



14 Inland Waters

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KEY FINDINGS

1. The total flux of carbon—which includes gaseous emissions, lateral flux, and burial—from inland waters across the conterminous United States (CONUS) and Alaska is 193 teragrams of carbon (Tg C) per year. The dominant pathway for carbon movement out of inland waters is the emission of carbon dioxide gas across water surfaces of streams, rivers, and lakes (110.1 Tg C per year), a flux not identified in the *First State of the Carbon Cycle Report* (SOCCR1; CCSP 2007). Second to gaseous emissions are the lateral fluxes of carbon through rivers to coastal environments (59.8 Tg C per year). Total carbon burial in lakes and reservoirs represents the smallest flux for CONUS and Alaska (22.5 Tg C per year) (*medium confidence*).
2. Based on estimates presented herein, the carbon flux from inland waters is now understood to be four times larger than estimates presented in SOCCR1. The total flux of carbon from inland waters across North America is estimated to be 507 Tg C per year based on a modeling approach that integrates high-resolution U.S. data and continental-scale estimates of water area, discharge, and carbon emissions. This estimate represents a weighted average of 24 grams of carbon per m² per year of continental area exported and removed through inland waters in North America (*low confidence*).
3. Future research can address critical knowledge gaps and uncertainties related to inland water carbon fluxes. This chapter, for example, does not include methane emissions, which cannot be calculated as precisely as other carbon fluxes because of significant data gaps. Key to reducing uncertainties in estimated carbon fluxes is increased temporal resolution of carbon concentration and discharge sampling to provide better representations of storms and other extreme events for estimates of total inland water carbon fluxes. Improved spatial resolution of sampling also could potentially highlight anthropogenic influences on the quantity and quality of carbon fluxes in inland waters and provide information for land-use planning and management of water resources. Finally, uncertainties could likely be reduced if the community of scientists working in inland waters establishes and adopts standard measurement techniques and protocols similar to those maintained through collaborative efforts of the International Ocean Carbon Coordination Project and relevant governmental agencies from participating nations.

Note: Confidence levels are provided as appropriate for quantitative, but not qualitative, Key Findings and statements.

14.1 Introduction: The Aquatic Carbon Cycle

14.1.1 Inland Waters in the Carbon Cycle

This chapter provides an assessment of the total mass of carbon moving from terrestrial ecosystems into inland waters and places this flux in the context of major carbon loss pathways. Also provided is evidence that the estimated carbon flux through inland waters is poorly constrained, highlighting several opportunities to improve future estimates of carbon flows through aquatic ecosystems. Inland waters are defined in this chapter as open-water systems of lakes, reservoirs, nontidal rivers, and streams (see Ch. 13: Terrestrial Wetlands, p. 507, and Ch. 15: Tidal Wetlands and Estuaries, p. 596, for assessments

of those ecosystems). Carbon within inland waters includes dissolved and particulate species of inorganic and organic carbon. The separation between dissolved and particulate carbon is operational and reflects, in general, a filtration through a 0.2- to 0.7-micrometer (μm) filter, where the larger material is considered particulate within freshwater environments. Using this definition classifies inland water carbon as dissolved organic carbon (DOC), dissolved inorganic carbon (DIC), particulate organic carbon (POC), and particulate inorganic carbon (PIC). Included within the DIC pool is dissolved carbon dioxide (CO_2).

Lakes, ponds, streams, rivers, and reservoirs are both the intermediate environments that transport,

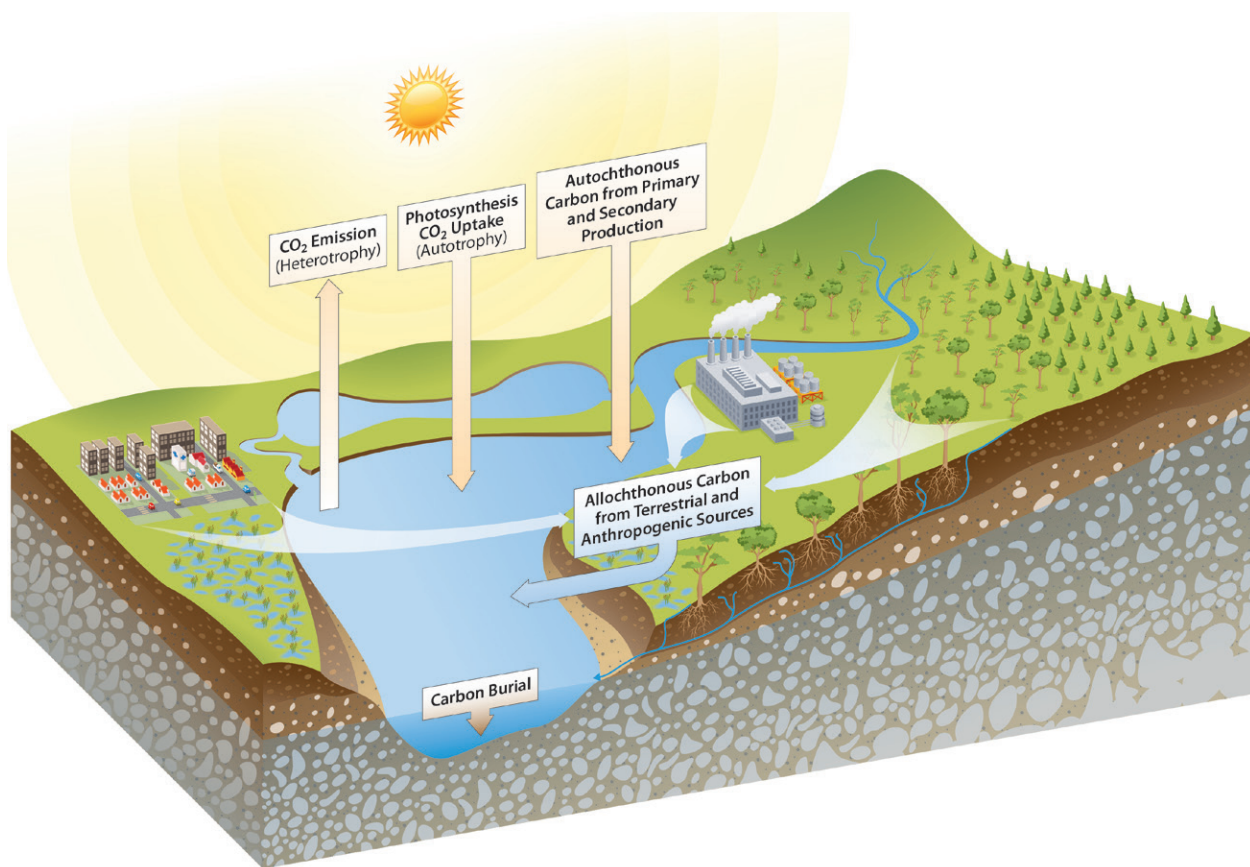


Figure 14.1. Carbon Flux Pathways in Aquatic Environments. Allochthonous carbon represents organic and inorganic carbon, including dissolved carbon dioxide (CO_2), that enters aquatic environments from terrestrial systems. Autochthonous carbon originates from primary and secondary production that uses either atmospheric CO_2 or dissolved inorganic carbon from the aquatic environment. Primary production within autotrophic systems is responsible for the net uptake of atmospheric CO_2 , while respiration and allochthonous inputs of carbon within a heterotrophic system are responsible for a net CO_2 emission to the atmosphere. Burial represents the deposition of autochthonous and allochthonous particulate carbon.

sequester, and transform carbon before it reaches coastal environments (Liu et al., 2010) and dynamic ecosystems that sustain primary and secondary production supporting aquatic metabolism and complex food webs. Inland waters comprise a small fraction of Earth's surface yet play a critical role in the global carbon cycle (Battin et al., 2009b; Butman et al., 2016; Cole et al., 2007; Findlay and Sinsabaugh 2003; Regnier et al., 2013; Tranvik et al., 2009). Over geological timescales, inland waters control long-term sequestration of atmospheric CO_2 through the hydrological transport of inorganic carbon from

terrestrial weathering reactions to coastal and marine carbon "sinks" as dissolved carbonate species (Berner 2004). Today, through anthropogenic land-use change, industrialization, damming, and changes in climate, the ecosystem structure and function of inland waters are changing rapidly. However, as presented in this chapter, the flows of carbon through inland waters represent a combination of both natural and anthropogenic influences, (see Figure 14.1, this page) as the science has not achieved a comprehensive ability to differentiate anthropogenic fluxes from natural fluxes. In the context of the North



American carbon cycle, the science discussed herein addresses current understanding of freshwater carbon cycling from the period since 1990 and highlights the need to focus on better identifying human impacts on the transport and biogeochemical cycling of carbon by inland waters.

14.1.2 Defining Carbon Within Inland Waters

Inland aquatic ecosystems are sites for biogeochemical carbon reactions that result in an exchange of particulate and dissolved carbon, CO₂, and methane (CH₄) among aquatic environments, terrestrial environments, and the atmosphere (Butman and Raymond 2011; Findlay and Sinsabaugh 2003; McCallister and del Giorgio 2012; McDonald et al., 2013; Raymond et al., 2013; Striegl et al., 2012). Carbon species in freshwaters originate from varied sources. Aquatic organic carbon consists of all organic molecules transported to or produced within inland waters and their various organic decomposition products. Inland water organic carbon originates from direct inputs from wastewater, surface runoff (typically, the largest contributor), groundwater, primary and secondary production within the aquatic environment, and atmospheric deposition. Inorganic carbon includes PIC and DIC. The mass balance of DIC in freshwater ecosystems is regulated by biological processes such as photosynthesis (consuming CO₂) and respiration (producing CO₂), along with air-water CO₂ exchange and geochemical reactions, including carbonate precipitation and dissolution (Tobias and Bohlke 2011).

Rivers are conduits that deliver carbon to the coast while maintaining strong CO₂ and CH₄ fluxes to or from the atmosphere (Cole et al., 2007; Stanley et al., 2016; Tranvik et al., 2009). Lakes and reservoirs are sinks of particulate carbon in sediments and also process and remineralize organic carbon to CO₂ and CH₄ gases that are then emitted to the atmosphere (Clow et al., 2015; Teodoru et al., 2012). Autotrophic carbon production in nutrient-enriched lakes and reservoirs can cause inland water bodies to be a sink of atmospheric CO₂ (Clow et al., 2015; Tranvik et al., 2009). The entrapment of sediments

by dams can facilitate aerobic and anaerobic organic carbon oxidation and thus the net production of CO₂ and CH₄ that escape to the atmosphere, with important implications to climate forcing (Crawford and Stanley 2016; Deemer et al., 2016). However, the balances among primary production, total respiration, carbon burial, and carbon gas emission in lakes and reservoirs remain poorly quantified (Arntzen et al., 2013; Teodoru et al., 2012).

Of the roughly 2.9 petagrams of carbon (Pg C) per year that enter inland waters globally, most are emitted as CO₂ across the air-water interface (Butman et al., 2016; Raymond et al., 2013) before ever reaching the ocean (Le Quéré et al., 2014). Recent estimates suggest that inland water surface carbon emissions may exceed 2 Pg C per year (Sawakuchi et al., 2017). In contrast, rivers export to the coastal ocean 0.4 Pg C per year of DIC and between 0.2 and 0.43 Pg C per year of organic carbon (Le Quéré et al., 2014; Ludwig et al., 1996; Raymond et al., 2013; Schlünz and Schneider 2000). However, the biogeochemical processes that produce and sustain both atmospheric carbon emissions and lateral fluxes remain unclear because physical and biological processes vary significantly across freshwater systems and along the hydrological continuum (see Figure 14.2, p. 572; Battin et al., 2008; Hotchkiss et al., 2015).

Carbon fluxes in inland waters are considered in Equation 14.1 in the context of a simple mass balance approach.

Equation 14.1

$$C_{aquatic} = C_{allochthonous} - [C_{emissions} + C_{burial} + C_{export}]$$

The dimensions of this equation are mass carbon (C) per unit time (e.g., Tg C per year) or mass C per unit area per unit time (e.g., units of g C per m² per year), where $C_{aquatic}$ represents the change of carbon stock in inland waters, $C_{allochthonous}$ is the input of allochthonous carbon into inland waters from land, $C_{emissions}$ is the total emissions of CO₂ and CH₄ from the water surface, C_{burial} is the total burial of POC in lakes and reservoirs, and C_{export} is

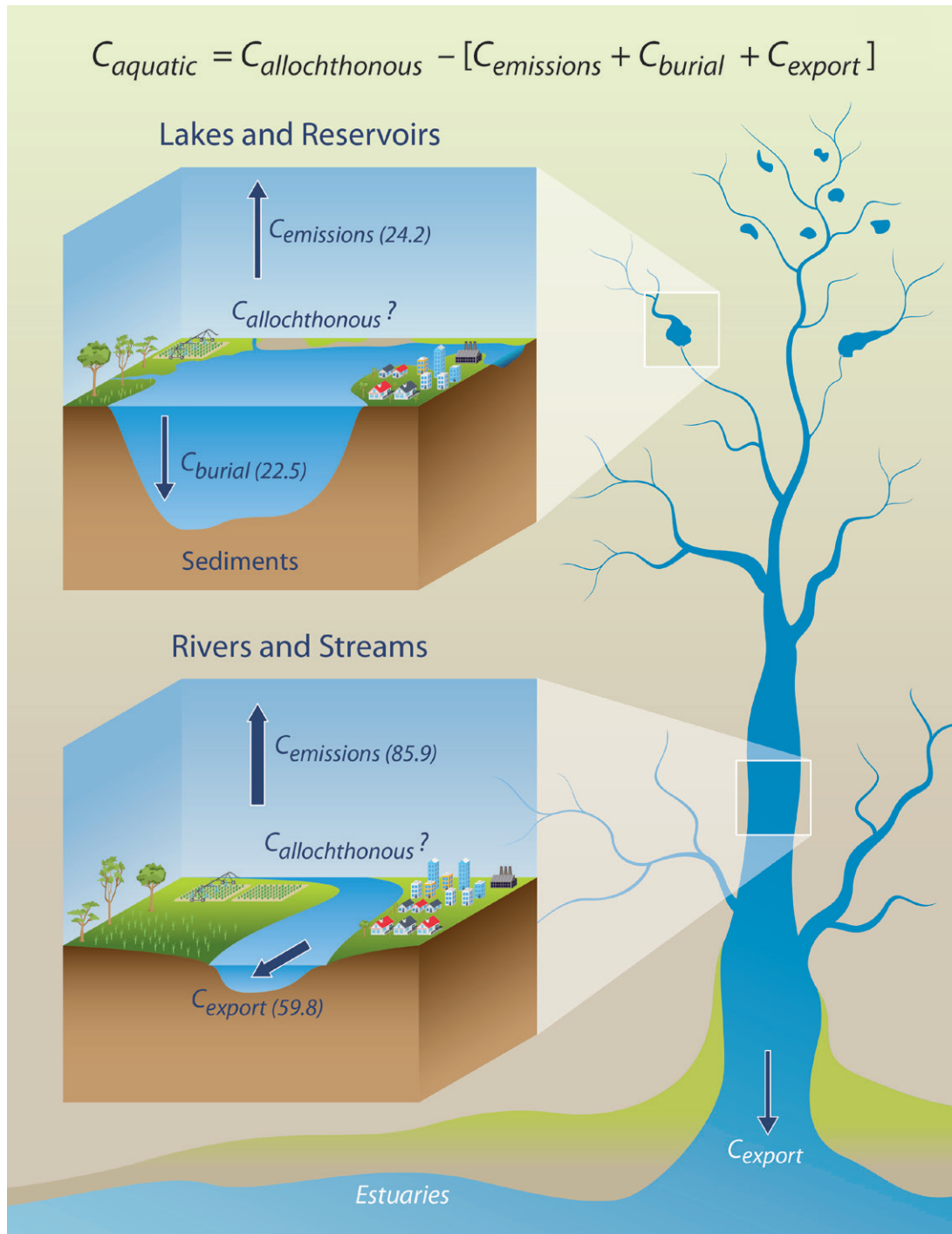


Figure 14.2. Carbon Fluxes from Inland Waters of the Conterminous United States and Alaska. All values represent total fluxes in teragrams of carbon (Tg C) per year. River fluxes represent total carbon fluxes to the point of the head of tide, or the highest flow gaging station not influenced by tidal movement. Individual fluxes from different land uses are not quantified but represented by the mass balance of all aquatic carbon fluxes. The total flux (see Equation 14.1, p. 571) is 193 Tg C per year. Further information regarding estimates of uncertainty are presented in Stackpoole et al. (2017a) and Butman et al. (2016).



the total export of inorganic and organic carbon to coastal systems. For this analysis, estimates of CH_4 emissions are not provided. Furthermore, changes in carbon stocks are assumed to be zero (i.e., assumption of steady state), which is reasonable over long timescales because of the rapid movement and turnover of carbon in lotic (flowing) and lentic (still) ecosystems. Hence, in this chapter, the flux of carbon from inland waters (the terms within brackets in Equation 14.1, p. 571) is assumed to be equivalent to the flux of carbon to inland waters, $C_{\text{terrestrial}}$. The use of this equation implies a fully constrained hydrological system. Adjustments have been made to U.S. flux estimates for carbon originating outside national boundaries.

14.1.3 Inland Waters of the United States and North America

The conterminous United States (CONUS) and Alaska contain over 45 million individual lakes and ponds greater than 0.001 km^2 . Excluding the Laurentian Great Lakes (see Section 14.1.4, p. 574), these lakes and ponds cover an estimated 179,000 to 183,000 km^2 (Butman et al., 2016; Clow et al., 2015; McDonald et al., 2012; Zhu and McGuire 2016) and include more than 87,000 reservoir systems (Clow et al., 2015; Hadjerioua et al., 2012). Streams and rivers in the United States and Alaska are estimated to cover 36,722 km^2 (Butman et al., 2016; Stackpoole et al., 2017b; Zhu and McGuire 2016). Combined, inland waters (except the Great Lakes) cover approximately 1.9% of CONUS and 3.9% of Alaska. Although 30-m resolution map products include inland freshwater bodies $>0.005 \text{ km}^2$ (Feng et al., 2015), large-scale water-surface map products currently do not capture smaller-scale water bodies ($<0.001 \text{ km}^2$), which have been linked with higher greenhouse gas (GHG) emissions rates (Holgerson and Raymond 2016). All stream and river areas in this chapter are estimated by scaling the relationships among discharge and water velocity, water depth, and stream or river width (Melching and Flores 1999; Raymond et al., 2012). Freshwater discharge to the coast of North America is dominated by the Mississippi, St. Lawrence, Mackenzie,

Columbia, and Yukon rivers, which have a combined discharge of $1,500 \text{ km}^3$ per year, about half the total freshwater runoff to the coast of North America (Dai et al., 2009).

The boreal area of North America constitutes one of the most lake-rich regions in the world. In Canada alone, there are an estimated 3.3 million water bodies greater than 0.01 km^2 in surface area and another 5.4 million in the smallest size category ($<0.001 \text{ km}^2$). All Canadian water bodies (excluding the Great Lakes) are estimated to cover 884,000 km^2 , or about 9% of the country's surface. In some large regions of northern Quebec and Ontario, inland waters cover up to 25% of the surface area. In Mexico, surface waters (excluding fluvial systems) are estimated to cover 25,769 km^2 , or 1% of the country's surface, and the total length of streams and rivers is estimated to be 633,000 km (INEGI 2017). The watersheds of Mexico's 33 main rivers cover 565,128 km^2 , and freshwater flow is dominated by the Grijalva and Usumancinta rivers, which drain to the Gulf of Mexico.

There are 87,359 registered dams in the United States (USACE 2016), more than 10,000 dams in Canada (Canadian Dam Association 2018), and 5,163 dams and reservoirs holding approximately 150 km^3 of water in Mexico (CONAGUA 2015). Dam construction in recent years has increased the volume of retained water by about 600% to 700% globally, tripling the transit time of water from land to sea (Vörösmarty et al., 2009). This trend is expected to continue globally with several large damming projects underway (Zarfl et al., 2014). Within the United States, nearly 2,500 dams provide 78 gigawatts (GW) of power; up to 12 GW potentially could be added by leveraging the installed dam capacity currently not being used for energy production (Hadjerioua et al., 2012). The U.S. Pacific Northwest and Southeast have the highest potential for future power generation (Hadjerioua et al., 2012). Reservoirs formed through the damming of rivers alter the natural flux of carbon and the dispersal of sediments (Dean and Gorham 1998), increasing the likelihood that organic carbon will be



remineralized to CH_4 and CO_2 compared to unrestricted conditions (Deemer et al., 2016; Rudd et al., 1993; Teodoru et al., 2012). Thus, the conversion of meandering rivers to a series of reservoirs potentially reduces the transport of carbon to the coast (Hedges et al., 1997), and it may increase the flux of CO_2 and CH_4 to the atmosphere (Deemer et al., 2016; Tranvik et al., 2009; Tremblay et al., 2005).

14.1.4 The Great Lakes

The Laurentian Great Lakes vary between being considered as part of the coastal domain or as inland waters because each of the five lakes is distinct in size and volume. In this chapter, these lakes are considered as inland waters, containing about 18% of the world's supply of surface fresh liquid water and 84% of North America's supply (www.epa.gov/greatlakes/great-lakes-facts-and-figures). Although interconnected, the lakes differ substantially in their physical, biological, and chemical characteristics. The largest, Lake Superior, has an average depth of 147 m and a water retention time of nearly 200 years, while the smallest, Lake Erie, has an average depth of 19 m and a retention time of about 3 years. Productivity ranges from oligotrophic in Lake Superior to eutrophic in Lake Erie. Water chemistry also varies substantially among the lakes, with mean alkalinity ranging from 840 micromoles (μmol) per kg in Lake Superior to 2,181 μmol per kg in Lake Michigan (Phillips et al., 2015).

Despite the large size of the Great Lakes, knowledge of their lakewide carbon cycle is relatively limited. Recent observational and modeling studies have helped elucidate some of the physical and biogeochemical processes governing the seasonal carbon cycle (Atilla et al., 2011; Bennington et al., 2012; Pilcher et al., 2015), but current CO_2 emissions estimates are poorly constrained and are excluded from regional carbon budgets (McDonald et al., 2013). Observations of surface partial pressure of CO_2 ($p\text{CO}_2$) suggest that the Great Lakes are in near equilibrium with the atmosphere on annual timescales but vary seasonally between periods of significant undersaturation and supersaturation (Atilla et al., 2011; Karim et al., 2011; Shao

et al., 2015). Autochthonous carbon from spring and summer productivity is respired at depth and ventilated back to the atmosphere during strong vertical mixing in late fall and winter, limiting burial (Pilcher et al., 2015). However, even highly productive regions, such as western Lake Erie, have been shown to be net sources of carbon to the atmosphere (Shao et al., 2015). Additional data are required to better understand the lakewide response to increasing atmospheric CO_2 and any resulting, decreasing trend in lake pH (Phillips et al., 2015). Further uncertainty arises from a long history of anthropogenic stressors that have significantly affected lakewide ecology and ecosystem services (Allan et al., 2013). A recent example is the proliferation of invasive *Dreissena* mussels throughout most of the Great Lakes. Filter feeding from these mussels coincides with substantial reductions in aquatic primary productivity, which probably has altered the lakewide food web and resulted in unknown impacts to the carbon cycle (Evans et al., 2011; Madenjian et al., 2010).

14.2 Historical Context

14.2.1 Early Understandings

The study of carbon cycling in lakes, streams, and large rivers started in the early part of the last century with the development of the ecosystem concept as a functional unit by which scientists could define the physical, chemical, and biological structure of the world around them. This concept was adapted from terrestrial to aquatic systems through seminal work (Lindeman 1942) partitioning the movement of energy, and as a result carbon, across trophic levels in lakes. A second concept relevant to carbon cycling in inland waters is the tracing of elements through natural systems, which has a long history in geochemistry and had developed prior to the notion of ecology. The convergence of these two concepts that define the interactions among biological, physical, and chemical environments was permanently established by the need to 1) improve water quality from eutrophication of freshwaters by agricultural fertilizer inputs and 2) understand the impacts of acid rain through the exploration of elemental cycling in whole lakes (Johnson and



Vallentyne 1971) and at the watershed scale (Likens 1977). Although carbon remained secondary to the tracing of nutrients and other chemical species, research clearly established that carbon from terrestrial systems provided energy to and influenced the structure of aquatic systems (Pace et al., 2004) and that the boundary between these two systems might not be so discrete. A rich field of ecosystem-based science subsequently developed that expanded dramatically into this century. In an attempt to synthesize carbon dynamics in freshwaters, a group through the National Center for Ecological Analysis and Synthesis produced a seminal paper that highlighted the magnitude of the flows of carbon through freshwaters at the global scale (Cole et al., 2007), laying the foundation for the research that supports this chapter.

14.2.2 First State of the Carbon Cycle Report

The *First State of the Carbon Cycle Report* (SOCCR1) identified rivers and lakes as a net sink of 25 Tg C per year into sediments across North America (CCSP 2007; Pacala et al., 2001; Stallard 1998). The total lateral transfer of carbon (including both DIC and DOC) to the ocean was estimated to be 35 Tg C per year (Pacala et al., 2001) and was considered highly uncertain. These estimates did not include Canada, Mexico, or the Great Lakes because of a lack of available data for each. It is important to note that all estimates for rivers were considered sinks or net transfers of carbon to the coastal environment, as well as storage of carbon in lake and reservoir sediments. Since 2007, the research community has widely accepted that inland aquatic ecosystems also function as an important interface for carbon exchange between terrestrial ecosystems and the atmosphere (Cole et al., 2007; Tranvik et al., 2009). Evidence summarized herein shows that, over short timescales, freshwaters function as sources of atmospheric CO₂. Also provided are improved estimates of burial in lakes and reservoirs and lateral transfer to the coast. The updated budget increases the total carbon fluxes from inland waters by a factor of two over those reported in SOCCR1 (see Table 14.1, p. 576) and alters the

previous perception of inland waters as a sink of atmospheric CO₂. These estimates of inland water fluxes, coupled with a better understanding of flow paths for carbon losses and export from wetland and coastal environments, provide evidence that the majority of terrestrially derived carbon moving through inland waters is released to the atmosphere as CO₂.

14.3 Current Understanding of Carbon Fluxes and Stocks

A more complete accounting of aquatic carbon has been a major advance in aquatic carbon cycle science, specifically the inclusion of CO₂ emissions from rivers and lakes to the atmosphere. Additionally, publications of high-resolution inventories of lake and river surface areas have enabled researchers to more accurately scale up local hydrology and chemistry datasets to regional and continental scales. One of the most important results from these new and rigorous assessments is the documentation of regional variability across Arctic, boreal, temperate, subtropical, and tropical ecosystems in North America.

14.3.1 Carbon Fluxes from U.S. Waters

Contemporary total inland water carbon fluxes from CONUS and Alaska were estimated with comparable datasets and methodologies (Butman et al., 2016; Stackpoole et al., 2016). Total aquatic carbon fluxes represent the sum of 1) lateral transport of DIC and total organic carbon (TOC) from river systems to the coast, 2) CO₂ emissions from rivers and lakes, and 3) carbon burial in sediments. Although burial in lake sediments also has been considered storage at the continental scale, this report considers burial as the removal of carbon from the aqueous environment and thus adds burial to the total flux (see Equation 14.1, p. 571).

The estimated total carbon flux from inland waters in CONUS is 147 Tg C per year (5% and 95%: 80.5 and 219 Tg C presented in Butman et al., 2016). In Alaska, it is 44.5 Tg C per year (31.4 and 52.5 Tg C presented in Stackpoole et al., 2016). These

**Table 14.1. U.S., North American, and Global Annual Carbon Fluxes from Inland Waters^{a-k}**

Source	United States ^a	Canada	Mexico	Great Lakes	North America	Globe (Pg C per Year)
	(Tg C per Year)					
Rivers and Streams						
Lateral Fluxes	59.8***	18.2 (TOC) ^b	ND	ND	105****	0.6–0.7 ^c
Gas Emissions	85.9**	ND	ND	ND	124.5**	0.7–1.8 ^d (2.9) ^e
Lakes and Reservoirs						
Burial	22.5**	ND	ND	2.7* ^h	155**	0.2–0.6 ^f
Gas Emissions	24.2***	ND	ND	ND	122**	0.6 ^g
Inland Aquatic Systems						
Total Carbon Flux	193***	ND	ND	2.3–36* ⁱ	507**	2.1–3.7 (4.9)
Net Carbon Yield (g C per m ² per year)	20.6***	ND	ND	ND	23.2**	16–17 (33)

Notes

- a) Butman et al. (2016); Stackpoole et al. (2016). United States includes the conterminous United States and Alaska.
- b) Clair et al. (2013).
- c) Dai et al. (2012); Meybeck (1982); Seitzinger et al. (2005); Hartmann et al. (2014b); Spitzky and Ittekkot (1991); Syvitski and Milliman (2007); Galy et al. (2015).
- d) Raymond et al. (2013); Lauerwald et al. (2015).
- e) All estimates in parenthesis derived from Sawakuchi et al. (2017).
- f) Battin et al. (2009a); Tranvik et al. (2009).
- g) Aufdenkampe et al. (2011).
- h) Einsele et al. (2001).
- i) McKinley et al. (2011).
- j) All fluxes include inorganic and organic carbon as well as particulate and dissolved species.
- k) Key: Tg C, teragrams of carbon; Pg C, petagrams of carbon; g C, grams of carbon; TOC, total organic carbon; ND, no data; Asterisks indicate that there is 95% confidence that the actual value is within 10% (*****), 25% (****), 50% (***), 100% (**), or >100% (*) of the reported value.

estimates combine for a total flux of about 193 Tg C per year, as presented in Table 14.1, this page. Carbon yields, which represent fluxes normalized by land surface area, are 18.6 g C per m² per year in CONUS and 29 g C per m² per year in Alaska. The higher value for Alaska is most likely related to the higher water surface area found across the state. Combined and weighted by area, the average yield for CONUS and Alaska is 20.6 g C per m² per year.

Rivers dominate total carbon fluxes from inland waters in CONUS and Alaska. Coastal carbon export is 41.5 Tg C per year (5% and 95%: 39.4, 43.5 Tg C) for CONUS and 18.3 Tg C per year

(16.3, 25.0 Tg C) for Alaska. River CO₂ emissions are 69.3 Tg C per year (36.0, 109.6 Tg C) and 16.6 Tg C per year (9.0, 26.3 Tg C), respectively.

Carbon burial in lakes and reservoirs is 20.6 Tg C per year (9.0, 65.1 Tg C) in CONUS and 1.9 Tg C per year (1.3, 2.8 Tg C) in Alaska, lower than the respective river fluxes to the coast. Lake emissions are 16.0 Tg C per year (14.3, 18.7 Tg C) in CONUS and 8.2 Tg C per year (6.1, 11.2 Tg C) in Alaska. Lake CO₂ losses to the atmosphere roughly equal the magnitude of carbon buried in lake sediments in CONUS, but lake CO₂ emissions are much greater relative to carbon burial rates in Alaska.



14.3.2 Carbon Fluxes from Canadian Waters

The Canadian climate and terrestrial landscape are highly heterogeneous, from temperate rainforests to Arctic desert. The transport and processing of carbon in Canada's inland waters are correspondingly variable. Although lake or river carbon cycling has been studied in several regions, significant gaps remain in this report's assessment of country-wide carbon transport and transformation in aquatic systems. The terrestrial carbon export rate to aquatic networks varies from $<1 \text{ g C per m}^2 \text{ per year}$ to $>20 \text{ g C per m}^2 \text{ per year}$ for both organic and inorganic fractions, though their relative importance is region-specific (Clair et al., 2013). A recent estimate for all the drainage basins in Canada suggests that 18.2 Tg of organic carbon is exported to the coast each year (Clair et al., 2013). Although DIC is the dominant form of carbon export from terrestrial systems in the Prairie provinces, Manitoba, Saskatchewan, and Alberta (Finlay et al., 2010), the balance shifts toward co-equality in Southern Quebec catchments (Li et al., 2015) and to a dominance of organic carbon in the boreal zone (Molot and Dillon 1997; Roulet and Moore 2006). The combined organic and inorganic lateral flux from land to the coast is currently unavailable.

While the vast majority of Canadian lakes and rivers are supersaturated in CO_2 and CH_4 relative to the atmosphere and thus act as sources (Campeau et al., 2014; del Giorgio et al., 1997; Prairie et al., 2002; Teodoru et al., 2009), alkaline and eutrophic systems can act, at least temporarily, as carbon sinks (Finlay et al., 2010). Generally, however, Canadian lakes are net heterotrophic through the degradation of incoming DOC (Vachon et al., 2016), with emission rates of CO_2 and CH_4 from lakes typically varying as an inverse function of lake size (Rasilo et al., 2015; Roehm et al., 2009) and positively with organic matter inputs (del Giorgio et al., 1999). Lakes of northern Quebec have accumulated more carbon per unit area than their surrounding forest soils but less than surrounding peatlands (Heathcote et al., 2015). Lake bathymetric shape and exposure

to oxygen are the primary determinants of carbon accumulation and of the efficiency of burial relative to the carbon supply (Ferland et al., 2014; Teodoru et al., 2012). At the whole-landscape scale, lake sediments account for about 15% of the accumulated carbon (Ferland et al., 2012).

14.3.3 Carbon Fluxes from Mexican Waters

Extensive data on carbon stocks and fluxes do not yet exist for Mexico, but a summary exists of several individual small-scale datasets about Mexican inland water carbon fluxes (Alcocer and Bernal-Brooks 2010). The state of knowledge presented herein regarding carbon cycling in the inland waters of Mexico focuses on lake GHG emissions and burial. Given the tectonic activity of Mexico, there has been an interest in understanding how the carbon emissions of volcanic lakes evolve across space and time. Carbon dioxide emissions from the lake inside El Chichón volcano, Chiapas, reportedly range from 0.005 to $0.016 \text{ Tg C per year}$, or $72,000$ to $150,000 \text{ g C per m}^2 \text{ per year}$ (Mazot and Taran 2009; Perez et al., 2011). More recently, research on Lake Alchichica showed that, on average, surface water $p\text{CO}_2$ was below atmospheric $p\text{CO}_2$ for 67% of the year, with an average surface water $p\text{CO}_2$ of 184 microatmospheres (μatm ; Guzmán-Arias et al., 2015). These findings suggest that deep, tropical, and warm monomictic lakes have the potential to take up atmospheric CO_2 through primary production and preserve most of the POC deposited to the sediments, creating important carbon sinks. Emissions of CH_4 may be as important as emissions of CO_2 across regions of Mexico. Although few studies have evaluated the CH_4 emissions from Mexican inland waters, the CH_4 flux from six Mexican lakes is estimated to be about $1.3 \pm 0.4 \text{ Tg CH}_4 \text{ per year}$, which constitutes 20% of Mexico's CH_4 emissions (Gonzalez-Valencia et al., 2013). The total CH_4 flux from 11 aquatic ecosystems in Mexico City was $0.004 \text{ Tg CH}_4 \text{ per year}$, 3.5% of the CH_4 emissions of the city (Martinez-Cruz et al., 2016). Fully quantifying the importance of anthropogenic inputs of CH_4 -producing organic materials through waste



streams is critical for better constraining these fluxes at the national scale.

Other research on inland water carbon dynamics in Mexico has focused on reservoirs. The CO₂ emissions of the Valle de Bravo reservoir, Estado de Mexico, calculated through the photosynthesis and respiration balance, was 0.34 g C per m² per year (Valdespino-Castillo et al., 2014). Carbon burial has been studied in a few Mexican lakes. A 3-year study determined that the well-characterized system of Lake Alchichica, Puebla, has a carbon burial rate of 25.6 ± 12.3 g C per m² per year (Oseguera-Pérez et al., 2013).

14.3.4 Carbon Fluxes from the Great Lakes

As previously suggested, a comprehensive assessment of carbon fluxes does not yet exist for all of the Laurentian Great Lakes. The best estimates for individual component carbon flux values for the Great Lakes come from Lake Superior. Primary production is estimated to be 5.3 to 9.7 Tg C per year, while respiration is estimated to be significantly greater at 13 to 83 Tg C per year (Cotner et al., 2004; Sterner 2010; Urban et al., 2005). External inputs of 0.68 to 1.03 Tg C per year (Cotner et al., 2004) of organic carbon are too small to account for this imbalance between primary production and respiration, suggesting significant sources of external DIC. However, modeling work suggests that previous respiration estimates were biased high because of spatial heterogeneity and found a much lower value of 5.5 Tg C per year (Bennington et al., 2012). Estimates do not yet exist for the balance between the amount of organic carbon buried in sediments versus the amount exported through rivers or emitted as CO₂ and CH₄. However, total carbon burial across all lakes may be on the order of 2.7 Tg C per year, with an areal sink of 15 g C per m² per year since 1930 (Einsele et al., 2001). Additional research is needed to constrain the fluxes of carbon from the Great Lakes.

14.4 Current and Future Trends

Whether carbon fluxes from inland waters are increasing or decreasing at the national or

continental scale remains unclear. Because carbon export from the terrestrial landscape is tightly linked to discharge, increases in discharge probably will lead to increases in carbon export (Mulholland and Kuenzler 1979). Current studies are arguing for an increase in discharge for many regions of North America, including the U.S. Midwest and New England; however, reductions in precipitation are predicted in the southern and western regions of the United States (Georgakakos et al., 2014). Human water use through irrigation also may be affecting the spatial variability of discharge, with lower discharge in regions of higher irrigation, an effect which may be mitigated by increases in precipitation (Kustu et al., 2011). However, future changes in precipitation that lead to regional drought will reduce the transfer of carbon from the terrestrial ecosystem into the aquatic environment, while simultaneously decreasing the total area of aquatic ecosystems. Other anthropogenic drivers also can impact fluxes. Evidence suggests that DIC fluxes have increased from the Mississippi River over time because of land-management practices associated with liming and irrigation for agriculture, as well as increases in precipitation across portions of the basin (Raymond et al., 2008; Tian et al., 2015). In the United States, about 30 Tg of lime are applied each year, resulting in a potential flux of 7.2 Tg of inorganic carbon per year in the form of bicarbonate, or an actual flux of approximately 5.4 Tg C per year, assuming that 25% is balanced by the export of products from weathering reactions other than carbonic acid (Oh and Raymond 2006). The total U.S. riverine flux of DIC is approximately 35 Tg per year (Stets and Striegl 2012). Thus, liming and fertilizer use may contribute about 15% of total river bicarbonate flux in the United States.

Calculations suggest that DOC export from the Mississippi River has increased since the early 1900s, primarily a result of land-cover change from forest and grasslands to managed agriculture (Ren et al., 2016). Tributaries to the Mississippi have been shown to have decreasing DOC as a result of wetland loss (Duan et al., 2017). However, DOC flux from the Mississippi River to the



Gulf of Mexico did not change from 1997 to 2013 (Stackpoole et al., 2016). Changing concentrations of dissolved CO₂ were identified in nine lakes in the Adirondacks, New York, where six showed significant increases and three showed significant decreases over 18 years (Seekell and Gudas 2016). The rate of change in both the positive and negative direction was found to be in excess of 12 μatm per year, well outside the rate of increase in the atmosphere. Increasing trends in these lakes were attributed first to basin-scale recovery from acid precipitation, resulting in an increase in soil CO₂ production in systems with little buffering capacity, where CO₂ can be a large contributor of inorganic carbon exported from the catchment. Also attributed were changes in DOC concentrations, export, and remineralization rates within the lake environment (Burns et al., 2006; Seekell and Gudas 2016). Globally, evidence indicates increases in the concentrations of organic carbon from a number of sources, a phenomenon termed the “browning” of waters. However, studies suggest that these increases are caused by regionally specific factors, including recovery from acid rain; increases in carbon export from soils; and the mobilization of permafrost carbon into stream systems (Evans et al., 2006; Lapierre et al., 2013; Monteith et al., 2007; Roulet and Moore 2006; Tank et al., 2016). Evidence also suggests that the active layer depth in permafrost soil has increased, mobilizing previously frozen carbon stocks (Neff et al., 2006). In addition, warming and related vegetation changes have increased DOC flux from the Mackenzie River to the Arctic Ocean (Tank et al., 2016). However, permafrost thaw and increased groundwater contribution to Arctic rivers also have been linked to increased mineralization of organic carbon in the subsurface and changes in the proportion of DOC and DIC exports in Alaska’s Yukon River basin (Striegl et al., 2005; Walvoord and Striegl 2007). Any decreases in organic carbon export, though, potentially may be offset by increased organic carbon runoff from vegetation change in low-lying regions (Dornblaser and Striegl 2015). The proportion of carbon mobilized under warming conditions

that is mineralized to CO₂ versus exported as DOC remains unknown. Furthermore, research indicates that permafrost thaw also has increased CH₄ emissions since the 1950s as a result of degrading lake shorelines that contribute aged carbon (Walter Anthony et al., 2016). However, these emissions cannot be quantified at the national or continental scales.

Changes in aquatic carbon fluxes are linked directly to the residence time of water in both terrestrial and aquatic environments (Catalán et al., 2016). In particular, as precipitation increases, reducing water residence time, so do organic carbon fluxes from landscapes (Bianchi et al., 2013; Yoon and Raymond 2012). Knowing the contribution of groundwater versus surface water in streams is also important to understand CO₂ fluxes from terrestrial systems (Hotchkiss et al., 2015). The removal of organic carbon in lakes, streams, and rivers is positively related to its residence time (Catalán et al., 2016; Vachon et al., 2016). The half-life of organic carbon in inland waters is about 2.5 years, much shorter than the decades to millennia required for soil systems to completely turn over (Catalán et al., 2016). Some studies hypothesize that increases in precipitation caused by an altered climate will move carbon that would be stored in soils into aquatic environments where remineralization may accelerate the return of organic carbon to the atmosphere as CO₂ in high and temperate latitudes (Drake et al., 2015; Raymond et al., 2016). In addition, the installation or removal of dams will directly affect the quantity and form of carbon in aquatic environments by shifting water residence time, water surface areas, and sediment loads. Predicting how the overall carbon balance will shift across North America remains difficult because of complex interactions between inorganic and organic carbon within aquatic systems and the importance of anthropogenic change at the landscape scale (Butman et al., 2015; Lapierre et al., 2013; Regnier et al., 2013; Solomon et al., 2015; Tank et al., 2016).



14.5 Global, North American, and U.S. Context

14.5.1 A Global Carbon Cycle Perspective

Understanding the fluxes of carbon through inland waters in the context of the global carbon cycle remains an active area of research today. Of particular interest are 1) terrestrial carbon fluxes to inland waters; 2) carbon transformations within inland waters, especially movement into storage reservoirs and the atmosphere; and 3) carbon fluxes to coastal waters and large inland lakes. Using Equation 14.1, p. 571, assessment of components of the inland water carbon cycle can begin at the global, regional, and U.S. scales.

Globally, the component with the least uncertainty is the flux of carbon to coastal waters. Estimates of DOC flux to the coast, for instance, have remained around 0.2 ± 0.05 Pg C per year for the last 30 years, although these estimates often are based on the same underlying dataset (Dai et al., 2012; Meybeck 1982; Seitzinger et al., 2005). The DIC flux of 0.35 Pg C per year has been shown to result from strong linkages between lithology and climate, coupled with better global products for these drivers (Hartmann et al., 2014b). Global estimates of the POC flux to coastal waters have changed because of a large and evolving anthropogenic signal from POC trapping behind dams, with a total flux of 0.15 Pg C per year (Galy et al., 2015; Spitzzy and Ittekkot 1991; Syvitski and Milliman 2007). The sum of DOC, DIC, and POC fluxes results in a C_{export} of 0.7 Pg C per year.

New global and ecosystem-specific estimates of CH_4 and CO_2 exchanges with the atmosphere have been facilitated by the growth of databases that capture measurements of these GHGs and by the ability to scale up estimates of inland water area and gas transfer velocity (Abril et al., 2014; Bastviken et al., 2011; Borges et al., 2015; Butman and Raymond 2011; Lauerwald et al., 2015; Raymond et al., 2013). New research suggests that Arctic and boreal lakes and ponds may release 16.5 Tg C per year (Wik et al., 2016), more than double previous

estimates (Bastviken et al., 2011) for a similar range of latitudes. Evidence now shows that lake and river size, topography, land cover, and terrestrial productivity affect the total carbon dynamics in freshwaters (Butman et al., 2016; Holgerson and Raymond 2016; Hotchkiss et al., 2015; Stanley et al., 2016). However, these relationships are based on limited empirical data, and, although progress is being made, a mechanistic understanding that links landscapes to inland water carbon fluxes is still lacking (Hotchkiss et al., 2015). Furthermore, the fluxes of CH_4 and CO_2 per unit area of water surface are extremely high for very small streams and ponds (Holgerson and Raymond 2016), but these systems are not easily detected with remote sensing and have very few high temporal frequency studies (Feng et al., 2015; Koprivnjak et al., 2010).

Carbon dioxide flux from inland waters to the atmosphere ($C_{emissions}$) at the global scale is due to mostly large river systems and currently is estimated at 1.8 to 2.2 Pg C per year (Raymond et al., 2013). Recent data from the Amazon suggest that total global emissions could be as high as 2.9 Pg C per year (Sawakuchi et al., 2017). Carbon burial represents another large removal process for aquatic carbon. Global inland water burial estimates are fairly uncertain, ranging from 0.2 to 0.6 Pg C per year as C_{burial} (Battin et al., 2009b; Tranvik et al., 2009). Assuming that the carbon stock of inland waters is not changing with time and using compiled values only (Raymond et al., 2013) lead to the maximum possible terrestrial input being approximately 3.7 Pg C per year (Raymond et al., 2013), which represents the total carbon needed to balance the loss through coastal export, burial, and gas emissions. Internal primary production and respiration are known contributors to gas emissions, as well as burial. Therefore, verifying this 3.7 Pg C per year currently is not possible due to the diversity of terrestrial and inland water ecosystems, temporal variability of fluxes, and lack of studies of small end-member ecosystems.



14.5.2 Comparison Between Global and U.S. Carbon Fluxes

The fluxes of carbon from the United States (CONUS and Alaska) represent those with the highest confidence reported here and will be evaluated against those at the global scale. A comparison of global versus U.S. estimates of aquatic carbon fluxes shows similar patterns in the relative magnitude of carbon flux pathways. Applying the conservative global estimate for carbon burial of 0.2 Pg C per year (Tranvik et al., 2009), carbon emissions across the air-water interface are 60% of the total flux at the global scale and 63% at the U.S. scale (see Equation 14.1, p. 571, and Figure 14.2, p. 572). In contrast to estimates in SOCCR1, these results suggest that half of all aquatic carbon fluxes are releases of gases to the atmosphere. At the global and U.S. scales, lateral fluxes from land to coasts represent 24% and 26% of the total, respectively. It is important to note that globally, POC entrapment through burial, if assumed to be 0.2 Pg C per year, is nearly 6% of the total flux of carbon from inland waters. This amount increases to 16% if the burial term is considered to be 0.6 Pg C per year (Battin et al., 2009b). The range of estimates for the proportion of carbon entering sediments (i.e., 6% to 16%) globally bounds the more refined modeling for CONUS that suggests burial is 10% of the total.

Global and U.S. CO₂ emissions equal 17 and 13.6 g C per m² per year, respectively, indicating that CO₂ emissions from U.S. inland waters are 20% less than the global average per unit land area. Carbon burial per unit area varies from 1.5 to 4.5 g C per m² per year, very similar to the 1.9 g C per m² per year estimate obtained for CONUS and Alaska. Overall, per unit area, the total carbon flux at the global scale is 25% greater (at 24.8 g C per m² per year) than the 20.6 g C per m² per year estimated for the United States. The discrepancies between the U.S. and global areal fluxes increase if recently estimated values (Sawakuchi et al., 2017) are used for the comparisons (see Table 14.1, p. 576). These discrepancies may be due to differences in methodologies but also may reflect spatial variability in inland

water ecosystem type. For example, the importance of tropical systems for carbon fluxes may drive the distribution of inland water fluxes at the global scale, even though tropical areas represent only a very small fraction of the ecosystems within CONUS.

14.5.3 Regional Differences of U.S. Carbon Fluxes

Carbon fluxes from inland waters differ across regions in CONUS, and the relative contributions of each flux component vary across space (Butman et al., 2016). In particular, lateral fluxes from the eastern portion of the Mississippi River basin are larger than gaseous emissions, while carbon burial dominates lake fluxes in the river's lower basin. Carbon dioxide emissions are dominant in systems that have steep topography and more acidic waters. Emissions of CO₂ are highest in the western regions of the Pacific Northwest, where both rainfall and topography drive large carbon inputs from primary production and topography enhances gas transfer (Butman et al., 2016). Inorganic carbon fluxes in the form of bicarbonate are large within watersheds with large areas of agriculture in the upper Midwest, an effect attributed to agricultural liming (Oh and Raymond 2006). Regional variability in inland water carbon fluxes is driven by the available inputs of carbon from variable land cover, as well as precipitation that facilitates the physical movement of that carbon from groundwater, soils, and wetlands.

14.5.4 North American Carbon Fluxes in Context

Total carbon fluxes from inland waters of North America were estimated using the results of the Regional Carbon Cycle Assessment and Processes (RECCAP) effort (see Table 14.1, p. 576) for emissions and lateral fluxes based on the scaling of empirical data (Hartmann et al., 2009; Mayorga et al., 2010; Raymond et al., 2013). The average burial rate of carbon based on land cover from CONUS and Alaska was used herein for calculations (Clow et al., 2015). The total carbon flux from inland waters is estimated to be 507 Tg C per year. About 48% of this carbon, or 247 Tg per year, consists of emissions across the air-water interface



from both lentic and lotic systems. The lateral flux of carbon to the coast is 105 Tg C per year, or 21% of the total. This estimate compares well with recent results derived from a spatially explicit coupled hydrological-biogeochemical model that suggest 96 (standard deviation 8.9) Tg C per year move laterally to coastal systems in North America (Tian et al., 2015). Finally, the burial of carbon within inland waters is estimated to be nearly 30% of the total flux, at 155 Tg C per year. These estimates are based on modeled export of carbon to coastal systems and broadly scaled estimates for CO₂ emissions derived from sparse datasets at high latitudes (Hartmann et al., 2014a; Raymond et al., 2013) and are considered uncertain.

14.6 Societal Drivers, Impacts, and Carbon Management

Human impacts on carbon movement and processing in inland waters include 1) land-use change that promotes the destabilization of soil carbon and increases erosion (Lal and Pimentel 2008; Quinton et al., 2010; Stallard 1998); 2) altered climate patterns that shift the timing and magnitude of precipitation and hydrological events (Clair and Ehrman 1996; Evans et al., 2007); 3) changes in nutrient and organic matter inputs that alter carbon processing and storage within aquatic environments (Humborg et al., 2004; Mayorga et al., 2010; Seitzinger et al., 2005); and 4) changes in temperature (Nelson and Palmer 2007). These effects are not independent of one another. However, inland waters are inherently difficult to evaluate in the context of carbon management, from either a sequestration or mitigation position. In contrast to forested ecosystems, the chemistry of inland waters changes rapidly on timescales from seconds to days in direct relation to the hydrological regime (Sobczak and Raymond 2015). Furthermore, the sources of carbon within inland waters are poorly characterized across spatial and temporal scales relevant to national-scale management decisions. A robust understanding of the impact that dams have on carbon transformation and fluxes to coastal systems would directly identify the connections between anthropogenic energy

and water resource needs and the carbon cycling of inland waters (Deemer et al., 2016; Maeck et al., 2014; Teodoru et al., 2012). The research community is currently unable to identify whether all dammed systems cause increased carbon emissions, but recent synthesis efforts suggest that CO₂ and CH₄ emissions increase under conditions of high nutrients and with large inputs of terrestrial carbon (Barros et al., 2011; Deemer et al., 2016; Teodoru et al., 2012). Worldwide there are more than 1 million estimated dams (Lehner et al., 2011); of these, over 87,000 have heights >15 m (World Commission on Dams 2000). Research is needed to evaluate the impact that this level of damming has on the aquatic carbon cycle.

14.7 Synthesis, Knowledge Gaps, and Outlook

14.7.1 Summary

Advances in the ability to manipulate large databases of carbon chemistry covering the United States, coupled with new methods for spatial analysis, have enabled new and robust estimates for carbon fluxes from inland waters in CONUS and Alaska. By identifying and including CO₂ emissions, the U.S. fluxes of carbon are estimated to be approximately 193 Tg C per year. These fluxes are dominated by river and stream networks exporting up to 59.8 Tg C per year to the coast and emitting nearly 85.9 Tg C per year as CO₂ to the atmosphere. Availability of data is limited from Mexican inland waters. Deep, tropical, warm monomictic lakes constitute carbon sinks primarily as POC, while shallow, tropical—and mostly eutrophic—lakes are sources of CO₂ and CH₄ to the atmosphere. Further data collection is needed to properly assess carbon cycling within inland waters at the national scale in both Canada and Mexico. However, based on estimates presented here, the carbon flux from inland waters is now understood to be four times larger than estimates presented in SOCCR1.

14.7.2 Key Knowledge Gaps and Current Opportunities

Peer-reviewed and detailed estimates are not currently available for carbon fluxes from inland waters



within Mexico and Canada. Further collaboration is necessary among monitoring efforts in these countries and the United States to properly develop a spatially explicit inland water database on carbon concentration and carbon fluxes across North America. In addition, robust estimates of annual carbon fluxes for the Laurentian Great Lakes are not yet possible, a surprising limitation given their importance as the largest inland waters on Earth. Preliminary data suggest that these systems vary from a net carbon source to the atmosphere in Lake Superior, Lake Michigan, and Lake Huron to a net carbon sink in Lake Erie and Lake Ontario. By combining a box model analysis with a literature review of respiration, river inputs, and burial, McKinley et al. (2011) conclude that the Great Lakes efflux lies between 2.3 and 36 Tg C per year. If future research suggests emissions near 2.3 Tg C per year, then the emission of carbon as CO₂ may be nearly balanced by carbon burial (Einsele et al., 2001). However, if new data suggest significantly higher emissions, such results would increase the importance of the Great Lakes with respect to total carbon fluxes from the United States and Canada. The Great Lakes are heavily affected by anthropogenic disturbance through nutrient enrichment and invasive species, with unknown impacts on carbon cycling.

Also unavailable is a comprehensive estimate for the contribution of CH₄ to carbon emissions for inland waters of North America. Data on CH₄ do not yet exist across space and time to properly scale to national and continental levels, though significant progress is being made (Holgerson and Raymond 2016; Stanley et al., 2016; Wik et al., 2016).

One major methodological advancement in past years is *in situ* probe systems (Baehr and DeGrandpre, 2004). Probes to measure aspects of the carbon cycle are becoming more accurate and affordable (Bastviken et al., 2015; Johnson et al., 2010), and the research community is advancing methodologies to process high-temporal datasets (Downing et al., 2012), identifying the role that storm events may play in carbon fluxes. The possibility now exists to instrument inland water systems

along the aquatic continuum from when water emerges from the terrestrial interface to when it is exported to the coast or large inland lakes. Such instrumentation will facilitate understanding of the transformations of terrestrial carbon during transport to inland waters and the controls on this transport. However, deploying sensor systems alone is not enough to ensure the development of the data needed to reduce uncertainties. The inland water carbon cycle science community must learn from the efforts of organizations like the International Ocean Carbon Coordination Project to develop standard approaches and reference materials for study comparison and reproducibility. Furthermore, future research needs to take advantage of developments in both large- and small-scale data acquisition and should attempt nested watershed studies across scales to understand the carbon cycling within inland water environments. These studies, coupled with new methods to quantify surface waters at the global scale, particularly small streams and ponds, will help further constrain the importance of inland waters to the Earth biogeochemical system under a changing climate (Pekel et al., 2016).

At 193 Tg C per year, the fluxes of carbon through inland waters of the United States are significant. The scaled value of 507 Tg C per year for North America represents an estimate that requires further science to reduce uncertainties. In the context of the overall cycling of carbon among terrestrial, wetland, and aquatic environments, there are important methodological differences that must be considered when using the estimates of carbon flux from inland waters. The aquatic carbon fluxes presented herein are derived from the modeling of fluxes to the coast, lake sediments, and the atmosphere. The quantification of the lateral flux of carbon to estuarine systems is perhaps the most well constrained, as it is derived from long-term monitoring of water flow and decades of direct measurements of carbon concentration. The emission of CO₂ from water surfaces is more uncertain. The difficulty of quantifying this emission is compounded by the ephemeral nature of small streams, along with a lack of detailed spatial information



on their total length and surface area. As suggested in this chapter, small streams and ponds represent a large fraction of the CO₂ emissions from inland waters to the atmosphere, important when scaling fluxes across the United States and the world. Furthermore, apportioning the carbon in an aquatic environment to its source (e.g., autochthonous versus allochthonous) currently is not possible. This gap in understanding removes an ability to differentiate, for example, soil respiration that simply has changed location into an aquatic ecosystem from in-stream respiration.

The importance of erosional fluxes of carbon to North American inland waters also cannot be properly assessed. The lateral transport of soil carbon and the concurrent fluxes of CO₂ returning

to the atmosphere in China suggest that upwards of 45 Tg C per year enter inland waters, thus representing a terrestrial carbon sink (Yue et al., 2016). However, this type of calculation does not fully account for replacement of carbon within soils, the remineralization of organic carbon during transport, direct inputs of inorganic carbon, or the lateral fluxes of dissolved carbon to the coast. Therefore, caution is warranted when including inland waters in a mass balance for total carbon accounting. To fully understand the role that inland waters play across the land-water continuum, studies must be conducted at the watershed scale, coupling terrestrial and inland water processes. These measurements will help constrain future modeling studies that require coupling between hydrology and biogeochemistry.



SUPPORTING EVIDENCE

KEY FINDING 1

The total flux of carbon—which includes gaseous emissions, lateral flux, and burial—from inland waters across the conterminous United States (CONUS) and Alaska is 193 teragrams of carbon (Tg C) per year. The dominant pathway for carbon movement out of inland waters is the emission of carbon dioxide gas across water surfaces of streams, rivers, and lakes (110.1 Tg C per year), a flux not identified in the *First State of the Carbon Cycle Report* (SOCCR1; CCSP 2007). Second to gaseous emissions are the lateral fluxes of carbon through rivers to coastal environments (59.8 Tg C per year). Total carbon burial in lakes and reservoirs represents the smallest flux for CONUS and Alaska (22.5 Tg C per year) (*medium confidence*).

Description of evidence base

Estimates for the export of carbon to U.S. coasts have been well documented through long-term observations (Stets and Striegl 2012) and syntheses (Butman et al., 2016; Stackpoole et al., 2016; Zhu and McGuire 2016). Carbon burial is derived from recent model results (Clow et al., 2015). Gaseous emissions of CO₂ were originally assessed in Butman and Raymond (2011) for streams and rivers and McDonald et al. (2013) for lakes and reservoirs of CONUS only. Previous data do exist to support inland waters as dominated by supersaturated conditions (Striegl et al., 2012; Tranvik et al., 2009).

The finding that the dominant pathway for carbon loss through inland waters is through surface emissions was identified in Richey et al. (2002) and Cole et al. (2007) and quantified for CONUS in (Butman and Raymond 2011). Estimates that support this finding for Alaska are presented in Zhu and McGuire (2016). McDonald et al. (2012) showed that across CONUS, lake carbon burial and lake emissions are similar in magnitude when considered at the national scale, with regional variation based on the input of dissolved inorganic carbon (DIC) to lake systems.

Major uncertainties

Large uncertainties exist for the emission of CO₂ from stream and river systems based on empirical estimates of the gas transfer velocity of CO₂ presented in Raymond et al. (2012). The modeling of gas transfer is poorly constrained under high-flow conditions in steep topography. High levels of uncertainty also exist regarding the temporal dynamics of both lentic and lotic CO₂ emissions (Battin et al., 2008; Striegl et al., 2012; Tranvik et al., 2009), where limited data exist to assess carbon gas concentrations under ice or storm flow conditions.

Uncertainties also exist regarding the use of the empirical model for carbon burial presented in Clow et al. (2015). Limited concentration data exist for lakes in Alaska, and there may be significant bias in the concentrations used to scale lake fluxes across regions (Stackpoole et al., 2017a; Zhu and McGuire 2016). These constraints may result in overestimates of emissions. In addition, limited data on carbon burial exist for northern latitudes, resulting in the use of empirical models derived from samples that do not capture the level of variability that exists across Alaska (Stackpoole et al., 2016).

Assessment of confidence based on evidence and agreement, including short description of nature of evidence and level of agreement

The overall confidence level of medium reflects 1) advancements in inland water spatial representations in a global information system (GIS) format to develop surface areas, 2) completion



of datasets enabling the calculation of lateral fluxes, and 3) advancements in databases relevant to sedimentation rates in U.S. lakes and reservoirs. Confidence is reduced because modeling approaches available to estimate gas transfer velocities used for calculating carbon emissions are limited, and there are few chemical measurements in small stream systems.

Summary sentence or paragraph that integrates the above information

For Key Finding 1, individual flux terms (i.e., lateral flux, CO₂ emission, and carbon burial) each have a medium to high level of certainty. This reflects the high confidence in the spatial representation of the chemical data for CONUS and Alaska, as well as the length of monitoring for water chemistry within CONUS and Alaska.

KEY FINDING 2

Based on estimates presented herein, the carbon flux from inland waters is now understood to be four times larger than estimates presented in SOCCR1. The total flux of carbon from inland waters across North America is estimated to be 507 Tg C per year based on a modeling approach that integrates high-resolution U.S. data and continental-scale estimates of water area, discharge, and carbon emissions. This estimate represents a weighted average of 24 grams of carbon per m² per year of continental area exported and removed through inland waters in North America (*low confidence*).

Description of evidence base

Initial data presented in SOCCR1 did not acknowledge emission of carbon across the air-water interface. The estimate of 507 Tg C per year is based on well-constrained estimates of water discharge presented in Mayorga et al. (2010), Seitzinger et al. (2005), and compared with Dai et al. (2009, 2012). Estimates for the export of carbon modeled with water discharge are provided through the Regional Carbon Cycle Assessment and Processes (RECCAP) effort of the Global Carbon Project. Gaseous emissions of CO₂ are presented in Raymond et al. (2013) based on similar methods presented in Butman and Raymond (2011). Areal rates of carbon flux through inland waters for CONUS and Alaska match those for North America.

Major uncertainties

Estimates and uncertainties to scale the emissions of CO₂ from streams, rivers, and lake systems from CONUS to North America have already been provided. However, the application of CONUS lake carbon burial rates derived from Clow et al. (2015) to the total lake areas from Aufdenkampe et al. (2011) is unique. The methods used an average burial rate of about 110 g C per m² per year, which is lower than those used in recent global estimates for lake and reservoir burial (Battin et al., 2009a). This burial rate is not dynamic and does not fully capture the spatial heterogeneity found across North America (Clow et al., 2015).

Assessment of confidence based on evidence and agreement, including short description of nature of evidence and level of agreement

Overall level of confidence is lower for the region of North America due to the different modeling approach, lack of data that exist in both Canada and Mexico, and the simplified application of U.S. data to a region that covers many different ecosystem types.

**Summary sentence or paragraph that integrates the above information**

For Key Finding 2, confidence is low for estimates of inland aquatic carbon fluxes for North America because of a general lack of data available from Mexico and Canada, including CO₂ emissions or burial estimates. Methods developed for datasets within CONUS were applied to these two regions.

KEY FINDING 3

Future research can address critical knowledge gaps and uncertainties related to inland water carbon fluxes. This chapter, for example, does not include methane emissions, which cannot be calculated as precisely as other carbon fluxes because of significant data gaps. Key to reducing uncertainties in estimated carbon fluxes is increased temporal resolution of carbon concentration and discharge sampling to provide better representations of storms and other extreme events for estimates of total inland water carbon fluxes. Improved spatial resolution of sampling also could potentially highlight anthropogenic influences on the quantity and quality of carbon fluxes in inland waters and provide information for land-use planning and management of water resources. Finally, uncertainties could likely be reduced if the community of scientists working in inland waters establishes and adopts standard measurement techniques and protocols similar to those maintained through collaborative efforts of the International Ocean Carbon Coordination Project and relevant governmental agencies from participating nations.

Description of evidence base

Methane CH₄ emissions can be a significant source of carbon to the atmosphere from Arctic lakes (Wik et al., 2016). Fixed-interval sampling protocols may miss large storm events and may critically bias estimates for total carbon fluxes to the coast (Raymond et al., 2012). Management of water resources in reservoir systems may influence the magnitude of carbon burial and emissions, driving systems to be more or less effective at storing or releasing carbon over time (Deemer et al., 2016).

Major uncertainties

Uncertainties are presented within the evidence base. Major uncertainties include 1) the relative importance of storm events or perturbations in the hydrological cycle to carbon export to coastal systems, 2) the magnitude of CH₄ fluxes over time and across seasonal and latitudinal gradients, 3) the role that management of water resources plays in the movement and storage of carbon over time, and 4) the lack of established protocols for comparable sampling and scaling of carbon emissions across inland waters.

Summary sentence or paragraph that integrates the above information

For Key Finding 3, overall spatial and temporal data are not adequate to estimate the magnitude of CH₄ fluxes from inland waters or to capture the influence of storm events or management on inland water carbon fluxes.



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