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Global warming potential is not an ecosystem property

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RUNNING HEAD: Greenhouse gas metrics and ecosystem fluxes

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ABSTRACT

Greenhouse gas metrics and ecosystem greenhouse gas fluxes should not be confounded with each other, either conceptually or in the language that we use to describe them. The global warming potential (GWP) and sustained-flux global warming potential (SGWP) are metrics that describe the relative radiative impact of different greenhouse gases and have been widely used to normalize greenhouse gas fluxes as CO_2 equivalents in order to facilitate comparisons. A clear application of definitions, the pursuit of scientific clarity, and the ability of language to influence our thinking collectively indicate that GWP and SGWP should not be used as synonyms for greenhouse gas fluxes. I examined journal articles that mentioned either of these metrics and were published in *Ecosystems, Global Change Biology*, or the wetland literature. A substantial fraction of these articles used GWP and/or SGWP in ways that were inconsistent with the original definitions of these terms as greenhouse gas metrics. Often, multiple meanings were used within the same article. Further, many articles used the names of the greenhouse gas metrics as synonyms for CO_2-equivalent greenhouse gas fluxes. I recommend that 1) GWP and SGWP should only be used following their original definitions as greenhouse gas metrics; 2) CO_2-equivalent greenhouse gas flux should be used as an accurate and descriptive framework for describing metric-weighted greenhouse gas exchanges; and 3) radiative balance is an appropriate alternate name for CO_2-equivalent greenhouse gas fluxes, but radiative forcing should only be used to describe changes in the radiative balance. There is a robust research community studying the role of terrestrial, wetland, and aquatic ecosystems as regulators of global climate. The use of clear, consistent, and unambiguous terminology will help us effectively communicate our findings to other scientists, ecosystem managers, and policy makers.

KEYWORDS: global warming potential, ecosystem–atmosphere exchange, carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), CO_2 equivalents, climate change, radiative balance, radiative forcing

MANUSCRIPT HIGHLIGHTS

- Greenhouse gas metrics can normalize ecosystem gas fluxes to a common baseline
- Often, the exact same terminology is used in reference to both metrics and fluxes
- For clarity and understanding, distinct terminology should be used for these concepts

INTRODUCTION

Modern climate change is predominantly caused by fossil fuel combustion and land use change, which have led to increasing atmospheric concentrations of greenhouse gases such as carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) (Myhre and others 2013). Anthropogenic emissions have substantially altered the global budgets of these gases (Syakila and Kroeze 2011; Friedlingstein and others 2019; Saunois and others 2020), which were historically dominated by natural exchanges between the atmosphere and terrestrial, wetland, and aquatic ecosystems. A multitude of climate-related impacts including rising temperatures, changing precipitation patterns, altered atmospheric chemistry, and rising sea level can influence ecosystem greenhouse gas dynamics, generating feedbacks that further influence rates of climate change. This has led to considerable efforts to quantify the importance of different ecosystems as sources and sinks of greenhouse gases and understand the role of ecosystems in regulating global climate (e.g., Matear and Hirst 1999; Whiting and Chanton 2001; Cole and others 2007; Dalal and Allen 2008). The recognition that ecosystem dynamics are responsive to environmental changes and management activities provides a framework for understanding how ecosystem greenhouse gas exchanges have already been altered, predicting how future perturbations to ecosystems may accelerate – or moderate – rates of climate change, and guiding management actions to achieve desirable climate outcomes (Canadell and Schulze 2014; Griscom and others 2017; Fargione and others 2018).

Because CO_2, CH_4, and N_2O differ in their atmospheric lifetimes and radiative efficiencies, it is necessary to normalize their fluxes in order to compare the radiative impact of, for example, changes in photosynthetic CO_2 uptake with soil CH_4 emissions. Over the last 30 years, this commonly has been done using the global warming potential (GWP) and, more recently, the sustained-flux global warming potential (SGWP; Neubauer and Megonigal 2015). The GWP and SGWP are examples of greenhouse gas metrics, relatively simple measures that compare how effectively different greenhouse gases trap infrared radiation. For brevity, I will use the shorthand S/GWP when collectively discussing these metrics. These metrics allow greenhouse gas fluxes to be normalized to the atmospheric behavior of CO_2 and expressed as CO_2 equivalent fluxes. This normalization to CO_2 was originally done because CO_2 is the most important greenhouse gas that has altered the global radiative balance, causing radiative forcing and climate change (Myhre and others 2013). Further, the normalization to CO_2 is useful for ecosystem studies where the sequestration of carbon due to CO_2 uptake is, often, partially offset by ecosystem emissions of other greenhouse gases.

When we calculate CO_2-equivalent greenhouse gas fluxes between an ecosystem and the atmosphere, we are actually calculating the radiative balance, which is a static measure of how Earth's energy budget is affected over a defined time horizon. More specifically, we are calculating the radiative balance due to our study system that is attributable to whatever greenhouse gases we measured; other factors including unmeasured greenhouse gas exchanges and ecosystem albedo also can affect Earth's energy budget (e.g., Bright and others 2015) but are not considered in S/GWP models. An underappreciated point is this: if the radiative balance does not change over time, then there will be no warming (or cooling) of the planet, no matter how much or in what ratio CO_2, CH_4, and N_2O are exchanged between the ecosystem and the atmosphere (Bridgham and others 2006). Climate change requires a perturbation to Earth's energy budget, which is the definition of the term radiative forcing. A change in greenhouse gas fluxes due to an environmental change (e.g., warming, nutrient pollution) or a purposeful management action (e.g., drainage of a wetland or construction of a dam) can lead to radiative forcing, which only then would lead to climate warming or cooling. Note that S/GWPs can be used to show that a change in the ecosystem greenhouse gas budget has caused positive or negative radiative forcing but do not directly say anything about the extent to which warming, cooling, or other aspects of climate change occur. To do so requires the use of different greenhouse gas metrics (e.g., global temperature change potential; Shine and others 2005), climate sensitivity factors (Sherwood and others 2020), and/or far more sophisticated climate models.

I have noticed that the S/GWP terms are often (mis)used in ways that are inconsistent with their original definitions as greenhouse gas metrics. My goals in this article are to 1) review the original definitions of S/GWP and how these metrics should be used to calculate CO_2-equivalent greenhouse gas fluxes; 2) explain why the usage of the S/GWP terms should be restricted to their original meanings; 3) quantify how authors across the broad fields of ecosystem science and global change biology are actually using S/GWP in the published literature; and 4) offer recommendations for terminology that can replace the incorrect usages of these terms.

GREENHOUSE GAS METRICS AND THEIR APPLICATION

The GWP was conceptualized in several papers from 1990 (Fisher and others 1990; Lashof and Ahuja 1990; Rodhe 1990) and has been discussed prominently in all five assessment reports of the Intergovernmental Panel on Climate Change (IPCC). The GWP is defined as the "time-integrated radiative forcing due to a pulse emission of a given component, relative to a pulse emission of an equal mass of CO_2" (p. 710 in Myhre and others 2013). The SGWP is the "time-integrated radiative forcing due to sustained emissions of a given component, relative to sustained sequestration of an equal mass of CO_2" (p. 44 in Neubauer and Verhoeven 2019). I have previously argued that the SGWP should be used in ecological studies since ecosystems continually exchange greenhouse gases with the atmosphere, something that is not captured by the one-time "pulse" emission basis of the GWP (Neubauer and Megonigal 2015). The two metrics can have either similar or dissimilar values, depending on the greenhouse gas and the time horizon over which radiative effects are considered (Table 1). There are many criticisms of the GWP that generally apply to the SGWP as well; for brevity, they will not be repeated here (but see Harvey 1993; Shackley and Wynne 1997; O'Neill 2000; Fuglestvedt and others 2003; Shine 2009). Various other metrics have been proposed to describe how greenhouse gases influence Earth's radiative balance and climate (e.g., Manne and Richels 2001; Shine and others 2005; Kirschbaum 2014) but none have been as widely adopted as S/GWP.

Numeric S/GWP values vary from gas to gas and as a function of the time horizon (Table 1). For any greenhouse gas, a S/GWP with value *x* means that a pulse emission (for GWP) or sustained annual emissions (for SGWP) of an amount of the gas will trap *x* times more infrared radiation than the same amount of CO_2 over the chosen time horizon. The S/GWP values are typically presented on a "per mass of gas" basis (Table 1; Myhre and others 2013; Neubauer and Megonigal 2015), giving them implicit units of mass of CO_2-equivalents (CO_2-eq) per mass of greenhouse gas. Standard unit conversion math can be used to present S/GWP values on a "per mole/molecule" basis or a "per mass of carbon (or nitrogen)" basis. For example, the 100-y SGWP for CH_4 is 45 on a mass basis and 16.4 on a per molecule basis (Table 1) due to the different molar masses of CH_4 (16 g mol^{-1}) and CO_2 (44 g mol^{-1}).

The S/GWP values provide a means of weighting the fluxes of different greenhouse gases by normalizing them to a common baseline. The deliberate use of "normalizing" in the previous sentence emphasizes that the S/GWP metrics compare the radiative effects of greenhouse gas *i* to those of CO_2 using a highly simplified modeling framework that does not capture all the climatic impacts of greenhouse gas exchanges; this normalization is not the same as a unit conversion, e.g., from grams to moles. The CO_2-equivalent flux for gas *i* ($CO_2\text{-eq}_{(i)}$) is the product of the flux ($F_{(i)}$) of the gas and its S/GWP over the time horizon of interest (Table 1):

$$CO_2\text{-eq}_{(i)} = F_{(i)} \times S/GWP_{(i)} \quad (1)$$

When considering the ecosystem–atmosphere fluxes of multiple greenhouse gases, the net CO_2-equivalent flux is the sum of the CO_2-equivalent fluxes of each individual gas. The units for $F_{(i)}$ and S/GWP must be compatible. For example, if a mass-based S/GWP value were used, $F_{(i)}$ also must use a mass-based unit (e.g., kg *i* m^{-2} y^{-1}, where kg *i* is the mass of entire greenhouse gas molecule (e.g., kg CH_4, kg N_2O), not just the portion that is carbon or nitrogen), which would yield a CO_2-equivalent greenhouse gas flux with units of kg CO_2-eq m^{-2} y^{-1}. The S/GWP values are always positive for CO_2, CH_4, and N_2O (Table 1), but the CO_2-equivalent greenhouse gas fluxes can be positive or negative for an individual gas and at the level of the ecosystem, depending on the direction and rates of greenhouse gas fluxes. This can be confusing because authors across different fields of study vary in how they assign positive and negative values to different greenhouse gas fluxes. Thus, authors should clearly state the relationship between the sign of the CO_2-equivalent greenhouse gas flux (positive or negative) and the direction of that flux (into or out of the atmosphere).

WHY NOT USE S/GWP FOR GREENHOUSE GAS FLUXES?

The clear application of definitions and consideration of units, the pursuit of scientific clarity, and the ability of language to influence our thinking all indicate that we should not use S/GWP to talk about greenhouse gas fluxes. In some respects, it is understandable that S/GWP would be used as a synonym for the exchange of gases between ecosystems and the atmosphere; after all, the S/GWP greenhouse gas metrics tell us about the relative effectiveness of different greenhouse gases at trapping infrared radiation over various time periods. When we calculate CO_2-equivalent greenhouse gas fluxes, we are similarly interested in knowing how Earth's energy budget is affected by fluxes in the form of an emission or consumption of greenhouse gases thorough a specific biogeochemical process (e.g., methanotrophy or denitrification) or by a specific ecosystem (e.g., rice paddy or freshwater reservoir). Here, I explain why greenhouse gas metrics and ecosystem greenhouse gas fluxes are very different things and should not be confounded with each other, either conceptually or in the language that we use to describe them.

Consideration of definitions and units

The definitions of GWP and SGWP are explicit in that they are comparing the radiative impact from a mass of a greenhouse gas relative to the same mass of CO_2. Because each S/GWP value is calculated as a ratio of radiative forcings, they are unitless numbers that have implicit units of mass of CO_2-eq per mass of greenhouse gas, where the mass units in the numerator and denominator are the same. These metrics describe a property of a greenhouse gas and can be used to normalize greenhouse gas exchanges to a CO_2-equivalent basis (Eq. 1), giving fluxes that have typical units of mass of CO_2-eq per area per time. The vastly different units – a unitless ratio versus a rate – are a powerful argument that using S/GWP as synonyms for ecosystem-scale greenhouse gas fluxes (e.g., Table 2) is inconsistent with the original definitions of these terms.

Scientific clarity

The use of clear and consistent terminology is necessary to facilitate effective learning and communication (e.g., Wandersee 1988; Wellington and Osborne 2001; Donohue and others 2016), so the existence of multiple meanings of S/GWP within the community of ecosystem scientists and global change biologists is antagonistic to scientific clarity, learning, and progress. While examining published research and review articles (see "Literature Survey," below), I read many articles that contained an extended version of this sentence: *"We used GWPs to calculate the GWP."* The intent of the authors of such sentences – and the likely interpretation of a knowledgeable reader – is that the first usage of GWP refers to the greenhouse gas metric and the second GWP refers a CO_2-equivalent greenhouse gas flux. Still, there is potential for confusion when the same term can differ in its specific meaning within a single sentence, in different parts of the same article, and between different articles (e.g., Table 2). Some authors of the articles I examined seemed to understand that they should not assign multiple meanings to the S/GWP term, but this was often resolved by (incorrectly) using S/GWP to describe the gas fluxes and then using different terminology (e.g., conversion factor or radiative warming potential) for the greenhouse gas metric.

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Communication of results

Alternate definitions of S/GWP were common in the literature that I analyzed (Table 2), but the climate science and climate policy realms are consistent in their use of GWP only as a greenhouse gas metric (note: the SGWP has not yet been widely adopted in those communities). In the Working Group I contributions of the five IPCC assessment reports, which cover the science of climate change, every single occurrence of GWP (n = 22–210 instances per report) was consistent with the original definition of GWP as a metric describing the relative radiative impact of a greenhouse gas (IPCC 1990, 1996, 2001, 2007, 2013). In the policy world, Article 5 of the 1997 Kyoto Protocol specifically states that countries should use GWPs to calculate the CO_2-equivalence of anthropogenic emissions (UNFCCC 1997). The same procedure is followed in the reporting of national greenhouse gas inventories, as illustrated by IPCC guidance: "The analysis [of greenhouse gas sources and sinks] should be performed using CO_2-equivalent emissions estimated using the global warming potentials for each gas" (p. 1.11 in Paustian and others 2006). I searched national inventory reports for a haphazard selection of countries – Australia, Canada, Germany, Japan, Latvia, Romania, Turkey, and United States – and the only usages of GWP were as a greenhouse gas metric (UNFCCC 2020). To promote clear communication between ecosystem scientists, climate scientists, and policy makers, it is essential that all of us are consistent in our usage of shared terminology.

Usage of language

The way we use language and vocabulary can unintentionally influence how we think about a topic. If we were to talk about the GWP of freshwater N_2O emissions or the SGWP of a tropical peatland, our use of S/GWP would convey the idea that a particular flux or a specific ecosystem has the *potential* to cause *warming* of the *globe*, simply because it exchanges greenhouse gases with the atmosphere. This can be – and often is – misleading. An ecosystem will not contribute to radiative forcing or climate change *unless* the radiative balance of the system has changed.

The usage of radiative forcing as a synonym for CO_2-equivalent greenhouse gas fluxes (see Table 3 and "Literature Survey" section, below) may derive from the fact that the IPCC reports (among others) discuss radiative forcing from greenhouse gases; an author might conclude that greenhouse gases emitted from ecosystems also must cause radiative forcing. The important distinction is that the IPCC reports are not discussing natural ecosystem–atmosphere greenhouse gas exchanges but instead are focused on things like emissions of CO_2 from fossil fuel combustion, CH_4 from extensive livestock operations, and N_2O from applications of synthetic fertilizers. Anthropogenic emissions like these represent departures from baseline greenhouse gas exchanges and therefore truly are radiative forcings. In contrast, the uptake and release of greenhouse gases from natural ecosystems do not cause radiative forcing, unless the exchange rates have changed over time (Neubauer and Verhoeven 2019).

The relationships between CO_2-equivalent greenhouse gas fluxes, radiative balance, and radiative forcing can be illustrated using an example of CO_2 and CH_4 exchanges in a tidal freshwater marsh undergoing experimental saltwater intrusion (Figure 1; data from Neubauer 2013). Under freshwater conditions, the CO_2-equivalent emissions of CH_4 exceeded the net uptake of CO_2 (that is, net ecosystem production), meaning that the radiative balance of this system was positive. However, as long as the radiative balance does not change, we can infer that the undisturbed marsh is not contributing to climate change. Saltwater intrusion reduced CH_4 emissions, leading to negative radiative forcing from this gas, while simultaneously reducing net ecosystem production, which caused positive radiative forcing from CO_2 (Figure 1). The net effect of these changes was that the overall radiative balance of the ecosystem increased, meaning that saltwater intrusion was leading to positive radiative forcing (i.e., warming) through its effects on greenhouse gas exchanges; quantifying other factors such as changes in ecosystem albedo and wetland extent would be necessary for a full accounting of the effects of saltwater intrusion on radiative forcing. Importantly, the measure of the overall warming effect is the *change* in radiative balance due to the saltwater intrusion (that is, the RF_{eco} arrow on Figure 1), not the overall radiative balance under either freshwater or saline conditions. This same concept was effectively captured in the subtitle of a recent paper about assessing the climatic impacts of freshwater reservoirs: “What does the atmosphere see?” (Prairie and others 2018). If what the atmosphere “sees” does not change, there is no potential for warming of the globe. To be clear, multiple perturbations including climate change, eutrophication, salinization, and acidification have altered ecosystem greenhouse dynamics, but it is not straightforward to determine if radiative forcing has occurred or to quantify its magnitude and direction. In order to avoid accidentally influencing our understanding of how ecosystems regulate climate, we should not be using terminology (e.g., S/GWP or radiative forcing) in ways that imply the presence of warming effects that may not actually exist.

LITERATURE SURVEY

To assess how the terms “global warming potential” and “sustained-flux global warming potential” are being used in peer-reviewed journal articles, I examined the journals *Ecosystems* and *Global Change Biology*, and the literature on wetlands from a wide variety of journals. Over a 1-week period in late July and early August 2020, I used the Web of Science, ProQuest, and Google Scholar databases to search for articles in the publications *Ecosystems* and *Global Change Biology* that contained “global warming potential” or GWP. I also used the search function on each journal’s website to search for the same terms. For the wetlands search, I added the additional search string “wetland OR marsh OR peatland OR bog OR fen OR swamp OR mangrove” to the three search engines but did not specify a publication name. The articles found with the above search terms were supplemented with searches in the same databases for journal articles that cited Neubauer and Megonigal (2015), the article that introduced the SGWP metric, and with other articles that I came across while reading through the literature. The articles were screened to remove those that were not relevant to this analysis. Major reasons for excluding individual articles were: 1) "global warming potential" or GWP appeared only in the References section; 2) GWP stood for something other than global warming potential; 3) the measurement or discussion of processes that produce greenhouse gases was not an integral part of the paper (e.g., I would exclude an article that sequenced the methanogen community but did not measure rates of methanogenesis) and, for the wetlands search, 4) the article was not substantially about wetlands.

The final datasets contained 34 articles from *Ecosystems*, 177 articles from *Global Change Biology*, and 781 articles from the wetland literature. There was some overlap between datasets in that the wetland dataset contained 17 articles from *Ecosystems* and 86 articles from *Global Change Biology*. In total, 889 unique papers were examined and analyzed, with the oldest paper dating to 1991 (Gorham 1991). For each article, I recorded whether GWP and/or SGWP was mentioned; the meaning(s) of S/GWP as used in the article; whether numeric values of S/GWP were provided (and, if so, the time horizon and implicit units for those numbers); if CO_2-equivalent greenhouse gas fluxes were calculated and what those fluxes were called; and the type of ecosystem or wetland studied. A full list of examined articles and the information extracted from each is available online from the publisher as electronic supplementary information.

Global warming potential was used without reference to SGWP in 90–93% of the articles (range reflects the three datasets), whereas only SGWP was used in 2–4% of the articles. Both terms were mentioned in the remaining 5–7% of the articles. A total of 78–85% of the articles used S/GWP in a way that was consistent with the original definition of these terms (that is, as a greenhouse gas metric) (Table 2). However, 32–54% of the articles used S/GWP in a different sense, with the most common alternate usages relating to a property of an ecosystem (9–18% of articles) or a property of gas emissions to the atmosphere (21–35% of articles; Table 2). As used here, the distinction between these alternate meanings is that the "property of an

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ecosystem" usage was assigned when S/GWP was applied to greenhouse gas fluxes that included changes in carbon storage in soils, sediments, and/or biomass, whereas the "property of gas emissions" usage was assigned when S/GWP was applied to gas emissions to the atmosphere (e.g., fluxes measured using dark chambers only) and/or when CO_2 fluxes were ignored entirely. Depending on the dataset, 18–32% of the articles defined S/GWP in two different ways.

Carbon dioxide-equivalent greenhouse gas fluxes were calculated in 47–61% of the articles by multiplying gas flux rates by S/GWP values (Eq. 1). More than 75 different self-defined terms were assigned to the fluxes calculated in this way, which I condensed into five broad categories (Table 3). The three most popular categories of terms were S/GWP flux (44–71% of articles), greenhouse gas flux (26–41%), and CO_2-eq flux (22–50%). It is notable that the percentage of articles using S/GWP terms to describe CO_2-equivalent greenhouse gas fluxes was considerably higher in the wetland dataset (71%) versus the *Ecosystems* and *Global Change Biology* datasets (44–49%). This difference was driven in large part by wetland studies done in wastewater treatment wetlands and rice paddies, which used S/GWP terms for the calculated CO_2-equivalent greenhouse gas fluxes more frequently (86–89% used a S/GWP term for this) than did studies that focused on mangroves, peatlands, or tidal marshes (50–67%). In the *Ecosystems* and *Global Change Biology* datasets, there was no difference between wetland and terrestrial ecosystems in terms of how often S/GWP terms were used as a descriptor of calculated CO_2-equivalent greenhouse gas fluxes. Regardless of similarities or differences between specific ecosystem/wetland types, it is clear from all three datasets that the S/GWP terms are frequently being (mis)used in ways that are inconsistent with the original definitions of these terms.

Numeric values for the S/GWP metrics were reported in 80–84% of the articles, although alternative self-defined terms were often applied to these values, including CO_2 equivalency factor, conversion factor, global warming strength, heat absorbing capacity, radiative forcing potential, radiative warming potential, and time frame factor. The majority of these articles (57–70%) stated that they were using S/GWP metric values for a 100-year time horizon whereas 8–11% used a different horizon or multiple horizons (e.g., 20 and 100 years). The remaining 21–32% of the articles stating S/GWP values did not report a time horizon, which is an important omission due the dependency of S/GWP values on time (Table 1). Of the articles where the implicit units for S/GWP were reported or could easily be determined from the article, authors most commonly presented S/GWP values per mass of gas (31–39% of articles), followed by per mole/molecule of gas (4–5%), and per mass of carbon or nitrogen (0–4%). Some authors correctly converted S/GWP values per mass of gas to other implicit units (Table 1), but others incorrectly reported the implicit units for the mass-based S/GWPs (e.g., using a mass-based S/GWP numeric value but stating that it had per-molecule units). I did not attempt to confirm the calculation of CO_2-equivalent greenhouse gas fluxes for all 889 articles that I examined, but I did notice that these calculations were done incorrectly in multiple studies, typically because the authors did not use compatible units for their gas flux rates and S/GWP values.

CONCLUSIONS AND RECOMMENDATIONS

In this article, I have outlined why we should use S/GWP when referring to these greenhouse gas metrics and why we should not use these terms as synonyms for greenhouse gas fluxes. This point has been raised before; for example, the IPCC cautioned that it is "important to distinguish between the integrated relative effect of an emitted kilogram of gas which is represented by a GWP and the actual radiative forcings for specific gas amounts" (p. 385 in IPCC 2001). It is clear that this distinction is not being made consistently in the ecosystem science and global change biology literature (Tables 2 and 3).

If it is incorrect to use S/GWP as a synonym for greenhouse gas fluxes from ecosystems, what terminology should be used? Throughout this article, I have been using the phrase "CO_2-equivalent greenhouse gas fluxes," which I propose as an appropriate framework for describing greenhouse gas exchanges that have been weighted by their S/GWPs (Eq. 1). This framework has the benefits that 1) there is consistency with the terminology used in IPCC reports and national greenhouse gas inventories; 2) it accurately describes S/GWP-weighted fluxes without implying a specific warming or cooling climatic impact; 3) phrases including "CO_2 equivalents" and/or "greenhouse gases" are already used fairly commonly to describe CO_2-equivalent greenhouse gas fluxes (Table 3); and 4) this framework is flexible in that specific greenhouse gases could be named and/or the word "fluxes" could be replaced with another word that better describes the exchanges measured in a particular study (e.g., "CO_2-equivalent CH_4 and N_2O emissions"). The phrase "radiative balance" would also be appropriate for describing CO_2-equivalent greenhouse gas exchanges, although it is much less established within the community of ecosystem scientists and global change biologists (used in this sense in only 4 of the 889 articles I examined). Further, authors should be clear when radiative balance calculations do not account for the radiative effects of other factors such as changes in albedo, ecosystem area, and offsite emissions (that is, greenhouse gases that are hydrologically exported from an ecosystem and then exchange with the atmosphere outside of the ecosystem boundaries; e.g., Bartlett and others 1985; Neubauer and Anderson 2003).

The use of clear, consistent, and unambiguous language is important when discussing scientific concepts, so it is a problem that GWP and SGWP are being (mis)used in ways that differ from the original, long-standing, and widely-accepted meanings of these terms. I offer the following overall recommendations:

- The usage of S/GWP should be limited to the original meaning of these terms as metrics describing the relative radiative impacts of equivalent amounts of different greenhouse gases.
- Greenhouse gas exchanges, when weighted by their S/GWPs, should be called CO_2-equivalent greenhouse gas fluxes. This phrase is accurate, descriptive, and consistent with the vocabulary of the climate science and climate policy worlds. When weighting

ecosystem greenhouse gas fluxes, the SGWP should be used (Neubauer and Megonigal 2015).

- The term radiative balance is an appropriate alternate descriptor for talking about CO_2-equivalent greenhouse gas fluxes. However, radiative forcing should be used only when talking about a change in the radiative balance. If greenhouse gas fluxes do not change, there is no radiative forcing and, therefore, no climate change arising directly from greenhouse gases. Radiative balance and radiative forcing assessments should clearly indicate which components were considered (e.g., greenhouse gas exchanges) and which were not quantified (e.g., albedo, offsite emissions, ecosystem extent).

These recommendations revolve around a set of only four key terms: S/GWP, CO_2-equivalent greenhouse gas flux, radiative balance, and radiative forcing (Table 4). The consistent use of well-defined terminology will help ensure that our science is clearly and accurately communicated among ourselves and with other scientists and policy makers that are interested in understanding the role that terrestrial, wetland, and aquatic ecosystems play in regulating the global climate.

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TABLE LEGENDS

Table 1: Global warming potentials and sustained-flux global warming potentials. Values are given over 20 y and 100 y time horizons in both mass-based and molar-based implicit units. The GWP values are from Myhre et al. (2013). The SGWP values are from Neubauer and Megonigal (2015). For N_2O, the mass-based and molar-based values are the same since CO_2 and N_2O have the same molar mass (44 g mol^{-1}). The GWP values for CH_4 are for "fossil CH_4" and, like the reported SGWP values, account for the radiative impacts of CO_2 that is produced when CH_4 is combusted or otherwise oxidized.

Table 2: Usages of the terms GWP and SGWP in the three datasets. A sample quote for each usage category is provided, with citations purposefully omitted. Data columns show the percent of articles in each category, with the number of articles in parentheses. There were 34 articles in *Ecosystems*, 177 articles in *Global Change Biology*, and 781 articles in the wetland dataset that used GWP and/or SGWP. Percentages in each column add up to >100% since S/GWP was sometimes used in multiple ways in a single article. GHG = greenhouse gas.

Table 3: Terms used to describe CO_2-equivalent greenhouse gas fluxes. Data columns show the percent of articles in each category, with the number of articles in parentheses. Examples of terms in each category are provided in the notes under the table. This table is descriptive of the analyzed datasets and the mention of a particular term does not imply that it was used (in)appropriately. There were 16 articles in *Ecosystems*, 102 articles in *Global Change Biology*, and 474 wetland articles that calculated CO_2-equivalent greenhouse gas fluxes. Percentages in each column add up to >100% since some articles used terms from multiple categories when referring to CO_2-equivalent greenhouse gas fluxes.

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Table 4: Summary of recommended terminology discussed in this article. The example sentence for the sustained-flux global warming potential is based on Table 1. All other example sentences are illustrative only and should not be interpreted as real scientific findings.

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TABLES

Table 1: Global warming potentials and sustained-flux global warming potentials.

		GWP		SGWP	
Gas	Implicit units	20 y	100 y	20 y	100 y
CO_2	mass CO_2-eq per mass CO_2	1	1	1	1
	mol CO_2-eq per mol CO_2	1	1	1	1
CH_4	mass CO_2-eq per mass CH_4	85*	30*	96	45
	mol CO_2-eq per mol CH_4	30.9*	10.9*	34.9	16.4
N_2O	mass CO_2-eq per mass N_2O	264	265	250	270
	mol CO_2-eq per mol N_2O	264	265	250	270

* for fossil methane

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Table 2: Usages of the terms GWP and SGWP in the three datasets.

Usage of S/GWP and sample quote	*Ecosystems*	*Global Change Biology*	wetland
1) Property of a gas	85% (29)	80% (142)	78% (613)
"We use a GWP factor of 34 for CH_4 relative to CO_2"			
2) Property of an ecosystem*	9% (3)	17% (30)	18% (143)
"…when assessing the net global warming potential of forest ecosystems"			
3) Property of gas emissions*	21% (7)	27% (48)	35% (276)
"Total GWP for CH_4 + N_2O was 1040 g CO_2 equivalents m^{-2} [per season]"			
4) Synonymous with radiative forcing	3% (1)	1% (2)	1% (4)
"…wetlands are expected to play a larger role in reducing global warming potential"			
5) Synonymous with greenhouse gas	0% (0)	0% (0)	<1% (1)
"… exclude flows of other GWP gases"			

* Articles could be assigned to either the "property of an ecosystem" or "property of gas emissions" categories, if appropriate, but not to both of them.

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Table 3: Terms used to describe CO_2-equivalent greenhouse gas fluxes.

Category	*Ecosystems*	*Global Change Biology*	wetlands
S/GWP flux*	44% (7)	49% (50)	71% (337)
Greenhouse gas flux†	38% (6)	41% (42)	26% (124)
CO_2-eq flux‡	50% (8)	22% (22)	24% (114)
Radiative/climatic flux§	6% (1)	11% (11)	8% (37)
Carbon flux¶	6% (1)	0% (0)	1% (4)
No specific term	0% (0)	7% (7)	1% (7)

* Includes GWP, SGWP, net GWP, comprehensive GWP, GWP load, integrated GWP, and total GWP.

† Includes greenhouse gas flux, greenhouse balance, greenhouse gas emissions, greenhouse gas equivalents, and greenhouse gas footprint.

‡ Includes include CO_2 equivalents, CO_2-eq balance, and CO_2-eq flux.

§ Includes include radiative balance, radiative forcing, climate forcing, climate impact, and global warming impact.

¶ Includes include carbon footprint, corrected net ecosystem production, and net carbon gas balance.

Table 4: Summary of recommended terminology discussed in this article.

(Sustained-flux) global warming potential: a greenhouse gas metric that describes the relative radiative impact of a standardized amount of gas over a defined time horizon.

Example: Over a 100-y time horizon, the *sustained-flux global warming potential* of CH_4 is 45 times greater than that of CO_2, on a mass basis.

CO_2-equivalent greenhouse gas flux: an ecosystem–atmosphere exchange of greenhouse gas(es) that has been weighted by the S/GWP of the gas(es).

Example: The *CO_2-equivalent emission of N_2O* from the ecosystem was 6.4 g CO_2-eq m^{-2} y^{-1}.

Radiative balance: a static measure of how Earth's energy budget is affected over a defined time horizon. The radiative balance is equivalent to the net CO_2-equivalent greenhouse gas flux if factors like albedo are ignored.

Example: Based on the rates of CO_2 uptake and emissions of CH_4 and N_2O, we calculated that the *radiative balance* of the ecosystem was 1.6 kg CO_2-eq m^{-2} y^{-1}.

Radiative forcing: a perturbation to Earth's energy budget due to changes in factors such as greenhouse gas fluxes, albedo, offsite emissions, and/or the amount of energy reaching Earth from space.

Example: The management action reduced the radiative balance of the ecosystem from 1000 to 750 g CO_2-eq m^{-2} y^{-1}, resulting in *radiative forcing* of –250 g CO_2-eq m^{-2} y^{-1} (i.e., net cooling).

FIGURE LEGEND

Figure 1: CO_2-equivalent greenhouse gas fluxes (i.e., radiative balances) for a tidal freshwater marsh in South Carolina, USA, undergoing experimental saltwater intrusion. Rates of CH_4 emissions, net ecosystem production (NEP), and the ecosystem balance of these fluxes are shown for freshwater and saline conditions. The treatment-related alterations in the radiative balance led to radiative forcing (RF), both at the level of individual fluxes and at the ecosystem scale. Original gas flux data from Neubauer (2013) were normalized to CO_2-eqivalents using the 100-y SGWP (Neubauer and Megonigal 2015). Error bars on the fluxes are omitted for clarity. Positive values indicate a (net) CO_2-equivalent greenhouse gas flux into the atmosphere.

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