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Carbon and Beyond: The Biogeochemistry of Climate in a Rapidly Changing Amazon

Kristofer Covey[1], Fiona Soper[2], Sunitha Pangala[3], Angelo Bernardino[4], Zoe Pagliaro[1], Luana Basso[5], Henrique Cassol[6], Philip Fearnside[7], Diego Navarrete[8], Sidney Novoa[9], Henrique Sawakuchi[10], Thomas Lovejoy[11], Jose Marengo[12], Carlos Peres[13], Jonathan Baillie[14], Paula Bernasconi[15], Jose Camargo[7], Carolina Freitas[16], Bruce Hoffman[17], Gabriela B. Nardoto[18], Ismael Nobre[19], Juan Mayorga[14,20], Rita Mesquita[7], Silvia Pavan[21], Flavia Pinto[22],Flavia Rocha[23], Ricardo de Assis Mello[24], Alice Thuault[15], Alexis Anne Bahl[14] and Aurora Elmore[14]*

[1] Environmental Studies and Sciences Program, Skidmore College, Saratoga Springs, NY, United States, [2] Department of Biology and School of Environment, McGill University, Montreal, QC, Canada, [3] Lancaster Environment Centre, Lancaster University, Lancaster, United Kingdom, [4] Departamento de Oceanografia, Universidade Federal do Espírito Santo, Vitória, Brazil, [5] Divisão de Sensoriamento Remoto, Earth System Science Center (Centro de Ciôncia do Sistema Terra), National Institute for Space Research (Instituto Nacional de Pesquisas Espaciais), São José dos Campos, Brazil, [6] Remote Sensing Division (Divisão de Sensoriamento Remoto), National Institute for Space Research (Instituto Nacional de Pesquisas Espaciais), São José dos Campos, Brazil, [7] National Institute for Research in Amazonia (Instituto Nacional de Pesquisas da Amazônia), Manaus, Brazil, [8] The Nature Conservancy, Bogota, Colombia, [9] Asociación para la Conservación de la Cuenca Amazónica, Lima, Peru, [10] Department of Thematic Studies - Environmental Change, Linköping University, Linköping, Sweden, [11] Department of Environmental Science and Policy, George Mason University, Fairfax, VA, United States, [12] National Center for Monitoring and Early Warning of Natural Disasters (CEMADEN), Sáo Paulo, Brazil, [13] School of Environmental Sciences, University of East Anglia, Norwich, United Kingdom, [14] National Geographic Society, Washington, DC, United States, [15] Instituto Centro de Vida (ICV), Cuiabá, Brazil, [16] Coordenação Geral de Observação da Terra, Instituto Nacional de Pesquisas Espaciais (INPE), São Paulo, Brazil, [17] The Amazon Conservation Team – Suriname Program, Paramaribo, Suriname, [18] Department of Ecology, Universidade de Brasília, Brasília, Brazil, [19] Amazon Third Way Project, Universidade Estadual de Campinas, São Paulo, Brazil, [20] Bren School of Environmental Science and Management, University of California, Santa Barbara, Santa Barbara, CA, United States, [21] Coordenação de Zoologia, Museu Paraense Emílio Goeldi, Belém, Brazil, [22] The Nature Conservancy, Brasilia, Brazil, [23] Department of Environmental Sciences, UFRRJ, Federal Rural University of Rio de Janeiro, Institute of Forests, Seropédica, Brazil, [24] Gerente do Programa Amazônia, World Wildlife Fund, Brasil, Distrito Federal, Brazil*

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***Correspondence:**
Kristofer Covey
kcovey@skidmore.edu

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The Amazon Basin is at the center of an intensifying discourse about deforestation, land-use, and global change. To date, climate research in the Basin has overwhelmingly focused on the cycling and storage of carbon (C) and its implications for global climate. Missing, however, is a more comprehensive consideration of other significant biophysical climate feedbacks [i.e., CH_4, N_2O, black carbon, biogenic volatile organic compounds (BVOCs), aerosols, evapotranspiration, and albedo] and their dynamic responses to both localized (fire, land-use change, infrastructure development, and storms) and global (warming, drying, and some related to El Niño or to warming in the tropical Atlantic) changes. Here, we synthesize the current understanding of (1) sources and fluxes of all major forcing agents, (2) the demonstrated or expected impact of global and local changes on each agent, and (3) the nature, extent, and drivers of anthropogenic change in the Basin. We highlight the large uncertainty in flux magnitude and responses, and their corresponding direct and indirect effects on the regional and global climate system. Despite uncertainty in their responses to change, we conclude that current warming from non-CO_2 agents (especially CH_4 and N_2O) in the Amazon Basin largely offsets—and

most likely exceeds—the climate service provided by atmospheric CO_2 uptake. We also find that the majority of anthropogenic impacts act to increase the radiative forcing potential of the Basin. Given the large contribution of less-recognized agents (e.g., Amazonian trees alone emit ∼3.5% of all global CH_4), a continuing focus on a single metric (i.e., C uptake and storage) is incompatible with genuine efforts to understand and manage the biogeochemistry of climate in a rapidly changing Amazon Basin.

Keywords: methane, nitrous oxide, climate change, black carbon, biogenic VOC emission, land use - land cover change

MAIN

Amazonia is the largest swath of tropical rainforest on the planet. A region unto itself, the forest drives a partially self-sustaining regional climate and hydrological system believed to be at increasing risk of sudden collapse (Sampaio et al., 2007; Lovejoy and Nobre, 2018). Far from homogenous, Amazonia incorporates montane to mangrove forests across a range of distinct soils and substrates, integrated by a biogeochemically-diverse riverine network that drives extensive seasonal inundation (Hess et al., 2015). Human impacts across the basin are equally diverse and heterogeneous, reflecting the numerous distinct ecological, political, socioeconomic, and cultural units that fall within its boundaries (**Figure 1**).

After a transient period of reduced deforestation and increased optimism (Davidson et al., 2012), rising agricultural conversion and illegal logging activities are again accelerating Amazonian forest loss (Carvalho et al., 2019). This resurgence has renewed concerns that the region is rapidly approaching a catastrophic "*tipping point*" (Sampaio et al., 2007; Boers et al., 2017; Lovejoy and Nobre, 2018). Numerous studies catalog the rapid rate of deforestation and forest degradation, the accompanying release of CO_2, and the net C balance of the region (e.g., Asner et al., 2012; Gatti et al., 2014; Brienen et al., 2015; Aragão et al., 2018; Bullock et al., 2020; Hubau et al., 2020). While they are the most often discussed, carbon dynamics are just one component of the Amazon Basin's manifold interactions with climate (**Figures 2**, **3**; **Supplementary Tables 1, 2**). Biogeochemists working across the land-climate subfields widely acknowledge the importance of non-CO_2 climate drivers and the need to integrate them in our widening understanding of forested ecosystems' role in regulating global climate. However, despite numerous calls to incorporate these less-recognized agents in forest climate accounting (Bonan, 2008; Jackson et al., 2008; Thompson et al., 2009; Schindler et al., 2020), few studies address the net effect of multiple synergistic or antagonistic climate interacting drivers simultaneously. Resolving the pattern, magnitude, and trade-offs between the full suite of forest–climate interactions, and their response to the nature and extent of anthropogenic change, is the central challenge limiting our understanding of the Amazon's global climate impact.

Defining a comprehensive radiative balance for the Amazon is a daunting task. Uncertainty in both the magnitude and direction of some forcing agents is high, and existing data across temporal and spatial scales cannot be readily synthesized. Although emission estimates for the major greenhouse gases are well-constrained, other important forcing agents either lack comprehensive Basin-wide emission estimates or have no broad consensus as to their CO_2 equivalence [CO_2e; e.g., biogenic volatile organic compounds (BVOCs)] (Yáñez-Serrano et al., 2020). Further stifling is the reliance on commonly reported CO_2e factors strongly dependent on arbitrary time horizons [e.g., 20- vs. 100-year global warming potentials (GWPs); GWPs for CH_4 differ by a factor of ∼3 (Myhre et al., 2013)]. Finally, because there is currently insufficient information to estimate the full impact of feedback processes (e.g., cloud cover or evapotranspiration response to coupled seasonal warming and drought; Marengo et al., 2018), current land use accounting is primarily focused on *direct* impacts (**Supplementary Table 1**).

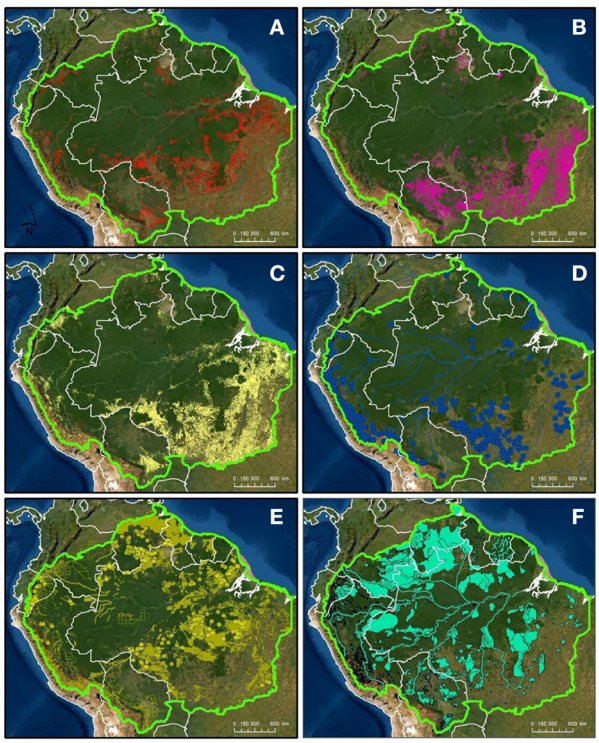

FIGURE 1 | Social and economic drivers of land use in the Amazon: **(A)** forest loss 2001–2019 (Hansen et al., 2013) (red shading), **(B)** fires 2001–2019 (RAISG, 2020) (pink shading), **(C)** agricultural and cattle areas (MAPBIOMAS Version 2.0, 2020) (yellow shading), **(D)** hydropower and reservoirs (RAISG, 2020) (blue points), **(E)** oil extraction and mining areas (RAISG, 2020) (yellow shading and points), and **(F)** fishing and hunting areas (RAISG, 2020) (aqua shading).

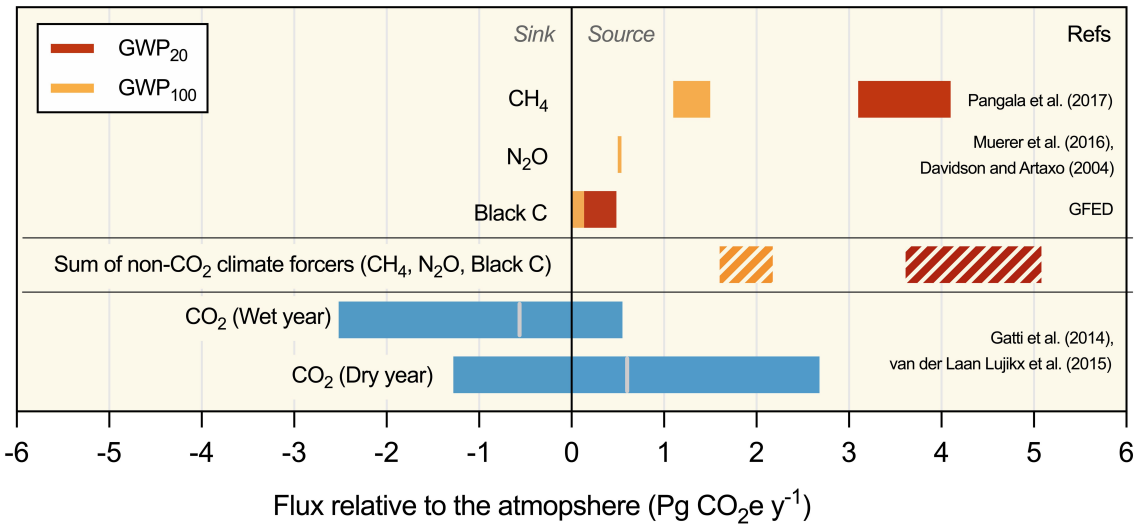

FIGURE 2 | Summary of annual fluxes for primary climate-forcing agents in the Amazon Basin, in Pg CO_2-equivalent at two global warming potential (GWP) time horizons (20 and 100 years). For CO_2, gray lines indicate means, plus the minimum and maximum uncertainty of five flux estimates for 2010 (anomalously dry year) and 2011 (wet year) that integrate both ecosystem productivity and biomass burning. These are the only years for which large-scale, inversion-based atmospheric C balance measurements for the basin are available. For CH_4 and black C, values are means ± 1 SD and for N_2O values represent a range. GWP factors are from IPCC AR5 (Myhre et al., 2013, 5) (CH_4, N_2O) or Bond et al. (2013; black C). There are no Basin-wide estimates of the total annual emission and GWP factors for biogenic volatile organic compounds (BVOCs), aerosols, and ozone. See **Supplementary Information** for flux calculations.

Droughts, related to El Niño (as in 1998 and 2016), or to warming in the tropical Atlantic (2005), or both (2010), impact the physiological response of Amazon forests, decreasing the availability to absorb atmospheric CO_2, as well as biodiversity and increasing risk of fires (Marengo et al., 2018). In spite of these substantive challenges, emerging research focused on non-CO_2 climate forcers allows us to begin the process of expanding our understanding beyond C. Here, we present a state-of-the-science synthesis of the inter-related climate effects of natural and anthropogenic change agents in the Amazon Basin and their persistent uncertainties with particular consideration given where the pattern and scale of the effect are large but not regularly considered alongside CO_2.

NET CLIMATE FORCING AT THE BASIN SCALE

Excellent work has been done detailing the biogeochemistry of region and its role in the global climate system (Davidson et al., 2012); however, despite a substantial increase in data and literature addressing various aspects of Amazon Basin's role in regulating global climate, a synthetic examination of the most recent Basin-wide emission estimates for the known climate forcing agents [specifically CO_2, CH_4, N_2O, and black C (BC)] shows (1) high uncertainty in the magnitude of climate-relevant emissions from the Basin; (2) disagreement in the best way to account for their climate forcing relative to CO_2 (e.g., choice of GWP factor; Bond et al., 2013), and (3) the critical role that non-CO_2 climate forcing agents play in determining the Basin's impact on the global climate system (**Figure 2**). Even accounting for this large uncertainty, integrating the suite of forcing agents for which data is available leads to the conclusion that the current net biogeochemical effect of the Amazon Basin is most likely to warm the atmosphere; the CO_2e from net C uptake is currently smaller than the combined CO_2e from N_2O, CH_4, and BC emissions under most emission scenarios (**Figure 2**; **Table 1**; **Supplementary Tables 1, 2**). This assessment is conservative in that it ignores additional factors such as the indirect climate forcing of BC (Bond et al., 2013), negative radiative forcing from the reflectivity of biogenic aerosols, and the potentially significant but poorly constrained secondary effects of BVOC emissions (Shrivastava et al., 2017) (see *Biogenic Volatile Organic Compounds* and *Black C* sections). The only scenarios where the net biogeochemical impact of the basin provides a positive climate service (net uptake of ∼0.5–1 Pg CO_2e year^{-1}) is when CO_2 uptake is considered to be at the highest end of published annual estimates (measured under the most favorable climatic conditions), and the 100-year GWPs are used to calculate CO_2e (**Table 1**). When 20-year GWP values are applied, the net emission is on the order of 1.3–8.2 Pg CO_2e year^{-1}; the ∼7 Pg CO_2e year^{-1} spread of values across scenarios indicates high uncertainty in these estimates, especially for CO_2 (**Table 1**). Further, because the majority of regional and global anthropogenic impacts are expected to decrease C uptake and increase most non-CO_2 forcing agents, we expect this source strength to grow (**Table 2**). Specific sources of uncertainty for each flux are described below.

INDIVIDUAL CLIMATE FORCERS AND PROCESSES

Carbon Dioxide

Net CO_2 exchange between Amazonia and the atmosphere reflects the balance of uptake by primary production and

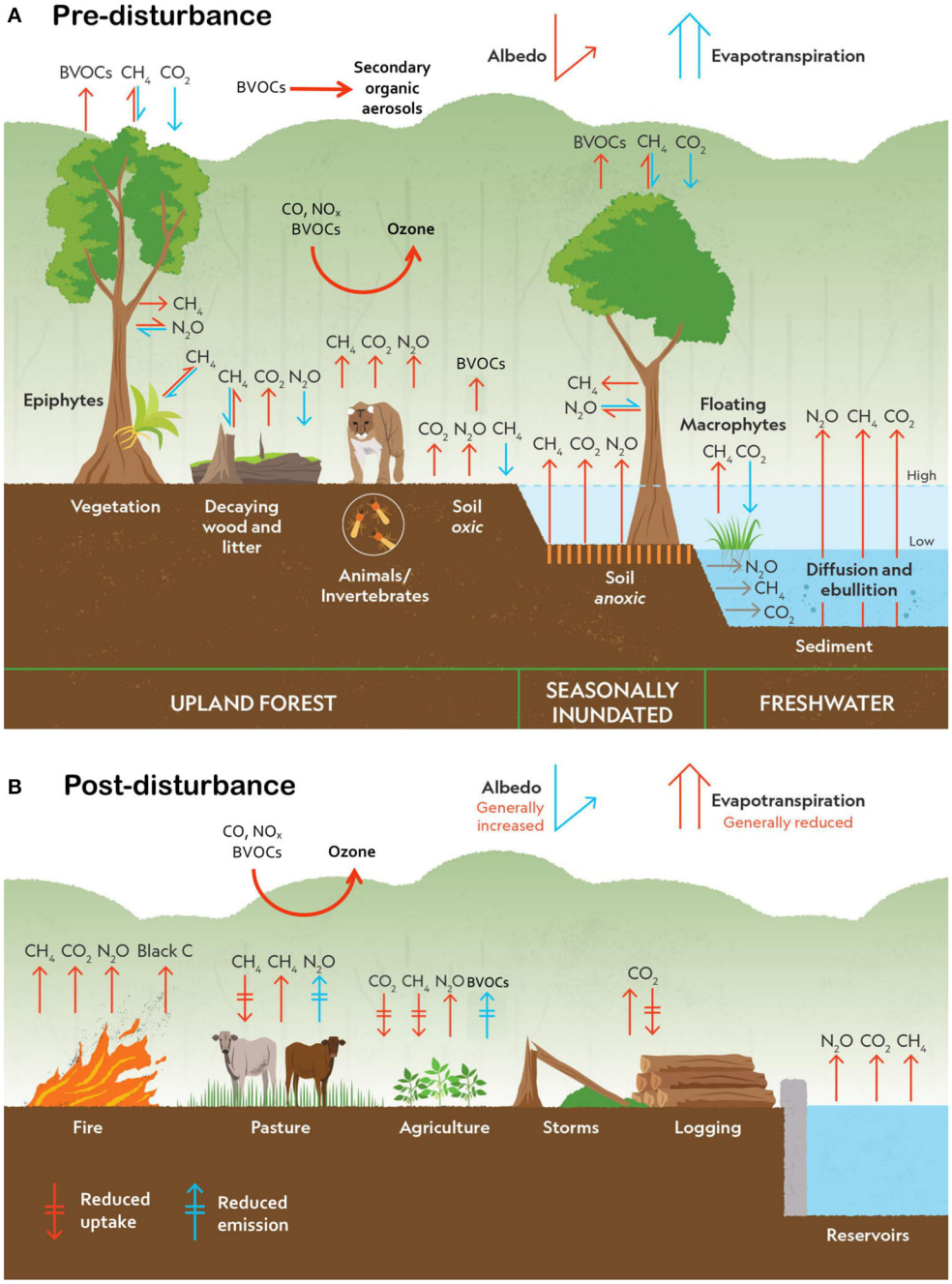

FIGURE 3 | Local-scale **(A)** pre-disturbance and **(B)** post-disturbance fluxes, biophysical forcing agents, and their associated short-term radiative forcing impact (positive, red; negative, blue; hashed arrows indicate a reduction in—as opposed to directional change to—a flux following disturbance) from undisturbed upland forests, seasonally inundated forests and wetlands, and freshwater ecosystems of the Amazon Basin. Note that because the magnitude of many of these effects is not well-defined, the arrow length is not proportional to source/sink strength.

weathering, and loss *via* respiration, decomposition of plant residues in the soils and water, and biomass burning. Because of the size of the total pool (the Amazon rainforest is one of the largest ecosystem C pools on Earth, storing ~150–200 Pg C; Feldpausch et al., 2012), even proportionally small changes in uptake or loss represent large net changes in CO_2 exchange with the atmosphere. The largest driver of CO_2 emissions from Amazonia is land-use change and forest degradation. When both clearance and regeneration are considered over the 20-year period from 1996 to 2017, these losses amounted to between 4.86 and 5.32 Pg C (Bullock and Woodcock, 2020). A great deal of work has focused on

quantifying CO_2 fluxes and the relative contribution of different drivers (**Supplementary Table 1**). However, the best available atmospheric C balance measurements (the gold standard method for net flux estimation) for the basin cover only a 2-year period (**Figure 2**) and are sensitive to climate and biomass-burning effects, which have strong interannual variability (Pan et al., 2011). Between 1990 and 2007, the basin appeared to be acting as a strong vegetation C sink as CO_2 with an estimated uptake of 0.42–0.65 Pg C $year^{-1}$ (Pan et al., 2011); however, recent work suggests that the magnitude of the C sink has been consistently declining (Brienen et al., 2015; Aragão et al., 2018). Land conversion, drought, and sustained long-term tree mortality (Aleixo I. et al., 2019) have driven a 1/3 reduction in aboveground biomass in the past decade as compared with the 1990s (Brienen et al., 2015; Walker et al., 2020). Aircraft-based air column measurements suggest that the basin as a whole actually lost 0.48 ± 0.18 Pg C $year^{-1}$ during the drier year of 2010 and was C neutral during the wetter year in 2011 (0.06 ± 0.10 Pg C $year^{-1}$). Survey data indicate a pronounced response to drought and a long-term average vegetation uptake of just 0.39 ± 0.10 Pg C $year^{-1}$, far lower than over the preceding decades (Gatti et al., 2014). More concerning still is that from 2010 to 2017, the basin appears to have acted as net source of 0.4 ± 0.2 Pg C $year^{-1}$, or 0.2 ± 0.2 Pg C $year^{-1}$ when extreme drought years are excluded from analysis (Gatti et al., 2019), but the results are sensitive to the area considered, and small drought impacts are noted over a more inclusive study area (van der Laan-Luijkx et al., 2015). Indeed, these regional-scale drought events can reduce biomass gains even in areas without observable precipitation deficits (Feldpausch et al., 2016). Taken together, the body of research investigating C flux dynamics in the Amazon Basin provides compelling evidence that one of the earth's largest C sinks is in steep decline and at increasing risk of becoming a regular source of C to the atmosphere.

Virtually all identified anthropogenic changes have increased or are expected to increase CO_2 emissions from the Basin; the lone exception is warming, where net impact will depend on the relative magnitude of increases in photosynthesis vs. respiration, as well as the magnitude and variability of associated hydrological changes (**Table 2**). Major short-term sources include combustion and deforestation associated with conversion to agriculture, extraction industries, or dams. Though fires lit directly for deforestation purposes have historically been the major driver of fire-related emissions, fires carrying through drought-impacted forests are increasingly dominant and expected to increase (Aragão et al., 2018). Longer-term committed (unavoidable) emissions come from current drought- or storm-associated tree mortality, subsequent decay and fire, and the degradation of soil C stocks following land-use change (**Table 2**). Likewise, this suite of near- and long-term change agents drives more diffuse forest degradation, further reducing future C sink strength (Rappaport et al., 2018).

The soil C pool is particularly vulnerable to loss catalyzed by land-use and climate change, which may also impact soil biodiversity with potential for myriad other downstream biogeochemical effects (Smith et al., 2015). The largest proportion of soil C is stored in the top 50 cm and decreases geographically along a gradient of soil age and evolution from the western to the eastern Amazon (Quesada et al., 2010). Converting forests to high-intensity grazing/introduced pasture, and eventually degraded pasture, decreases soil organic matter storage in the top 30 cm by ∼20% with most C either respired as CO_2 or eroded to waterways (Fonte et al., 2014; Navarrete et al., 2016). Warmer soil temperatures associated with global change are expected to accelerate soil microbial respiration rates, further increasing C loss (Cusack et al., 2018), though there is some evidence that microbial acclimation may attenuate these temperature-dependent emissions increases (Crowther and Bradford, 2013). Observations from primary forest in central Amazonia suggest a loss of 2.98 Mg C ha^{-1} (an average of 0.11 Mg C ha^{-1} $year^{-1}$) from the top 20 cm of soil between ∼1984 and 2012 (Barros and Fearnside, 2019), attributed potentially to warming.

Amazonian aquatic environments are also an important conduit transporting, storing, and processing C between land and the ocean (Davidson et al., 2012; Ward et al., 2017). Along the way, they transform and release terrestrial and aquatic organic matter as CO_2 (Raymond et al., 2013). Regional emissions assessments initially concluded outgassing from rivers and wetland represents an annual source of 470 Tg C $year^{-1}$ (Richey et al., 2002). However, many recent studies have increased the spatial and temporal coverage of measurements to include streams, small rivers, lakes, floodplains in different tributaries and the lower section of the Amazon River (de Fátima F. L. Rasera et al., 2013; Sawakuchi et al., 2017). This expanded assessment

TABLE 1 | Comparison of the published emissions ranges (see **Figure 2**) for CO_2 and non-CO_2 climate forcers and their net balance at two global warming potential (GWP) time horizons (20 and 100 years).

Net Pg CO_2e Uptake	Pg CO_2e sum of CH_4, N_2O, and Black Carbon 100yr GWPs			
		Low	Middle	High
		1.50	**1.80**	**2.00**
Low	**2.68**	4.22	4.48	4.71
Middle	**0.08**	1.62	1.88	2.11
High	**−2.53**	−0.99	−0.73	−0.50
Net Pg CO_2e Uptake	**Pg CO_2e sum of CH_4, N_2O, and Black Carbon 20yr GWPs**			
		Low	**Middle**	**High**
		3.80	**4.70**	**5.50**
Low	**2.68**	6.48	7.33	8.18
Middle	**0.08**	3.88	4.73	5.58
High	**−2.53**	1.27	2.12	2.97

*The scenarios show the sum of the CO_2e for available Amazonia-wide emission estimates across their estimated ranges shown in **Figure 2** (low, middle, and high, where the low/low scenario, for example, represents the sum of net positive forcing from all non-CO_2 at the lowest end of their published ranges, summed against the smallest annual net uptake of CO_2). Resulting positive values indicate a net increase in the CO_2e of the atmosphere (i.e., the inclusion of additional biophysical climate feedbacks results in net warming, 15 of 18 emissions scenarios presented in the table); negative values represent decrease in the CO_2e of the atmosphere (i.e., net cooling, three of 18 emissions scenarios).*

increased CO_2 emission estimates four-fold to 1.8 Pg C year^{-1} (Melack, 2016). Carbon and associated nutrients released into the Atlantic Ocean by the Amazon river plume result in a substantial C sink, both from direct sediment deposition and from stimulation of photosynthesis and subsequent associated sediment C deposition (Subramaniam et al., 2008). However, tidal floodplains and areas offshore and along the coastline where freshwater remains unmixed with ocean water could also represent significant sources of CH_4 and CO_2 (Sawakuchi et al., 2017) and would effectively reduce magnitude of the C sink of the Amazon plume. Across the land to ocean continuum, CO_2 (and also CH_4) originated by microbial respiration in soil can be transported through groundwater to streams and higher-order rivers (Neu et al., 2011; Call et al., 2018), and labile organic C from riparian zones can also be used for *in situ* respiration (Richey et al., 2009). Although C originating in wetlands may sustain most of the evasion of CO_2 from the Amazon River and its main tributaries (Abril et al., 2014), recent evidence also demonstrates that turnover of lignin and other terrestrially derived macromolecules in the Amazon River could fuel up to 50% of the river's bulk respiration, suggesting that a large fraction of these materials break down in rivers and are evaded

TABLE 2 | Expected direction of response to disturbance for climate forcing agents, associated confidence, and relevant literature citations.

	CO_2	N_2O	CH_4	BVOCs	Black C	Evapotranspiration	Albedo
Fire	5,10,61,66,74,102	19,20,21	20,21	?	28,54	22,44	33,39,42,46,68
Logging/Deforestation	5,7,10,14,74	43,65,79	43,79	11,47,108	a,2,16,89	9,67	48
Agriculture	34,49	21,34,83,84,92,101	21,84	94,95	104,107	23,24,54,67	33,37,48
Pasture	15,25,31,34	52,59,73,75,85,91,92,93	12,20,72,76,82	35,95	103,105–107	24,54,69	18,48,77,97
Drought	3,5,13,36,53,60,54,87,100	20,78,90	21,41,90,100	40,108	a,1,4,6,32,88,96		?
Warming	17,27,50,51,70	34,71	71,80	47,62,108	a,32	c	?
Reservoirs	80,98,99	38,98	38,80,98,99	b		b	33,48
Severe storms	57,58	?	?	108	?		?
Mining/Extraction	8,30,69	?	?	b		b	b
7 Hunting	63						

Responses refer to the short-term effects of disturbance events rather than ecosystem recovery dynamics or associated land-cover changes. Upward arrows indicate a net warming impact in the balance of forcing agents in the atmosphere relative to undisturbed state; this results from either increased positive (source) fluxes or decreased negative (sink) fluxes. For example, disturbances that reduce consumption of CH_4 in soils or uptake of CO_2 by vegetation are expressed as upward arrows. Blank cells indicate a lack of expected direct interactions between variables. Question marks indicate the absence of sufficient evidence to make predictions, or conflicting evidence on expected direction. Following the IPCC AR5, "confidence" is an objective measure encompassing level of evidence (number of studies, strength of effect) and degree of agreement among them. Logging includes clear-cuts, selective cuts, and road-cuts. Agriculture refers to intensive agricultural management (tilling and fertilization). Supporting citation details can be found in ***Supplementary Table 3*** *and the corresponding citation numbers in the associated* ***Supplementary Information****.*

[a] *Drought, warming, and fragmentation are expected to increase black C emissions by increasing fire frequency and susceptibility.*

[b] *Impacts inferred from an implied large reduction in vegetative biomass.*

[c] *Warming, drought, and evapotranspiration are interlinked such that they cannot be readily described in this format. See Evapotranspiration section.*

***Legend**: **LOW** **MED** **HIGH** .*

as CO_2 and do not reach the ocean as previously assumed (Ward et al., 2013). Degradation of these molecules can be intensified by a priming effect in areas where the river receives water from tributaries and wetlands that are rich in labile organic C, creating hotspots of C transformation (Ward et al., 2016).

NON-CO_2 FORCERS AND PROCESSES

Trace Gases

Amazonian terrestrial and freshwater systems support fluxes of a range of climatically significant trace gases, often switching between sink and source in response to pronounced seasonal shifts in inundation or anthropogenic disturbance (**Table 2**). N_2O and CH_4 are the best characterized and most significant of these, and it had been believed that for undisturbed ecosystems, the global warming impact of emitted N_2O and CH_4 (1.3 Pg CO_2e year^{-1}) was approximately balanced by that of CO_2 taken up by vegetation (Aragão et al., 2014). However, more recent work in the basin suggests CH_4 emissions from trees in wooded wetlands actually overwhelm their C sink effect (Pangala et al., 2017; Dalmagro et al., 2019). Upland soils and biomass burning also act as net sources of nitric oxide (NO) and nitrogen dioxide (NO_2) to the atmosphere (Bustamante et al., 2009). While not greenhouse gases themselves, these compounds are involved in the formation of radiatively-active ozone and CH_4 in the troposphere. A substantial amount of CO is emitted by Amazonian deforestation, particularly from smoldering combustion when the biomass is burned (Fearnside, 1997). This CO removes hydroxyl radicals (OH^-) from the atmosphere, thereby extending the average lifetime of the CH_4 that these radicals would otherwise remove (Saunois et al., 2019). CO is also converted to CO_2, a contribution to global warming that increases the C impact of Amazon Basin deforestation by 2.4–2.8% (Fearnside, 2000). Effects of disturbance and climatic variability on ecosystem trace gas fluxes are mediated predominantly by shifts in soil temperature, moisture (including sediment/soil inundation), gas diffusivity, and nutrient cycling, including increased nutrient inputs (Bustamante et al., 2009).

N_2O

Tropical forests are a globally important source of N_2O, and Amazon forest emissions range from 1.1 to 6.9 kg N ha^{-1} year^{-1} (Abril et al., 2014), with total basin emission estimated at 1.8–1.9 Tg N_2O-N year^{-1} (0.46–0.49 Pg CO_2e) (Davidson and Artaxo, 2004). This small range reflects a lack of recent comprehensive synthesis of emissions, rather than high confidence, and does not include emissions from tree stems in upland habitats that have also been recently identified as an important egress pathway for soil-borne N_2O (Dalmagro et al., 2019). Inversion models for South America constrain the upper limit of natural soil emissions at around 3 Tg, or 18% of global atmospheric emissions (Saikawa et al., 2013, 2014). While the majority of this source likely derives from microbial production in upland soils, N_2O can also be emitted from drying wetland sediments, biomass burning, hydroelectric reservoirs, riverine water columns, and from more recently recognized sources including inundated tree stems, decaying wood, and invertebrate activity (Koschorreck, 2005; Hu et al., 2016; Covey and Megonigal, 2019; Soper et al., 2019).

Disturbances have varied effects on N_2O production/consumption in soils and sediments, some of which have reasonable certainty in the direction of their effect, though not magnitude (**Table 2**, and references therein). Increased concentrations of N_2O over the basin are confidently associated with biomass burning. Similarly, soil compaction associated with land clearing and logging increases both soil N_2O and NO fluxes by between 30 and 350% (Keller et al., 2005; Meurer et al., 2016). N_2O emission from pasture soil varies seasonally, with most emissions occurring during the rainy months (Luizão et al., 1989). After an initial pulse, however, conversion generally reduces long-term soil N_2O and NO emissions as a result of declining N availability in aging pasture. Though fertilized and/or tilled agriculture is recognized as a large N_2O source globally, several studies find only modest increases when compared with intact forest in Amazonia. Reservoir construction in the Amazon could also increase net N_2O fluxes substantially—one study estimated an ∼80% increase (Guérin et al., 2008)—but data are present from a just small number of sites, and pre-dam data are limited. Although there are few climate manipulation studies from the global tropics, those that do exist demonstrate that global change factors will have contrasting effects on N_2O dynamics in soil. Throughfall exclusion experiments indicate that soil drying reduces N_2O emissions in upland forests (Davidson et al., 2008), whereas warming is expected to increase soil enzyme activity, thus enhancing soil N_2O emissions from humid tropical forests (Xu-Ri et al., 2012). As with other factors, drying and warming may also modulate N_2O emissions by feeding back to fire frequency and severity (Davidson and Artaxo, 2004).

CH_4

Soils and sediments can both produce and consume CH_4. Well-drained upland soils in the Amazon act predominantly as a net CH_4 sink, of 1–3 Tg CH_4 year^{-1} (Bustamante et al., 2009), whereas inundated soils, sediments, and vegetation act as a globally significant net source (Covey and Megonigal, 2019; Saunois et al., 2019). Methane oxidation significantly reduces the diffusive emissions of CH_4 from rivers and floodplains (Sawakuchi et al., 2016; Barbosa et al., 2018), and most of the CH_4 emissions from these sources may therefore be attributed to bubbles released from wetland sediments that bypass oxidation. Ebullitive fluxes estimates, however, remain highly uncertain due to the restricted spatio-temporal coverage of measurements and the episodic nature of ebullition (Melack et al., 2004). Emissions from vegetation can be both direct (*via* UV-induced abiotic production) and indirect (as a conduit between sediments and the C atmosphere which bypasses oxidization in the water column, and through microbial activity inside living and deadwood). Abiotic fluxes are likely small (Covey and Megonigal, 2019), but the transport of soil-borne CH_4 to the atmosphere by tree stems is the largest CH_4 egress pathway in the Basin, contributing ∼3.5% of all global CH_4 emissions (Pangala et al., 2017; Saunois et al., 2019). Additional, but smaller, contributions

come from native animals and livestock, invertebrates, and tank bromeliads (Bloom et al., 2010; Martinson et al., 2010).

Around 20% of the Amazon Basin is seasonally flooded, and recent developments suggest that previous bottom-up regional CH_4 emission estimates from these areas are unreliable (Melack et al., 2004). Average fluxes of 195 ± 25 kg CH_4 ha^{-1} $year^{-1}$ over the eastern part of the Amazon Basin (∼1 million km^2) have been observed by vertical CH_4 mole fraction profiles, likely dominated by seasonal and permanent wetlands (Basso et al., 2016). Extrapolation of inversion results to the whole of the Amazon Basin, using top-down regional estimates of CH_4 emissions based on regularly measured atmospheric profiles at four locations, yields a mean total CH_4 flux of 43 ± 6 Tg CH_4 $year^{-1}$, which is the equivalent of ∼8% of all global CH_4 emissions. This estimation agrees well with combinations of floodplain tree emissions (15 ± 2 to 21 ± 3 Tg CH_4 $year^{-1}$) and CH_4 emission from other transport pathways, namely, conduit from flooded sediments to the atmosphere *via* tree stems (21 ± 5 Tg $year^{-1}$) (Pangala et al., 2017). Hence, CH_4 emissions in the basin are larger than previously estimated and contribute ∼1.0–4.2 Pg CO_2e (**Table 1**; **Figure 1**). The lack of integration of these newly recognized fluxes from living tree stems is a critical weakness, limiting our broader understanding of the biogeochemical impacts of Amazonian land conversion.

Of the impacts that may increase the strength of sources in the Basin, wetland warming and reservoir construction could be the most significant. While drying may reduce the area of wetlands and in turn the source strength (Davidson and Artaxo, 2004), recent projections suggest that a 4°C temperature increase in tropical South American wetlands could double already substantial regional CH_4 emissions (Zhang et al., 2017). Inundation following dam construction decreases aquatic oxygen levels and increases anoxic organic matter decomposition, releasing significant amounts of CH_4 to the atmosphere. This effect is potentially 10 times stronger in tropical systems than for better-studied temperate dams (Barros et al., 2011; Fearnside, 2015). Actual reservoir emissions will vary with the flooded area, river chemistry (which varies markedly across the basin; Ríos-Villamizar et al., 2013), and the extent of pre-clearing, but simulations for 18 planned reservoirs indicate net emissions between 9 and 21 Tg CH_4 over the next 100 years (de Faria et al., 2015). Actual emissions may be substantially greater, however, due to downstream evasion associated with water passing through turbines and spillways (Fearnside, 2016).

In addition to direct CH_4 production during biomass burning, logging and conversion to agriculture tend to compact soil and reduce the strength of the soil CH_4 sink, sometimes shifting upland soils to net sources (Bustamante et al., 2009). Introducing ruminant livestock to the systems further increases source strength, accounting for ∼6% of total landscape CH_4 emissions in the eastern Basin (Basso et al., 2016). In intact forests by contrast, soil drying associated with climate change is likely to increase the CH_4 sink strength, though the magnitude of the effect is uncertain and short-term drought impacts could in fact have the opposite effect (Davidson et al., 2008) (**Table 2**). Finally, fire also serves as a substantial source of direct emissions, ranging in magnitude from 0.5 to 7.0 Tg CH_4 $year^{-1}$, depending on the severity of the burn season (Saito et al., 2016; Wilson et al., 2016).

Biogenic Volatile Organic Compounds

BVOCs are atmospheric trace gases (e.g., isoprenoids and methanol) produced during plant processes such as growth and communication (Laothawornkitkul et al., 2009), response to heat stress (Peñuelas and Llusià, 2003), or by soils (Bourtsoukidis et al., 2018), litter, and fungi (Yáñez-Serrano et al., 2020). BVOC emissions impact atmospheric reactivity, acting as precursors for the formation and growth of aerosols. Other less-studied positive climate forcing feedbacks include greenhouse effects such as involvement in tropospheric ozone formation, lengthening of the atmospheric lifetime of CH_4, increasing CO_2 production, and the release of latent heat during water condensation (Peñuelas and Staudt, 2010). A key question, both globally and in the Amazon Basin, is whether increased BVOC emissions have a net cooling or net warming effect (Peñuelas and Llusià, 2003). While some authors have suggested that BVOC emissions are a dominant control on the net forcing balance of forest ecosystems globally (Unger, 2014), others conclude that including more holistic modeling of atmospheric interactions suggests only modest impacts (Scott et al., 2018). Globally, BVOC emissions are large but not well-constrained, with most recent estimates at ∼760 Tg C $year^{-1}$ (Sindelarova et al., 2014). Tropical forests are a significant contributor with emissions from some tropical locations exceeding 1,000 kg ha^{-1} $year^{-1}$ (Guenther, 2002). Fluxes vary between Amazon ecoregions (Greenberg et al., 2004), but estimates suggest that 1–6% of net ecosystem productivity (C gain) can be re-emitted as BVOCs (Kuhn et al., 2007).

BVOC emissions are controlled by a diverse set of factors, including plant species and functional type, canopy structure, biotic factors like herbivory, and abiotic variables such as concentrations of other atmospheric gases, nutrient availability, and seasonal changes in temperature, precipitation and soil moisture, solar radiation, leaf area index, and leaf phenology (Peñuelas and Llusià, 2003; Laothawornkitkul et al., 2009; Yáñez-Serrano et al., 2020). Emissions are thus likely to be sensitive to change in both climate and land use in the Amazon Basin. A recent review by Yáñez-Serrano et al. (2020) summarizes these effects in detail. Satellite applications have increased the availability of emissions data and show that BVOCs have decreased by on average 2% per annum in recent years (Bauwens et al., 2016). Although there is significant uncertainty surrounding the impacts of global changes on BVOC production, with studies producing conflicting results, many scenarios suggest an overall increase in emissions (Peñuelas and Llusià, 2003). BVOC production generally increases with temperature, although once temperatures exceed a maximum, isoprene emissions decline sharply, especially in the tropics (Laothawornkitkul et al., 2009). Increases may also be associated with rising CO_2 concentrations that stimulate plant productivity or increase N_2O (Peñuelas and Llusià, 2003; Laothawornkitkul et al., 2009), but this has not been tested directly in the Amazon (Yáñez-Serrano et al., 2020). Responses to drought stress can be positive or mixed due to differences in leaf physiology, BVOC biochemistry, and study methods (Laothawornkitkul et al.,

2009; Yáñez-Serrano et al., 2020). Estimates from the Amazon Cuieiras Biological Reserve show that maximum emissions rates from primary forests occur in the late dry season (Alves et al., 2016), supporting observations that increased production follows warming and drought (Jardine et al., 2015; Pfannerstill et al., 2018). Finally, land-use change that reduces vegetation cover alters emissions. For example, isoprene emission fluxes in Amazonia may decrease substantially due to deforestation or tree mortality (Ganzeveld and Lelieveld, 2004), or where trees are replaced by grasses with a lower emission potential (Peñuelas and Llusià, 2003). This has been shown to result in a net positive radiative forcing in some cases (Scott et al., 2018; IPCC, 2019). Critical current knowledge gaps include regional production rates, species-specific rates, emissions of non-isoprenoid compounds, and responses to factors such as increased photosynthetically active radiation (Yáñez-Serrano et al., 2020). Until the understanding of the basic drivers of emissions at the leaf scale can be applied to estimate regional emissions, and broad agreement on the net forcing impact of BVOC emissions is reached, the climate impact of Amazon BVOCs will remain poorly resolved.

Ozone

Tropospheric ozone (O_3) is a highly reactive trace gas that plays a major role in atmospheric chemistry and acts as a greenhouse gas and an air pollutant, which has adverse effects on human health, crops, and vegetation (Cooper et al., 2014; Rowlinson et al., 2019). Due to its short life span of 23 days controlled by temperature, radiation, and precursor emissions from some natural but mostly anthropogenic sources, tropospheric O3's concentration is highly variable in space and time (Cooper et al., 2014). In the Amazon Basin, there is no significant direct source of tropospheric O_3. Concentrations largely depend on trace gases such as NO_x, CO, and VOCs (Trebs et al., 2012; Martins et al., 2018; Paralovo et al., 2019), and mirroring other interannual regional climate trends, variability in tropospheric ozone in the region is largely regulated by the El Niño-Southern Oscillation (ENSO) cycles (Rowlinson et al., 2019). Originating from biomass burning, urban, and biogenic emissions, these act as important sources of O_3 precursors. Their conversion to O_3 is regulated to some extent by the exchange between stratosphere and troposphere, as it is efficiently transported by intense convective activity to the upper troposphere, where regional and global circulations disperse them over long distances (Bela et al., 2015; Gerken et al., 2016). While regional smoke, haze plumes from biomass burning, and to some extent NO_x from soil are important contributors in the dry-to-wet transition season, biogenic emission of VOCs, particularly from the Amazon rainforest, is deemed important in the wet-to-dry transition season (Bela et al., 2015).

With increased biomass burning, deforestation, high-intensity agricultural land conversion, and rapid urbanization in the Amazon, anthropogenic emissions of O_3 precursors are on the rise (Artaxo et al., 2013; Bela et al., 2015), which has substantial impacts on the atmospheric radiation balance, can increase diffuse radiation and boost primary productivity (Sena et al., 2013), and can also reduce surface air quality (Artaxo et al., 2013). Additionally, due to dispersion of the urban anthropogenic plume of O_3 precursors, urbanization has the potential to significantly alter chemical composition and surface–atmospheric exchange processes far away from the source especially over pristine Amazon forests where these emissions are relatively low (Trebs et al., 2012; Gerken et al., 2016; Martin et al., 2017). Urban environments may also have a larger impact on the upper troposphere due to high solar radiation and intense convective transport (Alonso et al., 2010). Intense drought as predicted by future climate change scenarios and rapid land-use change in the region will tend to increase O_3 concentrations. The strongest sink of O_3 is dry deposition, which can occur through stomatal and nonstomatal uptake processes predominantly at night in forest canopy, consequently impacting forest growth. Soil and water surfaces and chemical losses such as reactions with nitric oxide are also O_3 sinks (Clifton et al., 2020). Conversion of Amazon rainforests to pastures or other agricultural land may therefore reduce the existing forest O_3 sink.

Aerosols

Small particles suspended in the atmosphere ranging from a few nanometers to micrometers, known as aerosols, are another important component of the climate system. They absorb and scatter solar radiation and significantly influence precipitation; because they provide cloud condensation nuclei, aerosols constitute an essential ingredient for cloud formation and development (Shrivastava et al., 2019). Moreover, some particles, known as ice nuclei, can initiate the formation of ice crystals inside clouds, providing a faster growth to precipitable droplet sizes compared with cloud condensation nuclei (Pöschl et al., 2010). The biosphere emits aerosols, which are processed by photochemistry, providing nuclei for cloud formation. This results in precipitation stimulating the formation of aerosol particles, making an intrinsic connection between aerosol and cloud processes, thereby sustaining the hydrological cycle (Pöschl et al., 2010; Pöhlker et al., 2012). The addition of these cloud condensation nuclei, in turn, reduces atmospheric temperature by reflecting sunlight from low clouds (Peñuelas and Staudt, 2010) and can also increase NPP *via* increases in diffuse radiation (Yáñez-Serrano et al., 2020). A recent analysis suggested biogenic aerosols above the central Amazon accounted for a radiative surface forcing of $-20\,W\,m^{-2}$, just under half of the overall aerosol effect (Palácios et al., 2020).

Sources of aerosols from the Amazon Basin include both high emissions from biomass burning and low but more consistent production of primary and secondary biological aerosol particles and components (Martin et al., 2010). Primary particles are produced by flora (release of pollen and fungal spores, leaf and soil debris, suspended microbes, and fragments of biological material), and secondary aerosols are formed due to the atmospheric photochemical oxidation and condensation of trace gases including VOCs to low-volatile compounds depositing on preexisting particles or nucleating new particles. In the atmosphere, these particles undergo continuous transformation through photochemical reactions, interactions, and cloud processing; ultimately, these particles deposit on vegetation surfaces through dry deposition, cloud scavenging, and precipitation and advection, transporting these particles

out of the Amazon Basin. Recent observations showing higher aerosol particle densities in the upper troposphere seem to indicate aerosol production there could be an important source to the boundary layer (Andreae et al., 2018). In addition to within-Basin sources, long-range transported natural and anthropogenic sources such as Atlantic marine aerosols, African aerosols consisting of Saharan dust, and biomass-burning aerosols from the Sahel region (Pöhlker et al., 2012; Moran-Zuloaga et al., 2018) are more frequent in the wet season (Sena et al., 2018) when enhanced concentrations of aerosol mass, crustal elements (Al, Si, Ti, and Fe) and potassium are observed, providing key nutrients to the Amazonian ecosystem (Martin et al., 2010; Pöhlker et al., 2012).

The Amazon Basin especially in the wet season is used as a laboratory to study pristine continental aerosol particles, which equates to pre-industrial values, against which the effects of human activities globally can be evaluated, including future analysis of anthropogenic influence on cloud formation and precipitation (Martin et al., 2010). With rapid urbanization, fire, deforestation, and land-use change, the region also provides a unique opportunity to investigate how chemical pathways of aerosol formation transition from preindustrial to urban influenced present-day condition (Davidson et al., 2012). Increased aerosol emissions due to these anthropogenic changes directly affect the radiative budget due to surface albedo changes and indirectly by acting as cloud condensation nuclei; changing cloud properties therefore have strong implications to convection, cloud formation, and ratio of direct to diffuse radiation and play a major role in modifying atmospheric composition (Sena et al., 2013). Land-use change from forests to crops to pasture also changes evaporation rates resulting in changes to atmospheric water vapor content and further enhances the effect of deforestation on the radiative balance (Sena et al., 2013). Furthermore, anthropogenic aerosol emissions enhance different pathways of secondary biological aerosol formation in the pristine forest (Shrivastava et al., 2019).

Black Carbon Aerosols

BC is particulate matter $> 2.5\,\mu m$ in diameter, which is formed mainly by incomplete combustion of fossil fuels, biofuels, and biomass, though the term is used to describe compounds with varying definitions. Though mean values are presented in **Figure 2**, estimates of GWP for BC vary by almost an order of magnitude and reflect the challenge of making direct comparisons with CO_2. Around 40% of global open fire emissions come from forest burning in the tropics, and emissions of 0.33 Tg C year^{-1} of BC have been reported for Latin America. BC emissions from forest degradation and deforestation for South America averaged 0.14 ± 0.09 Tg C year^{-1} for the years 1997–2016 (Global Fire Emissions Database version 4 GFED4, 2020) (**Figure 2**). Although the Amazon is certainly a large contributor to this figure, BC is not included in Brazil's Nationally Determined Contribution to the Paris agreement (Azevedo-Ramos and Moutinho, 2018). Biomass-burning aerosols absorb radiation directly (warming the atmosphere) and reduce radiation reaching vegetation but also increase diffuse radiation and cause indirect climate feedbacks that have been shown to increase net primary productivity in the Amazon rainforest by 1.9–2.7% (65–100 Tg C year^{-1}), and up to as much as 615 Tg C year^{-1} in an extreme fire year (Malavelle et al., 2019; Silva Junior et al., 2019). Other studies show that when including indirect interactions (such as impacts on cloud formation), net radiative forcing is dependent on emission rates of biomass-burning aerosols, having a modest cooling effect at low rates that switches to strong warming as atmospheric loading increases (Liu et al., 2020). As with other forcing agents described here, freshwater is an important factor in the transport and storage of BC. A significant amount of the total BC produced in the Amazon is temporarily stored in intermediate reservoirs along the freshwater continuum and eventually transported to the oceans, where it may potentially be sequestered (Coppola et al., 2018, 2019). Total fluxes of dissolved BC from the Amazon river have been estimated at 1.9–2.7 Tg year^{-1} (Coppola et al., 2019), most of it relatively modern in origin (Coppola et al., 2019). BC emissions also influence regional hydrology, catalyzing 3% of melting mass loss from nearby Andean glaciers (Magalhães et al., 2019). Widespread drought-intensified burning is likely to increase emissions in the future (Aragão et al., 2018).

Albedo

Albedo is a measure of diffuse reflection of incoming solar radiation. Conversion of forests to pastures or croplands tends to increase albedo, both because relatively dark forest land cover absorbs more radiation than more reflective open areas and as a result of aerosol formation owing to burning for clearance. Along the arc of deforestation, average albedo increases of 2.8% have been observed after land conversion (Loarie et al., 2010). Atmospheric aerosols can be both primary (e.g., BC) and secondary (e.g., secondary organic aerosols formed from BVOCs) and impact the albedo of the atmosphere both directly and *via* their impact on cloud formation, lifetime, and droplet size (increasing aerosols reduce droplet size but increase cloud cover acting to increase albedo) (IPCC, 2015). BC can reduce the albedo of surfaces after deposition (Ramanathan and Carmichael, 2008). Carbon dioxide equivalences of albedo changes are not standardized and are sensitive to the pattern, timing, and extent of underlying land-cover changes and the time horizon considered. Even considering this uncertainty, it is clear that unlike in higher-latitude forests (Bala et al., 2007), the local albedo-driven cooling effect of land clearance in Amazonia is far smaller than warming driven by increased C emissions and reduced evapotranspiration (Jackson et al., 2008).

Evapotranspiration

Evapotranspiration in the Amazon is a critical driver of local and regional climate, *via* surface cooling and water recycling, and an important control on vegetation pattern throughout the Basin (Salati et al., 1979; Sampaio et al., 2007; Boers et al., 2017; Lovejoy and Nobre, 2018). Regional changes in precipitation (detailed below) are mirrored by local-scale land-use-driven hydrological changes that in turn influence evapotranspiration. In general, anthropogenic changes that reduce vegetative biomass also reduce evapotranspiration and in turn intensify surface runoff, dry soils, alter moisture transport dynamics, and increase

local temperatures (Hayhoe et al., 2011; Dias et al., 2015). The effect of deforestation on soil moisture appears as a minor control on evapotranspiration in the wet season but emerges as an important biophysical driver following the onset of the dry season (Mallick et al., 2016). This seasonal dynamic is complicated by the fact that transpiration is likely an important factor triggering and sustaining the onset of the wet season (Wright et al., 2017). Although secondary and primary forests may have similar rates of evapotranspiration (Sommer et al., 2002), in those portions of the basin with rapid land-use change, dry season reductions in total evapotranspiration are strongly associated with increased local air surface temperatures (Sampaio et al., 2007). The aggregate effect of these local changes can then feedback into regional climate pattern delaying the onset and duration of the dry season (Leite-Filho et al., 2020). Increased dry season lengths also lead to reduced growth in secondary forests, which are in turn more vulnerable to drought stress (Elias et al., 2020), and at a greater risk of fire. Throughfall reduction experiments in mature Amazonian forests suggest primary forests are similarly sensitive (Nepstad et al., 2002). Even modest deforestation-driven reductions in rainfall can reduce convective available potential energy and increase convective inhibition, decreasing latent heat flux and further drying the atmosphere. Initiating cyclical decline, the subsequent reduction in rainfall together with intense warming can then further increase forest dieback. A complex-network analysis of atmospheric water fluxes in the Amazon suggests this self-amplification effect might further reduce Amazonian forest cover by 10–13% (Zemp et al., 2017). A study using the ED-BRAMS (Ecosystem Dynamics 2- Brazilian Regional Atmospheric Modeling System) coupled land–atmosphere model showed that the effects of tree loss on atmospheric moisture and local temperature were greatest along the arc of deforestation. These large changes in modeled local parameters, however, did not translate to greatly reduced precipitation, suggesting significant gaps in our understanding of atmospheric dynamics over the Amazon and/or uncertainties in model estimates of precipitation (Swann et al., 2015).

Nature, Extent, and Underlying Drivers of Anthropogenic Change Agents

Contextualizing the region's changing biogeochemistry is predicated not only on understanding the current state of the biophysical system and its potential responses to change but also on developing an integrated understanding of the social and economic drivers of dynamic resurgent land-use change (**Figure 1**).

Local: Deforestation and Land-Use Change

Historically, the Brazilian "arc of deforestation" along the southern and southeastern edges of the forest (largely a product of soybean cropping and meat production) was the epicenter of deforestation in the Amazon Basin (Nepstad et al., 2014), while smaller-scale migration-related processes dominated the Andean zone (Steininger et al., 2001), and gold mining was most intense in the northern Basin (Dezécache et al., 2017). In recent years, however, other countries in the region, such as Peru and Bolivia, have also experienced large-scale deforestation. In the case of Peru, the palm oil industry, combined with pressure from artisanal gold mining in the south, has triggered rapid deforestation, whereas the Bolivian Amazon has been more heavily impacted by soybean production (Asner and Tupayachi, 2016; Kalamandeen et al., 2018).

Since 2017, the processes driving deforestation across the region are widely seen as more dynamic and uniquely sensitive to the political decisions of regional governments (Fearnside, 2017; Carvalho et al., 2019). With the signing of the peace agreement in Colombia, even nominally protected areas previously occupied by revolutionary FARC guerrillas are now threatened by cattle grazing (Prem et al., 2019). In the Brazilian Amazon, deforestation rates have increased >60% since 2012 (4,600 km^2 $year^{-1}$) with ∼7,420 km^2 $year^{-1}$ lost between 2016 and 2018 (Aguiar et al., 2012). In 2019, the first year of the Bolsonaro presidential administration, 9,762 km^2 was deforested, a 30% increase over the previous year (PRODES, 2020). The increasing forest losses are linked to national and state political actions that compromise indigenous land rights, limit monitoring and enforcement, and attempt to inhibit conservation nongovernmental organizations (Ferrante and Fearnside, 2019).

Local: Fire

Both intentionally-set fires associated with land clearing and, increasingly, indirect uncontrolled drought-associated fires occur throughout the Basin and are abundant at forest edges especially in southern Amazonia (Brando et al., 2020). After a general decline compared with the previous decade, the high rate of fire detection in 2019 was strongly linked to a sharp uptick in deforestation, characterized by the highest rates seen since 2008 (Barlow et al., 2020; Cardil et al., 2020). This year was also characterized by exceptionally high fire counts occurring in protected areas (Barlow et al., 2020) and associated with a shift in governance that strongly reduced environmental protections and enforcement (Escobar, 2020). Even in periods of slowed land conversion, gross emissions from fires that carry through drought-affected forests (ignited by human activities such as adjacent secondary slash-and-burn or pasture burning) can offset half the C gained from reduced deforestation (Aragão et al., 2018). Fire incidence in the Brazilian Amazon increased by 36% in the 2015 drought, increasing the total area impacted by all fires to ∼800,000 km^2 (Aragão et al., 2018). Climatic shifts predicted by Earth system models are likely to amplify fire susceptibility, such that drought-associated fires, a leading cause of forest degradation, may exceed those arising directly from deforestation (Aragão et al., 2014). Model projections suggest an intensification of the fire regime in the southern Amazon could double the burned area to 16% by 2050, but this impact could be reduced substantially by avoiding new deforestation (Brando et al., 2020). Recovery of basal diameter can occur following fire, but canopy openings and drying residual biomass facilitate future fires (Berenguer et al., 2014), and the result is often a stable transition in forest structure and composition, reduced biodiversity, and biomass loss (Davidson et al., 2012).

Local: Agriculture

Historically, deforestation in the Amazon has been dominated by cattle ranching (Richards et al., 2014; Fearnside, 2017), although the impact of soy production has steadily increased (Nepstad et al., 2014). The two practices are interconnected, however, as cattle ranchers in consolidated frontiers sell their land to soy producers and subsequently advance new ranching frontiers deeper in the Basin (Richards et al., 2014).

Land-management practices following deforestation are as important in determining C dynamics and CO_2 emissions as land-cover changes (Berenguer et al., 2014; Luyssaert et al., 2014). The use of fire or machinery to remove the plant material after deforestation and prepare the soil (Marin-Spiotta et al., 2009), the introduction of exotic pasture and legume species (Mosquera et al., 2012), the use of fertilizers to increase pasture productivity (Fisher et al., 2007), and increased grazing intensity (Navarrete et al., 2016) are common land-management practices in Amazonia. As outlined above, these impacts can have various and sometimes contrasting net effects on albedo, evapotranspiration, and net fluxes of CO_2 and other trace gases (Davidson et al., 2012). The latter are likely highly dependent on management practices and not well-characterized for all systems.

Local: Reservoir Construction

The complex river drainage system of the Amazon Basin is interrupted by more than 190 dams, with an additional 246 hydroelectric reservoirs planned or currently under construction (Lees et al., 2016). These structures create habitat fragmentation that inhibits species migration, changes thermal river profiles, reduces water quality, and alters inundation frequency, timing, and extent across wetland and freshwater ecosystems (Lees et al., 2016), as well as acting as potential sources of trace gases and CO_2 (Fearnside and Pueyo, 2012; Fearnside, 2015). In unmodified systems, sediment transport by Amazonian rivers moves organic C and associated nutrients downstream, with some C deposited in floodplain lakes (Sanders et al., 2017). Dams interrupt this natural transport, with consequences for river productivity and fisheries (Forsberg et al., 2017; Latrubesse et al., 2017). Although dams offset emissions from fossil fuel derived electricity, their net climate impact may be greater than the power plants they supplant. An attempt to estimate the potential emissions from future reservoirs suggested that some may emit more than fossil fuel plants for many years (de Faria et al., 2015). However, current data suffer from inadequate spatio-temporal coverage and lag dam construction by several years, rendering regional estimates highly uncertain.

Local: Mining and Oil Extraction

Legal and illegal mining and oil extraction have both direct (deforestation, riparian disturbance, riverine sedimentation, and mercury/oil pollution) and indirect (infrastructure development, illegal hunting, overhunting, and forest fires) effects on Amazon biogeochemistry (Anderson et al., 2019). Between 2005 and 2015, deforestation beyond mining operation lease boundaries was estimated at 11,670 km^2, almost a tenth of the total Amazonian forest losses during that period (Sonter et al., 2017). In the Madre de Dios region of the Peruvian Amazon, gold mining accounts for deforestation of ∼61 km^2 $year^{-1}$, around half is made up of illegal mining along roads and streams (Asner et al., 2013). Though most have not yet been cleared, registered mining interests cover more than 1,000,000 km^2 of Amazonia, including indigenous or strictly protected areas (Ferreira et al., 2014) with plans to open at least two more large areas north of the Amazon River to mining and road building. Oil and gas drilling projects are also widespread, facilitating secondary deforestation in addition to their documented impacts to human health through water and food contamination (Anderson et al., 2019).

Local: Hunting and Overfishing

Animal-mediated shifts in plant community composition can have strong implications for vegetation biomass, and thus C stocks and future uptake rates, but have been explored by only a handful of studies. On land, extirpation of large-bodied frugivores (such as large primates and tapirs) by overhunting impacts forest community composition by replacing large-seeded, high-wood-density tree species with smaller-seeded, low-density species as a result of dispersal limitation. Overharvesting affects up to a third of remaining forest in the Brazilian Amazon, and field data and modeling indicate that eliminating large frugivores reduces aboveground forest biomass by 3–6% on average and up to 38% in certain areas (Peres et al., 2016). Similarly, the widespread overfishing of large frugivorous freshwater fish compromises seed dispersal (Anderson et al., 2011) and may drive similar impacts, though assessment data are very limited. Despite the importance to fishing and the many threats to aquatic biodiversity in the Basin (Anderson et al., 2019), the conservation of freshwater biota is limited compared with terrestrial fauna.

Global: Warming, Drought, and Hydrological Change

The Amazon Basin is characterized by hydrological complexity that is highly susceptible to global change. Freshwater and coastal ecosystems cover over one third of the Amazon Basin and are critically linked to their upland counterparts through riverine and atmospheric water exchanges (Castello et al., 2013). Seasonal processes of flooding and drought modulate ecosystem productivity *via* water availability and nutrient exchange. They also influence atmospheric chemistry both directly (as a control on evapotranspiration, and BVOCs, CH_4, and N_2O emissions) and indirectly through feedbacks to fire, tree mortality, and riverine C transport (Barichivich et al., 2018).

Interannual rainfall and river variability in Amazonia can be in part attributed to sea surface temperature variations in the tropical oceans. This is manifested as the extremes of the ENSO in the tropical Pacific, and the meridional SST gradient in the Tropical North Atlantic (TNA). During these warm EN events, convective suppression drives lower rainfall in the Amazon Basin and can be particularly extreme when warming is more pronounced in the eastern Pacific as opposed to more moderate effects when the central Pacific is the focus of warming (Jiménez-Muñoz et al., 2016). Most of the severe droughts in the Amazon region are El Niño-related (e.g., 1998, 2010, 2016; Marengo et al., 2018; Jimenez et al., 2019; Cai et al., 2020), and these events

are now occurring at a greater frequency than suggested by natural climate variability (Jimenez et al., 2019). However, in 1963 and 2005, the Amazon was affected by a severe drought that was not El Niño-related. Most of the rainfall anomalies that have happened in southwestern Amazonia are initiated by sea surface temperature anomalies in the TNA, including the recent "megadroughts" in 2005 and 2010 (Marengo et al., 2018; Jimenez et al., 2019).

Projections of an abrupt large-scale shift of the Amazon forest caused by climate change are still dominated by large uncertainties (Lapola et al., 2018). Despite rather low confidence in the 5th Coupled Model Intercomparison Project (CMIP5) ensemble mean projections of precipitation, some consensus can be found in the literature. There is high agreement that annual mean precipitation will decline in Amazonia, which is more pronounced in the eastern and south of the Amazon over the twenty-first century. Small changes in rainfall are projected under a moderate emission scenario. In line with observed historical precipitation trends, dry season length is also expected to expand over southern Amazonia. There is also generally model agreement for an increase in precipitation for the end of the twenty-first century over northwestern Amazonia (i.e., Colombia, Ecuador, and north of Peru) (Boisier et al., 2015).

No long-term unidirectional total rainfall trends have been identified in the Amazon region; however, a longer dry season has been observed in southern Amazonia (Marengo et al., 2018), and the positive precipitation trend observed in northwestern Amazon since 1990 may be a consequence of the intensification of the regional hydrological cycle (Gloor et al., 2013). Furthermore, interannual rainfall variability is intensifying and is reflected in both severe droughts (as in 1998, 2005, 2010, and 2016) and floods (1999, 2009, 2012, and 2014) (Marengo et al., 2016, 2018). Regional warming and reduced dry season precipitation can affect atmospheric moisture from Amazonia to southeastern South America, impacting regional hydrology and reducing stream discharge. Projected annual rainfall changes over the twenty-first century indicate that longer dry seasons will delay the onset of the rainy season and drive drought in eastern and southern Amazonia (Dai, 2013; Fu et al., 2013). Hydrological projections for the Madeira, Tapajós, and Xingu rivers and the Purus basin in western Amazonia suggest that the overlapping effects of decreasing precipitation and increasing temperature will reduce basin discharge (Dalagnol et al., 2017; Sampaio et al., 2019); however, others have suggested that discharge will increase with deforestation (Coe et al., 2009).

The combination of severe droughts and floods stress forests, especially if the flooding regimes of regularly inundated areas are perturbed outside of their natural range (Langerwisch et al., 2013). Amazonian droughts cause tree mortality and reduced biomass accrual (Feldpausch et al., 2016), facilitating fire (Aleixo B. et al., 2019), particularly at forest edges, where the microclimate is drier and hotter than in the continuous forest (Laurance et al., 2016). Large trees are most sensitive to these stressors, which is important because these trees regulate microclimate and forest C stocks. Although intact forests may be resilient to acute droughts, chronic droughts impact regional forest health (Gatti et al., 2014), and floods reduce C uptake in low lying forests (Araújo, 2002). Recent work also suggests a changing climate is driving widespread changes in forest composition, with a distinct shift toward large-statured taxa and dry affiliated genera (Esquivel-Muelbert et al., 2019). The future climate implications of this noted shift will depend on the extent to which these changes reflect a mitigating adaptation to a changing climate.

Although nearly 20% of the Amazon upland forests and ∼50% of riparian forests have been affected by land-use change, relatively few studies consider the impact of changes in vegetation cover on the Basin's water balance. Climate change scenarios from the CMIP5 used to model the hydrological and C cycles suggest that an increase in deforestation will intensify both floods and low-flow events (Abe et al., 2018). Hydrologic projections considering tropical forest conversion to pasture and farming result in lower rates of evapotranspiration and higher runoff, which counterbalance climate change effects on streamflow (Guimberteau et al., 2017). The Tocantins River has already seen seasonal flows altered by deforestation, with higher flows in the rainy season and lower flows in the dry season (Costa et al., 2003), and models predict that a similar shift in the Xingu River basin will greatly reduce hydroelectric power generation (Stickler et al., 2013). Hydrological intensification also affects riverine C balance, *via* outgassing from the Amazon River and the magnitude of export to the Atlantic Ocean, with nonlinear effects to be expected if deforestation is also considered (Langerwisch et al., 2016). Finally, changing hydrology may directly impact the deep C cycle by amplifying upland carbonate weathering in the Andes (Hilton, 2017).

Global: Severe Storms

Extreme precipitation events and convective storms cause blowdowns that are a leading cause of tree mortality in the Basin (Nelson et al., 1994; Negrón-Juárez et al., 2010), with synergistic implications for fire, fragmentation, and evapotranspiration (Marra et al., 2018; Silvério et al., 2019). Basin-wide potential mortality from a single squall in 2005 was estimated at 542 ± 121 million trees, equivalent to 23% of mean annual biomass accumulation (Negrón-Juárez et al., 2010). Biomass recovery can take up to 40 years and can shift community composition toward faster-growing soft-wooded species more vulnerable to future events (Ferrante and Fearnside, 2019). Convective storms, which are currently most common in the northwest region (Negrón-Juárez et al., 2018), are likely to increase in number and intensity with climatic warming (Negrón-Juárez et al., 2010); however, their impacts on future mortality patterns are not well-understood (Negrón-Juárez et al., 2018).

Integrating the Biogeochemistry of Climate in the Amazon Basin

Although much remains to be learned, the general impacts of the dominant change agents on C flux and storage, albedo, and evapotranspiration in the Amazon Basin are comparatively well-resolved. Increasing evidence indicates the importance of non-CO_2 trace gas and compound fluxes (especially CH_4), though far less is known about their pattern and magnitude (especially in the case of BVOCs). Despite this widespread uncertainty, it is increasingly evident that these non-CO_2 forcing

agents have at least as large an impact on regional and global climate as C (**Table 2**). Although they do not always respond synchronously, in many cases, local disturbance and global climatic change are expected to increase the net radiative forcing impact of the Amazon region *via* multiple pathways (**Figure 1B**; **Table 2**).

Given the substantive contribution of these less-recognized forcing agents, the next generation of Amazon studies must integrate a broader suite of climate-forcing agents and their feedbacks. These must explicitly address the combined effects of disturbance on the totality of these processes, and the resulting feedbacks on the local, regional, and global climate system. As with forests more broadly, refining the Amazonian impact on the climate system will require (1) additional empirical data to establish pre-disturbance baselines, including manipulative experiments that explore impacts such as increased temperature and drought, and (2) integrative coupled land–atmosphere models that capture both the complexity of the established forest system and biophysical feedbacks accompanying rapid land-use change. Numerous authors suggest integrating multiple forcing agents into ecosystem service markets and Earth system models (Nobre et al., 2016), but the vast majority of studies in the Amazon focus on a single forcing agent (i.e., C; **Supplementary Table 1**). Although many studies in the region compare fluxes across hydrological, land-use, or chronological recovery gradients, studies that integrate a range of forcing agents across these gradients are exceedingly rare; no studies have concurrently considered the full suite of forest–climate interactions even at a single site. Even in the case of one well-studied type of land-cover change, deforestation, assessing net effects by considering all forcers simultaneously is extremely challenging. For example, because simulations produce radiative forcing effects that range from −12 to +20% of the CO_2-only impact, it remains unclear the extent to which cooling from increased surface albedo offsets radiative forcing feedbacks of lowered BVOC emissions following deforestation (Ward and Mahowald, 2015; Scott et al., 2018). Other authors propose that warming from decreased evapotranspiration more than offsets cooling from increased albedo (Bonan, 2008). Warmer and drier regional climates then feedback to influence uptake of CO_2, fire frequency (and thus BC), and exchange of trace gases. A more integrated approach is clearly needed.

The effort to resolve trace gas emission estimates from freshwaters in the basin is another illustrative example of the complexity of just one piece of the challenge ahead. Uncertainty in Amazonian aquatic trace gas budgeting is a result of the paucity of measurements along the aquatic continuum, compounded by the difficulty of estimating the extent of these habitats (Melack, 2016; Ward et al., 2017). Better constraining emission controls and gas-transfer velocities in these aquatic environments are key targets for improving biogeochemical models of the Amazon. These models are necessary to refine emission estimates, which in turn could be used to better predict the climate consequences of anthropogenic impacts. While at the process level these challenges are shared with other geographic areas (e.g., avoiding double counting trace emissions from wetland soils), Amazon riverine systems are characterized by stark biogeochemical heterogeneity that does not have applicable analogs elsewhere (Ríos-Villamizar et al., 2013). These idiosyncrasies—coupled with the rivers' huge geographical extent, the number of ecosystem types they transverse, and the rate of surrounding landscape change—continue to confound our understanding of the Basin's biogeochemical influence on global climate.

Better constraining both terrestrial and aquatic fluxes requires integrating our growing understanding of fine-scale processes with ambitious field measurement campaigns linked to high-resolution top-down atmospheric measurements. Most of the trace-gas balance studies to date have focused on either very small spatial scales (like biometry and eddy covariance), which require a large degree of extrapolation, or on global-scale inversions, which fail to constrain tropical land masses even at the continental scale. Some airborne measurements have provided a regional flux picture in Amazonia by making regular vertical profiles of CO_2, CH_4, and N_2O that are broadly representative of regional scales ($\sim 10^5$-10^6 km^2) (D'Amelio et al., 2009; Gatti et al., 2010, 2014; Basso et al., 2016). However, measuring large-scale landscape mosaics is required in order to determine the relevant budget for a region or continent (Chou et al., 2002), and local field data are required to link disturbance and biogeochemical processes to atmospheric observations.

Following a decade of hope for a transition to a sustainable development pattern (Davidson et al., 2012), rapid deforestation and land-use change have returned to the Amazon. This resurgent change refocused popular attention on the fate of the Basin's vast C stocks. Our current understanding of the biogeochemistry of climate in the Amazon, however, suggests that positive forcing from non-CO_2 factors plays a large role in the regional and global climate system, now likely dominating the net radiative balance of the Amazon. More important than understanding the *status quo* of net radiative forcing of this more-diverse set of climate forcers is resolving their coupled responses to the accelerating local and global change agents at work in the basin and applying this understanding to manage the biogeochemistry of climate in the Amazon.

AUTHOR CONTRIBUTIONS

ZP, FS, and KC collated data. KC and FS led the writing of the manuscript, with text contributed by ABe, ZP, SN, SPan, LB, HC, JMar, PF, and HS. All authors provided valuable feedback on the manuscript, subject matter expertise, contributed to the workshop to formulate the study, and organized by KC, AE, and JB.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/ffgc.2021.618401/full#supplementary-material

Supplementary Table 1 | Studies reporting observed fluxes of forcing agents between the Amazon basin and the atmosphere.

Supplementary Table 2 | List of suggested additional sources concerning conceptual underpinning of biogeochemical cycling and global change in the Amazon Basin.

Supplementary Table 3 | Representative studies reporting observed, experimentally derived or modeled responses of forcing agents to disturbance, in the Amazon basin or elsewhere in tropical ecosystems. These sources were used to derive direction and confidence of changes in forcing agents in response to disturbance reported in **Table 2**.

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