full data record, while the right column shows two water years (1995–1996) to demonstrate the variation in export during the spring freshet vs. summer storms. Discharge is shown in the top pane to allow comparison of peak export with periods of high runoff, and the vertical dashed lines indicate January 1 of each year. Loads are based on long-term monitoring data collected by Stottlemyer and Toczydlowski (2006) and modeled using the Load Estimator model of Runkel et al. (2004). Input for the model included concentrations measured across a range of discharge conditions (≥12 measurements per year) and daily discharge. The model was run in one-year increments between 1988 and 2014.

concentrations are often below detection and uptake rates can be so low that they are difficult to detect using nutrient spiraling techniques in many Lake Superior tributaries (Coble, Marcarelli, Kane, and Huckins 2016). Therefore, P can be shunted from terrestrial ecosystems to Lake Superior with minimal instream transformation (Coble, Marcarelli, Kane, and Huckins 2016), where it may fuel the production of P-limited autotrophs and heterotrophs.

Changes in the relative rates of nutrient transport and instream uptake also contribute to seasonal variation in tributary nutrient loads. For example, terrestrial inputs were the primary control on the balance of C, N, and P in transport in the Ontonagon River during high discharge, but when discharge was low, the primary control shifted to instream biological processing (Frost et al. 2009). Smaller loads are delivered from the tributaries during the summer, fall, and winter when hydrologic transport is lowest (Figure 2), and when biological processing in tributaries is most able to modify nutrient loads and composition (Frost et al. 2009; Coble, Marcarelli, Kane, Stottlemyer, et al. 2016; Coble, A.A., A.M. Marcarelli, and E.S. Kane. "Year-Round Measurements Reveal Seasonal Drivers of Nutrient Uptake in a Snowmelt-Driven Headwater Stream." Unpublished manuscript, last modified July 2018). In contrast to baseflow, the spring freshet and summer and fall storms can export

large quantities of minimally processed DOC and inorganic nutrients (Figure 2) (Coble, Marcarelli, Kane, and Huckins 2016), and in spring uptake rates can be low or undetectable using nutrient spiraling techniques (Coble, A.A., A.M. Marcarelli, and E.S. Kane. "Year-Round Measurements Reveal Seasonal Drivers of Nutrient Uptake in a Snowmelt-Driven Headwater Stream." Unpublished manuscript, last modified July 2018). Therefore, it is likely that during spring runoff much of the material is shunted from terrestrial sources with minimal instream processing (e.g., Frost et al. 2009). There is also strong evidence for reciprocal interactions between N availability and DOM uptake and processing in small to mid-sized tributaries of Lake Superior, with N additions increasing the degradability of DOM measured using biodegradation assays in a laboratory experiment with water from a first-order tributary (Coble et al. 2015). DOM composition and DOC concentration have been identified as strong predictors of ammonium and soluble reactive phosphorus uptake rates across Lake Superior tributaries and among seasons (Coble, Marcarelli, Kane, and Huckins 2016; Coble, A.A., A.M. Marcarelli, and E.S. Kane. "Year-Round Measurements Reveal Seasonal Drivers of Nutrient Uptake in a Snowmelt-Driven Headwater Stream." Unpublished manuscript, last modified July 2018). Determining the timing and magnitude of N, P, and C exports and the instream processes that regulate these patterns is essential for understanding the fate and transport of these materials in the nearshore zone of Lake Superior.

Linking tributary export to nearshore processes in Lake Superior requires quantification of the spatial and temporal extent and variation in tributary export, which form nearshore plumes of water and exported material. To document plumes of nutrients and DOM entering Lake Superior from small to mid-sized tributaries, we conducted paired tributary and lake sampling for four tributaries in the Huron

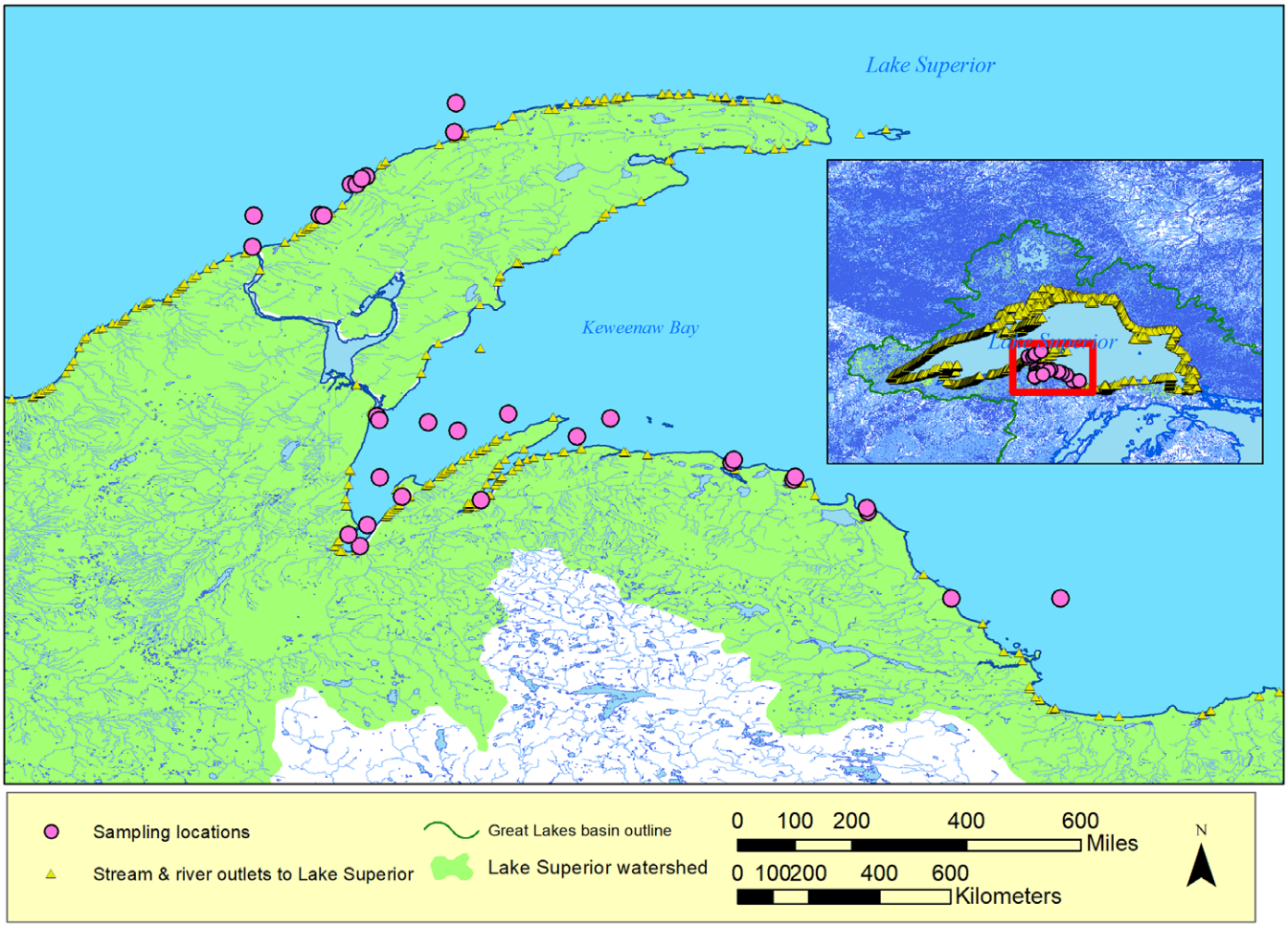

FIGURE 3. Map of the lake sampling locations included in 2013–2015 sampling events, shown with pink dots. The inset shows the location of the sampling region within Lake Superior, and tributary mouths are indicated by yellow triangles in both the figure and the inset. For the purpose of analysis, sites were classified by their location on the east vs. west side of the Keweenaw Peninsula.

Mountains region in 2013 (Little Garlic, Iron, Salmon-Trout, Pine) and for four tributaries on the west side of the Keweenaw Peninsula in 2014 (Calumet, Gratiot, Black/Hills, Eagle). Additional open water and tributary sites were sampled in each year to enhance comparisons (Figure 3; Table S1). We sampled tributaries as close to the mouth as access would allow. We then selected sampling points in the lake directly offshore from the river mouth, targeted to capture the input plume (referred to as "inside plume"; located 0.2–1.1 km from river mouths), paired with nearby sites that were a similar distance offshore but predicted to be outside of the tributary plume (referred to as "outside plume"; located 0.6–13.7 km from river mouths). It should be noted that lake sites were defined based on the potential for, not necessarily the presence of, a plume. Tributary locations were accessed by driving/hiking from land on the first day, and on the following day lake sites were accessed by research vessel. In 2013, sampling coincided with a large early summer storm, making conditions ideal for detecting tributary plumes, while sampling in 2014 coincided with a prolonged summer dry period, reducing the likelihood of observing large plumes. Regardless, we followed the same sampling approach in each of these two years. In addition, in 2015, we conducted a survey of nine lake sites in Keweenaw and Huron Bays on the east side of the Keweenaw Peninsula, with several sites located in tributary plumes (Falls River, South Entry of Keweenaw Waterway, and Silver River; Figure 3), but did not collect tributary samples (Table S1). We followed standard stream and limnological sampling approaches to characterize physical and chemical parameters (discharge, water depth, Secchi depth, temperature, conductivity, turbidity, concentrations of dissolved inorganic N [DIN], total dissolved P [TDP], DOC, chlorophyll *a*, DOM character using fluorescence and spectral analyses); detailed methods can be found in Supporting Information.

These sampling efforts along continua from tributaries, nearshore tributary plumes, and open waters of Lake Superior revealed distinct terrestrial influences on nearshore water chemistry and DOM character. In general, tributaries displayed higher concentrations of DOC and TDP, higher turbidity, and lower DIN than either lake or plume sites in all sampling years (Figures 4a–4c and 5). Tributary DOM had a terrestrial signal with spectral slope ($S_{275–295}$) indicating larger molecular weights, a greater degree of DOM humification index (HIX), and a greater percentage of highly processed humic-like and fulvic-like fluorescence (C1, C4) than either lake or plume sites (Figure 4d–4f). This suggests that tributaries enrich nearshore waters in DOC and TDP but dilute nearshore waters in DIN, and is consistent with the observations that C and P are shunted from terrestrial zones to the lake via tributaries, but N is more tightly cycled in tributaries. Fluorescence measurements ($S_{275–295}$, HIX, and parallel factor analysis C4/C1 in Figure 4) were particularly well suited for differentiating DOM from streams and open water in Lake Superior, and further distinguished DOM among western vs. eastern locations. We found that the degree of humification of DOM and turbidity were distinctly greater in plumes in eastern locations, when we sampled immediately after a storm event, than in western locations when antecedent conditions were dry (Figures 4 and 5). The C4/C1 ratio may provide a useful optical metric for measuring contributions of terrestrial DOM in offshore Lake Superior as it tracks the most evident change in DOM character from tributary to Lake Superior.

The fate of the DOM exported from tributaries into the nearshore Great Lakes depends directly on its degradability. The colored fraction of DOM (CDOM) is subject to photodegradation, which can release carbon as CO_2, and produce fractions that are both more and less bioavailable (Ma and Green 2004; Larson et al. 2007; Macdonald and Minor 2013; Madsen-Østerbye et al. 2018). The most biodegradable and photodegradable DOM is quickly mineralized and evaded to the atmosphere as CO_2, whereas less degradable DOM is more likely to be deposited as lacustrine sediments or transferred to long-term storage pools (McManus et al. 2003; Battin et al. 2009). Globally, small streams have particularly high rates of DOM uptake and processing, leading to higher rates of CO_2 emission from small streams relative to larger rivers (Butman and Raymond 2011; Hotchkiss et al. 2015). The composition of terrestrial DOM and its degradability can vary widely in space and time depending on its specific origin and how it is delivered to aquatic ecosystems (Buffam et al. 2001; Holmes et al. 2008; McLaughlin and Kaplan 2013). Small streams collect recent inputs of DOM from diverse sources, which therefore displays widely varying composition (Mosher et al. 2015). Enormous variability in the biodegradable DOC fraction (0%–72%) was observed across three Lake Superior tributaries spanning three orders of magnitude in watershed size, with the most biodegradable DOC exported from all watersheds during storms (Coble et al. 2015; Coble, Marcarelli, Kane, Stottlemyer, et al. 2016) (Figure 6). Residence time is also an important consideration; large networks offer a longer time for DOM to be processed and degraded (Frost et al. 2006; Casas-Ruiz et al. 2017), while small tributaries offer less time for instream processing before material reaches the nearshore zone.

Our surveys demonstrate that the formation and size of tributary plumes in Lake Superior is dependent on hydrologic conditions, and potentially the nearshore lake characteristics. Storm-elevated discharges and

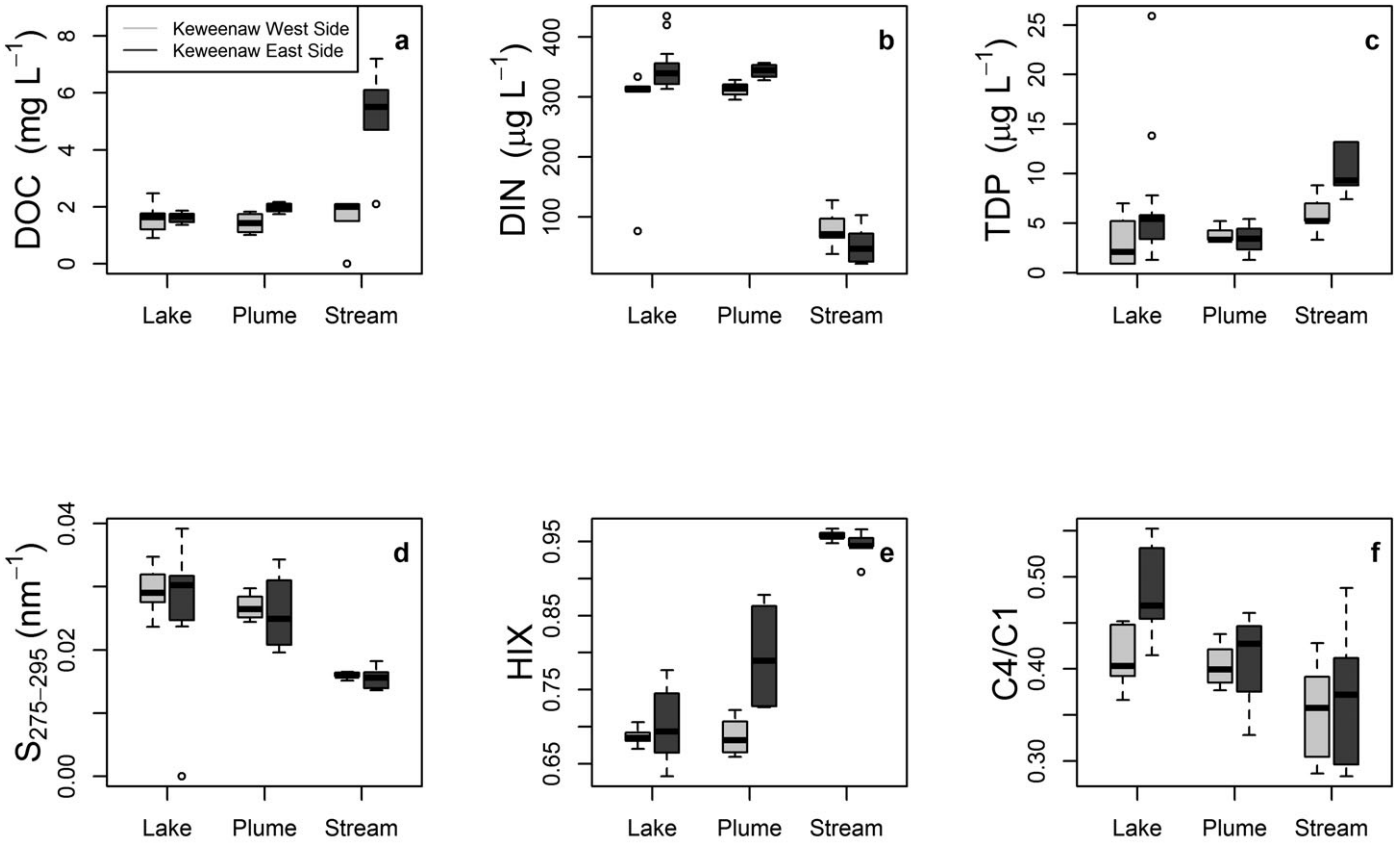

FIGURE 4. Comparison of water chemistry measured during 2013, 2014, and 2015 sampling cruises. Boxplots represent the first, second, and third quartiles; whiskers represent points within 1.5 times the interquartile range; small circles represent outliers. For comparison, sites have been divided into lake (open water and outside plume sites in Table S1), plume (inside plume in Table S1), and tributary sites. Sites have further been classified as located on the west side (2014 sampling) or east side (2013 and 2015 sampling) of the Keweenaw Peninsula. (a–c) Concentrations of key pools of carbon, nitrogen, and phosphorus, while (d–f) describe dissolved organic matter (DOM) characteristics. (d) Spectral slope was calculated from 275 to 295 nm ($S_{275-295}$), and can be used as a proxy for DOM molecular weight, which increases with decreasing spectral slope (Helms et al. 2008). (e) Humification index (HIX, range 0–1) characterizes the humification status of DOM with larger values associated with a greater degree of humification (Ohno 2002). (f) A parallel factor analysis (PARAFAC) was performed using MATLAB software (MATLAB®; The Mathworks, Natick, Massachusetts), and the PLS-toolbox (Eigenvector Research Inc., Wenatchee, Washington) on 387 excitation–emission matrices from various waterbodies including streams, lakes, and peatlands from across the Upper Peninsula of Michigan (detailed methods included in Supporting Information). Here, we present the ratio of PARAFAC components C4–C1 (C4/C1) because it was the most informative component ratio in our study for differentiating DOM in plumes. This is consistent with the assumption that C1 is attributed to terrestrial derived material and C4 is attributed to material derived in offshore environments (Osburn et al. 2016). DIN, dissolved inorganic N; TDP, total dissolved P.

loads of nutrients mobilized from watershed and instream sources certainly contributed to the distinct plumes of DOC and turbidity we observed from tributaries in June 2013 (Figure 5). In comparison, during low flow conditions in August 2014, plumes were not detected on the west side of the Keweenaw Peninsula (Figure 4). Lack of any observable plume is also attributed to lake hydrodynamic conditions in that region. In-lake conditions on the west side of the Keweenaw Peninsula are dynamic with strong winds, variable bathymetry, and the Keweenaw Current, a northeast flowing coastal jet that can exceed 60 cm/s and dominates water movement and mass transport in that region of the lake during summer and fall (Chen et al. 2001; Budd 2004; Green and Eadie 2004). The Keweenaw Current can transport the Ontonagon River plume up to 80–100 km to the northeast during summer (Budd 2004), so that smaller tributary plumes in this region may be difficult to discern from the already riverine-influenced surface waters, and may account for the distinct DOM composition we observed in open water lake samples collected from the eastern vs. western sites (Figure 4). In contrast, tributary plumes may be more distinct and less quickly diluted along the east side of the Keweenaw, where coastal embayments and the presence of the Keweenaw Peninsula itself results in slower or little nearshore current or eddies (Budd 2004; Bennington et al. 2010). Optically distinct waters, identified using cluster analysis of optical properties derived from remote sensing

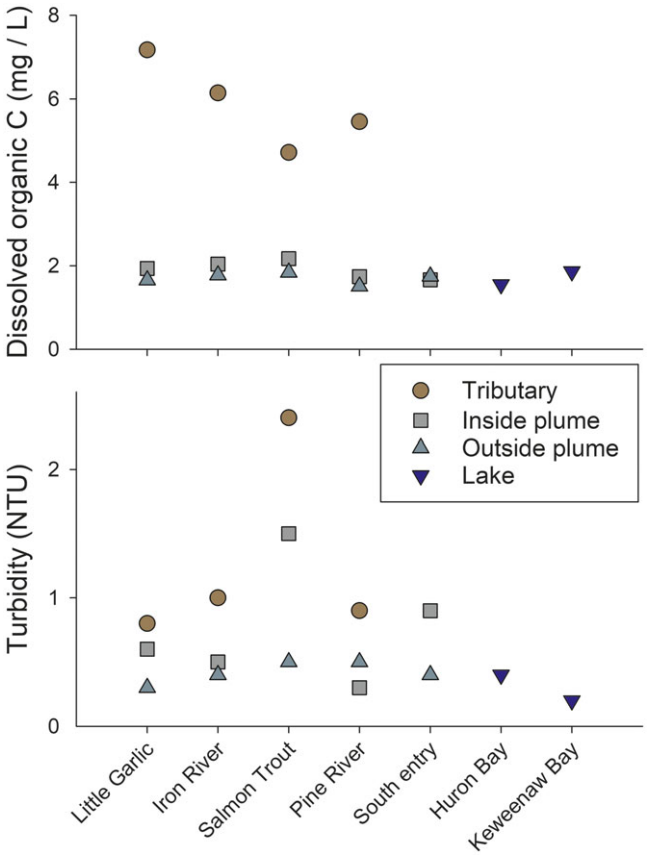

FIGURE 5. Elevated concentrations of DOC and turbidity were detected in most plumes sampled in 2013 in the Huron Mountains region on the east side of the Keweenaw Peninsula, which occurred within 24 h of an early summer storm event. NTU, Nephelometric Turbidity Unit.

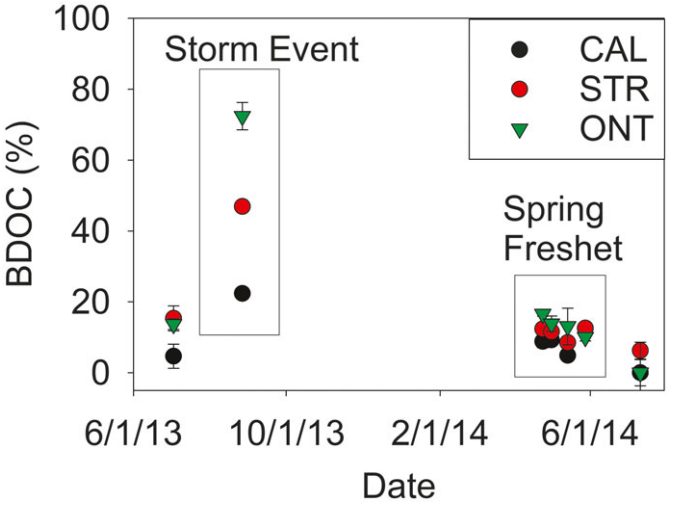

FIGURE 6. Biodegradable organic carbon (BDOC) as a percentage of the total DOC concentration, measured in three tributaries of Lake Superior (data from Coble, Marcarelli, Kane, Stottlemyer, et al. 2016). BDOC percentage varied widely during a late summer storm event compared to estimates during the spring freshet. CAL, Calumet Watershed; STR, Salmon-Trout River; ONT, Ontonagon River.

including CDOM absorption and backscattering, are often evident along the east vs. west side of the Keweenaw Peninsula (Trochta et al. 2015). The differences in CDOM and particles that lead to these optical distinctions would be due to both water circulation as well as tributary inputs. However, these distinctions vary temporally (Trochta et al. 2015), and are influenced by lake mixing, stratification, and circulation (Budd 2004; Urban 2009b; Bennington et al. 2010), along with tributary runoff (Green and Eadie 2004). Formation of lake ice and thermal bars would also restrict circulation and trap tributary plumes in the nearshore zone during times of peak tributary discharge (e.g., spring runoff; Auer and Gatzke 2004; Makarewicz, Lewis, Pennuto, et al. 2012). Characterizing the size and DOM load of tributary plumes, how they vary with tributary size, how they are transported by in-lake hydrodynamics, and how long they persist across the full suite of seasonal dynamics in Lake Superior will be key for understanding and predicting future changes in these process due to global change.

WILL GLOBAL CHANGE ALTER TRIBUTARY–LAKE SUPERIOR INTERACTIONS?

The hydrologic and biological controls on connections between Lake Superior and its tributaries are vulnerable to ongoing and future climate change. While this region is characterized by a persistent snowpack throughout the winter, the timing of snowpack initiation and runoff have been shifting in the Great Lakes region over the last five decades (Andresen 2007; Sebestyen et al. 2011). The amount of winter precipitation is projected to increase by 20% by midcentury (Hayhoe et al. 2010; Basile et al. 2017), but temperatures are also expected to increase by 2°C–3°C during this time period (Hayhoe et al. 2010). Therefore, peak snow water equivalents could decline owing to an increased proportion of precipitation falling as rainfall, midwinter thaws, and/or an earlier freshet. These shifts in regional climate are already underway; for example, median snowmelt has been occurring about 20 days earlier in the 2000s compared with the 1960s in northern Minnesota (Sebestyen et al. 2011). In addition, long-term monitoring in the Lake States region has shown an increase in the number of large storm events by 10–15 storms per year over the last century (Hayden and Hayden 2003), which corresponds with a 5% increase in the frequency of extreme precipitation events measured in the last four decades (NOAA 2018). The countervailing effects of increased winter precipitation in a

warmer, yet more variable climate add complexity to any predictions of how DOC and nutrient export during peak freshet may change in the future (e.g., Figure 2; Urban et al. 2011; Musselman et al. 2017). Exactly how the physical effects of diminished duration and extent of snow pack affect nutrient exports and biological processes needs to be examined along continua of soils, tributaries, and ultimately Lake Superior.

While patterns of water, DOM, and nutrient delivery from tributaries are likely to change in the future, Lake Superior is itself vulnerable to climate change. Surface water temperatures of Lake Superior have been increasing at a faster rate than regional air temperatures (Austin and Colman 2008) as a result of declining winter ice cover and an increase in the duration of lake stratification from 145 to 170 days per year (Austin and Colman 2007; Cline et al. 2013; Zhong et al. 2016). Increases in primary production in Lake Superior over the past century have been attributed to increases in surface water temperature and a longer period of seasonal stratification (O'Beirne et al. 2017). Over the next few decades, we anticipate that ice cover will further diminish, storm frequency and intensity will increase, and lake temperatures will continue to climb. Climate change is also projected to change patterns of lake level fluctuations, with recent analyses suggesting high lake water levels similar in magnitude to those observed in the long-term record, but more extreme low water levels (Angel 2013; Gronewold et al. 2013). These in-lake changes have important consequences for the fate of tributary inputs. Altering the timing of the spring freshet relative to thermal bar or ice formation will dictate whether tributary plumes are trapped in the nearshore zone or mixed into the offshore waters of Lake Superior. Increasing water temperatures and duration of stratification will alter the depth at which tributary inputs are delivered into the near shore and whether tributary inputs are retained in the epilimnion or shunted into the hypolimnion and long-term storage pools. In addition, warming temperatures will alter rates of organismal productivity and habitat use in tributaries, river mouths, and the lake littoral zone.

The way that processes in tributaries and Lake Superior will interact under future climate change is difficult to predict, as illustrated by the potential changes in DOM dynamics. DOM concentrations and loads have been increasing in many temperate and boreal freshwater bodies over the last few decades (Yallop et al. 2010; Urban et al. 2011; Filella and Rodríguez-Murillo 2014; Räike et al. 2016), with changes in climate and hydrologic regime suggested as potential drivers among others (Freeman et al. 2001; Erlandsson et al. 2008; Preston et al. 2011). DOM loading from watersheds is vulnerable to changes in hydrologic regime (Köhler et al. 2008; Räike et al. 2016); the future climate in this region will likely shift snowmelt-driven DOM loading to earlier in the spring (Sebestyen et al. 2011), and increase DOM loading during the ice-free seasons due to more large rain-driven events (Figure 2) (Hayden and Hayden 2003). Fluctuating lake levels could also increase flushing of wetlands and tributary mouths, which could increase DOM and suspended particles, with rapidly flushed DOM potentially more biodegradable and photodegradable than current inputs (e.g., Figure 6). Thus, it is reasonable to hypothesize an increase in the overall terrestrial DOM load to Lake Superior in the coming decades, as well as a shift in the seasonality of delivery from tributaries.

Even if this expectation is borne out, predicting the ecological effects of future DOM loading in Lake Superior is complicated due to the interacting effects of changing DOM and nutrient loads, and nonlinearities in the responses of lake ecosystems (Solomon et al. 2015). Potential consequences include a change in thermocline depth and stratification strength, an altered light regime influencing primary productivity and the effectiveness of visual predators, and a shift in microbial populations and activity (Solomon et al. 2015). For instance, enhanced fluxes of terrestrial DOM both provide an organic matter subsidy to nearshore bacterioplankton and simultaneously decrease light availability to phytoplankton. Large events that deliver pulses of CDOM can limit rates of primary production for a month or more (Minor et al. 2014), but also may deliver pulses of phosphorus enhancing rates of primary and bacterial production. Remarkably, photolysis of accumulated recalcitrant DOM in response to a period of high light levels following the 1997–1998 El Niño has been linked to a shift of the Lake Superior ecosystem from autotrophic to heterotrophic (Brothers and Sibley 2018). Thus, long-term changes in quantity and quality of DOM interact with climate to drive the net metabolism of Lake Superior.

Understanding the ecological consequences of such complex and interactive physical and biogeochemical processes will require a variety of research approaches in both tributaries and the lake, including long-term measurements and site comparisons, coupled process-based physical–biological models, and experiments at multiple spatial scales (Carpenter 1998). Particular attention should be paid to potential shifts in the nearshore light regime, and variation in light or nutrient levels, which could alter the balance of light vs. nutrient limitation in the nearshore zones. Efforts that leverage long-term records of climate variability while also embracing the considerable spatial and temporal variation in open water, terrestrial watershed, and tributary properties using novel sampling techniques

are required to forecast the full suite of ecological responses possible under a changing climate.

HOW CAN EMERGING TECHNOLOGIES BE USED TO ADDRESS UNKNOWNS IN THE STUDY OF LAKE SUPERIOR–TRIBUTARY INTERACTIONS?

Gaps in monitoring programs inhibit detailed exploration of the spatial and temporal dynamics of tributary plumes in the nearshore zone of the Great Lakes and prediction of how those dynamics may respond in a changing climate. Most monitoring and sampling programs on the Great Lakes lack measurements of nutrient cycling processes, are too infrequent to characterize temporal variability in conditions, and do not operate over the winter (Gronewold and Fortin 2012; Baskaran and Bratton 2013; Sterner et al. 2017). The spatial and temporal distributions of overall monitoring efforts in the open waters of Lake Superior are limited, and although the number of nearshore monitoring buoys has increased as part of the Great Lakes Observing System in recent years (e.g., Read et al. 2010), few are located close enough to tributary mouths to provide consistent estimates of inputs or plumes. Monitoring of tributary inputs is similarly limited to a small number of large tributaries that are continuously monitored for discharge and some nutrients (Robertson 1997), and a few very small tributaries (<2 km^2) that have been the sites of whole-watershed studies (Stottlemyer et al. 1998; Stottlemyer and Toczydlowski 2006). More intense, short-term monitoring and sampling efforts are typically positioned in close proximity to university and government research groups, creating an overrepresentation of specific locations in our understanding of whole-lake processes. For example, the most complete temporal characterization of primary production and respiration rates are focused on transects off the Keweenaw Peninsula, which has characteristically unique hydrodynamic conditions, and the Western Basin, where the influence of Duluth and the St. Louis River provide a stronger anthropogenic footprint than in other regions of the lake (e.g., Sterner et al. 2004; Urban et al. 2005; Sterner 2010). Detailed studies of tributary inputs and processes are similarly localized, focused on the St. Louis River and north and south shore streams around Duluth (Wold and Hershey 1999; Minor et al. 2012, 2014; Lehto and Hill 2013), central south shore tributaries between Ontonagon and Marquette, Michigan (Frost et al. 2006, 2009; Hoellein et al. 2007; Burtner et al. 2011; Coble, Marcarelli, Kane, and Huckins 2016; Coble, Marcarelli, Kane, Stottlemyer, et al. 2016), and a few studies on the eastern south shore (e.g., Back et al. 2002; Collins et al. 2011). Yet most of these studies are limited in their temporal and/or spatial extent, and thus not useful for determining magnitude or seasonality of loads or tributary–lake interactions. Because tributary inputs are patchy in both space and time, quantifying and characterizing them will require focused sampling efforts during key periods of tributary runoff and relative to changes in in-lake conditions like stratification, thermal bar formation, and ice cover. The largest tributary plumes are generated by large runoff events, such as spring runoff and storms, often during periods when lake ice and/or weather conditions limit access for sampling vessels on Lake Superior. Furthermore, access to nearshore plumes associated with small tributaries is very difficult via traditional sampling vessels. Therefore, novel data collection approaches are required to adequately characterize tributary inputs and their contributions to lake-wide processes in Lake Superior and the other Great Lakes.

Environmental monitoring at high temporal and spatial resolution is being rapidly advanced by combinations of robust sensors that can be deployed in place for long times and autonomous or semiautonomous aquatic and airborne platforms that can sample a selected area dynamically. When deciding what and when to monitor, the most obvious variables to differentiate tributaries from Lake Superior water are temperature, which shows more extreme seasonality in tributaries vs. the main body of the lake; CDOM, which has higher concentrations in tributaries (Figures 5 and 6); and nitrate, which has higher concentrations in the lake (Figure 5). Deployable sensors for CDOM and nitrate have detection ranges that could detect expected concentrations in both tributaries and the nearshore of Lake Superior. Lake-wide spatially distributed stream, river, and lake sensors deployed to monitor tributary discharge and water chemistry can improve and refine estimates of N and C export from tributaries into the Great Lakes at relevant temporal and spatial scales. Continuous, long-term deployment in both tributaries and the nearshore is required to capture unpredictable, short-term input following storms, while also integrating across annual snowmelt and summer dynamics. Deploying sensors on mobile autonomous or semiautonomous platforms such as gliders or autonomous underwater vehicles (Page et al. 2017) could greatly improve estimates of tributary plume sizes and timing, but a boat or shore access is still required for safe deployment or retrieval.

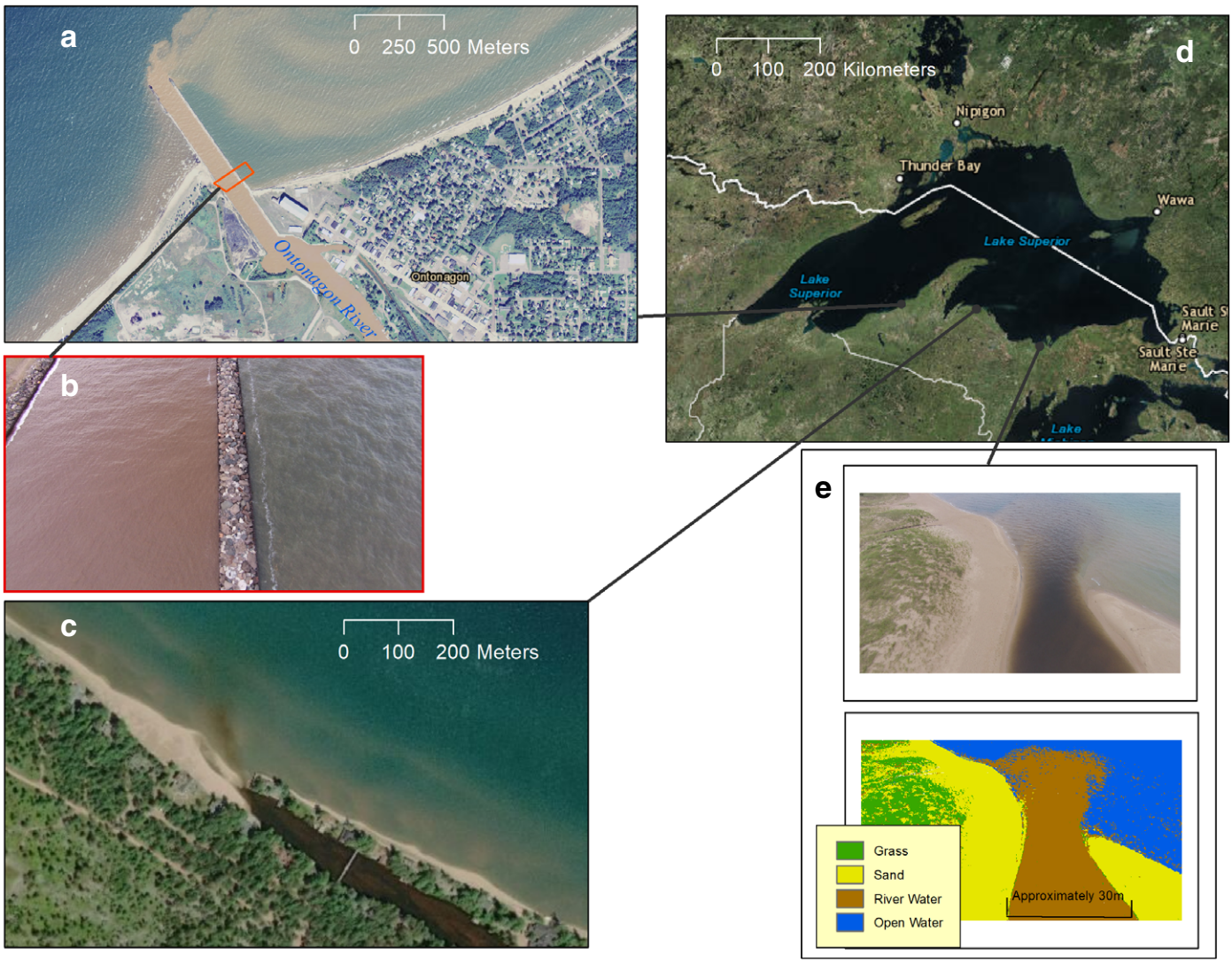

FIGURE 7. Remote sensing provides the capability to characterize river outlets at high resolution. (a) A National Agriculture Imagery Program image of the Ontonagon River collected on September 6, 2016 shows a sediment plume entering Lake Superior. (b) An unmanned aerial vehicle (UAV)-collected image of the Ontonogan River Channel area (approximate location shown by red box in (a)) collected on October 14, 2014 shows the color difference between sediment-laden river water relative to Lake Superior water. (c) The Pine River mouth in a DigitalGlobe satellite image on August 21, 2015 shows a plume of colored DOM-rich waters entering Lake Superior. (d) The location of each of the images in Lake Superior is shown on an Environmental Systems Research Institute basemap. (e) UAV-collected image on June 25, 2015 shows a plume at the Au Train River with classification into four categories (grass/sand/river water with visible colored fraction of DOM/open water) using an object-based classification with eCognition (Definiens AG 2009).

Airborne remote sensing also offers exciting opportunities, particularly for monitoring the size, timing, and duration of tributary plumes and comparing or scaling their influence across the nearshore zone of Lake Superior (Figure 7). Recent advances in satellite remote sensing algorithms for Lake Superior now allow estimation of CDOM along with suspended sediment and chlorophyll *a* in nearshore environments (Shuchman et al. 2013). However, satellite-based remote sensing of open water characteristics is limited by the high frequency of cloudy days (Schwab et al. 1999), which frequently coincide with the very storms that drive tributary export and development of plumes. Unmanned aerial vehicles (UAVs) are emerging as an ideal flexible, low-cost platform for rapid data collection with multiple sensors such as multispectral cameras, light detection and ranging devices, and thermal infrared imagers that will benefit ecological studies (Anderson and Gaston 2013). In particular, the ability of UAVs to collect very high-resolution (e.g., cm-scale) data can improve the documentation of small tributary plumes as well as overall nearshore conditions (Figure 7) (Lomax et al. 2005; Lucieer et al. 2014). The ability to collect spectral profile data and multispectral imagery to characterize water color and quality, as well as

temperature data to detect thermal characteristics from tributaries directly at their output to Lake Superior using UAVs provides an opportunity to monitor with a spatial and temporal intensity that is currently impossible with satellite-based remote sensing. Imagery collected from UAV platforms can be analyzed and classified similar to that collected from satellites (Figure 7), and provides the advantage of allowing on-demand collection by an operator located on either shore or a boat at relatively low cost. UAVs can also be used to collect data when conditions on the lake are inaccessible due to ice, wind/waves, or cloud conditions, thereby providing an opportunity to classify tributary inputs under the full range of weather and hydrologic conditions throughout the year. Combined systems of emerging remote sensing techniques, sensor networks, and on-the-ground sampling and experimentation are needed to address the current and future unknowns regarding lake–tributary interactions outlined in this synthesis.

CONCLUSION

We have demonstrated considerable variability in the amount and character of nutrients and DOM delivered by tributaries to Lake Superior, with changes in seasonal or storm events and lake hydrodynamic conditions. Quantifying these inputs and understanding their importance for biological processes in Lake Superior will require detailed spatial and temporal monitoring across the full range of tributary sizes, geographic regions, and annual ecological and hydrologic conditions. Terrestrial processes related to hydrologic connectivity, water holding capacity, and runoff will likely change with the predicted future changes in climate, which have consequences for the timing, amounts, and composition of tributary inputs to Lake Superior. Application of existing and emerging approaches and tools, including environmental sensors and remote sensing techniques, is needed to better assess changes in these inputs. Point measurements of tributary export must be scaled up to understand the size of tributary plumes, the total mass of input, and the concentration peaks. Pulsed inputs of DOM and nutrients, particularly those associated with predictable events like spring runoff, may coincide with the presence and key life cycle stages of microbes, plants, and animals that disproportionately rely on the nearshore zone of Lake Superior (Vadeboncoeur et al. 2011). Stimulation of primary and secondary production in the nearshore by inputs of limiting nutrients could have bottom-up effects on the food web, if the timing of inputs and organism needs are coincident. Understanding these ecological linkages are key for predicting the long-term consequences of climate change for the organisms and human communities that rely on Lake Superior, as well as the other Great Lakes and their tributaries.

SUPPORTING INFORMATION

Additional supporting information may be found online under the Supporting Information tab for this article: Text describing field and laboratory methods for the tributary and nearshore sampling efforts 2013–2015, a table and a figure with site characteristics and water quality data for this sampling, and a figure showing the model components for dissolved organic matter characterization.

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