A Literature Review of GWP*:

A proposed method for estimating global warming potential (GWP*) of short-lived climate pollutants like methane.

GLOBAL DAIRY PLATFORM

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A note from the Project Partners

This literature review has been commissioned by the Global Dairy Platform GWP* Research Project Steering Group, which includes farming, academic, and non-government organisation (NGO) representatives from dairy and beef sectors across the globe.

The intent of the Steering Group is to direct a process of increased understanding of methods used to account for the contribution to global warming from methane so that informed policy decisions to reduce livestock climate impacts can be made. This process of increased understanding involves multiple stages, with the first stage being a literature review on the topic of methane and how it behaves in the atmosphere compared to other climate gases, particularly nitrous oxide and carbon dioxide. This review fulfills the first stage of the process. Subsequent stages will include scenario modelling and policy implications.

The intent of the literature review is first and foremost to support livestock sector decision making by providing robust and correct science in relation to methane. Ruminant industries recognise the urgent need to continue to reduce climate impact. This can only be achieved through carefully exploring the behaviour and biological processes related to methane in the atmosphere and identifying how this relates to current methodologies applied by the UN greenhouse gas (GHG) reporting process and voluntary commitments in the private sector. This literature review explores these scientific and policy relationships by detailing the carbon cycle, GHG-induced global warming, variable atmospheric behaviours of GHGs relevant to the livestock sector, and metrics available for accounting for GHG emissions. An outline of the GWP* metric and its importance in understanding the shorter atmospheric lifespan of methane relative to carbon dioxide and nitrous oxide is also explored.

While the review focuses on methane and the GWP* metric, it does not conclude which metric is preferrable. Rather, because the GWP* metric addresses different policy questions than the current metric, GWP100, the review provides guidance for further work to generate additional knowledge of how policy development can be improved by appreciating multiple metrics in conjunction with each-other.

Several gaps remain to increase understanding of methods used to account for the contribution to global warming from methane.These include how GWP* could be included in carbon footprint or emission intensity calculations and where it is not possible; how the adoption of GWP* by the UN GHG reporting process would differentially impact countries depending on whether herd sizes are expanding or contracting, how the adoption of GWP* by the UN GHG reporting process would affect non-livestock sectors, and, as discussed above, how multiple metrics (particularly GWP* and GWP100) can be used in combination to promote sustainable agriculture. The scenario modelling and policy implications stages of the process will address some of these gaps and, in doing so, strengthen the objectivity and scientific evaluation of GWP* compared with other GHG accounting metrics and present industry and government policy implications of adopting the GWP* metric in addition to, or alongside, other metrics.

Methane is the second leading cause of global warming but has the shortest lifespan.

Executive Summary

Increasing atmospheric concentrations of the three primary greenhouse gases (GHG), carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) are responsible for the majority of atmospheric warming.

From the science of climatology, we understand CO_2, CH_4, and N_2O have very dissimilar characteristics. CO_2 is by far the most prevalent gas and the leading cause of global warming. It serves as the reference gas against which all other GHGs are compared. Methane is the second leading cause of global warming but has the shortest lifespan. Nitrous oxide is also a long-lived GHG however its concentration and emission rates are the lowest of the three gases.

Methane is the primary GHG of interest in this report because it is a primary emission from ruminant livestock. A new metric (GWP*) has been proposed in the scientific literature that provides an improved method to assess the actual impact of methane on temperature change.

The atmosphere is a fluid, ever-changing environment with regional variations. The potency of a GHG is determined by radiative forcing (RF) and length of its atmospheric residency but these two variables are not fixed characteristics of a gas. They may be affected by pre-existing atmospheric concentration, temperature, humidity, seasonality, energy sources and the abundance of hydroxyl radicals (OH) in the air.

> *There is a need to accurately quantify source emissions in order to effectively target emission reductions and create sinks.*

This all must be accomplished within the various cultural and socio-economic global communities. Development of a standardized method for assessing the climate impacts of different GHGs is necessary to identify key sources and develop strategies for emission reductions with minimal disruption to commerce and culture, especially in industries that emit several different GHGs concurrently. Diversity of key characteristics of GHGs makes this task challenging.

The current standard is the Global Warming Potential (GWP), which was proposed in 1990 despite its limited applicability with respect to short-lived climate pollutants (SLCPs). Nearly 30 years of use has created inertia for this metric leading to wide acceptance. Currently, most investigators, reporters, and assessment tool developers use it without full understanding of its limitations. However, the importance of methane, the primary SLCP, has brought renewed interest to the GWP metric to assess the warming effects of SLCPs.

Two alternative metrics, GWP* and Global Temperature Change Potential (GTP) are reviewed to determine their suitability as substitutes for GWP. GTP switches focus from equating the atmospheric burden of GHGs over a specified time period, to estimating the temperature change of a given gas at a future date in time.

While GTP may have more utility to policymakers and be more easily understood by the public, it has several critical drawbacks. The first being it is more complex to compute because of additional data required. Secondly, the uncertainty around the estimate (prediction error) is exceptionally large (±75% for GTP_{100}) compared to ±40% for GWP_{100} (Chapter 8, AR5). So, while this metric may have some utility as a support metric for a GWP, it probably cannot be used as a replacement.

The second proposed metric is GWP* which addresses the most severe shortcoming of the current GWP, which is appropriate handling of SLCPs.

This drawback of GWP has severe consequences for assessment of CH_4, and therefore is directly important to the livestock industry. For long-lived climate pollutants (LLCPs), also known as stock pollutants, like CO_2 and N_2O, GWP is sufficient to make equivalences. However, the methodology of GWP treats SLCPs and LLCP in the same way, which causes errors in estimates outside a very narrow window of mitigation strategies. These errors can be so severe that GWP will indicate, even under declining CH_4 emissions, there remains an estimated warming effect whereas there is actually a relative cooling effect.

> *GWP* is neither a replacement for, nor independent of GWP; rather it is an enhancement of GWP.*

Based on peer-reviewed published evidence, it appears GWP* as presented in three peer-reviewed papers, using the metric CO_2-we, is a superior metric to GWP in predicting future temperature change and should be considered as an enhancement to GWP for SLCPs like methane.

Introduction

The intent of this review is to summarize the impact of a new global warming metric generically called Global Warming Potential* (GWP*) to enhance the current GWP metric for short-lived climate pollutants (SLCP), most specifically methane.

Atmospheric warming is a complex process involving many factors including multiple gases, sources, sinks, and physics in a dynamic atmosphere.

The Carbon[1] Cycle

The vast majority (~80%) of earth-bound ^{12}C (6.6 x 104 gigatonnes (Gt)) resides in the lithosphere (rocks such as shale, limestone, marble, dolomite, carbonates, graphite, and diamond, the last two of which are pure carbon) and fossil fuels, e.g. coal, oil, and natural gas (methane). The remaining 20% resides in the ocean, atmosphere, living organisms, and surface soil.

Carbon moves between these reservoirs in a systematic way called the "Carbon Cycle". Any process that shifts the balance of carbon from one reservoir (sink) to another alters the carbon cycle. When the atmosphere is the recipient of additional carbon-based molecules, temperature increases (Riebeek & Simmon, 2011).

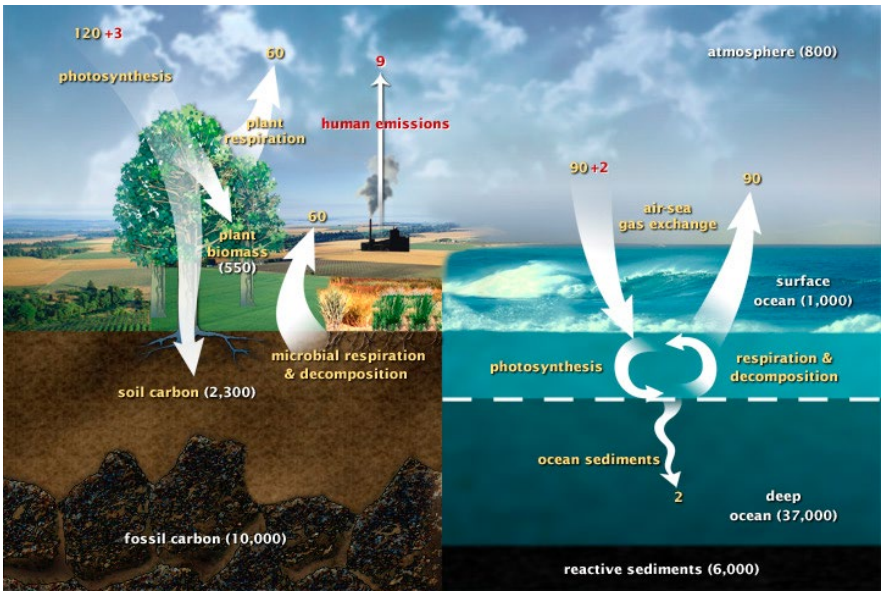


Figure 1. This diagram shows the movement of carbon between land, atmosphere, and oceans.

Yellow numbers are natural fluxes, and red are human contributions in gigatons of carbon per year. White numbers indicate stored [sequestered] carbon. Diagram adapted from U.S. DOE, Biological and Environmental Research Information System.

Source: *https://public.ornl.gov/site/gallery/detail.cfm?id=445&topic=&citation=&general=carbon&rserestsection=BERPublic*

Figure 1 illustrates how the effect of human activity, primarily through burning of fossil fuels, alters the balance of carbon in the various reservoirs. In this illustration, increased photosynthesis offsets one-third of the anthropogenic emissions and the ocean absorbs another 22%, leaving the balance (45%) of additional carbon in the atmosphere.

Essentially, human activity, such as mining, energy production through burning of fossil fuels, and certain manufacturing processes like cement production have shifted and accelerated release of carbon from long-held deep earth sinks depositing excess carbon residues in the atmosphere creating global warming and lowering ocean pH. Furthermore, increasing net global deforestation is shifting the balance between sources and sinks of major GHGs.

To offset increased carbon in the atmosphere, essentially two options exist for reducing or eliminating emissions of additional carbon compounds into the environment: 1) minimize mining and use of fossil fuels and/or 2) employ methods for additional carbon sequestration to soil, plants, and/or the ocean.

Release of "new" carbon, from fossil fuels currently overwhelms the oceans ability to act as a natural carbon sink. Thus, additional absorption of CO_2 by the oceans is often called "climate change's evil twin" because additional CO_2 decreases the pH (increases acidity) of the ocean, as CO_2 combines with H_2O to form carbonic acid. It is estimated the oceans have absorbed 476.3 Gt of CO_2 since the beginning of the Industrial Age (~1750) with an additional 20 t being absorbed annually. This has resulted in the oceans becoming 30% more acidic in the past 200 years, greater than any increase in the past 50 million years. The impact is the weakening of shells on crustaceous marine life and damage to coral reefs (The Ocean Portal Team, 2018).

> *Thus, carbon sequestration in plants and soil is of far more immediate importance in order to protect both atmosphere and the oceans.*

If all increases in GHG emissions were reduced to zero, in other words, current levels were maintained, the atmosphere will establish a new stable temperature point as the carbon cycles came back into balance. However, reaching this balance may take centuries as the atmospheric GHGs would continue to accumulate and their impacts on climate still persist.

1 Note: The word "carbon" may refer to the element carbon or to a group of compounds containing carbon. The context within which the word carbon is used will determine which definition is appropriate.

Physics of Global Warming

Greenhouse gases warm the earth by absorbing solar radiation and re-emitting it in the infrared spectrum. Greenhouse gases absorb the thermal infrared radiation and thus act like a blanket which traps heat under the blanket or glass as in a greenhouse, warming the inside of the greenhouse to temperatures significantly warmer than the exterior temperature, thus the name "Greenhouse Gas".

Some warming enables life on Earth by warming the atmosphere to a temperature at which human life can exist. There are dozens of GHGs and their effect on global warming varies widely.

The two key characteristics of a GHG are 1) its ability to absorb and redirect energy known as radiative forcing (RF) (see glossary for definition) and 2) its persistency in the atmosphere after being released or emitted.

Radiative forcing is primarily dependent upon the solar radiation absorbed by the structure of the GHG molecule. Absorption occurs when the appropriate frequency causes the chemical bonds between the atoms within the molecule to vibrate and rotate thus removing energy from the sunlight.

Radiative forcing, or the amount of energy absorbed, is measured in watts per square meter (W/m^2). Radiative forcing efficiency is typically reported based on mass, e.g. per t; thus, the reported RF is also affected by the pre-existing concentration of the gas in the atmosphere.

Therefore, care must be taken when comparing RF between gases because the concentration of different gases varies at a constant weight due to varying molecular weight (MW).

For example, the MW of CO_2 is 44 whereas the MW of CH_4 is 16. Therefore, there is ~2.75 times more molecules of CH_4 per t than in one t of CO_2. This difference amplifies the RF of CH_4 compared to an equivalent mass of CO_2.

The persistency of a GHG is measured by half-life, or the amount of time it takes one half (½) of an emission, or pulse, to degrade into other gases or absorbed by a sink thus changing its atmospheric warming impacts. The decay curve for a GHG is an exponential curve meaning that every half-life interval, one half of the remaining gas pulse disappears (e.g. ½, ¼, $^1/_8$, etc.).

For example, a pulse of gas with a half-life of one year will take approximately 11 years to disappear completely (<0.1% remaining). The exponential decay curve for methane compared to CO_2 is illustrated in Figure 5.

Greenhouse Gas Inventory Summary

Table 1. Characteristics of the Three Most Common Greenhouse Gases

Gas	% by Volume[2]	Atomic or Molecular Weight	% by Mass[3]	Half-life[1]	GHG	Potency	% of Annual Emissions by Mass[4] (2014)
Carbon Dioxide (CO_2)	0.04%	MW 44	0.12%	1,000s of yrs[1]	Yes	+	76%
Methane (CH_4)	0.0002%	MW 16	0.0002%	8.6 yrs[5]	Yes	++	16%
Nitrous Oxide (N_2O)	0.00003%	MW 44	0.0001%	114-120[5] yrs[6]	Yes	+++	6%

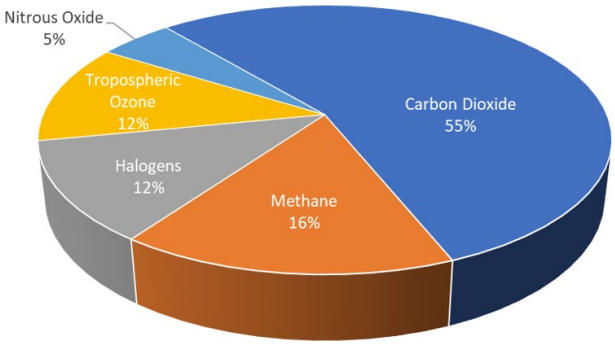
***Sources:** [1] Wikipedia, 2019; [2] Calculated; [3] Hausfather, 2008; [4] IPCC, 2014; [5] Muller and Muller, 2017; [6] Montzka, S.A. et. al.*

Table 1 provides a summary of the most common GHGs in Earth's lower atmosphere (troposphere). The three major global warming gases important to agriculture are: Carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). The impact of a GHG is dependent upon its radiative forcing, its atmospheric concentration, and its atmospheric residency or lifetime.

Figure 2. provides an overview of the contribution to atmospheric warming of the major GHGs sans water vapor which is an important feedback mechanism but does not contribute directly to warming. Halogens and tropospheric ozone do not have application to agriculture.

Following is a discussion of CO_2 and CH_4, together accounting for 71% of warming potential due to anthropogenic GHGs (Figure 2) and the core discussion with regards to estimating the global warming potential (GWP) of CH_4 compared to CO_2.

Figure 2. Anthropogenic GHG Contributions to Global Warming



Source: Acconia, 2019
Note: Percentages have been adjusted slightly to add to 100%

Carbon Dioxide

Carbon dioxide (CO_2) is the standard or reference gas by which the climate effects of all other GHGs are compared.

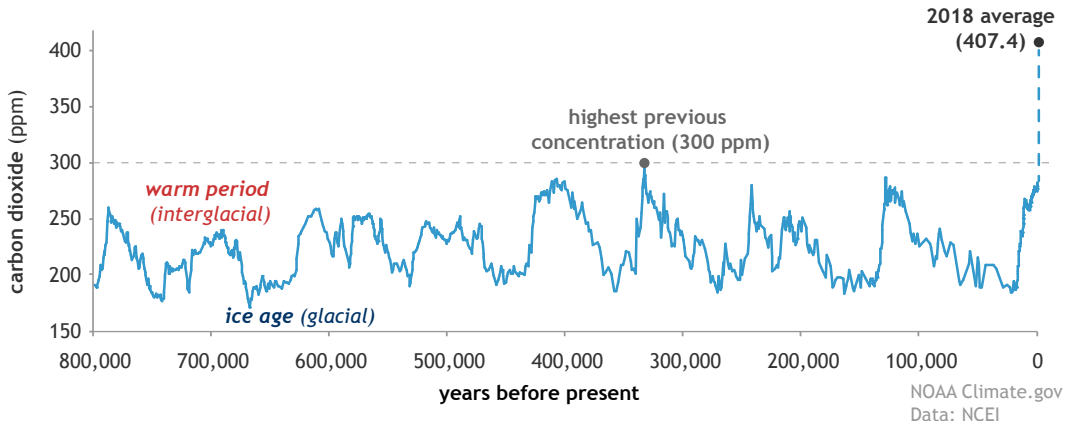
The impact of CO_2 on global warming is so overwhelming, because of its exceedingly long persistency in the atmosphere, that it is often called the "thermostatic control" for Earth's atmospheric temperature as dictated by its concentration in atmosphere. While N_2O and CH_4 absorb more energy per molecule than CO_2, CO_2 is far more abundant and persists longer than the other two gases (Table 1).

Furthermore, an increase in atmospheric CO_2 causes the oceans to absorb more CO_2 which increases acidity. Since the beginning of the Industrial Age, ocean pH has dropped from 8.2 to 8.1, a 30% increase in acidity; a more significant increase than it appears because pH is measured on a logarithmic scale (Lindsey, 2018).

Three processes exist for removing (sequestering) CO_2 from the atmosphere: absorption by the oceans, photosynthesis, and soil sequestration. They operate at different rates and are generally at capacity removing biogenic and natural CO_2 emissions. Therefore, anthropogenic CO_2 tends to overwhelm nature's ability to absorb it. Thus, anthropogenic CO_2 typically lasts for thousands of years which is considered the half-life of CO_2.

Figure 3. CO_2 during ice ages and warm periods for the past 800,000 years

Source: Lindsey, 2018



The atmospheric concentration of CO_2 has fluctuated considerably over the past 800,000 years as indicated by ice core samples from prehistoric times and direct measurement in the past two centuries (Figure 3). In addition to the annual fluctuation, there is also seasonal fluctuation in which emissions are lower in spring and summer when seasonal plants and trees are in bloom absorbing increased amounts of CO_2 through photosynthesis (Lindsey, 2018). The current concentration of CO_2 is at its highest level in the past 3 million years (Ritchie & Roser, 2018).

Over the past 800,000 years, atmospheric concentration has ranged from approximately 175 ppm to 275 ppm with cycles averaging about 100,000 years in length as seen in Figure 3. Low periods coincided with ice ages and the high periods were interglacial periods. This trend was true until the beginning of the Industrial Age in which there has been a steady increase in CO_2 concentration such that by 2017 the concentration of atmospheric CO_2 was 405 ppm.

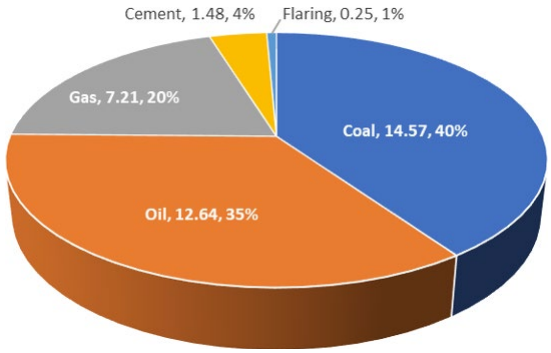
Annual anthropogenic emissions of CO_2 at the beginning of the Industrial Age is estimated to have been 9.35 megatonnes (Mt) and from 1900 to 2017 emissions increased from 2.0 gigatonnes[2] (Gt) annually to over 36.2 Gt (Ritchie & Roser, 2019). The current increase of atmospheric CO_2 is about 100 times the natural increase that occurred during the end of the previous Ice Age 11,000 to 17,000 years ago (Lindsey, 2018).

> *The vast majority of CO_2 emissions are from respiration of living creatures, known as biogenic sources, however, respiration is not considered a contribution to global warming.*

For example, humans exhale an average of slightly more than one kg of CO_2 daily dependent on activity level. This converts to 2.8 Gt of CO_2 exhaled annually by humans, which is a small portion of all biogenic sources (Palmer, 2009).

While natural CO_2 emissions far outweigh anthropogenic sources, it is the latter that contribute to global warming because natural emissions are offset by natural sinks (primarily the oceans, photosynthesis, and buried organic matter). Anthropogenic sources overwhelm the natural cycles of emissions and sinks as shown in Figure 1, thus increasing the atmospheric burden of CO_2 which in turn increases atmospheric temperature.

Figure 4. 2017 Anthropogenic Sources of Global CO2 Emissions



Source: Ritchie & Roser, 2019 *Note: Decimal numbers are billion tonnes (bt)*

As shown in Figure 4, burning of fossil fuels is by far the largest contributor to the anthropogenic CO_2 burden with 95% being sourced from burning coal, oil, and natural gas (land use, land-use change and forestry emissions are not considered here). Examining the change in historical contribution of these fuels, one can see at the beginning of the Industrial Age, coal was the overwhelming primary contributor with almost no other competitor. As time has progressed first oil started taking an increasing share of emissions followed by natural gas. In the past 10 years, cement production has also begun to contribute a measurable share.

2 One Mt equals one million tonnes. For consistency, one billion tonnes is referred to as a gigatonne (Gt). Some references preferred to use the abbreviation bt which has been converted to Gt.

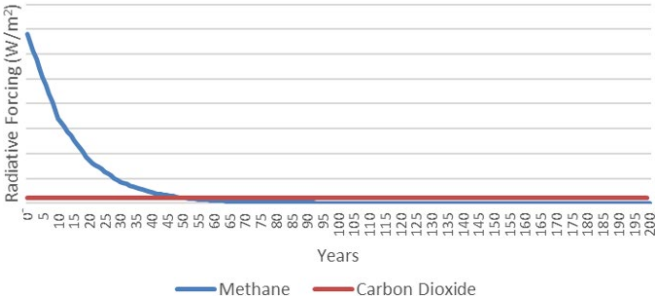
Methane

Methane (CH_4) is the second most important greenhouse gas. Methane is of key importance to animal agriculture due to a significant portion of anthropogenic labeled sources being from food production, most specifically ruminants.

The fact that CH_4 is an SLCP has also created more interest in methane. The half-life of CH_4 is 8.6 years (Table 1). Thus, while CH_4 has a stronger warming effect, on a mass basis, the impact persists in the atmosphere for a much shorter time than CO_2 (Figure 5). As a result, an emission pulse of CH_4 is nearly gone (<1%) by 60 years whereas most anthropogenic CO_2 persists.

This is a reason CO_2 is the primary gas regulating atmospheric temperature. It is also why so much emphasis is placed on reducing CH_4 emissions; faster progress can be made toward lowering atmospheric concentrations of CH_4, than of CO_2 and therefore a more rapid means of slowing global temperature rise (Allen, 2015; Haines et al., 2017). Yet regulating SLCPs will not attain the goal of sufficiently reducing global warming. Reduction of all GHGs need to be the goal if we are to meet the 1.5°C cap on global warming by 2050. A scientific debate is ongoing over this impasse (Bowerman et al., 2013; Pierrehumbert, 2014).

Figure 5. Illustration of Warming Potential of Equal Pulses by Mass of Methane and Carbon Dioxide Over Time



Methane does not compete for sink removal with CO_2 because CH_4 sinks differ from CO_2 sinks.

> *Removal of atmospheric methane occurs at three locations: 84% to 88% in the troposphere, 7% to 8% in the stratosphere, and the remaining 5% in the soil.*
>
> ***(Env. Change Inst., 2005 and Lynch, 2019)***

The primary sink for methane is through oxidation. Most oxidation occurs in the troposphere where CH_4 combines with hydroxyl radicals (OH) to eventually form one molecule of CO_2 and two of H_2O. Hydroxyl radicals are known as the "detergent" or "cleanser" of the atmosphere. During this process other intermediate compounds form such as ozone (O_3) which is a pollutant in the troposphere which will retard plant growth and acts as a GHG.

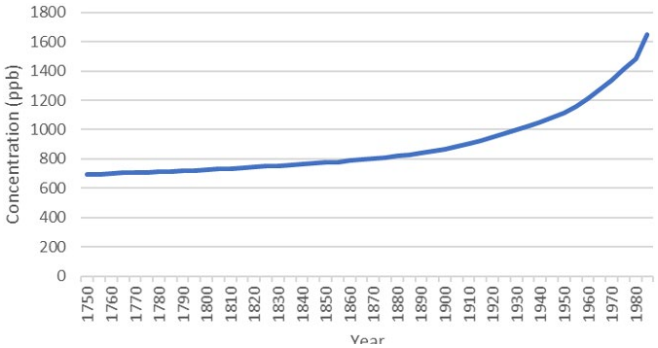
Hydroxyl radicals are formed when ultraviolet light from the sun strikes O_3 in the presence of water vapor. The O_3 is photolyzed and the free oxygen steals a hydrogen from an H_2O molecule to form two hydroxyl radicals.

The formation of OH is rather constant from year to year but varies by temperature and humidity with regions and seasons of highest humidity and temperature having the highest OH concentrations such as in the tropics and during summer months in temperate regions (Riedel & Lassey, 2008). This creates seasonal fluctuations of atmospheric methane concentration of ±10 ppb with methane levels being lowest in summer months and highest in the winter (2nd Degree Institute, 2020).

A complication of increasing methane concentration is its half-life will increase due to increased demand and therefore depletion of OH, increasing methane's radiant forcing. Hydroxy radical depletion is exacerbated by the fact that methane competes for access to OH with other pollutants like carbon monoxide (CO), nitrogen dioxide (NO_2) and various hydrocarbons (Env. Change Inst., 2005; Riedel & Lassey, 2008).

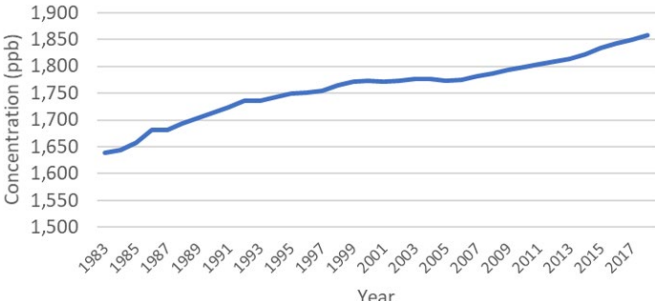
Some methane will escape oxidation in the troposphere and rise to the stratosphere where oxidation also occurs. Some oxidation will still take place with hydroxyl radicals, but oxidation will also take place through interaction with chloride radicals. Lastly, the remaining 5% of CH_4 will be removed by methanotrophic bacteria resident in soil which oxidizes methane into CO_2 (Env. Change Inst., 2005). Methane decay in the stratosphere is responsible for approximately 50% of the water vapor in the atmosphere.

Figure 6a. Global Atmospheric Concentration of Methane (1750-1985)



Source: 2 Degrees Institute, 2019

Figure 6b. Annual Global Concentration of Methane (1983-2018)



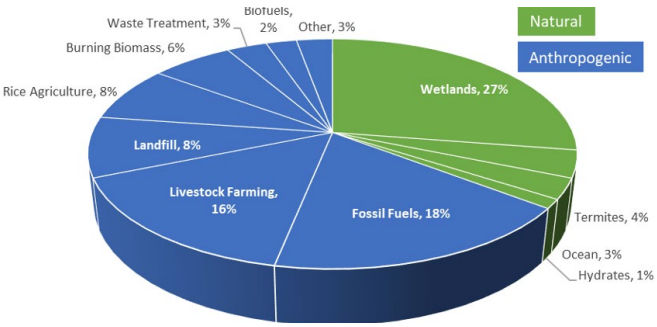
Source: 2 Degrees Institute, 2019

As of June 2019, the atmospheric methane concentration was 1,860.2 ppb (2 Deg. Inst., 2019), or a total burden of 5,160 megatonnes (Mt), assuming 1 ppb equals 2.78 Mt (Env. Change Inst., 2005). This level is 2.7 times greater than most of the previous millennium when concentration remained steady at roughly 680 ppb from 1000 AD until the beginning of the Industrial Age in 1750. This near tripling of methane concentration in the last two centuries compares to a 50% increase in CO_2 concentration during the same period.

Figure 6a illustrates the gradual increase in atmospheric methane concentration that began with the beginning of the Industrial Age and by the early 20th century began a much more rapid increase. The rate of increase in methane concentration slowed in the 1990s as can be seen in Figure 6b such that by the 10 years spanning 1997 to 2006, it remained virtually level at 1,770 ppb.

Since 2006, methane concentration is again increasing at 6.9 ppb annually which translates to an additional atmospheric burden of 19.2 Mt of CH_4 annually.

Figure 7a. Global Methane Emission Sources (2001-2006)



Sources: Averages of: Env. Change Inst., 2005 and Bousquet, P. et al. 2006

It is believed the major sources of methane appear to have been identified, however quantifying their individual contributions has proved to be challenging. Many sources are variable by location and season. Several studies have attempted to quantify individual source contributions, but definitions of individual sources are variable and there is a wide range of estimates (Env. Change Inst., 2005). This Oxford review summarized data from 6 studies. Results from these studies plus an additional report (Bousquet, et al., 2006) were averaged to create the graph in Figure 7a.

Sources in Figure 7a. are divided into natural and anthropogenic. Methane from wetlands, in which anaerobic consumption of organic matter is the single largest contributor, adding 27% of the atmospheric methane burden. Hydrates refers to methane which is crystalized and frozen in ice which exists in permafrost and on ocean floors and in long frozen ponds and lakes in polar regions. Taken together, the identified natural sources are estimated to contribute 35% with the remaining 65% being defined as anthropogenic sources.

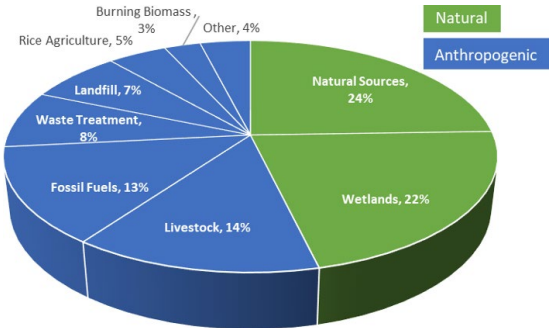
Methane from fossil fuel production which includes fugitive emissions from coal mining and the drilling, pumping, storage and transport of oil and gas from pipelines, tanks, coal seams and other processes contribute 18% of the total annual emissions which is 27% of the anthropogenic emissions. Agriculture in general contributes 24% overall with livestock contributing 16% which is higher than another published estimate of 14.5% of anthropogenic CH_4 emitted by livestock in 2013 (Garnett, et al., 2017).

These estimates are for the period 2001 through 2006, which as noted in the description of Figure 6b, was a period absent any appreciable increase in methane emissions. If that trend had held, it would have meant that methane would have stopped contributing additional warming to the atmosphere as sinks caught up with sources. However, as also noted, methane emissions started rising again in 2006.

As researchers investigated possible causes for the renewed increases, initial reports placed the blame on renewed burning of tropical rainforests and woodlands to make room for grazing animals and crop production and on the increase in cattle as families moved out of poverty in the developing world (Voiland, et al. 2018, and Pearce, 2016).

A more recent study by Howarth (2019) comes to a different conclusion. After correcting earlier studies for the ratio of ^{12}C:^{13}C, Howarth concluded that "shale-gas production in North America over the past decade may have contributed more than half of all of the increased emissions from fossil fuels globally and approximately one-third of the total increased emissions from all sources globally over the past decade". This conclusion if corroborated, alters the estimates in Figure 7a. Nisbet et al. (2020) summarized that the post-2006 surge of CH_4 may include increases of biogenic emission, changes of chemical sinks of CH_4 by atmospheric OH and Cl, increased fossil fuel emission along with decreased biomass burning, increased up taken of forest soil, and some combinations of these effects.

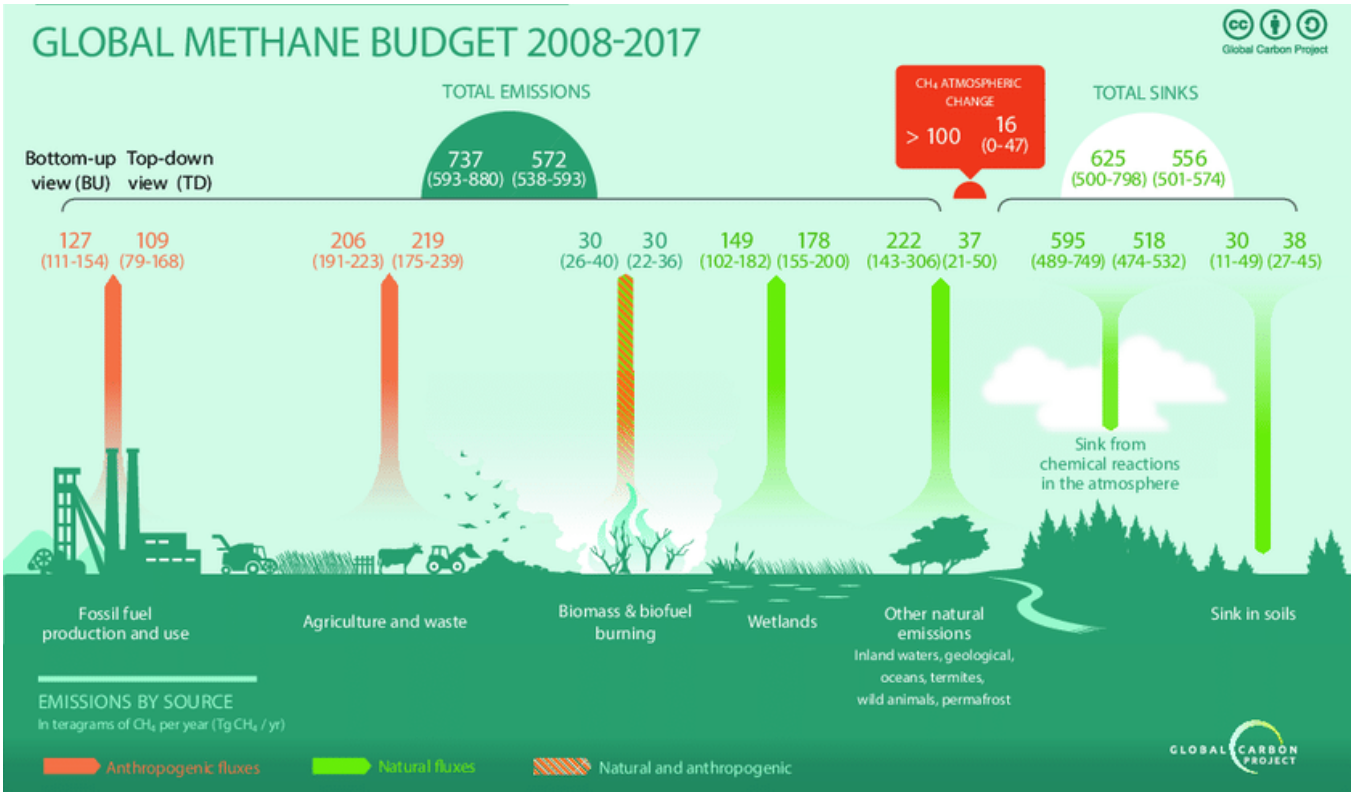
Figure 7b. Global Methane Emission Sources (2002-20012)



Sources: Averages of: Fairlie, S., 2018 and Turner et al,. 2015

Later estimates of methane sources are shown in Figure 7b. Many estimates in Figure 7b are consistent with estimates in Figure 7a with the exception that natural emission sources, including Wetlands, are significantly larger, at 46% total emissions, in Figure 7b. However, "Natural Emissions" were not as well broken out in the Fairlie (2018) data as in other source lists.

Global Methane Budget



Source: Saunois, M., 2020

The latest Global Methane Budget published by Global Carbon Project (Saunois et al. 2020) estimated that the global decadal mean CH_4 emission was 572 (538–593) Mt/yr[3] during 2008–2017, with the natural sources contributed 215 (176–248) Mt/yr and the anthropogenic emissions contributed 357 (334–375) Mt/yr between the same decades.

Accounting systems must be open to adding emerging sources of CH_4. Recently, a previously unidentified large source of hydrocarbon was discovered; the seabed of the Red Sea, an area of the globe with more than half the oil and gas reserves in the world (Galey, 2020). Furthermore, as global warming continues, the polar ice sheets and permafrost are melting at a much faster rate than was earlier predicted and may overwhelm all anthropogenic sources (Env. Change Inst., 2005, Welch & Orlinsky, 2019).

Scientists such has Zimov (2005) have been warning for quite some time that the melting permafrost would release previously sequestered stores of methane as these sources were uncovered from melting ice and permafrost releasing frozen organic matter into newly transformed wetlands. One existing example are ponds in Alaska releasing CH_4 through ice holes which is being flared off (Welch & Orlinsky, 2019). The concern is great because release of these major sequestered stores of methane could re-enter the atmosphere, moving it towards runaway warming due to the destruction of sinks that have countermand accelerating emissions. There is evidence that IPCC is examining and recommending updates to methodology for GHG inventories (IPCC, 2019). It is unclear, however, as to how soon these updates will take effect in new methane inventories and whether there will be consistency in the categories of methane sources or simply revised methods of capturing metrics.

Nitrous Oxide

Nitrous oxide (N_2O) has by far the highest RF on a mass basis of the three agricultural GHGs and is relatively long-lived.

However, it accounts for just 5% of atmospheric warming due to its low change in concentration. With respect to agriculture, it is primarily emitted during fertilizer application, whether it be organic (manure) or inorganic (commercially produced) and during manure treatment. It is relatively long lived GHG at 114 to 120 years (Table 1).

As such, there needs to be efforts to reduce and/or offset N_2O emissions. However, being a long-lived climate pollutant (LLCP), discussion of N_2O will end here in this review because its global warming potential (GWP) when compared to CO_2 does not appear to be greatly affected by the proposed revised estimates of GWP* because N_2O is not a SLCP. The primary purpose of GWP* is to address the difference in global warming effects of an SLCP compared to the LLCP CO_2.

3 Authors of the Saunois, et al., 2020 used the term teragram (Tg) which has been converted to megatonne (Mt) for consistency within this document. One Tg equals one Mt.

Global Warming Potential (GWP)

"Global Warming Potential" (GWP) is the metric formally established for international climate policy as established in the Kyoto Protocol and the draft Paris Agreement for standardized Life Cycle Assessment (LCA) carbon footprinting approaches (Lynch, et al., 2020 and ISO 14044; UNFCCC, 1998, 2015) to aid policymakers in establishing actionable goals to reduce global warming using a simple metric that aggregates the effects all GHGs together.

Unfortunately, as noted earlier, radiative forcing efficiency, atmospheric persistency, both of which are affected by concentration and emission rate contribute to a GHG warming potential, vary considerably from gas to gas. Therefore, it is difficult to compare the relative effects of the various gases to each other, each with their own characteristic residence time, RF, and emission rate on a one-for-one basis. However, GWP is the metric that has been established and used for the past 30 years to combine the effects of all GHG into a single numeric metric.

"The GWP of a greenhouse gas is defined as the cumulative radiative forcing from the instantaneous release [pulse] of one kg of trace substance relative to that of a one kg of a reference gas" (IPCC, 1990) and estimated using the following equation:

$$GWP_i \equiv \frac{\int_0^{TH} RF_i(t)\,dt}{\int_0^{TH} RF_r(t)\,dt} = \frac{\int_0^{TH} a_i \cdot [C_i(t)]\,dt}{\int_0^{TH} a_r \cdot [C_r(t)]\,dt}$$

(Eqn. 1) Source: IPCC, 1990

in which the numerator refers to the cumulative area under the graph of relative forcing for the gas of interest (i), (e.g. methane in Figure 5) and the denominator is the area under the graph for the reference gas (r), (e.g. CO_2 in Figure 5), from the point in time of the equivalent, by mass, pulse emissions (0) across a specific time horizon (TH). The reference gas is virtually always CO_2 which therefore is defined as having a GWP of unity (1). The most commonly used time periods are either 20 years (GWP_{20}) or 100 years (GWP_{100}), with 100 years being the norm used to report aggregated GHG emissions, including some IPCC communications. It is important to keep in mind that the reference is to a given mass (weight) and not volume (concentration).

Alternatively stated, the GWP for a GHG in question is the ratio of the integral cumulative warming effect of that GHG over a time period (typically 20 or 100 years) compared to the concurrent integral cumulative warming effect of CO_2 over the

same period (Eqn 1). As the concentration of a GHG increases, the warming effect per unit area (W/m^2) increases. Therefore, as either the warming effect of the GHG in question, or that of CO_2 changes, the GWP for the gas in question will also change. A third factor that will cause a revised RF is the addition of feedback mechanisms, which plays a role in the resulting change of surface temperature caused by the RF of GHGs. Some feedback mechanisms can dampen RF while others increase its intensity.

Since its establishment in 1990 by IPCC, the GWP_{100} of methane has increased due to the changes in estimating the indirect forcing, feedback mechanisms, and the lifetime of CH_4, etc. The first published GWP_{100} for one t of CH_4 was equivalent to 20 t of CO_2 as stated in IPCC Assessment Report 1 (AR_1). In succeeding AR reports it has increased successively from 20 (AR_1), to 23 (AR_2), to 25 (AR_3), to 28 (AR_4). Most recently, it now stands at 34 (AR_5), due to the improvements of several methane feedback mechanisms, notably the end-products of CH_4 decay (CO_2 and stratospheric H_2O) and the creation of an intermediate product (O_3). All three of these products are GHGs themselves and therefore act to enhance the RF of methane. Policy makers have been making efforts to cope with the continually changing GWPs to establish meaningful targets per the 2015 Paris Accords.

The current "standard" climate metric, GWP_{100}, enables comparison of climate impacts of different GHGs by translating them into CO_2-equivalent (CO_2-e) which provides a quantitative basis for international carbon trading. However, there has been long standing criticism of the metric dating back to at least 2000 (O'Neil, B.C., 2000) and others (Shine et al., 2007) including IPCC itself (IPCC, 2013) in stating "No single metric can accurately compare all consequences of different emissions, and all have limitations and uncertainties." Quoting from the first major report produced by the IPCC in 1990, the article explains "Global Warming Potentials" were introduced as "a simple approach … to illustrate the difficulties inherent in the concept." "The problem with developing the concept is that people might use it. Worse, they might use it and ignore all the caveats that attended its development" (Frame et al., 2018). This is exactly what has happened and as a result, GWP_{100} has developed its own inertia, and therefore is difficult to undo (Fairlie, 2019).

> *The major issue is that GWP treats short- and long-lived climate pollutants in the same way, which cannot capture the contrasting differences in behaviors of the two.*

Specifically, using GWP_{100}, methane is treated the same as long lived climate pollutants (LLCP), like CO_2. Lynch (2019) offers an explanation that illustrates the difference. Another way to describe an LLCP is as a "stock pollutant". Because of its long life, a stock pollutant builds up over time even at very low emission rates, like continually storing boxes in a warehouse without removing any. Lynch (2019) uses the analogy of a bathtub in which the drain is plugged. Regardless of the rate of flow of water into the bathtub, even a small drip, it continues to fill.

On the other hand, an SLCP is called a "flow pollutant". In this case the bathtub drain is open such that when the incoming flow is less than or matches the outgoing flow, the tub will either stabilize or drain. Only if the flow is increased to be greater than the outflow will the tub begin to fill. This difference makes it nearly impossible to express the impact of an SLCP on global temperature change in terms of an equivalent LLCP. And therein lies the key caveat for the current expression of GWP. Additionally, by treating flow pollutants (SLCP) as equivalent to stock pollutants (LLCP) there is a tendency to primarily focus on the flow pollutants at the excuse of "buying time" to work on the stock pollutants when both must be worked on simultaneously.

A fundamental result of treating a flow pollutant (SLCP) as a stock pollutant (LLCP), is that under declining emissions scenarios, the current GWP metric indicates continued atmospheric warming until the flow rate goes to zero, when in fact, if the emission rate falls below the sink rate, atmospheric concentration of the flow pollutant will fall which means the warming will be reduced from the current level. Because methane is a flow pollutant whereas CO_2 is a stock pollutant, methane anthropogenic reduction goals are between 44% and 67% to the 2010 level to achieve the maximum 1.5°C global temperature increase by 2050 whereas anthropogenic CO_2 reduction goals are nearer 100% (IPCC 1.5° target).

GWP*

In response to these ongoing criticisms of the current GWP calculation and the fundamental result stated above, scientists at the Environmental Change Institute and the Food Climate Research Network, both of Oxford University have proposed a new metric called GWP* using the metric is CO_2-e* instead of CO_2-e (Allen, et al., 2018a) which was eventually replaced yet again by CO_2-we (Cain, et al., 2019a). GWP* is neither a replacement for, nor independent of GWP; rather, it is a new use of GWP in assessing the climate contribution of SLCPs. "Instead of measuring a pulse emission of CO_2 against an [SLCP] pulse of the same mass, GWP* compares a pulse of emission of CO_2 with an increase [or decrease] in the emission rate of the [SLCP]" (Fairlie, 2019). This requires both current and historical emission rates over a period of time (Δt).

As explained by Lynch, et al., 2020, "The main difference between GWP* and static metrics such as GWP_{100} is thus: with static metrics, individual emission are directly equated by a single value that can only represent one particular impact at or over a stated time, and which cannot fully capture the temporal differences between the impacts of different gases; but for GWP*, "equivalent CO_2 can vary in order to describe the dynamic responses over any time-frame of interest." Furthermore, the authors go on to state "… as this problem occurs for any static concept of equivalence, it cannot be overcome by using alternative metrics or alternative time-horizons … which reveal similar limitations for the 20-year Global Warming Potential (GWP_{20}) and the 100-year Global Temperature Change (GTP_{100})."

To date, four peer reviewed manuscripts introducing, documenting, validating, and explaining use of GWP* have been published (Allen, 2015; Allen, et al., 2018a; Cain, et al., 2019a; and Lynch, et al., 2020). The key improvement made by GWP* is that it links the temperature impacts of a sustained SLCP emission to a pulse emission of CO_2 which enables SLCPs to be considered in a framework of cumulative emissions. Although the term GWP* was not yet proposed, the first paper provides the foundation for the GWP* with explanations on how GWP* is derived (Allen, 2015). The second paper focuses on the validity of GWP*, demonstrating that it provides a more well-behaved metric with less error variation than GWP and provides a more precise prediction than GWP for future atmospheric SLCP burden predictions, especially those with long time horizons, given several emission mitigation strategies for methane. There are also several self-published explanatory papers explaining in lay terms the fundamentals of the switch to GWP* (Lynch, 2019; Cain, 2019b; Fairlie, 2019; Frame et al., 2018; Allen et al., 2018b). The Lynch, et al. (2020) paper also includes a simplified equation which only requires known SLCP emission rates for the current time and either a backward- or forward-looking time interval.

Two equivalent methods for estimating CO_2-e*, one based on emission rate of the SLCP, the other based on the radiative forcing of the SLCP are put forth in the second paper proposing GWP* (Allen, M.R., et al., 2018a). Both equations are dependent upon the integral calculus GWP (Eqn 1). "GWP is defined as the Absolute GWP (AGWP) for a given climate forcing agent [GHG]

(the radiative forcing due to a pulse emission of that agent integrated over a time-horizon H) divided by the AGWP of CO_2. Conventional CO_2-e emissions for an SLCP are defined simply as emissions mass multiplied by the GWP:

$$E_{CO2\text{-}e} = E \times GWP_H$$

(Eqn. 2)

Where: E equals the mass emission for a GHG and H is the forward time horizon" and GWP_H is the GWP estimated as according to IPCC (1990) over time horizon H (Allen, M.R., et al., 2018a, Lynch, et al., 2020).

For GWP*, instead of integrating over the time interval of the SLCP, the time-integral of the rate of change in emissions of the SLCP is performed. The revised formula based on a change in emission rate of the SLCP becomes:

$$E_{CO2\text{-}e*} = (\Delta E_{SLCP}/\Delta t) \times GWP_H \times H$$

(Eqn. 3)

Where: ΔE_{SLCP} equals the change in emission rate of the SLCP over the time interval Δt, GWP_H is the SLCP GWP, and H is the forward time horizon (Allen, M.R., et al., 2018a).

The equivalent equation using radiative forcing of the SLCP instead of the change in rate of emissions is as follows:

$$E_{CO2\text{-}e*} = (\Delta F/\Delta t) \times (H/AGWP_{H(CO2)})$$

(Eqn. 4)

Where: ΔF is the change in the SLCP radiative forcing and $AGWP_{H(CO2)}$ is the Absolute GWP for CO_2 for forward time horizon H (Allen, M.R., et al., 2018a).

The third published paper by Cain et al. (2019a) and two follow-up self-published reports (Cain et al., 2019b; Allen, et al., 2018b) address several limitations in the original GWP* method described in Allen, et al. (2018a). The original GWP* method slightly underestimated the impact of SLCPs because the climate does not respond immediately to a change in radiative forcing.

The revised method addresses this issue with the revised metric CO_2-warming-equivalent estimated directly from reported emissions and the GWP* metric was revised to CO_2-we, replacing CO_2-e*. "Thus, SLCPs can be incorporated directly into carbon budgets consistent with long-term temperature goals because every unit of CO_2-we emitted generates approximately the same amount of warming, whether it is emitted as an SLCP or a LLCP. This is not the case for conventionally derived CO2-e" (Cain, M., et al. 2019a). This revision is key for adoption of GWP* by researchers, report writers and tool developers.

The revised GWP* is called the CO_2-warming equivalent (CO_2-we) estimated with the following equation:

$$E_{CO2\text{-}we} = GWP_H \times \{[r \times (\Delta E_{SLCP}/\Delta t) \times H] + [s \times E_{SLCP}]\}$$

(Eqn. 5)

Where: "$E_{CO2\text{-}we}$ is the estimated CO_2-we, GWP_H is the conventional global warming potential for a given SLCP over time-horizon H, ΔE_{SLCP} the change in SLCP emission rate over the preceding Δt years, E_{SLCP} is the SLCP emissions for that year, and r is the weighting factor given to the impacts of changing the rate of SLCP emissions, while s is the weighting given to the impacts of the current emission rate (stock contributions), respectively" (Cain, M., et al. 2019a, Lynch, et al., 2020).

The difference between Eqn 5 and Eqn 3 is r=1 and s=0 in Eqn 3, eliminating current year emissions for the SLCP (E_{SLCP}) in Eqn 5. The suggested Δt is 20 years in order to smooth out the annual variation in the SLCP emissions thus improving the correspondence with temperature response (Allen, M.R., et al., 2018a). The values for r and s are scenario dependent as determined by the third-party user and it is advised that the value of s and r should be constrained to $s + r$ =1 (Allen, et al., 2018a). A more detailed description of the effects of r and s and their effects on the estimate of CO_2-we and its relationship to CO_2-e* are provided in Cain, M., et al. (2019a) and Lynch, et al. (2020). Unfortunately, the method for determining r and s is complex involving multiple linear regression using data from the AR_5 database. However, mean values of r = 0.75 and s = 0.25 provide a generally robust fit for methane based on the three emission scenarios (Cain, M., et al., 2019a) which is also supported by Lynch, et al., (2020).

Lynch, et al. (2020) spend a good deal of their report demonstrating the utility and advantages of GWP* in estimating the atmospheric warming effect of various scenarios of CH_4 emission rates and strategies to reduce emissions as compared to GWP. The graphic contrasts presented in the examples are compelling. Lynch goes on to state that:

"Because recomputed GWP_{100} values for methane are used, that GWP* is compatible with emissions reporting under the Paris Rulebook agreed at COP24, provided cumulative and short-lived pollutants are reported and aggregated separately in emissions reporting and nationally determined contributions."

Furthermore, "separate aggregation and reporting of cumulative and short-lived pollutants in all communications between parties and the U.N. Framework Convention on Climate Change (UNFCCC) would substantially enhance transparency of the UNFCCC process and ensure climatically important information is not lost." These are critical points for the acceptance of GWP* as a meaningful metric in compliance with UNFCCC policy.

Given $\Delta E_{SLCP} = E_{SLCP(t)} - E_{SLCP(t-\Delta t)}$, where ($t$) represents the time of the current emission and (t-Δt) is the time of original emission provides a way to algebraically simplify Eqn. 5 even further to:

$$E_{CO2\text{-}we} = [[((H \times r)/\Delta t) + s) \times E_{SLCP(t)}] - [((H \times r)/\Delta t) \times E_{SLCP(t-\Delta t)}]] \times GWP_H$$

(Eqn. 6)

Given the parameters: H, t, Δt, r, and s, are defined as part of the scenario at hand, they become constants for a particular scenario. Lynch et al. (2020) provide an example in their Eqn. 3 in which H=100, Δt=20 yr, r=0.75, s=0.25, in which they demonstrate how Eqn. 6 reduces to:

$$E_{CO2\text{-}we\ (SLCP)} = (4 \times E_{SLCP(t)} - 3.75 \times E_{SLCP(t-20)}) \times GWP_{100}$$

(Eqn. 3 in Lynch et al., 2020) (Eqn. 7)

This example demonstrates how easily $E_{CO2\text{-}we\ (SLCP)}$ may be estimated from known emission pulses and traditionally defined GWP. It must be kept in mind that Eqn. 7 is specific to a very limited example as defined by the parameters in Lynch et al. (2020). However, the multiplicative factors for $E_{SLCP(t)}$ and $E_{SLCP(t-\Delta t)}$ (4 and 3.75 respectively in Eqn. 7) can be defined apriori for a multitude of scenarios and tabulated so that they do not have to be recalculated for every scenario but rather sourced from a look up table (See Appendix A). If we define the coefficient for $E_{SLCP(t)}$ as $C_{(t)}$ and the coefficient for $E_{SLCP(t-\Delta t)}$ as $P_{(t-\Delta t)}$, then:

$$C_{(t)} = (((H \times r)/\Delta t) + s) \times GWP_H$$

(Eqn. 8)

$$P_{(t-\Delta t)} = ((H \times r)/\Delta t) \times GWP_H$$

(Eqn. 9)

Now, Eqn. 6 can be simplified yet again to:

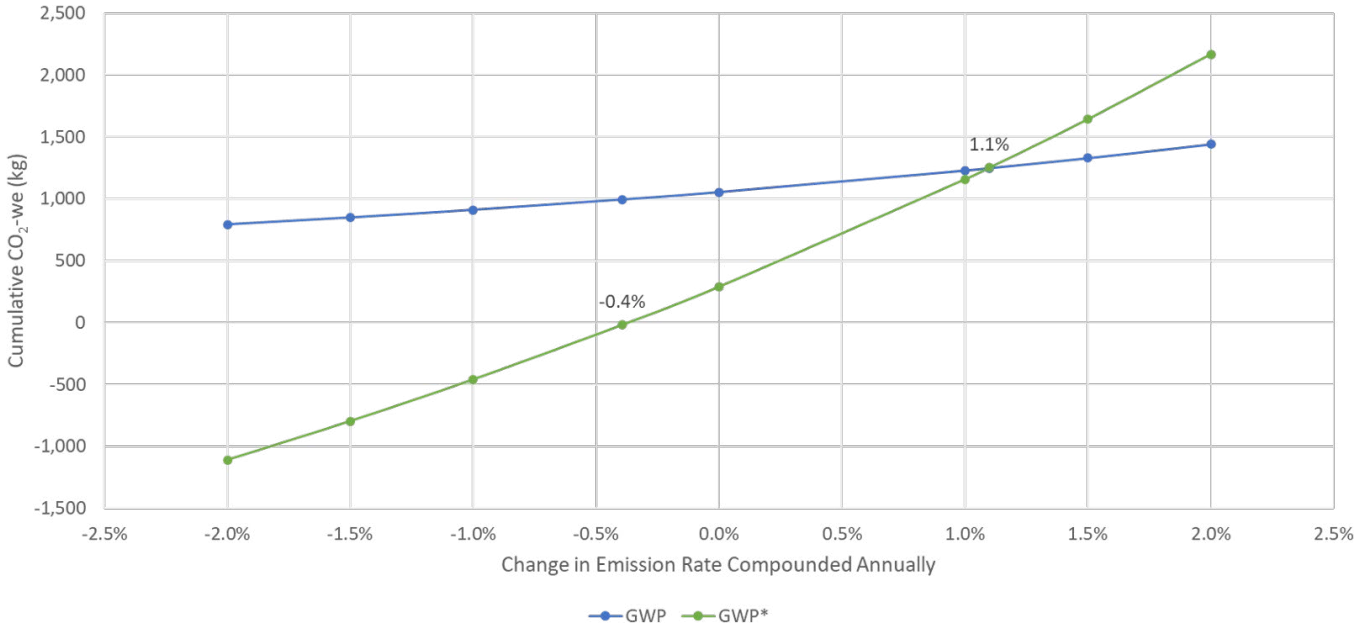
$$E_{CO2\text{-}we\ (SLCP)} = (C_{(t)} \times E_{SLCP(t)}) - (P_{(t-\Delta t)} \times E_{SLCP(t-\Delta t)})$$

(Eqn. 10)

Importantly, Eqn. 10 represents a single-point estimate for $E_{CO2\text{-}we\ (SLCP)}$. Thus, unlike CO_2-e which only requires a single point estimate of one emission pulse, GWP* requires at least two emission pulse estimates at different points in time in order to account for the emission rate change required to estimate CO_2-we. Thus, when only one emission pulse is known, CO_2-we is equivalent to CO_2-e from GWP_{100}.

The graphs in Figure 8 were patterned after an exercise published by Cain, et al. (2019b), to contrast the difference in the 30-year cumulative warming estimates for GWP_{100} and GWP^*_{100} under various scenarios of annual change in CH_4 emission rates. In each case, the initial annual pulse emission is one kg of CH_4. There were nine separate annual rate change scenarios compounded annually over 30 years (-2.0%, -1.5%, -1.0%, -0.4%, no change (0), +1.1%, +1.5%, and +2.0%).

Figure 8. 30-year Cumulative Methane Warming Estimates Comparing Various GWP_{100} to GWP_{100}* Behaviors#



Note: Initial emission pulse in year-zero is 1 kg, r = 0.75, s = 0.25

Note that regardless of various changes in emission rate, GWP estimates (blue line) of cumulative CO_2-e is always positive (continued warming), even under declining emission scenarios. That is a significant short-coming when GWP is used to evaluate the cumulative warming effect of SLCPs; the accumulation of CO_2-e will never reach zero until all CH_4 emissions cease. This is because GWP does not account for the short-lived nature of SLCPs. The most noticeable observation, however, is the difference in behavior (slope) of GWP and GWP* estimates under scenarios from decreasing emissions to increasing emissions which has a much greater effect on the implication of various changes in emission rates of CH_4 on cumulative atmospheric warming than GWP.

Early lay discussions within animal agriculture have focused on the left side of the GWP* line (green line), highlighting the possibility for "relative cooling" when GWP* is used to estimate the cumulative warming effect of reduced methane emissions. Examining the behavior more closely however, several other characteristics must be noted. First, a relative cooling effect does certainly exist when methane emissions can be reduced at a rate greater than 0.4% annually. This effect can offset increases in other GHG emissions during the same period. Between a 0.4% annual decrease and no change (0%) in CH_4 emissions, there is in fact a warming effect. This is due to lag time by the climate to react to a change in emission rate. According to Allen, et al (2018a), this delay "averages 10 years between changes in SLCP emission rates and their associated CO_2-e* emission rates but has no impact on cumulative CO2-e* emission."

Moving to the right side of the GWP* line, at an annual emission increase of approximately 1.1%, GWP provides an equivalent estimate of cumulative warming effects to GWP*. However, as annual emissions increase at rates greater than 1.1%, GWP* estimates are greater than GWP estimates. Thus, it would be a mistake to believe that GWP always overestimates the effect of changing CH_4 emissions. This illustrates that not only is GWP insufficient to predict warming (cooling) rates when annual emissions are decreasing, it is also insufficient for predicting warming rates when annual emissions are increasing except within a very narrow range of change. These results agree with similar conclusions by Lynch, et al. (2020).

Finally, it needs to be pointed out, especially to those communities that argue that GWP* would put an unfair burden on developing countries, at rate changes between 0% and 1.1%, GWP* provides lower cumulative warming estimates than GWP, which work to their advantage when assessing progress. In fact, it is possible that evaluating cumulative warming under GWP* will shift more of the burden of global warming from methane emissions from agriculture to energy production.

The introduction of CO_2-we for SLCPs does not preclude estimating the total CO_2-we burden from an industry or operation with multiple differing GHG emissions. The CO_2-we for CO_2 is simply the mass of CO_2 emitted because CO_2 is the reference gas with a CO_2-we always equal to unity (1). The CO_2-we estimates for LLCPs do not stray from GWP CO_2-e estimates, thus CO_2-we for N_2O is roughly equal to its CO_2-e. Thus, combined cumulative CO_2-we emission is equal to the sum of the appropriate CO_2-we for each individual GHG (Cain, M., 2020) as in the following equation.

$$E \text{ total } (CO_2\text{-we}) = E\ (CO_2) + E\ (CO_2\text{-we (SLCP)}) + E\ (CO_2\text{-e (LLCP)})$$

(Eqn. 11)

GWP* overcomes another limitation of GWP. GWP_{100} does not directly relate to a temperature response, a shortcoming when setting emission reduction goals. However, a simple coefficient known as TCRE (**T**ransient **C**limate **R**esponse to cumulative carbon **E**missions) can be multiplied by cumulative CO_2-we to obtain an approximate estimate of temperature change due to the change in CO_2-we experienced. This calculation is possible because an approximate linear relationship exists between cumulative CO_2 emissions and temperature change. The TCRE coefficient for CO_2 is 0.4 K°/Tt CO_2 (see Figure 3C in Lynch, et al, 2020). It needs to be noted that multiplying TCRE by the cumulative CO_2-we emission is a slight under-estimate (conservative) of the expected temperature change, however, Lynch et al. (2020) go on to state "there will remain applications where more complex methods are preferred, but the ease of calculating GWP* will likely prove a significant advantage for many purposes." It needs to be noted, when temperature change is estimated using GWP* and TCRE, the parameters that increase uncertainty of GTP also increase the uncertainty of temperature change according to GWP*, and is likely in the range 0.8 to 2.5 C per Tt CO_2 (IPCC, 2013).

Work continues to promote understanding and acceptance of GWP* by the originators of the metric. There are now four detailed peer-reviewed publications (Allen, 2015; 2018a; Cain, M., et al., 2019a; and Lynch, et al., 2020) describing the issue with GWP in detail and proposed improvements with evidence to demonstrate the superiority of GWP* in predicting future global temperature change.

Literary evidence now exists for IPCC to determine the suitability of GWP* for inclusion in their reports. While, the fourth GWP* peer-reviewed publication greatly enhances the ability for third-party users to apply the procedure, further efforts are being made by the FCRN team to expand the educational material to aid other researchers, investigators, and tool developers on methodology they can use to properly estimate CO_2-we.

Criticisms and Alternatives to GWP*

GWP* is not without its critics and competing alternatives exist to estimate a more appropriate global warming potential for GWP.

Schleussner et al., (2019) reported that interpreting the Paris Agreement goals with GWP* can lead to inconsistencies in the mitigation architecture of the Agreement that is significantly different from the standard metric GWP.

> *Further exploration is needed with respect to incorporating the information provided by GWP* into the processes of making mitigation policies.*

Right on the heels of the publication of Cain, M. et al., (2019a) is an peer-reviewed paper in press by Rogelj, J., et al. (2019) commenting that "because the comparison factors for non-CO_2 GHGs under the GWP* metric depend on past emissions, they raise questions of equity and fairness when applied on any but a global level." They point out that "adoption of GWP* would put most developing countries at a disadvantage … ". It is somewhat enigmatic as to how "fairness" comes into play regarding physics. The authors argue that the GWP* metric is a credible metric on a global scale but not on a country scale. In effect, the point they are making is equivalent to saying if global emissions are the sum of country emissions and are illustrated as a pie chart, it is acceptable to shrink the pie as a whole but not on a piece-by-piece basis because those with the smaller pieces will have to shrink more than the larger pieces on a percentage of the size of their piece. The authors suggest four alternatives to GWP*, all of which are based on per capita calculations (constant emissions/capita; constant warming/capita; minimal methane warming/capita; and zero reference/capita). They go on to describe the properties of each proposal and the logic behind them.

While there certainly is disproportionate responsibility between countries for reducing emissions, with developing countries often at a disadvantage, especially with respect to methane because often their livestock are a primary source of emissions, estimating a GWP based on per capita calculations ignores the global nature of the world economy as well as the fact that atmospheric warming is a global phenomenon regardless of where the source emission occurred. Global trade deals in products that in and of themselves have significant carbon footprints. Developed countries are large exporters of finished products, including food, to developing nations. Using milk as an example, estimating a GWP on a per capita basis for large dairy exporting regions, like the E.U., U.S., Australia, and New Zealand, puts those areas at a disadvantage given the significant amount of dairy exported to developing countries when in fact the point of consumption should be charged with the carbon emissions burden as is the case with fossil fuels. Granted, sustainability is dependent upon economic

viability, environmental responsibility, and social integrity. However, to mix policy strategies into physical climatic metrics is backwards. The metrics should influence the policy but, the other way around. The "unfairness" to developing countries is not self-evident within the algorithms of GWP* and counterpoints due to global trade can be easily made.

In a different vein, a proposal to replace GWP with a metric called Global Temperature Change (GTP) was proposed previously (Shine et al., 2005). As opposed to GWP and GWP* which both estimate the CO_2-equivalent mass of a given GHG, GTP estimates the change in global mean temperature for a selected year in the future. "In other words, … what will be the temperature change in future year X in response to the radiative forcing of a certain GHG emission" (CORE, 2011). There are at least four critique papers on GTP that form a consensus about the potential benefit and disadvantages of GTP (CORE, 2011; Wang, C-K., et al., 2013; Makhnatch, P., et al., 2014; and EFCTC, 2016). Most appealing is GTP provides an actual temperature or temperature change metric and its implications are certainly more intuitively understood by the public and policymakers than a CO_2-equivalent burden. This said, a temperature change estimate can be made by multiplying cumulative GWP*'s CO_2-we metric by the TCRE coefficient, the enormous uncertainties from the climate sensitivity system should always be recognized. Furthermore, several drawbacks exist with the GTP method.

The GTP metric is more difficult to compute than any GWP. Furthermore, the results are based on a single point in time as opposed to accumulated over a time horizon and therefore does no account for any rate change for SLCP as is the case with GWP*. Thus, two emissions may produce the same temperature change at a given point in the future but may have followed much different trajectories in arriving at the point making intermediate consequences unknown (CORE, 2011). This is an important distinction because unknown intermediate effects of a harmful trajectory could exact critical unforeseen consequences that make the endpoint temperature moot. Furthermore, with all estimates of an unknown variable, there is uncertainty inherent in the estimate known as error variance. The uncertainty for the absolute GWP_{100} of CO_2 is estimated to be ± 26% (EFCTC, 2016), which in turn affects all GWPs and GTP for all gases that use CO_2 as a reference. For GTP, there are additional contributions from parameters not contributing to GWP that include ocean heat uptake and climate sensitivity. These additional parameters increase the uncertainty for GTP and make it a very imprecise metric. An uncertainty value of less than ±25% would be much more acceptable in order to be considered an improvement over the uncertainty of GWP_{100}.

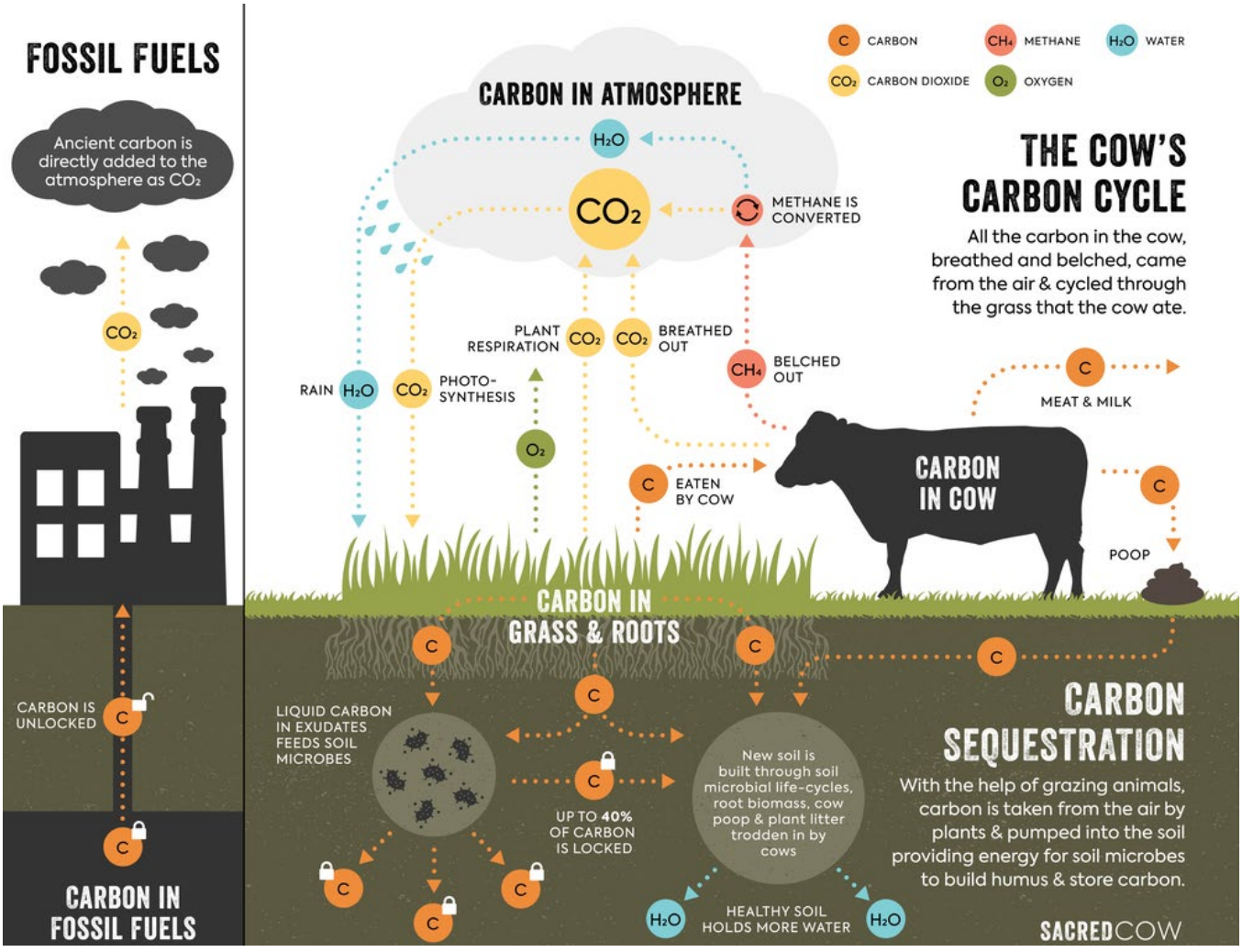
Given the large prediction uncertainties and the inability to track the trajectory of future estimates, only the endpoint, it seems unlikely that GTP would make a suitable replacement for either GWP or GWP*. However, it could perhaps be a useful adjunct metric provided adequate error ranges are provided. In fact, in the previous absence of other alternatives to GWP_{100} and considering GWP_{100}'s weaknesses with respect to SLCP, Brazil has in fact adopted GTP as the metric of choice in declaring its intentions for achieving the objective of the United Nations Framework Convention on Climate Change (COP24, Brazil).

> *There exists, one further shortcoming of all GWP estimates; the accounting for methane burden does not consider the biogenic nature of methane emissions from living creatures…*

Despite biogenic sourced CO_2 is not counted in the atmospheric CO_2 burden and arguments are being made that landfill gas (CH_4) should be carbon neutral (Env. Change Inst., 2005).

Ruminants have existed in great numbers for millions of years. The earliest ruminants appeared during the early Miocene Age in the Iberian Peninsula between 14 and 16 million years ago (DeMiguel, et al. 2008). Thus, ruminants were a part of the natural eco-system long before cattle, goats and sheep were domesticated, each about 10,000 years ago (Bollongino et al., 2012; Hirst, 2018; Hirst, 2019) and have been naturally contributing to atmospheric methane burden for millions of years. The carbon from ruminant enteric methane is of biogenic origin emanating from the methanogenic bacteria and protozoa resident in the rumen consuming cellulose in the plant matter eaten by ruminants. These microbes convert, via fermentation, cellulose (a complex carbon molecule) from the plant matter consumed by their host, into volatile fatty acids which the liver metabolizes into glucose, the main energy source for the host. Methane is a byproduct of the digestive fermentation process in the rumen. It is this adaptation that allows ruminants to survive through the consumption of plant matter that has no nutritional value to humans and other monogastrics. Furthermore, carbon containing organic fecal matter is recycled back into the soil thus sequestering a portion of the consumed carbon (Figure 9).

Figure 9. Cattle Carbon Cycling Vs. Fossil Fuels



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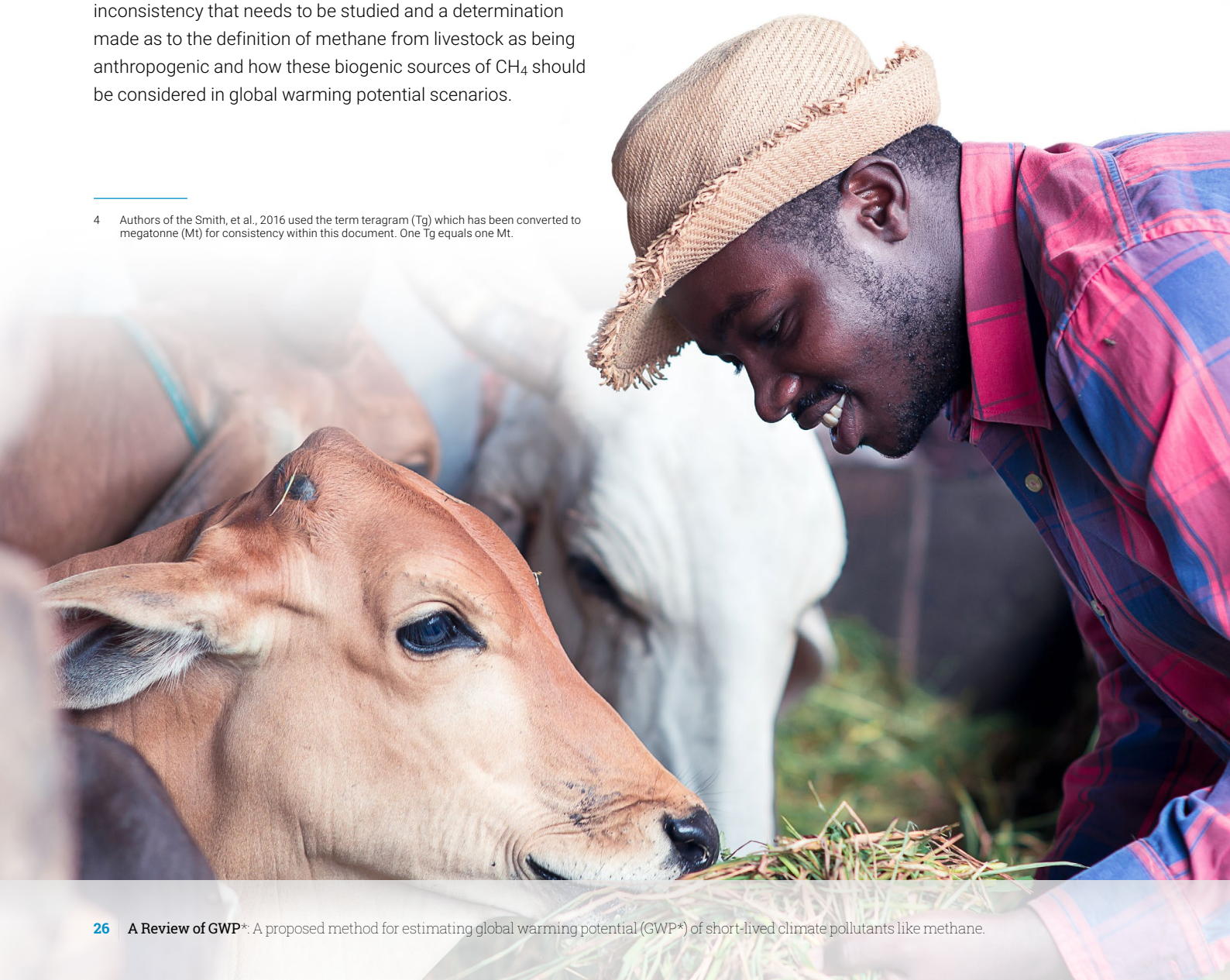
Reducing livestock populations, as some advocate (Ripple, et al., 2014), will not necessarily reduce animal populations on grazing land and therefore not reduce ruminant methane. Wildlife is opportunistic and when suitable ecosystems are vacated by domestic livestock it is likely this land will be repopulated by wild ruminants as has been demonstrated in Tanzania's Serengeti Wildlife Park where wildebeest herds have grown from 250,000 in the early 1960s to 1.5 million by 2004 (Fairlie, 2018). Given wild ruminants may not replace domestic livestock to the same extent that livestock thrive today, the replacement value could still be very significant (Manzano and White, 2019). Historical estimates indicate that pre-Industrial Age wild ruminant CH_4 emissions were nearly as large as present day livestock emissions. Hristov (2012) estimated that prior to the buffalo extirpation in the North American plains, CH_4 emissions from wild ruminants was 86% of current day domestic livestock in the U.S. if a population of 50 million bison is assumed. This could very well be a conservative figure. Smith, et al. (2016) estimated that global wildlife CH_4 emissions between 1800 and 1850 (138.5 Mt/yr)[4] were similar to current day modern livestock emissions (147.5 Mt/yr) or 94% of current day CH_4 emissions. It is therefore, noted that none of the GWP metrics (GWP_{100}, GWP*, or GTP) consider the biogenic nature of CH_4 as is done with CO_2. This is an inconsistency that needs to be studied and a determination made as to the definition of methane from livestock as being anthropogenic and how these biogenic sources of CH_4 should be considered in global warming potential scenarios.

In light of the fact that a major source of their GHG emissions come from agriculture, New Zealand has recently announced its environmental policy will now consider the effects of biogenic methane differently from other GHG gases, including anthropogenic CH_4 (NZMFE, 2019 and Wamsley, L., 2019). This represents a novel policy approach to methane emissions and necessitates new metrics.

> *GWP* will be a step in that direction but GWP* does not account for the biogenic nature of CH_4, only the fact that it is a SLCP.*

This policy also supports the notion that a more precise and consistent or standard methane inventory process is required.

4 Authors of the Smith, et al., 2016 used the term teragram (Tg) which has been converted to megatonne (Mt) for consistency within this document. One Tg equals one Mt.



Summary Conclusion

With respect to assessing global warming, policymakers need simple metrics for understanding the complex nature of multiple GHGs in order to set actionable goals for achieving 1.5°C maximum increase in atmospheric temperature by 2050.

GWP was developed as a simple metric with which to aggregate effects of multiple GHGs with differing warming potentials based on their RF and atmospheric residency, despite multiple warnings and caveats about its shortcomings.

Over the past 30 years, GWP has become the standard metric despite the shortcomings. GWP's primary shortcoming is in its limitation to accurately reflect the actual climate impacts from SLCPs. GWP overestimates the change in warming effect of an SLCP in the case of decreasing rates of emission, to the point of indicating a warming effect when in fact a cooling effect is actually occurring. Much above a 1% increase in an SLCP, GWP underestimates the increase in warming effect. Because methane is a major SLCP and the second leading cause of global warming, this weakness of the GWP metric is critical, especially to livestock (ruminant) agriculture. Concern over the validity of GWP for SLCP has in fact caused three countries (Brazil, Uruguay, and New Zealand) to explore the use of alternate metrics to express the impact of SLCP.

Scientists have developed a revised GWP metric, CO_2-we, using GWP* methodology which enhances GWP by inclusion of the rate of change of SLCP emissions in the calculations to convert SLCP emissions to a CO_2-we. Four peer reviewed publications demonstrating the validity, effectiveness, and application of the GWP* metric, are in print. The GWP* metric requires only one additional SLCP emission rate specification and one extra step in computation to estimate CO_2-we from CO_2-e. Collection of at least a second emission separated in time should not be a burden for any organization or country monitoring their methane emissions on a regular basis to demonstrate progress towards an emission reduction goal.

> *Because GWP* methodology is an enhancement of GWP methodology, not a replacement, it is important that each individual GHG contributions are reported separately.*

As well as the CO_2-we of SLCPs, to comply with UNFCCC rules, enhance communication, and preserve important climatic information.

Lastly, utilization of the TCRE coefficient, CO_2-we can be translated into an approximate estimate of temperature change associated with the change in CO_2 burden. This is not possible with GWP (CO_2-e) estimates. Further investigation is needed to incorporate the information from GWP* on SLCP mitigation into current processes of making mitigation policies.

With respect to livestock, the ramifications of the GWP* metric are profound in that when incorporated into regional assessments, it may become evident that decreases in emissions may have already caused a relative cooling effect in the regions where ruminant populations have declined and/or productive efficiency is increased.

> *The GWP* metric, in combination with the TCRE, make it possible to develop scenarios in which the temperature effect on the atmosphere can be estimated.*

However, and unfortunately, there continue to be shortcomings in methane inventory accounting methods which have effects on estimating the environmental impact of livestock, especially ruminants. These include inconsistent classifications of methane sources, overlooking new sources of methane emissions, accounting for release of sequestered carbon, discounting completely the biogenic nature of livestock emissions, and lack of accounting for current and historic wild ruminant populations.

NOW WHAT? – Implications and Impacts of Adoption of GWP*

A common question with any change, is "is it fair?" The first understanding is that there is need for some GHGs in the atmosphere to create sufficient warming for life to exist. The second understanding is that GHGs exist as part of the carbon cycle and it is only when the cycle becomes unbalanced between sources and sinks that a shift in warming or cooling takes place.

The warming potential of a specific GHG is due to its radiative forcing (RF) and persistency in the atmosphere, and there is wide variation between GHGs with respect to both traits. Carbon dioxide is the most common GHG by far and it remains in the atmosphere for millennia. It has by far the greatest effect on atmospheric warming and serves as the reference by which to compare all other GHG's warming effect. The challenge is making this comparison when there is a significant time difference between the atmospheric residency of a GHG compared to CO_2, which is the case with methane, which has a half-life of 8.6 years compared to thousands of years for CO_2.

The GWP conversion to equate the warming effect of GHGs to CO_2 was developed as a "simple" means by which policymakers, plant operators, reporters and others could translate the effect of GHG emissions relative to CO_2. This was done with full knowledge that GWP had caveats and weaknesses with respect to short-lived climate pollutants like methane. However, the problem with GWP, is that it provides a single point estimate in time for the warming effect of a single pulse of a GHG, and only considers the integrated RF for both SLCP and CO_2. Thus, GWP provides an adequate translation to CO_2-e for long lived climate pollutants like N_2O, but not for SLCPs. As a result, this also negates the ability of GWP to be used to associate temperature change to SLCP emissions burden. To address this shortcoming of GWP, GWP* has been introduced as an enhancement to GWP. In fact, GWP* is rooted in GWP methodology because when only one emission estimate is available, the GWP* formula reverts to a GWP estimate of CO_2-we.

With any improvement, adoption of GWP* necessitates change. Change is often viewed as a problem with winners and losers when in fact, if the change provides a benefit to the greater good of all, then previous circumstances were inherently flawed. Those flaws may have benefited an undeserving few and put undue burden on the remainder. With respect to methane emissions, under the GWP methodology, the impacts from those that have been reducing methane emissions cannot be correctly reflected and the fact that they have been helping to reducing the warming of the atmosphere has not yet been recognized. At the other end of the spectrum, increasing sources of methane emissions, such as previously unidentified sources of natural emissions like the Red Sea, evolving natural sources such as the melting of Arctic permafrost, or relatively new anthropogenic sources such as recovery of oil from shale, have not been shouldering their share of the warming effect of methane.

In conclusion, it is difficult to state that "increasing accuracy" of a measurement is fair or unfair. It simply provides better information on which to make the most informed decisions. The ability to send mankind to the moon depended on accurate calculations. Likewise, reduction of global warming, which affects us all and even more so, our children and grandchildren, requires accurate information in order to identify key opportunities to reduce the warming effect, project change in the global temperature, set effective goals, and monitor progress towards those goals. Stated simply, GWP* provides more accurate information regarding SLCP emissions than GWP. Lastly, GWP* is only part of the improvement of more accurate information. It is also imperative that methane inventory processes and measurements be improved. This includes inclusions of previous unidentified sources of methane, new sources, and better information on animal census data for both wild and domestic ruminants.

Appendix

GWP*$_H$ Table of Coefficients ($C_{(t)}$ and $P_{(t-\Delta t)}$) for Δt = 0 to 50

Δt (yr)	GWP*$_{20}$ H=20, GWP$_H$=86, r=0.75, s=0.25		GWP*$_{100}$ H=100, GWP$_H$ = 34, r=0.75, s=0.25	
	$C_{(t)}$	$P_{(t-\Delta t)}$	$C_{(t)}$	$P_{(t-\Delta t)}$
0	86.00	0.00	34.00	0.00
1	1,311.50	1290.00	2,558.50	2,550.00
2	666.50	645.00	1,283.50	1,275.00
3	451.50	430.00	858.50	850.00
4	344.00	322.50	646.00	637.50
5	279.50	258.00	518.50	510.00
6	236.50	215.00	433.50	425.00
7	205.79	184.29	372.79	364.29
8	182.75	161.25	327.25	318.75
9	164.83	143.33	291.83	283.33
10	150.50	129.00	263.50	255.00
11	138.77	117.27	240.32	231.82
12	129.00	107.50	221.00	212.50
13	120.73	99.23	204.65	196.15
14	113.64	92.14	190.64	182.14
15	107.50	86.00	178.50	170.00
16	102.13	80.63	167.88	159.38
17	97.38	75.88	158.50	150.00
18	93.17	71.67	150.17	141.67
19	89.39	67.89	142.71	134.21
20	86.00	64.50	136.00	127.50
21	82.93	61.43	129.93	121.43
22	80.14	58.64	124.41	115.91
23	77.59	56.09	119.37	110.87
24	75.25	53.75	114.75	106.25
25	73.10	51.60	110.50	102.00
26	71.12	49.62	106.58	98.08
27	69.28	47.78	102.94	94.44
28	67.57	46.07	99.57	91.07
29	65.98	44.48	96.43	87.93
30	64.50	43.00	93.50	85.00
31	63.11	41.61	90.76	82.26
32	61.81	40.31	88.19	79.69
33	60.59	39.09	85.77	77.27
34	59.44	37.94	83.50	75.00
35	58.36	36.86	81.36	72.86
36	57.33	35.83	79.33	70.83
37	56.36	34.86	77.42	68.92
38	55.45	33.95	75.61	67.11
39	54.58	33.08	73.88	65.38
40	53.75	32.25	72.25	63.75
41	52.96	31.46	70.70	62.20
42	52.21	30.71	69.21	60.71
43	51.50	30.00	67.80	59.30
44	50.82	29.32	66.45	57.95
45	50.17	28.67	65.17	56.67
46	49.54	28.04	63.93	55.43
47	48.95	27.45	62.76	54.26
48	48.38	26.88	61.63	53.13
49	47.83	26.33	60.54	52.04
50	47.30	25.80	59.50	51.00

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Abbreviations

ARn	IPCC Assessment Report where n is an ordinal number 1 to 5 with AR5 being the most recent
AW	atomic weight
C	carbon
CFC	chlorofluorocarbon
CH_4	methane
CO_2	carbon dioxide
CO_2-e	carbon dioxide equivalent. A commonly used means to express different GHGs as an equivalent quantity of carbon dioxide. Typically, it is the 100-year global warming potential as defined by IPCC but other methods have also been proposed which can give a quite different picture of the impacts of various GHGs.
CO_2-e*	carbon dioxide equivalent as determined by the first method used to estimate GWP*
CO_2-we	carbon dioxide warming equivalent estimated by the revised method to estimate GWP*
EPA	United States Environmental Protection Agency
FAO	United Nation's Food & Agriculture Organization
g	one gram
GHG	greenhouse gas
GWP_n	global warming potential where n represents a time horizon in years, typically 20, 50 or 100. GWP_{100} is now considered the standard as published by IPCC
GWP*	an alternative application of global warming potentials to derive carbon dioxide equivalents that primarily relates the change in the rate of short-lived GHGs, such as methane, to a fixed quantity of CO_2, rather than a direct equivalence between emissions of both short and long-lived GHGs.
Gt	Gigatonne equal to one billion tonnes
GTP	Global Temperature Change
H_2O	water
IPCC	Intergovernmental Panel on Climate Change is the United Nations body for assessing the science related to climate change
K^o	degrees Kelvin. One degree Kelvin equates to one degree Celsius.
Kg	one kilogram equal to 1,000 grams
LLCP	long-lived climate pollutant
LCA	live cycle assessment
Mt	megaton which equals one million metric tonnes
N_2	nitrogen
N_2O	nitrous oxide
O_2	oxygen
O_3	ozone
OH	hydroxyl radical
pH	measure of acidity with 7 being neutral, higher numbers basis, and lower numbers acidic
ppb	parts per billion
ppm	parts per million
RE	radiative efficiency
RF	radiative force
SLCP	short-lived climate pollutants
t	one metric tonne equal to 1,000 kg or million grams
Tg	A teragram equals one trillion grams or one million tonnes
TCRE	Transient Climate Response to cumulative carbon Emissions
Tt	a teratonne equal to one trillion tonnes
UNFCCC	U.N. Framework Convention on Climate Change (framers of the COPxx meetings)
W/m^2	watts per square meter

Glossary

Albedo The proportion of light or radiation that is reflected by a surface

Anaerobic Activity or processes that require an absence of oxygen

Anthropogenic Originating from human activity

Aerobic Activity or processes that require oxygen

Atomic Weight The mass of a single atom of a specific element which relates primarily to the number of protons and neutrons in the most stable (at rest) form of the atom.

Biogenic Originating from biologic processes

Biomass Dry weight of plant-based material that has been harvested or is available on an area of land. Typically, it refers to the use of plants not used for food or fiber but rather burned for energy capture.

Carbon (C or ^{12}C) A basic element with a usual molecular weight of 12 due to 6 protons and electrons each and 6 neutrons. Some forms of carbon have 7 or 8 neutrons known as ^{13}C and ^{14}C respectively. These alternative forms of carbon degrade into C^{12} at a known rate.

De Minimis Too small to be considered

Dimer A molecule or molecular complex consisting of two identical atoms or molecules linked together

Enteric Relating to or originating in the digestive system. Enteric fermentation is a natural part of a ruminant's digestive process.

Extirpation Extinction of a species within a region or defined area

Flow pollutant A gas with a relatively short atmospheric lifetime, AKA SLCP, e.g. methane

Global warming potential (GWP) A commonly used means of quantifying the strength of different greenhouse gas emissions relative to carbon dioxide. It is derived from estimating the total change in atmospheric energy balance resulting from a pulse emission of the gas, relative to CO_2, over a specified time frame (typically 100 years).

Greenhouse gas (GHG) A gas that can capture and retaining heat from sunlight thus warming the atmosphere

Half-life The time it takes for ½ of a substance to disappear

Halogens Fluorinated and chlorinated (halogenated) molecules used in manufacturing, electrical equipment, refrigeration and air conditioning, medicine, metallurgy and as aerosol propellants. Compounds include CHC, HCFC, HFC, PFC, SF_6 and NF_3.

Hydrate A crystalline structure in which water is bound with another element or compound to for a solid. In the case of this document, "hydrate" will refer to methane hydrate

Hydrogen (H) The most basic element with an atomic weight of one because of normally having one proton and one electron.

Hydroxyl radical (OH) A highly reactive molecule responsible for the initial reaction leading to most methane destruction in the atmosphere and important for the removal of many other atmospheric pollutants. Radicals are molecules or atoms with an unpaired electron, usually making them very reactive.

Intergovernmental Panel on Climate Change (IPCC) - An intergovernmental body of the United Nations, dedicated to providing the world with an objective, scientific view of climate change, its natural, political and economic impacts and risks, and possible response options. The IPCC's parent organization is the World Meteorological Organization.

Isotope An alternative form of an element because of a variation in the number of neutrons in the nucleus

Lifetime Length of time a pulse or part thereof persists in the atmosphere

Lithosphere Rocks of the Earth's crust

Methane (CH_4) The second most common greenhouse gas made up of one carbon and four hydrogen atoms with a molecular weight of 16

Methanogenic A process or organism that produces methane

Methanotrophic A process or organism that consumes methane

Molecular weight (MW) The sum of atomic weights of all the atoms making up a molecule.

Nitrogen (N) Element with an atomic weight of 14 in its most common state in nature due to its 7 protons and 7 neutrons

Nitrous Oxide (N_2O) Compound consisting of two nitrogen atoms and one oxygen atom with a molecular weight of 44

Oxygen (O) Element with an atomic weight of 16 in its most common state in nature due to its 8 protons and 8 neutrons

Ozone (O_3) Atmospheric compound made up of 3 oxygen atoms which high above the earth protects the earth from ultraviolet radiation from the sun, however in the troposphere is considered a pollutant with GHG effect and harmful to human health.

Photolysis The decomposition or separation of molecules by the action of light

Radiative efficiency (RE) A measure of greenhouse strength for different greenhouse gases, defined as the change in radiative forcing per change in atmospheric concentration of a gas

Radiative forcing (RF) A measure of how different factors (including greenhouse gases) change the balance between incoming and outgoing energy in the atmosphere. Expressed as the change in energy balance per unit area (Wm^{-2}), over a given timeframe, typically comparing contemporary conditions to preindustrial conditions. In more simple terms, it is the difference between insolation (sunlight) absorbed by the Earth and energy radiated back to space.

Rate of decay The speed at which a substance is disappears or is broken down into component parts, usually expressed in terms of a half-life

Residence time Time required for a pulse emission of a GHG to be removed from the atmosphere by natural processes.

Ruminant A mammal with a four chambered stomach. The first chamber which is known as the rumen is an organ in which plant feedstuffs not normally digested by monogastric (single stomach) animals are broken down by bacteria and protozoa into proteins and sugars through fermentation which releases methane as a byproduct. Examples of ruminant animals include: domestic species such as cattle, sheep, goats, llama, water buffalo and camels; and wild species such as bison, deer, elk, moose, caribou, mountain goats, big horn sheep, giraffes, yak, water buffalo, gazelles, impalas, musk ox, wildebeest, and among others.

Sequester To hide or take out of circulation and deposit in a sink

Sink A storage place out of the atmosphere or a method of decay

Stratosphere The second layer of atmosphere up from the Earth's surface extending from 10 km to 50 km up. The stratosphere is where the protective ozone layer resides, protecting the Earth surface from radiation from the sun and where commercial aircraft fly.

Stock pollutant Gas with a long atmospheric lifetime, AKA LLCP, e.g. carbon dioxide

Tonne Metric ton which equals 1,000 kilograms or 2,204.6 pounds

Troposphere Lowest level of the atmosphere in which most lifeforms live and extends 6 to 10 km above the Earth's surface which is the boundary of the next level called the stratosphere.

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