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Article

Increased Transparency in Accounting Conventions Could Benefit Climate Policy

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Abstract: Greenhouse gas accounting conventions were first devised in the 1990's to assess and compare emissions. Several assumptions were made when devising these conventions that remain in practice, however recent advances offer potentially more consistent and inclusive accounting of greenhouse gases. We apply these advances, namely: gross accounting of CO₂ sources; linking land use emissions with sectors; using Effective Radiative Forcing (ERF) rather than Global Warming Potentials (GWPs) to compare emissions; including both heating and cooling emissions, and including loss of additional sink capacity (LASC). We compare these results with conventional accounting and find that this approach boosts perceived carbon emissions from deforestation, and finds agriculture, the most extensive land user, to be the leading emissions sector and to have caused 60% (32%-87%) of ERF change since 1750. We also find that fossil fuels are responsible for 17% of ERF, a reduced contribution due to masking from cooling co-emissions. We test the validity of this accounting and find it useful for determining sector responsibility for present-day warming and for framing policy responses, while recognising the dangers of assigning value to cooling emissions, due to health impacts and future warming.

Keywords: emissions accounting; Agriculture emissions; deforestation; effective radiative forcing; emission sectors; animal agriculture; fossil fuel

1. Introduction

Greenhouse gas accounting conventions have played a major role in framing our understanding of what human activities cause climate change, and in guiding policy responses [1]. Several assumptions were made when these accounting conventions were first developed, because land use emission processes were unclear, land carbon emissions were thought to be part of a self-balancing biosphere carbon pool, and aerosol cooling and atmospheric interaction of emissions were little known. These assumptions include the focus on fossil fuel emissions, the adoption of net land carbon accounting, exclusion of aerosol cooling and the arbitrary choice of 100 year GWPs to compare gases [2].

Since these conventions were framed climate science has advanced and estimates of biosphere and ocean carbon flux have improved. One recent advance in emissions accounting – consistent gross CO₂ accounting – has substantially boosted the value of land use emissions, particularly deforestation, placing fossil fuels second to land use as a carbon emission source [3]. A second development - emissions-based Effective Radiative Forcing (ERF) – has removed the need for time period-related metrics to compare different gases, enabling potentially more accurate estimates of climate impact of each gas [4]. Thirdly, when cooling emissions are included, these advances allow us to better determine responsibility for present day warming and to re-examine policy responses. Newly available time series datasets, together with ERF models constrained to observations, now allow us to more fully answer the question “What human activities have caused present-day warming?”

The aim of this study is to consolidate arguments supporting these advances, to combine and apply these to emissions data from 1750-2020, to compare their impact, and to establish sector responsibility for present-day warming. The novel aspect of this study is to determine the combined effect of these proposed advances, to test their validity and to explore their usefulness to climate policy.

2. Review of Novel Emissions Accounting Advances

2.1. Consistent CO₂ Emissions Accounting

The IPCC inventory category Land Use/Land Use Change and Forestry (LULUCF) reports *net* CO₂ emissions and sinks on 'managed' land, whereas all other emissions, CO₂ or otherwise, are reported as *gross* [5]. Wedderburn-Bisshop 2024 reviews the arguments supporting consistent *gross* accounting and its implications, finding that LULUCF has released more CO₂ than fossil fuels, with *gross* emissions 2.8 times greater than *net* since 1750 [3]. Consistent accounting thereby boosts the relative climate impact of sectors causing LULUCF emissions, notably agriculture and forestry.

Presently, convention dictates that 100% of fossil carbon is counted but only a third of LULUCF carbon is counted (the part that remains in the atmosphere to cause warming). The inconsistency here is that carbon emissions from all sources have an equal proportion remaining in the atmosphere. To be consistent, carbon emissions from all sources could be assessed as *net or gross*. Here we adopt the latter.

Extending this reasoning, slash and burn agriculture – where regrowth follows deforestation – has been noted as an example where net accounting may be justified. However, photosynthesis cannot be claimed as anthropogenic, other than plantings, as it occurs *despite* human intervention. Making the distinction that Nature is responsible for plant growth and humanity responsible for deforestation underlines the need for full gross carbon accounting to more fully describe sources and sinks [3].

Net LULUCF CO₂ accounting was also justified with the reasoning that fossil fuel carbon is 'truly new carbon', additional to the biosphere carbon pool. Gross carbon accounting (consistent with treatment of all other emissions) reasons that old growth deforestation carbon is equally 'new carbon'.

2.2. Inclusive Accounting

Sector contributions are incomplete due to conventional partial accounting. This is most obvious in the case of fossil fuels, where co-emitted aerosols, whose cooling has until now masked most CO₂ warming, are rarely reported [4]. Including short term emissions leads to a more comprehensive and inclusive inventory, however there are other factors that must be considered, such as the dangers presented by aerosols to human health [6] as well as implications for longer term warming (see 5.3).

Partial accounting is also evident in attributing land use emissions to agriculture. Although several authors have looked at comprehensive land and agriculture emissions, eg [7,8], net accounting is used and past deforestation is overlooked. Fossil carbon emissions overtook land emissions in the 1960's, but warming from past land carbon emissions continues. This can be rectified by incorporating past deforestation as done here, or by including carbon opportunity cost in yearly inventories [9]. Agricultural fire emissions are also partially and inconsistently accounted, as discussed in Supplementary Material.

2.3. Using ERF for Sector Comparison

Debate on how to compare the various greenhouse emission species has been robust, particularly comparing CO₂ to methane [10], hindering agreement on mitigation effectiveness and sector comparisons [11]. 100-year Global Warming Potentials (GWP₁₀₀) are the conventional IPCC metric, but recent advances in emissions-based Effective Radiative Forcing (ERF) and derived Global

Surface Air Temperature (GSAT) change, as described in the IPCC's AR6 Section 6.4 and Supplementary Material 6.SM.1 [4], present a more comprehensive and less time period-related means of comparing emission species.

Emissions-based ERFs are tested and constrained with historic observations, making them ideal for this study of warming since 1750 [12]. ERF is believed to produce more accurate estimates of climate impact for agriculture because conventional GWP use can distort mitigation effectiveness [13]. Although ERFs are seen to be most useful for this study, the benefit of GWPs is that their time periods can be chosen for future climate target dates [11]. Matthews et al., 2009, validate the use of sector cumulative emissions, finding that climate response is not sensitive to background concentrations or timing of those emissions [14].

Aviation is comparable to agriculture in that it produces an array of long- and short-lived emissions, aerosols, as well as water vapour and cloud impacts. ERF is now commonly used in aviation climate impact studies as the most accurate means of comparing these disparate emissions and impacts [15].

2.4. Loss of Additional Sink Capacity (LASC)

Land use change such as deforestation not only causes landscape carbon loss but also prevents future additional vegetation carbon storage that would have occurred, mostly due to CO₂ fertilisation. The 1850-2021 timeseries used here is from Dorgeist et al., 2024, who estimate LASC to be 2.7Gt CO₂ /year for the period 2012-2021 [16].

3. Materials and Methods

3.1. Data Sources

Carbon emission timeseries from 1750 to 2020 are from the Global Carbon Budget, with Houghton and Castanho 2023 (H&C) LULUCF gross CO₂ data, LASC from Dorgeist et al., 2024, with timeseries data for all other emission species from PRIMAP-hist, CEDS and FAO data plus fire emissions from the GFED4. Data source references are given in Table S1. Data on land use carbon deficit are from Erb et al., 2018 [17], and crop outputs are further allocated using biomass flows from IPCC AR5 chapter 11[18]. Detailed data on agricultural emissions is now available (e.g., [19]), but these studies do not capture past deforestation.

Emissions-based ERF values since 1750 are from the IPCC's AR6 Section 6.4, and Supplementary Material 6.SM.1 [4], with error updates from Roesch et al., 2024 [20]. Data are limited to the 11 emission species for which emissions-based ERF is documented [4], being carbon dioxide (CO₂), methane (CH₄), nitrous oxide (N₂O), halocarbons, nitrogen oxides (NO_x), non-methane volatile organic compounds (NMVOCs), carbon monoxide (CO), sulphur dioxide (SO₂), organic carbon (OC), black carbon (BC) and ammonia (NH₃). Land use albedo change is from AR6 chapter 7 [21].

This study has not applied time-discounted land carbon emissions. We believe that no discount rate is warranted when using gross accounting of CO₂ as we do here, because cumulative ERF is calculated for the entire period from 1750, and any discounting based on carbon drawdown could be equally applied to fossil fuel and LULUCF carbon emissions because they share the same fate: biosphere drawdown with a remaining airborne fraction.

3.2. Attributing ERF and GSAT to Sectors

Sectors have been chosen to demonstrate the impact of these accounting advances, being 'Fossil Fuel'; 'Industry'; 'Agriculture', further divided into 'Animal Agriculture' and 'Other Agriculture'; 'Forestry'; 'Waste'; and 'Other'. Animal Agriculture is identified separately due to its high emissions and land use. These sector groupings require dissecting to finer detail, but for the purpose of this study, they demonstrate the concepts. The agriculture categories include land and production emissions only, and do not include on-farm fossil fuel use, processing, or distribution.

Please see Supplementary materials Section 2 for a full description of Methods. In brief, methods are as follows: Proposed accounting changes as listed in Table S2 items 1, 2 and 4 are acquired from published datasets as per Table S1, and ERF is applied in the following manner:

1. For each emission species, cumulative emissions and sector contribution proportions are taken from the data and multiple studies as referenced, presented in Tables S4 and S5.
2. ERFs for each emissions species, as published in AR5, are then allocated to sectors in the derived proportions (Table S5).
3. ERFs for each sector are then the sum of ERFs for each species attributed to each sector (Table S6).

3.3. Errors and Accuracy

Uncertainties are drawn from the source data and published ERF estimates as referenced. Land use emissions are variable from year to year, however the use of cumulative emissions from 1750-2020 minimises any variability influence.

Recent fossil fuel CO₂ emissions are known to +/- 5% [22], however biosphere carbon flow uncertainty is in the order of +/-20% [23]. Aerosol cooling is an important contributor to this assessment that has an even higher uncertainty, in the order of +/-70% [4]. Sector ERF uncertainty estimates are given in Results. These uncertainties imply that this study gives an indicative, rather than exhaustive result, however agriculture emissions are conservative.

Gross LULUCF CO₂ emission values from Houghton and Castanho, 2023, are conservative because: a) deforestation emissions are based on FAO *net* in-country data, thereby excluding re-clearing [24,25]; b) gross forest loss from finer-grained remote sensing studies indicate that forest loss exceeds current estimates [26,27], perhaps four times greater in extent than previous assessments [28]; and c) emissions are understated due to narrowly defined managed land [29].

Additionally, there are two major reasons why these values are conservative. Firstly, this study is limited to emissions from 1750-2021, ignoring the 1,100Gt CO₂ deforestation emissions prior to 1750 [30]. Secondly, carbon from agricultural fires that suppress forest regrowth is excluded for reasons given in Supplementary Material, which, if included, would double agricultural carbon emissions [31].

Several recently published data sets document agricultural emissions to a greater detail than that used here, e.g., [32,33], however these use conventional net land carbon accounting and are not directly relatable to the sectors as used here. This offers a useful area for further study.

4. Results

It should be noted that these results are based on the following assumptions: 1. That land use carbon emissions are accounted in full, rather than with conventional net accounting (see 2.1); 2. That both heating and cooling emissions due to each sector be included (see 2.2); and 3. That emissions-based ERFs are more suitable for assessing warming from each gas. Results of applying proposed accounting changes listed in Table 1 are given in Supplementary Table S6, and Figure 1 and 2 below.

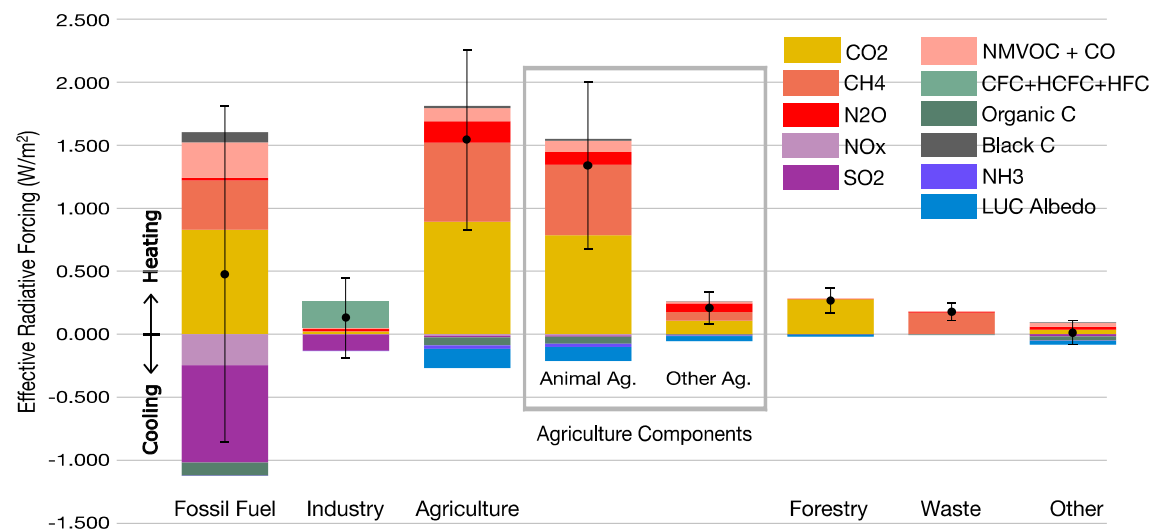


Figure 1. Effective Radiative Forcing by sector and emission 1750-2020. Data are from Table S5.

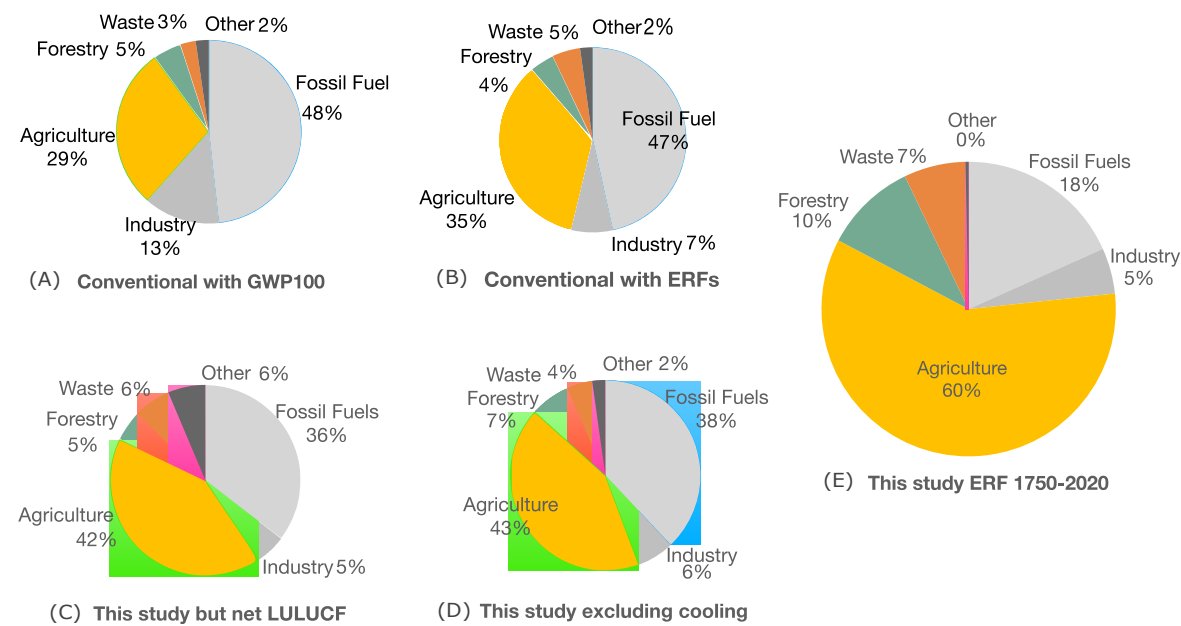


Figure 2. Accounting comparisons of sector responsibility for present-day warming (1750-2020). (A) and (B) show conventional accounting with GWPs and ERFs. (C) and (D) show the impact of gross/net LULUCF and excluding cooling emissions, and (E) shows the impact of all proposed accounting changes.

4.1. Consistent Gross LULUCF CO₂ Accounting

Of the accounting advances applied here, consistent gross CO₂ emissions accounting is the most unconventional but consequential. Gross accounting finds that since 1750 agriculture has emitted 98% as much CO₂ as fossil fuel, and forestry has emitted 30% as much CO₂ as fossil fuel.

Forestry carbon emissions (timber harvest and wood fuel) are estimated here proportionally to land carbon deficit. However, comprehensive forestry sources and sinks can be quite complex, e.g., [34], therefore our Forestry estimate here should be seen as indicative.

4.2. Sector ERF and GSAT

ERF of each emission species is attributed to sectors as described in 3.2, and derived sector ERF and GSAT values are presented in Table S6.

This attribution finds that agriculture has caused 0.74°C (0.47°-0.99°C) net GSAT warming from 1750 to 2020, with 86% of this (0.64°C, 0.42°-0.85°C) attributable to animal agriculture. Fossil fuels have caused 0.21°C (-0.44°-0.85°C) net GSAT change due to strong SO₂ and NO_x aerosol cooling. Methane, having no cooling co-emissions, is responsible for 0.60°C (0.41°-0.78°C) warming. Inclusive accounting finds that fossil fuel warming is 0.79°C together with 0.59°C cooling from co-emissions, whereas agriculture has caused 0.86°C warming but only 0.13°C cooling, with most of the cooling from land use albedo change and organic carbon from fires.

Figure 1 presents results from Table S5, showing sector ERF due to each emission species and land use albedo change.

Figure 2 compares the impact of each of the accounting changes using the full 1750-2020 datasets. Figure 2A shows the results of conventional accounting (including the use of GWP₁₀₀), and 2B shows the same data but using IPCC published ERF values. Note that ERF values reflect greater warming from methane.

Figure 2C-E show the impact of proposed accounting changes. Both C and D are similar in sector proportions, indicating that the impact of using conventional net LULUCF and the impact of excluding cooling emissions are of similar scale. Figure 2E shows the sector results of applying all proposed accounting changes, summarising the results of Figure 1. Here we see that gross LULUCF and the inclusion of cooling emissions have a rather dramatic impact on sector responsibility for present-day warming, with agriculture dominating at 60% of warming.

4.3. Validation and Sensitivity Analyses

Gross LULUCF carbon accounting and sector attribution: Present-day land use offers a reasonability test on land carbon emissions, being the result of all previous land use changes. The 2019 IPCC report on climate change and land [35] finds that grazing pastures take up 37% of the ice-free land; managed forests 22%; and cropland 12%, with built-up land taking up 1%. Grazing therefore uses 75% of agricultural land, with cropland using 25%. This compares with the carbon deficit as used here of 49% for grazing, 25% for crops, 23% for forestry and 2% for infrastructure. This comparison is reasonable considering that cropland emissions are greater due to higher original forest cover, and about half of grazing land was originally grassland, resulting in lower carbon loss.

A sensitivity analysis was carried out using 15% higher and 15% lower gross LULUCF carbon emissions. This increased/decreased total carbon emissions, but the relative ranking of sectors did not change.

Sector contributions using ERF rather than GWPs: In other studies using this methodology, Dreyfus et al., 2022 [36] used ERF in a similar way, finding that fossil fuels had caused 20% of net global warming to 2015. Here we find fossil fuels caused 17% of net warming to 2020 (Figure 2E). In addition, Dreyfus et al. found methane to be responsible for 50% of GSAT temperature rise, whereas we find it to have caused 49% of net GSAT.

As a comparison with GWPs, from 1750 to 2020, 4216Gt of CO₂ and 26.4Gt of methane was emitted from all sources, causing 2.058W/m² and 1.195W/m² ERF respectively. Cumulative methane emissions therefore caused 92 times more ERF than CO₂ since 1750 by weight. This value can be partially explained by the use of gross carbon accounting, but is greater than the conventional GWP₂₀ factor of 82. If emissions were tabulated each year using the conventional GWP₁₀₀ factor, this would have underestimated methane's ERF.

A sensitivity analysis was carried out using the same ERF dataset, but with emission sector proportions from recent emissions data (from 2000 to 2021). This approach is a test on sensitivity to sector proportions such as fossil fuels becoming the dominant CO₂ emission source circa 1965, and the dramatic rise in all emission species, particularly the 250% rise in airborne methane. As expected,

the fossil fuels/industry sector rose slightly in ranking, but agriculture remained the leading emissions sector.

5. Discussion

5.1. Significant Findings

This work clearly identifies agriculture as the leading cause of present-day global warming, substantially due to CO₂ from past and present deforestation, followed by methane. Unlike fossil fuels, agriculture has produced minimal cooling emissions to offset its warming.

Within this sector, animal agriculture provides 'low hanging fruit' mitigation opportunities that could benefit several Earth systems, particularly biodiversity and climate. Animal agriculture is the greatest methane emitter, but it also offers the greatest carbon opportunity cost/drawdown potential.

This accounting brings into focus the impact of methane, which has caused a substantial 49% of total net GSAT temperature change and 70% of net fossil GSAT, but has little cooling co-emissions, as noted by others [36]. As noted in Section 4.3, the use of GWP₁₀₀ understates present-day warming from methane. Methane therefore presents itself as a prime target for mitigation, particularly because it is the only means available to slow warming in the near term [36,37].

5.2. Usefulness of This Accounting

This accounting is seen as useful because it:

- Offers a more comprehensive and transparent account of sectors driving climate change.
- Properly values emissions from past deforestation that are not visible with conventional greenhouse inventory accounting, but which still contribute to warming.
- Values current deforestation and avoided deforestation more consistently.
- Provides a more transparent and less contentious means to compare emission species.
- Re-focuses our attention on forests as a major climate disruptor, giving reason for optimism because deforestation is reversible.

Also, this accounting is beneficial in levelling the global north/south divide, in that developed countries deforested long ago can be compared with those experiencing active deforestation. At present, Brazil is being pressured to reduce deforestation, principally by the developed world, and as beneficial as that would be, this accounting would refocus critical attention on previously deforested nations as well as those experiencing current deforestation.

5.3. The Dangers of Aerosol Cooling

Including aerosol cooling is considered necessary for a comprehensive assessment of global warming, however that most cooling aerosols have a strong negative impact on health [6], and aerosol ERF values still have high uncertainty [38].

Cooling aerosols, as shown in Figure 1, although they are short-lived, have masked 75% of ERF from fossil fuel warming, but when skies clear of aerosols this will result in future warming. This is the 'Faustian bargain' [39] that may cause additional near term warming by as much as 0.5-1.1°C if cooling emissions are reduced [40]. Efforts to reduce aerosols due to their health impacts are proving effective [41], threatening additional warming in coming decades [38]. Cooling aerosols have been proposed as a geoengineering measure, however this introduces the prospect of 'cooling credits', that may dangerously distort carbon markets [42]. Also, most cooling aerosols have a strong negative impact on health [6]. The prospect of decreased aerosol cooling emphasises the urgency for quitting fossil fuels and drawing down legacy carbon.

Although its value is uncertain, its cooling impact is well accepted, as well as the understanding that short term emissions have a long term impact through climate-carbon feedback [43].

While uncertainties are high, a change to sector ranking is unlikely because LULUCF CO₂ emissions presented here are conservative for reasons given in Section 3.3.

5.4. Policy Implications

Choice of accounting conventions causes dramatic differences in sector responsibility for present-day climate change as seen in Figure 2. This indicates a pressing need to review accounting conventions and policy implications.

Within our global climate change experiment, we are running a highly successful aerosol geoengineering project that has prevented 0.9°C warming. This suggests that a continuation of this project away from population centres – where it has negative impacts – may be effective in meeting climate goals.

While quitting fossil fuels remains urgent, this accounting re-focuses our attention on forests. Normalising and adopting gross deforestation emissions accounting would support policies aimed at reducing deforestation and preserving forests, because deforestation and avoided deforestation carbon costs increase in value by a factor of 2.8 [3]. Forest restoration may also benefit from policies informed by a greater appreciation of the role of past deforestation in causing climate change, placing emphasis on this, the most effective, lowest cost natural mitigation option [44]. Knowing that clearing, or re-clearing in particular, re-releases an increasing proportion of fossil carbon [3] informs policy that destruction of forest of any age could be seen in the same way as burning coal.

The greatest obstacle to large scale drawdown is finding enough land. Based on carbon deficits from Erb et.al., 2018, we find that land used for animal agriculture has a carbon deficit of about 540Gt CO₂, equivalent to the last four decades of fossil carbon emissions. When we consider carbon opportunity cost as well as methane emissions, this confirms other findings that strong controls on animal agriculture would have a transformative impact on climate change [45].

Agriculture becomes the major disruptor of five planetary boundaries: biosphere integrity, land system change, freshwater change, biogeochemical flows [46], and now climate change. This emphasises the need for policies to address this sector if we are to have a liveable future. Agricultural subsidies globally have been described as overwhelmingly harmful [47]. Initiatives aimed at reducing harmful agricultural subsidies and initiatives such as the EU Green Deal are susceptible to industry influence, and misinformed and uninformed debate has enabled harmful agricultural industries to obstruct understanding and policy [48]. These accounting advances may usefully support policy reform.

6. Conclusion

This study aimed to review arguments for, and to apply accepted advances in emissions accounting that challenge conventions, to determine sector responsibility for present-day climate change, and to test their impact and usefulness to policy. These results appear to achieve the aim of portraying sector warming contributions more comprehensively and transparently. While there are reservations related to the inclusion of high uncertainty aerosol cooling, we believe this accounting is defensible. These results reinforce the value of forests and identify high emission sectors, which we believe will lead to better informed mitigation actions and assist our transition to the age of drawdown.

Supplementary Materials: S1 Table: Timeseries emission data sources. S2 Table: Methodology for attribution of LULUCF carbon emissions to sectors. S3 Table: Attribution of emission species to sectors. S5 Table: Attribution of emission species proportions to sectors. References [17–19,22,25,31,49–58] are cited in the Supplementary Materials.

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Conflicts of Interest: The author is biased against industrial scale deforestation, witnessed while monitoring deforestation for the Queensland government. This did influence the study topic, however every effort was made to make sure my personal judgement was unbiased.

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