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PAPER

The utility of novel environmental impact metrics in UK ruminant mitigation

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Abstract

Much of the UK land sector's environmental impact comes from the production of beef and dairy. Conventional metrics, which understate both the impact of methane reductions and the carbon opportunity cost of land, attribute most of this impact to enteric methane and land-use change from imported soy for feed. Recent developments in agricultural impact metrics necessitate investigation into whether continued reliance on conventional metrics could undermine national (and global) progress on climate and deforestation targets. This article estimates emissions and land use impacts associated with cattle in the UK and applies various combinations of metrics under four futures simulating a range of technological and policy levers. We find that the use of alternative metrics can highlight the potential impact of interventions that might have been overlooked when using conventional metrics, particularly encouraging more efficient production by including the carbon cost of foregone sequestration. We suggest that a range of metrics should be considered to ensure mitigation strategies which deliver on global outcomes, and show that estimates of absolute sectoral impact are acutely sensitive to methodological choices in how it is measured. We also find that the rank-ordering of different intervention strategies for the UK is largely insensitive to metric choice, though this may not be the case for all agricultural systems.

1. Main

Globally, agriculture accounts for nearly a third of greenhouse gas (GHG) emissions [1][7], and uses about half of the world's vegetated land [2]. 75% of this agricultural land area is dedicated to rearing livestock, either as pastureland or to grow feed crops [3]. Much of these climate and land use impacts can be attributed to cattle-rearing for beef and dairy products [4]. As scientists and policymakers explore possible pathways to mitigate these impacts at the country-level [5], there has been debate pertaining to how they should be measured, namely with regards to methane and land use. This debate has been particularly active in the UK in recent years, with farmer interest groups advocating for alternative methods of accounting for the impact of methane, and claiming to have one of the most efficient livestock systems [6, 7]. According to UK national statistics, agricultural production accounts for just over 10% of national emissions [8] and uses 69% of the country's land area [9]. A large proportion of these impacts comes from the production of beef and dairy [10–12]. This paper will use the UK cattle system as a case study to explore the discourse around metrics

[7] Calculated using Global Warming Potential over a 100 year time horizon.

used to quantify GHG emissions and land use and will assess the implications of applying each metric in a variety of mitigation scenarios representing hypothetical policy and technology interventions.

The objective of this analysis is to shed light on the role that metric choice could play in the development of national mitigation strategies in the livestock sector, and how those choices could hinder or facilitate progress on global environmental objectives.

1.1. GHG metrics

The production of animal-based products results in emissions of carbon dioxide, nitrous oxide, and methane. The sources of these emissions include the production and application of nitrogen fertilizers, energy use, manure management, and enteric fermentation [13]. Methane, unlike nitrous oxide and carbon dioxide, is a relatively short-lived climate pollutant. Long-lived GHGs accumulate in the atmosphere, while methane breaks down after about 12 years [14]. This property can be overlooked by conventional GHG metrics.

The global warming potential (GWP) metric is calculated as the relative radiative forcing caused by a pulse emission of a non-CO_2 GHG relative to that due to a pulse of CO_2 over a given time horizon [15, 16]. GWP calculated over a 100 year time horizon (GWP_{100}) is the most common metric at both the corporate and national levels [17, 18]. Methane is a very strong climate-forcer over a decadal time horizon. Thus, some argue that equating it with carbon dioxide over 100 years underestimates the consequence of increasing—and the benefit of decreasing—methane emissions [19, 20]. GWP is sometimes also reported over a 20 year time horizon, though critics claim this over-incentivizes methane reductions and would allow entities to avoid reduction of $CO_{2,}$ which accumulates over time [21].

While GWP (specifically over 100 years) has been widely used, it has also faced criticism. Some have argued that climate objectives can be more optimally met by tracking each GHG' contribution to radiative forcing over time, rather than trying to use a common unit over an arbitrary time horizon [22, 23]. Others argue that radiative forcing is less relevant for policy than other outcomes such as temperature change or loss and damage [22, 24]. More recent developments in emissions metrics bring attention to the problems that arise when comparing long- and short-lived GHGs.

First published in 2016, GWP* (GWP- star) compares emissions of different GHGs in terms of CO_2-warming-equivalent emissions, recognizing the difference in how cumulative and non-cumulative GHGs behave in the atmosphere [25–27]. Rather than equating the impacts of short-lived GHGs to those of CO_2 for a given parameter over a chosen time-horizon, the calculation for GWP* is based on the rate of change of short-lived GHGs over a 20 year period [28]. Thus, at least 20 years of historical methane data, or some estimate of what methane emissions were 20 years ago, are required for the calculation. This rate of change mechanism distinguishes it from metrics such as conventional GWP. Using this approach, the results reflect the effect of long-term contribution to warming of changes in annual rates of methane emissions [29].

GWP* also has limitations. Critics argue that the dependence of the GWP* calculation on recent emissions is advantageous for developed countries where increases in methane emissions occurred in the past, while disadvantageous for developing countries [30, 31]. Whether constant methane emissions or zero methane emissions are considered the counterfactual heavily influences the perceived impact of current methane emissions [32, 33], but does not affect the perceived impact of a permanent change in methane emissions, such as what could be induced by a policy intervention. For example, metrics which incorporate the rate-of-change of emissions (sometimes referred to as 'flow' metrics) like GWP* can obscure the warming caused by historical increases in methane that occurred more than 20 years ago [34, 35]. Thus, it has been argued that GWP* does not appropriately incentivize near-term mitigation, although in reality GWP_{100} understates the warming impact of new methane emissions by a factor of 4–5 [36]. We can think of the cooling that would have occurred in the absence of the baseline level emissions as a climate cost of maintained methane.

In recent years, several studies have applied GWP* to assess the warming impact of national livestock systems of Global North countries, either looking at historical effects or the impacts of possible mitigation strategies [37–39]. In each case, the selection of a relatively recent baseline leads to favorable results from negligible to moderate mitigation efforts, potentially encouraging the perverse policy incentives described above. In an effort to address this particularity of GWP*, we introduce a new application called GWP*c (in which 'c' represents the annualized cumulative emissions calculated using GWP* following the cessation of mitigation efforts). This application, which is described further in Section S.1 of the Supplement, highlights what happens when we consider the effects of mitigation decisions through the end of the century with regards to the relative perceived near-term benefit (or consequences) of using GWP*.

Meanwhile, others have explored the longer-term implications of methane-focused versus carbon-focused mitigation [40], and conducted a comparative study of the use of GWP* and GWP_{100} in life cycle assessment (LCA) literature [41]. The analysis in this paper builds on these studies, particularly McAuliffe *et al* [41] who advocate for more holistic consideration of metrics. Specifically, we build on this previous analysis by exploring the implications of metric choice beyond mid-century and incorporating novel land use metrics.

1.2. Land use metrics

In addition to GHGs from the production of food and feed products, agriculture is also responsible for GHGs from altering natural ecosystems both in the past and present [11, 42, 43]. There is an ongoing debate regarding the allocation of these fluxes to land-based products.

The IPCC defines land-use change (LUC) as 'a change in land cover and an associated change in carbon stocks' [44, 45]. Direct LUC (dLUC) is calculated based on the emissions of conversion from one land cover to another, allocated over a 'lookback period', conventionally 20 years [46, 47], which parallels the calculation for GHGs under GWP*, resulting in similar characteristics and drawbacks between the two metrics. One estimation of dLUC at the country level, sometimes called statistical LUC, uses a tool built by Blonk Consulting group using FAOSTAT data on both land cover and area per crop [48, 49]. This approach has been used to calculate LUC by recent life-cycle meta-analyses using a statistical method that assigns emissions to crop expansion in countries which are experiencing net agricultural expansion (regardless of whether or not that crop expands into forests or other land cover types) [11, 50][8].

This practice in LCAs has the effect of treating existing agricultural land as 'free.' So long as agriculture is done on existing cropland or pasture, the amount of land required is irrelevant to emissions, thus rendering the efficiency of food production per unit area irrelevant.

The carbon impact not accounted for by dLUC can be framed as the foregone sequestration or 'prevention of regeneration' of natural ecosystems [51]. As a proxy, LCA methodology includes the concept of 'land occupation,' which is the difference between the carbon stock of current vegetation and natural vegetation that would occur in the absence of human appropriation of land [52]. One paper by Schmidinger and Stehfest (2012) presents a method for estimating the 'missed potential carbon sink' if occupied land were to be regenerated over a given time horizon [42]. This method builds on an earlier calculation of human appropriation of net primary production [53] to then extrapolate the impacts of that appropriation on the climate.

The carbon opportunity cost (COC) builds on these previous land occupation concepts, offering a metric that acknowledges the foregone sequestration created by human-appropriated land use [54, 55]. According to the concept of COC, as defined in Searchinger *et al* [55], the allocation of land for human uses has climate costs compared with alternatives. Like with all economic costs, the alternative with the highest climate value is the COC. If land were not used for one activity (whether beef, crops or biofuels), one could continue to use this land to produce food for others. If not thought of in this way, another alternative would be allowing the land to regrow native vegetation and sequester carbon. Searchinger *et al* [55] argues that in a world that still has expanding agricultural land, the higher value use in terms of agricultural productivity can be viewed as avoided land use conversion elsewhere. It can be approximated as the difference between native potential and present-day carbon stocks on all land on Earth used to generate a particular product divided by the total global output of that product (see section S.1 of the supplement). When COC is calculated at the farm-level, the result is sensitive to changes in yield. In this analysis, we use the global (or regional) average because of variation in productivity from place to place. The way COC is calculated in this paper (and in Wirsenius *et al* [56]) can be thought of as the carbon 'benefit' of producing food in the UK rather than anywhere else. COC accounts for the relative efficiency of UK crop production because, if land were taken out of production where yields are higher, more land would be needed elsewhere on average to make up for lost production. Thus, we model the benefits of yield gains in that COC can be reduced as yields improve. Both Searchinger and Schmidinger apply roughly a 30 year amortization period (approximately equivalent to a 4% discount rate) on the grounds that it aligns with the time horizon selected by policymakers to mitigate climate change [55, 57]. This reflects a policy judgment that near-term mitigation is more valuable for multiple reasons, including the costs of near-term damages, the extended time that provides for technology and political will to evolve to fully address climate change before crossing tipping points, and the time value of money.

Note that social cost of carbon calculations typically assume lower discount rates, closer to 3% although this use is not strictly analogous for two reasons: it is applied to climate damages rather than emissions and removals, and the COC calculated by Searchinger *et al* accounts for the fact that emissions from LUC do not all occur in the first year.

The metrics therefore are conceptually quite different. Both GWP_{100} and COCs reflect the climate costs of pulse emissions. However, GWP_{100} focuses only on effects over 100 years while COCs allocate greater value to effects over a shorter time frame. By contrast, GWP* measures the effect on indefinite long-term

[8] Note that this method cannot be easily used to measure the dLUC of imported animal products unless the feed inputs and pasture yields used in the country of origin are known and are disaggregated for each animal system.

warming of permanent changes in methane emissions. One implication of these differences is that GWP_{100} and COCs each have utility to individuals or companies in that they measure the effect of emissions or the use of land independent of the actions of others. By contrast, GWP* is mainly useful as a metric for measuring a permanent *global* change in methane emissions.

The widely-used GWP_{100} metric implicitly adopts a 40 year timescale, since this is the time over which a tonne of CO_2 has the same warming impact as one tonne CO_2-equivalent of methane, and hence the value of GWP_{100} is similar to the adoption of a 3% discount rate [22, 58, 59]. For consistency with previous studies, here we use a 4% discount rate for the calculation of COC, and use GWP_{100}, noting the discrepancy in timescales of interest (30 versus 40 years). Arguments can be made both for adopting a higher discount rate in GWP calculations (for example, the GWP_{20} measure, for which some have advocated to be reported alongside GWP100 [20, 60], is equivalent to a 7% discount rate), or a lower discount rate in COC calculations.

Given that we understand how these metrics work mathematically, and the functions they serve scientifically, the analysis explores the extent to which the choice of one metric versus another matters for mitigation incentives in the context of UK cattle production. If metrics and mitigation outcomes are misaligned, we risk missing global climate targets and weakening food security.

2. UK cattle emissions baseline and mitigation scenarios

National emissions accounting only includes emissions that occur within national boundaries and does not include the impacts of producing inputs to agricultural systems such as synthetic fertilizers or feeds. On the other hand, a product LCA might include both upstream and downstream emissions from the supply chain [61]. The analysis presented in this paper does not include production emissions (PEMs) that occur downstream of the farm such as transport or waste management. However, we do include upstream impacts such as the production of synthetic fertilizers or animal feeds because land managers can make decisions regarding which products to purchase as well as quantities. This method is aligned with an 'operational control' approach [62], which includes the emissions categories over which land managers have agency at the point of the farm. Although the inclusion of these impacts outside national boundaries goes beyond the requirements of legal targets set by the UK government, including them shows how decisions on farms can contribute to progress on global climate and land use outcomes, which may differ from strategies incentivized by conventional national emissions accounting.

We use several datasets described in the Methods to calculate a baseline for the year 2019 for UK beef and dairy PEMs and land use, shown in figure 1. The baseline numbers are disaggregated by GHG to the greatest extent possible. The calculations for the categories included in the IPCC agriculture, forestry, and other land uses guidance are aligned with the results of the UK National Inventory Report [12]. Domestic COC dominates the baseline due to the relatively large land area within the UK dedicated to grazing.

These emissions are then projected to 2050 under four different scenarios described in table 1. These scenarios are not taken from national or corporate policy, but rather represent varying levels of ambition and different points of intervention to assess how they would affect emissions profiles using different combinations of metrics. This is a bounding exercise, where the real outcome is likely to be somewhere between the extremes, with the middle scenarios serving to explore the mitigation potential of different levers. By being transparent in our assumptions, we can use these scenarios to assess the consequences of doing nothing and the potential benefits of doing everything under combinations of metrics.

3. Effects of using alternative land use and GHG metrics

For more ambitious scenarios, the choice of GHG metric considerably changes the perceived magnitude of mitigation potential for a given intervention, whereas the influence of the land cost metric used is considerable regardless of mitigation ambition (figure 2). When we consider the long-term implications of using GWP* for each of the four scenarios, using an annualized version of cumulative emissions from 2050–2100 noted as GWP*c, we show that the negative contribution to warming (or cooling effect) caused by methane reductions using GWP* in more ambitious scenarios is short-lived. If the agreed-upon national policy objective is to minimize contribution to long-term future warming, this finding can be applied to inform the timing and level of ambition of methane mitigation required to make progress towards that goal.

From these results, we also see that the greatest percent reduction between scenarios comes from improved production efficiency (particularly when COC is included in the baseline). The difference between the INT and all existing technologies scenarios for any metric is marginal, suggesting that the choice of GHG metric becomes less important in scenarios of moderate mitigation ambition. Between these two scenarios, land use efficiency remains constant. We also do not assume that any land is 'made free' to be taken out of

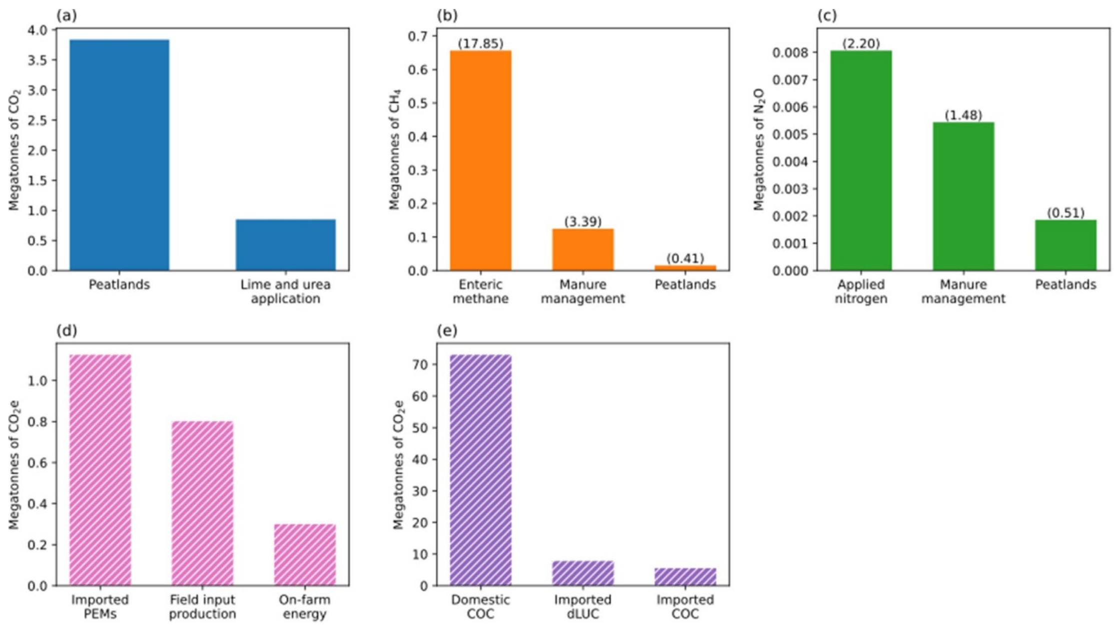

Figure 1. UK beef and dairy production emissions (a)–(c) and land use emissions (d)–(e) by source and greenhouse gas in 2019 (baseline). In (b) and (c), the numbers in brackets represent the emissions in Mt of CO_2-equivalent emissions using GWP_{100} to show the scale relative to the other categories. The relative contribution of the carbon cost of land use and land use change compared to agricultural production emissions is more than an order of magnitude larger. CO_2e emissions (bottom center and bottom left) denote categories that could not be further disaggregated by greenhouse gas. Hatched categories are not included in the IPCC's agriculture, forestry and other land uses emissions accounting guidance and are thus not included in the UK's national targets, but are considered important under the operational control approach utilized here. The additional categories included were chosen based on those used in Searchinger *et al* [63].

Table 1. UK cattle production emissions between 2019 to 2050 are analyzed using projections based on the assumptions outlined in the table. In all scenarios, an increase in production of 25% is assumed to account for projected increases in food demand between 2019 and 2050 in all four scenarios. The percent changes in emissions and land use for all scenarios, and yield gains for the INT scenario can be found in the supplementary materials (tables S.2–5).

Scenario	Production emissions (PEMs)	Land use costs
Business as usual (BAU)	Emissions from agriculture are not mitigated	Yields and feeds do not change
Intensification (INT)	Emissions reductions from improved feed conversion efficiency (FCE)	Feed requirements decrease due to improved FCE, plus yields improve at an ambitious rate
All existing technologies (AET)	Mitigation technologies that already exist (though may be nascent) are scaled up to achieve moderate emissions reductions	Feed improvements and yield gains are the same as INT
Breakthrough technologies (BRT)	New, highly ambitious methods of emissions mitigation are developed by 2050 and are implemented at scale	Assume additional 25% reduction of land use costs due to further yield gains and FCE improvements on top of INT

production as is often the case in 'land sparing' scenarios. Rather, we show the effects of improved efficiency through the application of the COC metric. Though it is true that some interventions which reduce PEMs will also improve land use efficiency, the latter impact would not be reflected by conventional metrics that do not incorporate COCs in scenarios such as these where UK agricultural land use remains constant and there is no conversion to other land cover types such as forestry. In other words, the land savings show up only with COC as an emissions reduction.

With the prevalence of 'net-zero' strategies across multiple sectors and at jurisdictional scales [22, 58, 59, 64, 65], we must consider the efficacy of a mitigation strategy to the extent that the strategy is aligned with global climate targets. Some have made the argument that, because the goal of the Paris Agreement is to 'pursue efforts' to avoid 1.5 °C of warming, policies should focus on managing the contributions of emissions to end-of-century warming [19], assuming no further warming thereafter. Alternatively, the target of the Paris Agreement could be framed in terms of keeping peak warming 'well below 2 °C'. To understand the role that cattle mitigation could play in meeting these targets, we evaluate the impact of cumulative emissions from cattle production on future temperature.

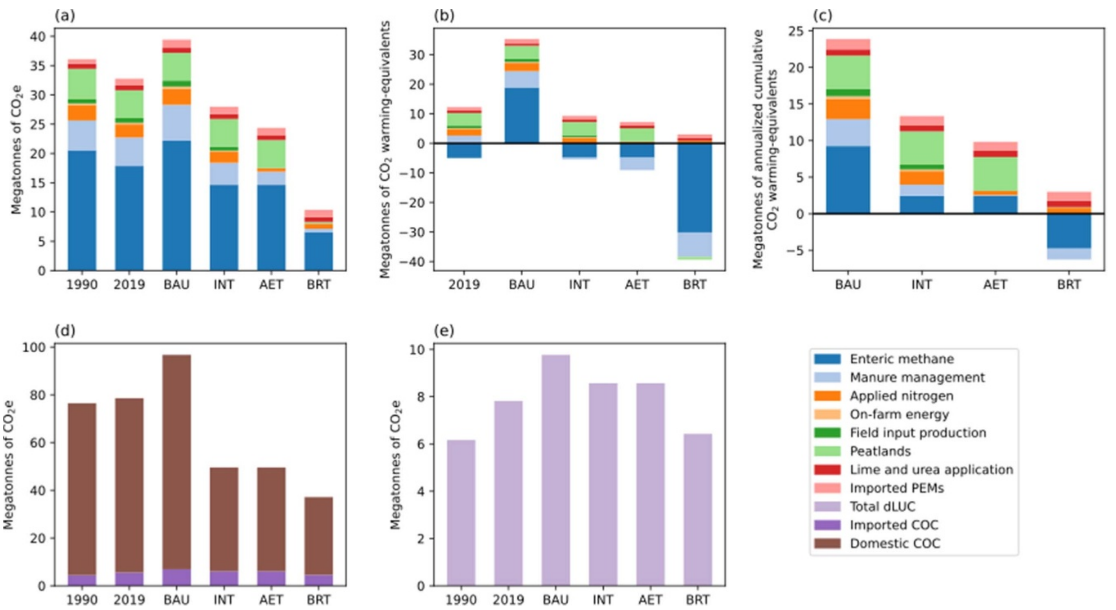

Figure 2. From top left, plots show emissions from UK cattle production calculated using GWP100 (a), GWP* (b) and GWP*c (c) for the earliest possible historical base year and four 2050 futures disaggregated by emission source. These four scenarios are business as usual (BAU), intensification (INT), all existing technologies (AET) and breakthrough (BRT). GWP*c represents the annualized cumulative emissions from 2050 to 2100 to demonstrate the long-term implications of near-term interventions. The inclusion of this novel application of GWP* demonstrates that the benefits of decreased (or consequences of increased) methane emissions pre-2050 are temporary in order to holistically account for end-of-century effects. The bottom row represents the land use costs of UK cattle production calculated using COC (d) and dLUC (e) for historical base years and future scenarios. Note the relative scale of land use costs relative to GHG emissions, as well as the degree to which more efficient production is rewarded when COC is included. This occurs because COC includes the cost of using domestic land in addition to offshored land use. Additionally, there is no domestic dLUC because the UK has seen no (or very little) native ecosystem loss in between 1990 and present.

The left axis of figure 3 shows cumulative emissions to 2100 (assuming no further mitigation after 2050) calculated with each combination of land and emissions metrics, as well as the emissions metrics without land costs. The right axis shows the contribution to warming in degrees Celsius calculated using the finite-amplitude impulse response (FaIR) model for emissions with and without each land metric.

We point out that the sharp increase in the first 20 years using warming-equivalent emissions (blue) is due to our decision to neglect pre-1990 emissions. GWP* requires a choice to be made around the base-year, and additionally pre-1990 data were limited. Nevertheless, the explicit focus here is on the warming impact of methane emissions after 1990: including the impact of pre-1990 emissions would change the height of the curves, but would not significantly change their shape from 2010 onwards, and hence does not affect the relative long-term impact of different policy interventions. This is an important general point about the use of warming-equivalent emissions: decisions on the choice of reference year to begin calculations of warming may affect the stated absolute impact of a sector or activity, but the treatment of emissions more than a few decades ago do not affect the estimated impact of decisions made from this date forwards. Regardless, the shapes of the contribution to warming lines generally follow the shape of the GWP* emissions profiles. By the end of the century, cumulative emissions under GWP* and GWP_{100} approximately converge because of the choice of 100 year time-horizon [66]. However, if the priority is to achieve the lowest possible peak temperature between now and 2100, the effect of emissions on temperature between now and the end of the century is critical.

Additionally, to include COC in figure 3, we must de-amortize the emissions factors, and the emissions from COC must not accumulate. This is necessary because COCs do not represent a flux of GHGs going into the atmosphere year-on-year. Rather, they can be conceptualized as a one-off emission occurring in the base year (1990). For each year thereafter, the accumulated value is simply the difference in COC for that year relative to the previous year. In this sense, we capture the idea that decreasing land use represents a decrease in emissions while an increase in demand for land is thought of as an increase in emissions. For this reason, the lines including COC in figure 3 start at a non-zero value in 1990.

Figure 3 shows that, while GWP* more closely aligns with the modeled temperature impact in the near-to-midterm, the GWP* and GWP_{100} lines tend to converge by the end of the century. This is the case in all scenarios except the breakthrough (BRT) scenario in which there is a slightly more noticeable discrepancy (with GWP* more closely mapping to temperature). In all cases, particularly in the near-to-midterm, the

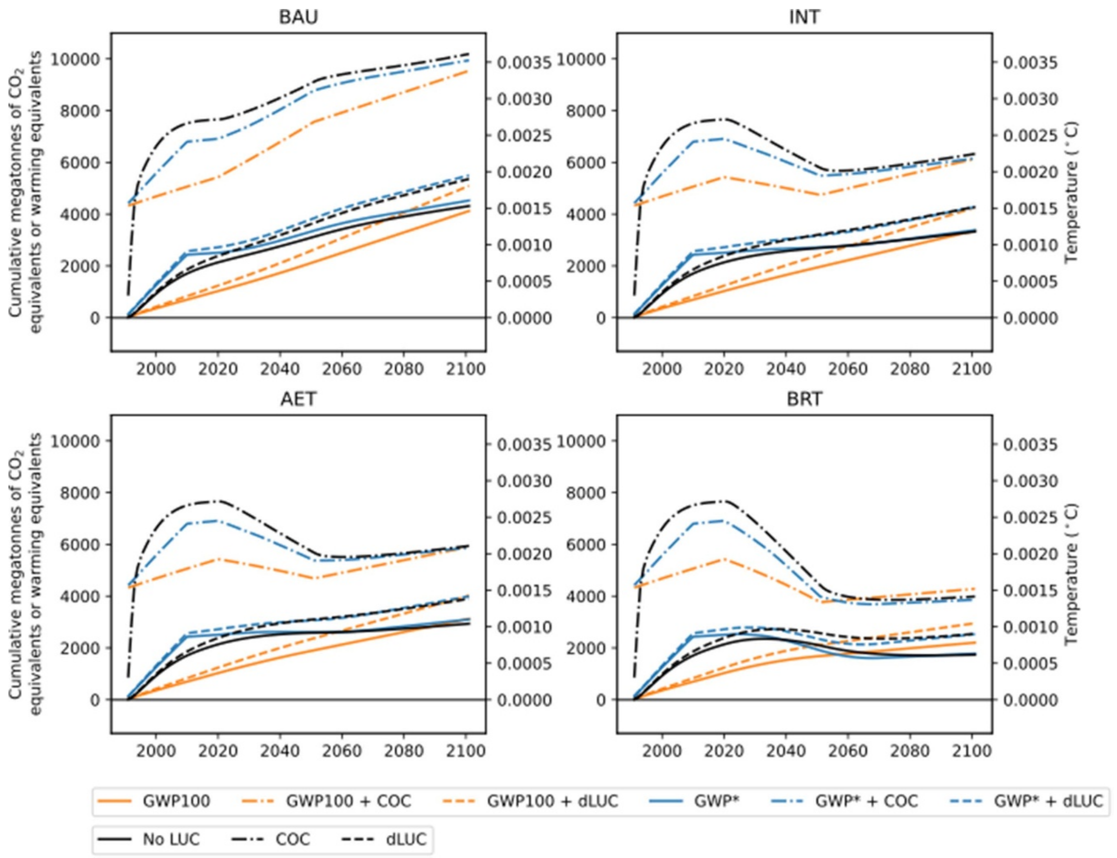

Figure 3. Left axis shows cumulative emissions from cattle production (Mt) of all greenhouse gases from 1990 to 2100 for the four scenarios under GWP* (blue) and GWP_{100} (orange), with COC (dot-dash), dLUC (dash) and without any land use metric (solid). The right axis shows additional warming relative to 1990 with each land use metric and without, shown in black. The solid black line shows warming without land use, black dashed shows warming with dLUC, and black dot–dashed shows warming with COC. The figure shows that, on a centennial timescale, cumulative emissions measured using GWP* are more closely aligned with the trend of those emissions' impact on temperature. Note that GWP_{100} (CO_2-e) and GWP* (CO_2-we) are measuring two different things which, some have argued, brings up an issue of whether the two can reasonably be included in the same figure or calculation [40]. We address this discrepancy with the distinction of units on the *y*-axis, and show the results in this way because comparison of the two metrics happens, whether warranted or not. Through our analysis we discuss the limitations of doing so.

shape of emissions under GWP* matches the temperature curves more closely than GWP_{100}. This reaffirms previous findings in the literature around methane that GWP* is useful in understanding warming impacts between now and 2100 to minimize peak warming. This calculation also finds that the difference between metrics matters more in more ambitious mitigation scenarios. Importantly, only in the BRT scenario does contribution to further warming cease in this century.

On the matter of the land metrics, the rank ordering of outcomes is the same in each scenario—COC is always highest, followed by dLUC. The warming impact from COC alone accounts for between 30%–50% of the total contribution to warming by the end of the century.

4. Discussion

This analysis is a critical assessment of conventional and alternative methods of agricultural emissions accounting and points out important considerations as developed nations with ambitious climate targets decide how to tackle the complex objective that is feeding the world within planetary boundaries. In summary, the relative ambition of various mitigation strategies is heavily influenced by the choice of metrics used to track both GHGs and the carbon costs of using land for agriculture, but the perceived preference for different outcomes is unaffected. Hence, while decisions regarding which GHG metric to use and whether to consider the COC of land affect the absolute perceived impact of UK cattle, they do not affect the relative benefits of decisions going forward.

Our results in figure 2(b) show that the use of GWP* can generate the perception that methane reductions offer a pathway for emissions from cattle production to appear 'net zero by 2050′ although meeting the goals of the Paris Agreement at a global scale requires all industries, agriculture included, to sustain no further warming for many decades. The longevity of stabilized warming, however, is dependent

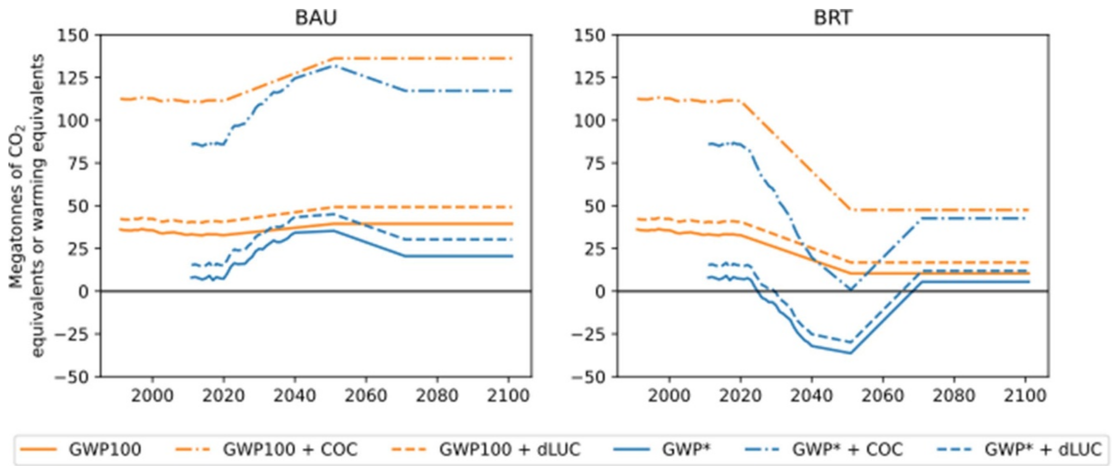

Figure 4. Historical and projected emissions attributable to UK cattle production under GWP_{100} (orange) and GWP* (blue), considering methane alone (solid), including impact on CO_2 using dLUC (dashed), and COC (dot–dashed) for the BAU (left) and BRT (right) scenarios. The GWP* lines show the long-term implications of interpreting penalties and benefits due to changes in methane. The inclusion of COC makes baseline emissions significantly higher, but highlights opportunities for greater reductions through improved production efficiency in the BRT scenario.

on mitigation of long-lived GHGs as demonstrated by the use of GWP*c in figure 2(c). We point out that 'net zero' under GWP* can essentially be interpreted as 'no contribution to further warming relative to a baseline.' This is demonstrated in the BRT scenario, in which cooling due to reductions in methane emissions counteract warming from residual long-lived GHGs in the near-term. This is very different to the interpretation of net zero using GWP_{100}, which is not relevant for temperature outcomes, but rather the balance of sources and sinks of GHGs equated to one another based on radiative forcing effects over 100 years.

By focusing attention on the effect of changes in emissions, ongoing cattle production can technically cease to contribute to warming increases at the national level. However, even continued beef and dairy production can hold up temperatures, thus GWP* should not be used to justify leaving methane out of mitigation strategies. Even if global agricultural methane is technically contributing no further warming, this could cause temperatures to stabilize above 2 °C, meaning the goals of the Paris Agreement would not be met as a result. Nevertheless, the potential for temporary cooling due to methane abatement can still be considered while simultaneously working towards achieving net zero emissions of long-lived GHGs.

The notion that warming-based metrics provide a potential route to net zero warming for the agricultural industry fuels the misperception that these calculations somehow flatter livestock production [31]. Indeed, many countries and jurisdictions with high (albeit stable) methane emissions have advocated for the adoption of GWP* on the misunderstanding that it would alleviate the pressure to ambitiously reduce methane, particularly in the livestock sector [67–70]. In fact, the reverse is true: warming-based metrics increase the incentive for near-term methane reductions. To that effect, a response from the scientists behind GWP* to a critique from Cain *et al* explains that whether entities should choose to undo warming caused by methane but not CO_2 is a distinct policy issue, the resolution of which is facilitated by GWP* and its use in understanding the effects on temperature of mitigation decisions [33].

The long-term effects of using GWP* are demonstrated in figure 4, which shows the two most extreme scenarios of emissions from UK cattle. In the business as usual (BAU) scenario, methane emissions increase in the absence of mitigative efforts, while the BRT scenario involves ambitious emissions reductions in every category, assuming the rapid development of mitigation technologies that are not readily available today. In the former scenario, emissions measured with GWP* rise more steeply than under GWP_{100} but converge around mid-century, while the latter sees a steeper reduction and a greater divergence from GWP_{100} at mid-century. Conversely, the end-of-century differential is greater in the BAU case in comparison to BRT. This suggests that metric choice under ambitious mitigation is more important in the near-term. However, as we find in figure 3, the end-of-century warming impact is largely determined by the choice of land use metric, meaning the choice of GHG metric is less important in the long-term.

In figure 3, we set all pre-1990 emissions to zero and explain why this is necessary to be able to compare cumulative emissions to warming. We do not make the same assumption in the calculation for figure 4 because doing so would result in a sharp increase in emissions from 1990 to 2010, which would distract from the purpose of the figure. The purpose of figure 4 is to show ongoing rates of emissions, which are more relevant to and, in the case of CO_2-we emissions, proportional to contributions to the ongoing rate of warming. Hence, we here calculate GWP* emissions using historical emissions up to 1990 because we are not focusing on the cumulative impact of emissions since then. The difference between figures 3 and 4 illustrates the impact of decisions regarding the treatment of historical emissions on the absolute level of ongoing emissions, as well as how it does not affect the predicted impact of decisions going forward.

The inclusion of land use emissions metrics in the scope of assessment can offer new points of intervention that might not otherwise have been pursued. For example, improving the efficiency of land use through intensification (INT) and improved feed conversion efficiency (FCE) has the highest relative mitigation potential, particularly when using COC. Unlike other 'land sparing' modeling, we do not assume that INT in one place leads to native vegetation in that same country. The calculation of COC assumes that it is not possible to say where the land sparing would occur. It is therefore more apt to say that producing more food in one place avoids conversion of native ecosystems elsewhere. We also do not assume that any land is taken out of production.

The most impactful option for mitigating dLUC is to stop buying feeds such as soy from areas of high deforestation, although this intervention would have no effect when using COC because COC is origin-agnostic. In theory, dLUC disincentivizes sourcing of products linked to recent deforestation such as soy and cocoa [47]. In practice, as data at the country level is most common, dLUC incentivizes shifting supply of such commodities from the Global South to the Global North where deforestation happened long ago [71]. As a result, leakage becomes extremely likely when dLUC is reported at the sub-global level so long as demand remains constant. Thus, we reaffirm that major opportunities to incentivize progress on global land and climate targets are being undervalued or disregarded due to this convention in livestock impact assessment. Section S.2 of the Supplement contains further analysis around the mitigation potential of soy sourcing using COC and dLUC.

This analysis is a bounding exercise which uses hypothetical mitigation scenarios to model different levels of ambition. Because the scenarios do not attempt to predict future conditions in a robust way, results are not prescriptive, but rather illustrative. Additionally, we highlight gaps in the data required to model UK livestock emissions. We find that reliable information on the quantities and types of feed used specifically for cattle were particularly lacking, thus the impact of feed production has substantial uncertainty. Due to these data gaps, our analysis relies on certain assumptions, many of which are crude, though we identified the most significant uncertainties and tested them with sensitivity analyses. These assumptions are discussed in the Methods.

There are mathematical symmetries between these metrics that must be acknowledged. Both GWP* and dLUC are calculated using a 20 year lookback period. Thus, GWP*, like dLUC, can also lead to leakage when reported at the sub-global level.

There is a second symmetry to consider between COC and GWP*, particularly when they are thought of as cumulative over time. Both metrics allow for the consideration of 'opportunity costs' as a mitigation strategy. As previously discussed, COC is the opportunity cost of using land for one purpose as opposed to another. Similarly, constant rates of methane emissions represent an opportunity cost in that they 'hold up' temperatures relative to a world in which those emissions are absent. For this reason, we must look at the rate of change from one year to the next (COC), or over 20 years (GWP*) to more appropriately represent the effects of interventions using these metrics over time.

While COC and GWP_{100} can incentivize certain actions without the need for global reporting, they also have shortcomings. COC has been criticized because it represents avoided sequestration rather than an annual carbon flux. It therefore does not reflect additional emissions or removals, which are the focus of national inventory reporting. GWP_{100} has also been shown to be equivalent to a 'social cost of emissions' with a specified discount rate [72]. Both metrics have been criticized due to the dependence of the results on the selected time horizon.

There are two important conclusions to be drawn from this analysis. First, in the case of UK ruminant mitigation, the rank-ordering of mitigation performance of policy options is insensitive to the choice of emission or land-use metric, which primarily only affect the perceived absolute level of harm caused by the cattle industry. Hence the impact of metric choice on actual, forward-looking decisions may be overstated in ongoing discourse. Note that there may be other contexts, such as where an intervention trades a decrease in nitrous oxide for an increase in methane, where metric choice does affect rank-ordering of mitigation decisions, so a case-by-case consideration of these effects is warranted.

While metric choice does affect assessments of absolute or total harm, these are even more sensitive to other arbitrary choices that are often overlooked, such as the choice of initial year from which to evaluate historical responsibility. Note that this is only the case because we assume a given rate of production in this analysis. The perceived benefits of reducing production are acutely sensitive to metric choice: with dLUC, reducing production is always beneficial, with COC, reducing production is only beneficial if land-use in a region is less productive than the global average. This point is especially relevant in the current policy landscape where the feasibility of many climate strategies for the land sector (including that of the UK Climate Change Committee) depend almost entirely on 'freeing-up' land by reducing agricultural production and assuming a change in national diets. Whether or not this is a plausible future and thus a reasonable assumption remains a critical question which warrants further investigation.

Second, the only scenario which results in the UK cattle sector ending its contribution to ongoing warming (BRT) involves mitigation with a level of ambition that is not currently technologically possible without reducing the UK's share of global meat production. Whether or not reducing production would be a good thing for the global environment depends on current and near-term trends in UK farming efficiency relative to competitors, and on global dietary trends.

We reiterate that land use and climate impacts beyond the national boundary are not included in conventional national emissions accounts. Given the scale of these impacts, regardless of metric chosen, and that conventional accounting leaves open the option to meet national climate targets by offshoring agriculture elsewhere, this analysis highlights how points of intervention are affected by changes to spatial and temporal boundaries.

Impact on temperature aside, producing more food on less land is important for preserving and restoring global biodiversity, food security, and other valued outcomes within the food system. Thus, policymakers should consider setting targets based on a desired outcome; if the priority is minimizing global pressure to convert land, COC is the most helpful metric. If the objective is to minimize supply-chain emissions associated with deforestation, dLUC is potentially more informative, but creates perverse incentives such as potentially diverting feedstock supplies to countries that have less stringent LUC targets. If the aim is to minimize contributions to warming, GWP* is more informative than GWP_{100}, but is sensitive to historical data and hence opens contestable issues about responsibility. Ultimately, if conventional metrics are not creating sufficient incentive to drive progress towards global targets around climate and land use, we suggest an alternative approach. Therefore, we cannot rely on convention, nor can we rely on a single number to achieve multiple complex outcomes. Holistic consideration of a wider range of land use and GHG metrics, while recognizing their limitations, could help lead the land sector to remain within multiple planetary boundaries.

5. Methods

This analysis uses data exclusively for cattle in the UK. For LCA accounting purposes, cattle are either categorized as calves, heifers, dairy cows, bulls, or beef cattle. LCA literature typically distinguishes a beef herd and a dairy herd depending on the product coming from the herd (though note that about 50% of the UK's beef output comes from cattle which originate in the dairy herd [73]). The UK National Inventory Report (NIR) only provides a population breakdown into dairy and non-dairy rather than the five categories listed. Additionally, individual cattle can shift between dairy and beef herds, making the allocation of impacts even more complex in the context of this analysis. According to a DEFRA dataset on herd populations, dairy cows are defined as milk-producing female cows in the dairy herd over the age of 2 years [74]. Cows that are producing milk consume more feed and emit more enteric methane per head than other populations, thus it is reasonable to break apart the national herd in this way to model them separately. For this reason, it is difficult to model non-milk-producing cattle in the dairy herd (i.e. heifers and calves) separately from the beef herd. Thus, our calculations were done in terms of 'dairy-producing' and 'non-dairy producing' as this better represents the disaggregation of data available in the NIR, as opposed to separately modeling the dairy and beef herds.

The calculations in this paper used a modified version of the Excel model created for an analysis of mitigation opportunities for the Danish land sector [63].

5.1. PEMs

This analysis used several datasets, primarily the UK NIR and feed data from DEFRA [75]. Because the NIR data for 2021 were not yet finalized at the time of analysis and we take a 3 year average, we used a base year of 2019 with the average taken from 2018 to 2020 to account for annual fluctuations. All PEMs are disaggregated by GHG whenever possible, which is necessary to apply different metrics. However, some sources were only available in CO_2-equivalent units (GWP_{100}) and cannot be disaggregated by GHG. This is not a major source of error because, for the categories where emissions cannot be disaggregated (on-farm fuel use, nutrient input and pesticide production, COC, and dLUC), the dominant GHGs are carbon dioxide and nitrous oxide. This would therefore not affect the outcome if GWP* were applied, which would only be influenced by fluxes in methane. The emissions categories from the Agriculture section of the NIR which distinguish between emissions from cattle and other animals are limited to enteric methane and manure management (methane and nitrous oxide).

Drained peatland emissions are reported in the NIR (annex section 3.4) broken down into CO_2, N_2O, and CH_4 per hectare per year along with the total drained area. Applied nitrogen (organic, synthetic, and crop residue) emissions only involve N_2O, and are also reported in the NIR. The rates of nitrogen application for each crop can be found in table S.6 of the Supplement. However, on-farm energy use is available in CO_2-equivalents. To estimate emissions from on-farm energy, we used another DEFRA dataset [76], which provides an amount of diesel used per hectare of cropland. We then used a conversion factor from FAOSTAT to convert liters of diesel to CO_2e. This value could not be further disaggregated. We also estimated barn energy consumption. In a 2021 analysis of the Danish livestock sector, we estimated 0.1 GJ electricity per dairy cow slaughtered per year [63]. In the absence of any more relevant data, we use this figure with the understanding that it is likely an overestimation because most livestock in the UK graze on pasture, whereas Danish dairy cattle live mostly in barns, which are more energy intensive.

Other than for enteric methane and manure management, data is only available at the national level rather than by product or livestock type, and thus requires some reasonable method for allocating an amount to cattle. Most other PEMs categories (applied nitrogen, lime and urea, and pesticide and fertilizer use) are dependent on the area required to produce the feed or roughage for beef and dairy production. However, data were not readily available on the breakdown of each feed type by animal. Instead, a dataset from the Agriculture and Horticulture Development Board (AHDB) provided the quantity of feed by crop (i.e. wheat, barley, etc) and a second dataset from the same source reported total feed quantity by animal type (i.e. cows, sheep, etc) [77]. According to the latter dataset, cattle consume 37% of feed in the UK, however this figure does not include roughage. Thus, we assumed that 37% of all feeds are used for cattle. This ratio has not materially changed significantly since the early 1990s (at which point it was between 38%–40%). This assumption is a likely source of error because not all animals consume feed baskets with the same composition. This assumption allows for the estimation of emissions sources which are not delineated by animal type. For example, we assumed that 37% of lime and urea emissions can be attributed to feed used in cattle production, and that 37% of drained peatland used for cropland is producing crops for cattle. Note, however, that we make separate assumptions for the consumption of grass and forages.

For land dedicated to cattle grazing, we assume that 70% of total grazing land is used for cattle because only cattle and sheep graze on peatland, and cattle consume 70% of digestible feed (including grazing) according to the NIR's supporting data [78]. This ratio also has not changed since the early 1990s as determined using data from the 1990–2019 common reporting format. We apply this ratio to peatland dedicated to grazing. The NIR source used distinguishes the differentiated uses of upland from lowland peat. This is an important consideration because most upland peat is used for grazing while lowland peat is dedicated to horticulture. The disaggregation of the NIR data allows for the consideration of these differences.

All PEMs categories were reported between 1990 and 2019, with projections to 2050 under the mitigation strategies described in table 1. The UK NIR 1990–2019 report provides this back-data for enteric methane, manure management, peatland, and applied nitrogen, which we scaled based on the 2019 value calculated specifically for cattle [12]. We used the FAOSTAT quantity for fertilizers and pesticides used in 1990, also scaled for cattle based on the 2019 value, then linearly interpolated between 1990 and 2019. Lastly, the NIR provides areas of drained peatland for 1990 and 2019 only, which we also scaled and linearly interpolated [12].

Descriptions of each category of emissions can be found in section S.4 of the supplement. Additionally, the historical emissions used in our calculations can be found in the supplementary materials (table S.7).

5.2. Domestic and imported feed

In addition to PEMs, this study's focus on measuring land use required detailed analysis into the feed allocated to cattle systems. Domestic feed data came from DEFRA, which provided the quantity of each crop that is used as feed [75]. We used a three-year average (2018–2020 for a base year of 2019) to minimize effects of fluctuations.

Quantities of imported feed crops which are also produced domestically (i.e. wheat, which is imported and produced domestically) are provided by the same DEFRA dataset used for domestic feed quantities, although it does not specify the quantities of imported crops used for feed. We estimated the quantity of imported crops used for feed based on the proportion of domestically produced crops that are used for feed. For example, if 50% of domestic wheat is used for feed (according to DEFRA), we assume 50% of imported wheat is used for feed. For the remaining feed crops which are not produced domestically, we assumed 100% are used for feed. This is likely to be a reasonable assumption because the imported feed crops are not typically used for human consumption (e.g. oilseed cakes).

Domestic feed quantities in the DEFRA feed dataset are available back to the 1980s, so we averaged 1989–1991 values to get a base year of 1990, and an average of 2018–2020 for a 2019 value (both with 37% scaling factor for cattle). Imported crops also produced domestically are available through the same dataset. However, imported crops not produced domestically are only available back to 1992 through the AHDB dataset. Thus, we used an average from 1992 to 1994 (implied 1993 base year) as a proxy for 1990, and a 2018–2020 average for 2019. Domestic and imported feed quantities were then linearly interpolated between 1990 and 2019. The quantities of domestic feeds used in the calculations can be found in the supplementary materials (table S.8).

Lastly, we included an estimation of the PEMs from imported feed. These are the emissions from applied nitrogen and lime, farm equipment, transportation, and processing for feed crops produced abroad. Because most feed used in the UK (but not all) comes from Europe, we used the average emissions factor of the European region and the global value, as was done in a 2020 WRI report, which also provides regional emissions factors for Europe [56].

5.3. Land costs and imported feed PEMs calculations

The back-data from 1990 to 2019 and projections under various mitigation scenarios to 2050 were analyzed using various combinations of land and emissions metrics. The analysis applies combinations of GWP_{100} and GWP* for PEMs and dLUC and COC for land use costs.

The COC calculations used an average of the Global and European factors used in Wirsenius *et al* [56]. These values are currently being updated, though the most recent published values were used in this analysis. The dLUC data comes from an early free version of the Blonk LUC tool [79] which was used in the 2018 Poore and Nemecek food LCA meta-analysis [11]. The tool uses a 2010 base year with a 20 year look-back based on when the FAO's Forest Resource Assessment was completed. This data, which has not been recently updated, is used to calculate weighted-average emissions factors for each imported feed based on the quantities of each feed from each origin, and the dLUC factors of each origin. The quantities of feed from each origin come from the FAOSTAT trade matrix [80]. Note that the Blonk data includes emissions factors per hectare for CO_2, N_2O, and CH_4. However, COC cannot easily be disaggregated in the same way. Thus, to maintain consistency across the land metrics, dLUC is also only aggregated as CO_2e using GWP_{100} constants.

In the calculation of cumulative COCs, we apply de-amortized values from the background data of the calculator built for Searchinger *et al* [55]. This data gives the global historical native carbon stock lost to date due to the production of a certain crop and the total carbon stock of that crop, globally. These difference between these two values, divided by the global output of that crop, gives us the de-amortized COC which can be counted cumulatively.

Emissions factors for PEMs of imported feed, COCs, and dLUC can be found in table S.9 of the supplement. De-amortized COC values are in table S.10 of the supplement.

5.4. COC for pasture

Because grass and forage consumption is not reported alongside other feedstuffs, we must make a series of plausible assumptions to calculate the land use costs of UK cattle grazing.

According to a report on UK Agriculture from the Scottish Government, the UK dedicates approximately 5.2 million hectares to grazing [81]. We then apply the previously stated assumption that cattle utilize 70% of the country's grazing land based on the NIR figure that cattle consume 70% of digestible energy out of all ruminants (cattle and sheep) to allocate 3.7 Mha to cattle. Based on calculations from a previous comparative study [56], the native potential carbon stock for pasture in the UK is 137 tC per hectare, and regional average pasture yields are 6 tC per hectare, resulting in an average carbon loss of 131 tC per hectare. After amortizing this carbon loss over a 30 year period, we get a COC factor of 16 tonnes of CO_2e per hectare of pastureland, or 0.73 tonnes of CO_2e per tonne of grass. The native potential carbon stock is calculated using CAPRI land cover data at 0.5° resolution overlaid with the supplementary global carbon loss data from Searchinger *et al* [55].

5.5. Mitigation scenarios and production increases

The mitigation scenarios in this analysis are defined by assumed percent changes in each emissions category and feed quantity applied linearly between 2019 and 2050. The percent changes for each emissions category in the INT scenario are based on the results of analysis of FCE improvements in Denmark due to a lack of equivalent data in the UK [56]. The percent reductions in the Existing Technology and BRT scenarios are also based on the analysis from the same paper (which analyzed the potential mitigation of all technologies in one scenario), but here are split into two scenarios of varying levels of ambition.

The results of the analysis also depend on the assumed percent increase in production applied linearly between 2019 and 2050. Projected percent increases vary by product and by region [4]. Previous analysis applies a 45% increase based on global projections [56], however this is likely an overestimate for livestock in the UK given that production of beef and dairy has remained approximately stable over the past several decades [82]. However, the market for livestock products is global, and it is possible that if demand grows significantly in other parts of the world (as projections suggest), countries like the UK and other countries in Europe could increase production to meet demand. Thus, we chose a middle-of-the-road value of 25% applied linearly across all four scenarios included in the analysis and conduct a sensitivity for other values, both higher and lower (see supplement section S.5). This increase is applied uniformly across the beef and dairy herds, assuming no changes to production efficiency, which we model separately. We found that the choice of percent increase does not impact the favorability of each metric.

In the scenarios which involve significant yield gains, we do not assume any land is taken out of production. While many models explore the potential for afforestation due to either yield gains or shifting diets [83–85], and indeed this is the implied trajectory in the UK national land sector strategy, we do not include this in our calculation based on historical trends. Since 1990, land area dedicated to agriculture in the UK has not changed. However, meat and dairy production has, on average, stayed fairly constant despite a decline in heads of cattle, implying improvement in yields over that time period [82]. Thus, we assume any yield gains would result in either lower imports or higher exports, as opposed to changes in land cover. We assume any increases in yield gains would go towards meeting global increases in demand for food, thus avoiding the need to clear land elsewhere [4].

For the sake of these stylized scenarios, we assume that emissions do not change after 2050 as this is in line with most national UK climate scenarios (such as the CCC). This means that, whether emissions are increasing or decreasing pre-2050, emissions level out from 2050 to 2100. Of course, this is unrealistic, but for our purposes of exploring the implications of metric choice particularly regarding methane, it is useful to show what happens when the rate of change of emissions stagnates. To address the result shown in figure 2(c) which suggests that strategically timed abatement of methane measured under GWP* can be used to 'appear' climate-neutral by 2050, we apply GWP*c to demonstrate that these benefits do not last to the end of the century.

GWP*c is the annualization of cumulative emissions from 2050 to 2100, after mitigation (or increases) of emissions has leveled out. Including this calculation shows that cooling is only possible so long as methane emissions are decreasing. In the case of UK cattle, the end-of-century warming impacts are significantly dampened relative to the effect of GWP* in 2050 (see figure 2(b)).

5.6. FaIR model

The FaIR model is a climate model that converts emissions profiles into temperature (contribution to warming) [86]. The model calculates the contribution to warming of our scenarios by first calculating the temperature impacts of a given shared socioeconomic pathway (SSP, in this case SSP245), which is a projection of emissions based on a set of assumptions about future mitigation, or lack thereof. Then, the model is run a second time with the emissions of that SSP, less the emissions of the scenario in question (e.g. UK beef under the BAU scenario). Thus, the temperature impact of our scenario is the difference between the results of these two runs. For each of the four mitigation scenarios in this analysis, we calculate contribution to warming for PEMs alone as well as with COC and dLUC included.

While it is valuable to report discounted COC in annual attributional accounts to provide a snapshot of land use each year, conceptual issues arise when incorporating COC into a cumulative emissions profile due to the use of a discount rate. To apply COC in a warming model, we must de-amortize the emissions. COC is not a flux of emissions entering the atmosphere every year as is the case with other sources such as fossil fuel use, enteric methane, etc. Rather, COC can be represented as a pulse of emissions in year 0 equal to the COC in that year, after which the emissions do not accumulate. However, if COC increases, the difference between that year and the previous year is accumulated. Likewise, a reduction in COC (such as through improved efficiency) would be represented as a removal. A table of the de-amortized COC emissions factors can be found in supplement table S.10.

Data availability statement

The data that supports the findings of this study are openly available in the supplementary files of this article.

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Contributions

J Z, H B, and M A equally contributed to conceptualization of the study and interpretation of its results. J Z developed the methodology, collected the data, and wrote the original draft. J Z, M A, and T S conducted the analysis. M A, T S, and H B reviewed and edited the draft. M A acquired funding for this research. M A, T S, and H B supervised this work.

Ethics declaration

J Z's Doctoral studies are fully funded by Hilton Food Group, however all intellectual property is property of the University of Oxford. Additionally, Hilton Food Group may not prevent J Z from submitting publications or a thesis based on the findings of the research. Hilton Food Group members have not influenced or contributed to the findings of the research. M A has declined payment from the National Cattlemen's Beef Association for recent speaking engagements.

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