The role of the European small ruminant dairy sector in stabilising global temperatures: lessons from GWP* warming-equivalent emission metrics

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Abstract

Recent calls advocate that a huge reduction in the consumption of animal products (including dairy) is essential to mitigate climate change and stabilise global warming below the 1.5 and 2°C targets. The Paris Agreement states that to stabilise temperatures we must reach a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases (GHG) in the second half of this century. Consequently, many countries have adopted overall GHG reduction targets (e.g. EU, at least 40% by 2030 compared to 1990). However, using conventional metric-equivalent emissions (CO_2-e GWP_{100}) as the basis to account for emissions does not result in capturing the effect on atmospheric warming of changing emission rates from short-lived GHG (e.g. methane: CH_4), which are the main source of GHG emissions by small ruminants. This shortcoming could be solved by using warming-equivalent emissions (CO_2-we, GWP*), which can accurately link annual GHG emission rates to its warming effect in the atmosphere. In our study, using this GWP* methodology and different modelling approaches, we first examined the historical (1990–2018) contribution of European dairy small ruminant systems to additional atmosphere warming levels and then studied different emission target scenarios for 2100. These scenarios allow us to envision the necessary reduction of GHG emissions from Europe's dairy small ruminants to achieve a stable impact on global temperatures, i.e. to be climatically neutral. Our analysis showed that, using this type of approach, the whole European sheep and goat dairy sector seems not to have contributed to additional warming in the period 1990–2018. Considering each subsector separately, increases in dairy goat production has led to some level of additional warming into the atmosphere, but these have been compensated by larger emission reductions in the dairy sheep sector. The estimations of warming for future scenarios suggest that to achieve climate neutrality, understood as not adding additional warming to the atmosphere, modest GHG reductions of sheep and goat GHG would be required (e.g. *via* feed additives). This reduction would be even lower if potential soil organic carbon (SOC) from associated pastures is considered.

The national inventories for greenhouse gas emissions (GHG) are considered the main instrument to formulate actions on national climate policies, such as the commitments for the Paris Agreement on climate change. However, these inventories have shown many shortcomings that need to be overcome using broader frameworks that incorporate key additional perspectives. GHG national inventories for livestock consider only direct biogenic emissions, so any mitigation measures ignore potential knock-on effects and trade-offs outside farm boundaries (e.g. pre-farm gate through fertiliser manufacturing or concentrate production) or through on-farm electricity/fuel usage. Life cycle assessment (LCA) approaches provide a more comprehensive framework to incorporate such off-farm and energy-related secondary effects. Although LCA-based approaches are very useful tools for climate and food policy, their large variation is to be considered when using average world-wide LCA-based GHG values (e.g. Gerber *et al.*, 2013) for recommendations rather than values tailored to industrialised countries (Harwatt, 2019). In order to be useful for country-level policies, LCA values must be specific enough to differentiate among production systems and countries.

There have been different studies attempting to estimate the contribution of European small ruminant systems to climate change *via* GHG emissions. Bellarby *et al.* (2013) examined overall GHG emissions in the EU27 livestock sector for the year 2007 and estimated GHG emissions from production and consumption of livestock products. They also reviewed available mitigation options and estimated their potential. Similarly, Weiss and Leip (2012) investigated overall GHG emissions (as LCA from cradle to farm gate) from EU-27 livestock in the

year 2004 and explored the implications for the total GHG emissions, including different estimations of land use and land use change associated CO_2 emissions. Gerber et al. (2013) investigated GHGs from livestock supply chains for one year (2010), providing disaggregated LCA-based results for different species (e.g. sheep and goats), product orientation (dairy v. meat), production systems (grassland v. mixed systems) and regions. To our knowledge, however, there is not, to date, a study that focuses on how European small ruminant dairy systems have contributed to global temperatures changes in an integrated manner, i.e. considering: (i) GHG emissions from a LCA approach, (ii) a historical time series evolution perspective and (iii) the effect on global temperatures rather than GHG emissions.

For the rest of the century, European small ruminant dairy systems, as well as other activities within the agricultural sector, are expected to pursue climate neutrality in order to contribute to the goal of the Paris Agreement on climate change regarding stabilising of global temperatures. Achieving climate neutrality in terms of metric-equivalent emissions, as is conventionally done for long-lived gases (e.g. CO_2), would require that the sector progress towards net 0 cumulative CO_2-e emissions by the year 2050. The Paris Agreement specifies that a balance between anthropogenic emissions by sources and removals by sinks of GHGs must be reached in the second half of this century.

Net zero is clear for CO_2 and other long-lived GHGs, but not for CH_4. Methane has a natural removal sink through chemical oxidation resulting in CH_4 having a life of approximately 12 years in the atmosphere (IPCC, 2013). Methane behaves very differently from CO_2 such that if we maintain global CH_4 emissions at the current level the concentrations of methane will then stabilise and not contribute further to global warming. This contrasts with CO_2 where constant emissions lead to a constant warming rate and reduced emissions still lead to a reduced warming rate until they decline to zero. This problem can be avoided by re-defining climate neutrality (Ridoutt, 2020) in terms of 'warming-equivalent' emissions. In this sense, the new Global Warming Potential-star (GWP*) metric (Allen et al., 2018; Cain et al., 2019; Lynch et al., 2020) allows the expression of all emissions (i.e. long v. short-lived) in warming equivalents (CO_2-we), which in a common cumulative framework correlates well with the resulting atmospheric temperature increase (Cain et al., 2019).

In this paper we illustrate the contrasting climate impacts resulting from emissions of CH_4, CO_2 and N_2O using GWP and GWP* methodologies. This has important implications for how we consider 'zero emission' or 'climate neutral' targets for sectors emitting different compositions of GHG.

Material and methods

Historical contribution of GHG emissions from dairy small ruminants in Europe (FAO region) and EU-27 on temperature change/warming

In order to estimate the historical warming associated with dairy sheep and goats in Europe, we need first to have their historical LCA-based GHG emissions. To our knowledge and to date, there is not such a calculation. There are, however, LCA-based GHG European calculations for single years (e.g. Weiss and Leip, 2012; Gerber et al., 2013) and specific LCA-based studies analysing the GHG emissions from different dairy production systems (as for Spain, e.g. in Batalla et al., 2015 or in Escribano et al., 2020). In an attempt to derive historical European emissions, we

used a combination of information: (i) LCA-based European studies for one year, (ii) Historical data on changes in productivity parameters and breeds for Spanish sheep and goats as a proxy of how European production systems have changed in the last decades and (iii) LCA-based GHG emissions for different Spanish production systems and breeds (full details are provided in the online Supplementary File: general approach in Section 1, (i) Section 2, (ii) and (iii) Section 3). We chose to develop two extrapolations in order to check if choosing different methods can affect the consistency of final results, but it is important to point out that producing an accurate historical GHG emissions calculation was beyond the scope of this study.

For assessing how this sector's emissions have contributed to global warming since 1990, we constructed a cumulative emissions framework on the basis that there is almost a linear relationship between the amount of CO_2 emitted and the resulting atmospheric temperature increase (IPCC, 2013). This is the basis that most countries are adopting for reductions and targets of 'net zero' CO_2 emissions by 2050. Two approaches were used and subsequently compared: (i) Calculating emissions as CO_2-e and assuming that all the 3 GHG accumulate in the atmosphere and (ii) an alternative approach, where temperatures for long-lived GHG gases (i.e. CO_2 and N_2O) depend on the accumulation of emissions (as approach 1), but for short-lived gases (i.e. CH_4) temperature would depend on the rate of emissions. For the latter alternative approach, we used the GWP* approach developed by Allen et al. (2018), which includes the differentiation rate and uses for cumulative metrics the CO_2-we (CO_2-warming equivalent as defined by Cain et al., 2019) instead of CO_2-e. A simple coefficient known as TRCE (transient climate response to cumulative carbon emissions) can then be multiplied by cumulative CO_2-we to obtain an approximate estimate of temperature change due to the change in CO_2-we burden experienced, as explained by Lynch et al. (2020). The TCRE metric represents the robust near-linear relationship between global warming and cumulative CO_2 emissions. Essentially, the TCRE estimates for every 42 $GtCO_2$ emitted, the global temperature will increase by between 0.009 and 0.011°C (Rogelj et al., 2018).

The GWP* methodology (full details are given in the Supplementary File: Section 4) was applied for the species, regions and extrapolations shown in Table 1.

Description of policy scenarios on GHG mitigation from European and EU-27 dairy small ruminant activity

We forecasted different pathways of GHG emissions from the European small ruminants' dairy system (no changes, 0.4, 0.6 and 0.8% annual GHG reductions) and assessed how these scenarios would be contributing to the global temperature targets for the 2018–2100 period using the cumulative CO_2-we framework approach previously described and the TRCE coefficient. We carried out this exercise for the 6 different combinations that were used to calculate the historical contribution. It must be noted that although these scenarios do not represent concrete measures to reduce GHG emissions, they could be used to interpret known measures. For illustration purposes and as an example of these potential mitigation measures, we simulated for dairy sheep production systems in the European FAO region the gradual introduction of a feed additive (3-NOP) that can reduce about 30% CH_4 from enteric sources in sheep (Martínez-Fernández et al., 2014), and do so without loss in efficiency (Hristov et al., 2015; Lopes et al., 2016). We assumed this 30% reduction as potentially

Table 1. Details on the species, regions and extrapolations basis for the different historic scenarios

	Species	Region	Year basis	study (year basis)	Model-year basis	Study for extrapolation
SHEEPEUR1	Sheep	FAOEurope	2010	Gerber *et al.* (2013)	GLEAM	Batalla *et al.* (2015)
SHEEPEUR2	Sheep	FAOEurope	2010	Gerber *et al.* (2013)	GLEAM	Batalla *et al.* (2015), Escribano *et al.* (2020)
GOATEUR1	Goat	FAOEurope	2010	Gerber *et al.* (2013)	GLEAM	Batalla *et al.* (2015)
GOATEUR2	Goat	FAOEurope	2010	Gerber *et al.* (2013)	GLEAM	Batalla *et al.* (2015), Escribano *et al.* (2020)
SREU271	Sheep + goats	EU27	2004	Weiss and Leip (2012)	CAPRI	Batalla *et al.* (2015)
SREU272	Sheep + goats	EU27	2004	Weiss and Leip (2012)	CAPRI	Batalla *et al.* (2015), Escribano *et al.* (2020)

achievable and used SHEEP-EUR-1 for 4 different scenarios varying in timeline for full introduction of the 3-NOP as a mitigation measure (20, 40, 60 and 80 years).

For all the scenarios mentioned above, we included as an alternative emissions projection, that pathway of net GHG emissions that considers CO_2 offsets due to estimations of potential soil organic carbon (SOC) sequestration as approximated using data from Batalla *et al.* (2015) (SOC-1), and Batalla *et al.* (2015) and Escribano *et al.* (2020) (SOC-2) (full details are given in the online Supplementary File in Section 3). This approach estimates the annual SOC that can potentially be sequestered averaged over 100 years following the approach by Petersen *et al.* (2013). This approximation is subject to large uncertainties and requires several assumptions such as: no-tillage is carried out, SOC is not at its level of C saturation and nor does it consider climatic and soil factors. For our projections of SOC between 2020 and 2100, we are assuming that the annual C sequestration estimated for the 2018 year could be maintained until the end of the century.

Results

Contribution of historical European small ruminant activity to global temperature change (1990–2018)

Europe (FAO region): When comparing CO_2-e and CO_2-we for the different species and extrapolations for European dairy sheep (Fig. 1, top) and dairy goats (Fig. 1, bottom), we observe that GHG emissions differ considerably when expressed as CO_2-e from when expressed as CO_2-we. This is true for both annual (Fig. 1, left) and aggregated (cumulative: Fig. 1, right) values. Correspondingly, warming estimations reflect that the CO_2-we metric results in much lower temperatures than using CO_2-e. In addition, whereas the extrapolation method influenced the total cumulative CO_2-we, it did not affect the cumulative GHG emissions expressed as CO_2-e.

EU-27: Similar to the previous case, a comparison of CO_2-e and CO_2-we for aggregated small ruminant systems in the current European Union member countries (SR-EU27-1) for the period between 1990 and 2018 also showed great differences depending on the way we express GHG emissions and associated warming (Supplementary Fig. S13).

Impacts of GHG mitigation scenarios from European small ruminant activity on global temperature change (2020–2100)

When observing the scale of warming that would result from different GHG emission reduction pathways in sheep (Fig. 2, top) and goat (Fig. 2, bottom) dairy production systems in the

European FAO region, data show that keeping constant GHG emissions up until the end of the century would contribute to some net warming effect. Reducing annual GHG emissions reduces this warming effect. If annual GHG emissions are below 0.8% (dairy sheep) or 1% (dairy goats) per year, no additional warming to the atmosphere is observed in the simulation. More ambitious GHG reduction pathways would contribute to further cooling of the atmosphere in this period. When we considered emissions offsets due to potential SOC sequestration as an alternative calculation (scenarios + SOC), the pathway showed much lower associated warming than without consideration of SOC stock changes.

If this same observation is done at the level of the current European Union member states for aggregated small ruminant data (Supplementary Fig. S14), keeping constant GHG emissions from small ruminants' dairy production systems in the EU-27 up until the end of the century would contribute to some net warming effect. Reducing annual GHG emissions reduces this warming effect. If annual GHG emissions are reduced beyond 1.2%, no additional warming to the atmosphere was observed in the simulation. Again, more ambitious GHG reduction pathways would contribute to further cooling. There are no differences between the two approaches for extrapolation of GHG.

Mitigation example (3-NOP feed additive introduce to the European dairy sheep systems)

As expected, the faster the gradual inclusion of the 3-NOP additive in the diet was, the larger the reduction was on the warming effect of each of the dairy sheep scenarios for the European FAO region (Fig. 3). In particular, when the full implementation of the measure happened as fast as in 20 years, European dairy sheep systems would not add extra warming for the first 40 years (until 2060: Fig. 3, left). Including the potential SOC sequestration results in any of the scenarios of 3-NOP feed additive inclusion would mean there would be no additional warming for the years to come up until 2100 (Fig. 3, right).

Discussion

Although a number of studies indicate that milk production in Europe has led to large GHG emissions (e.g. Lesschen *et al.*, 2011) and there have been urgent calls to drastically reduce milk consumption (Harwatt, 2019), our estimates indicate that, in terms of historical warming (1990–2018), their conclusions do not apply to small ruminants. When linking emissions to their resulting temperature we found that for both EU-27 and European FAO region dairy small ruminants have not caused
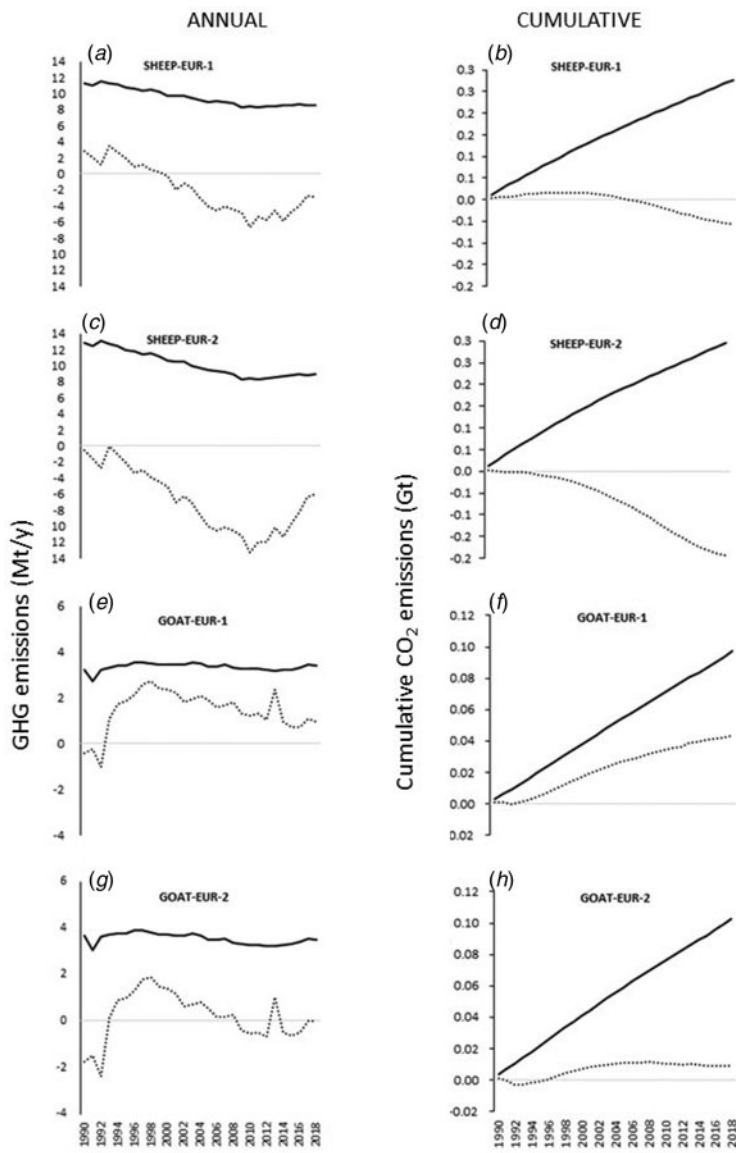
Fig. 1. Corresponding annual (left panels) and cumulative (right panels) GHG emissions from dairy sheep (a:d) and goat (e:h) systems in Europe (FAO region). Solid lines: emissions calculated using the global warming potential GWP_{100} metric (CO_2-e). Dotted lines: emissions calculated using the GWP* metric (CO_2 warming equivalent, CO_2-we). Values use extrapolation of GHG emissions based on Batalla *et al.* (2015) (EUR-1) and Batalla *et al.* (2015) and Escribano *et al.* (2020) (EUR-2).

additional warming in the 1990–2018 period. Conventional application of CO_2 metric-equivalent emissions using GWP_{100} results in much larger estimated CO_2 equivalent emissions than through the use of CO_2 warming-equivalent emissions using GWP*.

We also observed very different trends in cumulative GHG emissions when considering the conventional GWP metric against the new GWP* metric. The differences between CO_2-we and CO_2-e emissions are caused by CO_2-we capturing the weighting given to the reduction in CH_4 emissions rate in the preceding decades which leads to a temperature decrease. In this sense, we can see that the use of CO_2-e over-states the impact of CH_4 emissions on this particular historic emissions trajectory.

Greenhouse gas emission trends were consistent across the different methodologies used. As expected, the use of different models (GLEAM-EUR *v.* CAPRI-EU27) and extrapolations (e.g. EUR1 *v.* EUR2) for the historical analysis resulted in different absolute GHG and associated warming values. However, their trends were similar for all their combinations, which allows us to think that our findings are valid in spite of the limitations in data availability. For the future scenarios, the differences amongst

extrapolations were very small, which reinforces the robustness of this approach.

Our extrapolations indicate that there has been a reduction in total GHG emissions and a change in GHG emissions profile of the European and EU-27 C footprint of the small ruminants' milk. This is in spite of milk production from small ruminants in Europe having increased steadily, ca. 10 and 25% for sheep and goat milk production in the period 1990−2018 (data sourced from FAOSTAT). The larger expansion of goat dairy systems compared to sheep ones has resulted in differences in warming impact between the two: whereas changes in dairy goat GHG emissions have resulted in some level of increased warming, larger emission reductions in dairy sheep systems have compensated it.

In particular, there seems to be a large reduction in CH_4 emissions intensity (i.e. CH_4/kg milk), and in N_2O emissions intensity (i.e. N_2O/kg milk) and an increase in CO_2 emissions intensity (i.e. CO_2/kg milk, derived from fossil fuels use and land use change) (detailed in online Supplementary File in Section 5, Supplementary Fig. S7). Improvements in reproduction management, which have led to greater reproduction efficiency (smaller
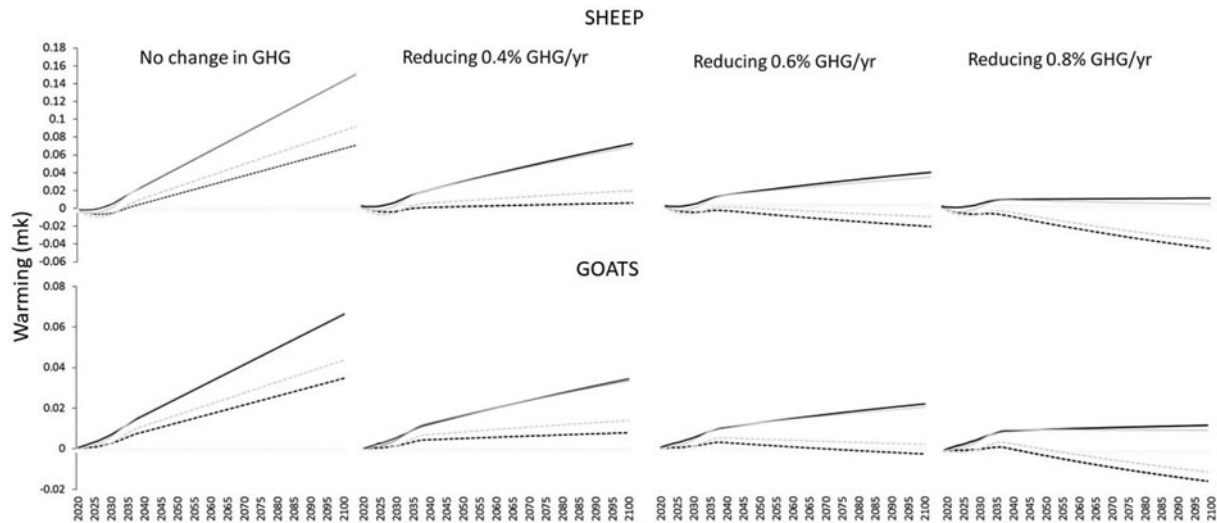
Fig. 2. Warming resulting from different GHG emission reductions pathways considering the full life cycle assessment for sheep milk production (top panels) and goat milk production (bottom panels) in Europe (FAO region) in the period 2020–2100. Values show no change (left) and then 0.4, 0.6 and 0.8% annual reduction in total GHG emissions. Black lines: values use extrapolation of GHG emissions based on Batalla *et al.* (2015) (EUR-1). Grey lines: values use Batalla *et al.* (2015) and Escribano *et al.* (2020) (EUR-2). Solid lines are without including potential SOC sequestration, dotted lines include sequestration.
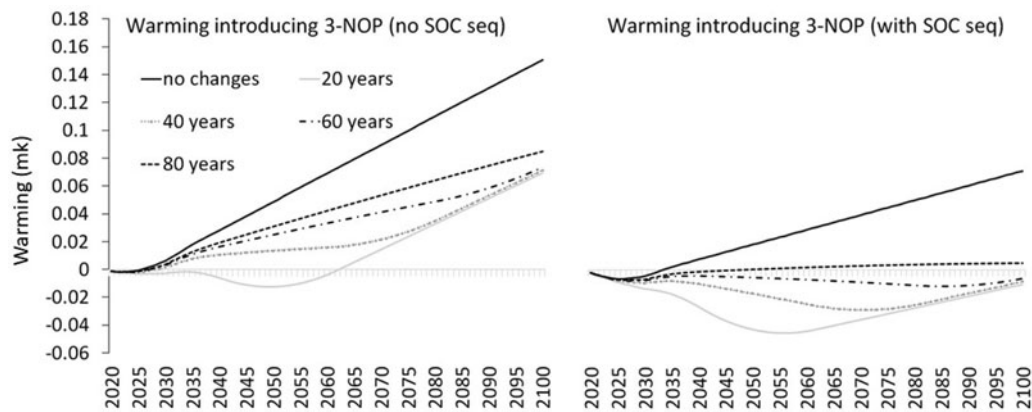

Fig. 3. Warming resulting from gradually (in 20, 40, 60 and 80 years) introducing the 3-NOP feed additive in dairy sheep production systems in the European FAO region for the period 2020–2100 for scenarios without (left) and including potential SOC sequestration (right). Values use extrapolation of GHG emissions based on Batalla *et al.* (2015) (SHEEP-EUR-1).

herds required per unit of milk produced) and a certain intensification linked with breeds that are more productive as well as higher fodder inputs of superior quality are expected to have caused both the reduction of the overall GHG footprint and the shift in GHG emission forms.

The shift between smaller CH_4 (short lived) to larger CO_2 (long lived) emissions implies that a fast cooling effect may be seen (reduction of CH_4) at the expense of, to a certain extent, some increased level of warming for the long-run (increase of CO_2). However, since reduction rates in CH_4 intensity have been much larger than CO_2 increases, such trade-off seems to have had limited warming implications for the future in this particular case. This should, nevertheless, be taken cautiously: the reduction in CH_4 emissions by livestock no longer grazing on marginal areas may have been replaced by methane-emitting wild herbivores that would be occupying their former grazing niches in the ecosystem (Manzano and White, 2019). It is known that European wild herbivores are expanding into abandoned marginal grazing areas (Milner *et al.*, 2006), so the net

amount of CH_4 arising from the whole wild and domestic grazing system may have stayed around the same values.

Higher levels of intensification are expected to exacerbate this trade-off in emissions of short-lived gases to long-lived gases. This trade-off may be further imbalanced considering that N_2O (a long-lived gas) has been found to follow a non-linear response to N inputs for both temperate (Cardenas *et al.*, 2010) and tropical (Tully *et al.*, 2017) systems. Higher levels of intensification will lead to higher N_2O emission rates, thus potentially increasing the amount of long-term warming effect. This effect has not only been recognised in the literature, but it has been indicated as potentially implementable in national inventories of GHG in the last IPCC Refinement (IPCC, 2019).

Scenarios for the small ruminant sector in Europe (for both sets of countries considered) to achieve zero warming effect for the next years to come in the twenty-first century involve modest (0.8–1.2%) annual GHG reductions considering the LCA sectorial boundaries. This approach, based on real warming rather than on CO_2-e (metric-equivalent) neutrality, could induce changes in

GHG reduction strategies in compliance with the Paris Agreement if compared to those arising from within a cumulative carbon framework (Lynch et al., 2020). Strategies prioritising long-term climatic effects would be less concerned about biogenic CH_4 targets, and design stronger efforts to reduce fossil CO_2 emissions. Conversely, other strategies focused on short-term methane action, which trust effective carbon capture and storage technologies for the distant future, could be reinforced by using warming-equivalent emission metrics.

Rather than implying that these GHG reductions would require parallel reductions in milk production, mitigation measures that have been widely studied (e.g. Hristov et al., 2013) and are already applicable could also contribute to these reductions. For example, there are some feed additives that can lower the CH_4 output from the rumen. In this sense, our results for dairy sheep indicate that an introduction of the feed additive 3-NOP, assuming its full potential was achieved as a long-lasting effect, would be sufficient to reduce additional warming to close to zero in the next decades (i.e. be climatically neutral) and to maintain the same European sheep milk volume and production systems structure as those from 2018. This is especially true if we considered the potential for SOC sequestration in our calculations and/or we introduced this 3-NOP measure at a fast pace of 5% per year (in volume of milk produced). Interestingly, the speed of introduction makes a big difference for the near-term transition period but much less of a difference by the end of the century, suggesting that a slower introduction of 3-NOP would lead to almost the same, but delayed for some decades, temperature stabilisation. This would contrast with any measure that targets a reduction in a long lasting gas (e.g. CO_2), which would result in much larger temperature stabilisation should its introduction be delayed. There are other specific examples of promising feed additives, such as those from red algae extracts (Kinley et al., 2020) that have resulted in up to a 50% reduction in CH_4 emissions.

In general, there are many other potential mitigation measures to reduce GHG emissions for small ruminants in temperate regions (Jones et al., 2014). Those measures that improve animal fertility or longevity, which have an impact on the replacement rate of the herd, will reduce overall GHG emissions intensity (Jones et al., 2014).There is also certain scope to reduce GHG emissions via improvement of animal health, animal productivity (through animal data interpretation for example, Belanche et al., 2019) and changes in the animal diet. Measures that improve the overall efficiency of the systems, such as the replacement of conventional feed by agricultural by-products (Romero-Huelva and Molina-Alcaide, 2013; Marcos et al., 2020), have been found to significantly reduce the total C footprint of the milk from small ruminants' systems too (Pardo et al., 2016).

Grasslands, and consequently grassland-based small ruminant systems, have the additional advantage of acting as a carbon sink, which can be exploited for GHG mitigation (Stanley et al., 2018). Different European studies (e.g. Salvador et al., 2017; Eldesouky et al., 2018; Horrillo et al., 2020; Sabia et al., 2020) indicate that considering the potential of on-farm SOC sequestration could offset the C footprint of sheep and goat milk by up to 90%. In this study, we estimated values of SOC sequestration potential for current small ruminant systems in Europe that could offset about 17–23% of the C footprint, depending on the assumptions chosen. This SOC sequestration could partly offset CO_2 emissions from fossil fuels use and land use change. Our approximation indicates that, if SOC sequestration is considered and assumed to remain at our estimated current levels (i.e. offsetting 16% or 23% of total C

footprint), reductions of 0.5% or 0.6% GHG annually would be sufficient to avoid adding any additional warming in the period 2020–2100 for European sheep and goat systems, respectively. Actual SOC sequestration is, however, still subject to large uncertainties and our approximation is not meant to be considered as a robust SOC value but, rather, as a useful illustration of the importance of improving the SOC sequestration estimates. Soil organic C (SOC) tends to have large accumulation rates during the first 20 years after a change in management (assuming a particular management leads to SOC sequestration), but the rate of change slows down considerably afterwards (Powlson et al., 2011). We have not considered this or the fact that SOC sequestration benefits can be reversed if management changes to a situation where soil is degraded or ploughed up for arable systems.

Our potential SOC sequestration approximation for the historic period of 1961–2018 indicated a large reduction of potential SOC sequestration in time (about 80% expressed as kg CO_2/L milk) driven by a change in production systems structure. As the sector has intensified and improved both the quality of the feeding and the reproductive performance of the animals, enteric-CH_4 has shrunk. However, this has been achieved at a certain expense of SOC sequestration, since part of the feeding improvement has been caused by increasing housing periods and decreasing reliance on permanent grasslands, especially for grazing. This type of pollution swapping issue has been previously described for cattle dairy systems by Vellinga and Hoving (2011).

In conclusion, our study illustrates with a real example how GWP* provides an improved method to assess the impact of methane, creates actionable goals to achieve the mandated maximum 1.5°C increase in average temperature by 2050, and evaluates current policies proposed for such goals. In our case, we used a timeline for 2100. As has been highlighted by Lynch et al. (2020) and shown in our study, using GWP_{100} does not even indicate the correct direction of temperature change during periods of declining CH_4 emissions, and new GWP* metrics offer a much more appropriate picture. This is especially important when assessing medium/long term (>100 years) periods and when comparing production systems and species with different GHG profiles. Although GWP* has raised questions of equity and fairness for its application in international climate policies (Rogelj and Schleussner, 2019; Smith and Balmford, 2020), the analysis of such criticisms is beyond the scope of our paper. However, most countries with large historic agricultural CH_4 emissions that are capable of reducing their additional contribution to warming (i.e. negative cumulative CO_2-we), which are the centrepiece for the fairness argument, could still maintain their historically high contribution to global warming at a steady rate. This would be equivalent to a country achieving net zero CO_2 emissions, as CO_2 remains in the atmosphere for millennia. However, the difference is that this CH_4 source is an opportunity to undo past contributions to global warming, the same way as CO_2 removal and C storage would be. Moreover, these countries have abundant natural grazing ecosystems in their territory that can host many wild methane-producing herbivores. Total abandonment of grazing in natural rangelands is likely to be a very ineffective climate change policy (Manzano and White, 2019).

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