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

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## SUPPLEMENTARY FILE

## Contents

In this supplementary file we include the information about:

1. General approach to derive full time series of GHG emissions for dairy small ruminants in Europe and EU-27 (1961-2018)
2. the data sources for European and EU-27 GHG emissions and modelling approaches (GLEAM and CAPRI)
3. extrapolation of GHG emissions for Europe and EU-27 to a full time series of GHG emissions (1961-2018)
4. GWP* as a metric for estimation of climate change impacts
5. European trends in GHG emissions from small ruminant systems during 1961-2018: results
6. Historical and scenario warming estimate for small ruminant systems in EU-27: results

## 1. General approach

We first used the GHG emissions calculations ($CO_2$-e for $CO_2$, $CH_4$ and $N_2O$) from dairy small ruminant production systems in the Europe FAO region on the single-year data by Gerber *et al.* (2013) (Europe) using the GLEAM model, while for the 27 current members of the European Union (EU-27) we used data from Weiss & Leip (2012) using the CAPRI model. We used both approaches to illustrate the range of results that could be expected for different modelling methodologies. Each calculation (i.e. Europe FAO Region, and EU-27) was extrapolated to a full-time series (1961-2018) by using data on historical changes in Spain and two different LCA-based GHG approaches based on Batalla *et al.* (2015) (EUR-1, EU-27 1) and Batalla *et al.* (2015) and Escribano *et al.* (2020) (EUR-2, EU-27 2). We chose to develop 2 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.

## 2. Emissions data for small ruminant production systems from two different approaches (Europe-FAO region and model GLEAM) and EU-27 (model CAPRI)

*Europe (FAO region) data sourcing*

We used the dataset available for Europe at FAO (2017), where GHG emissions (C footprint) are estimated for different livestock production systems (grassland-based, mixed systems) using the GLEAM model (MacLeod *et al.* 2018), based on activity data (e.g. animal numbers) and productivity parameters from 2010. GLEAM adopts a life-cycle approach and calculates the emissions arising along the supply chain from cradle to retail point. This allows for calculation of GHG emissions of specific commodities, rather than just the total emissions from an agricultural subsector (MacLeod *et al.* 2018). Greenhouse gas emissions are expressed as a total as well as per unit of protein to allow comparisons between species. For this study we only used the small ruminant dairy systems.

The C footprint from the whole livestock supply chains is calculated and comprehensively disaggregated into $CO_2$, $CH_4$ and $N_2O$ emissions from pre-farm, on-farm and post-farm gate sources. Four main processes are considered: enteric fermentation, manure management, feed production and energy consumption.

Enteric $CH_4$ emissions are calculated using a modified IPCC (2006) Tier 2 approach that incorporates an equation that relates the % of gross energy intake converted to methane ($Y_m$) with feed digestibility (DE).

Emissions from manure management involves both $CH_4$ and $N_2O$ emission. Methane and $N_2O$ (direct and indirect) emissions from manure are calculated using a TIER 2 approach based on IPCC (2006). For $N_2O$ estimation, it requires an estimation of both the rate of N excretion per animal and the proportion of the excreted N that is converted to $N_2O$. The N excretion rates are calculated using the formulae set out in FAO (2017) and N intake depends on the feed DM intake and the feed N content.

For feed production, GLEAM calculates $CO_2$ emissions from expansion of feed crops and pastures into natural areas such as forests, from manufacture of fertilizers and pesticides for feed crops and from feed transportation and processing. For $N_2O$ emissions GLEAM calculates the $N_2O$ from the use of nitrogenous fertilizers and by direct application of manure and grazing both in pastures and crop fields. Nitrous oxide emissions are calculated using IPCC (2006) Tier 1 methodology. For our study, we updated $N_2O$ from manure application and grazing using Efs from IPCC (2019) as there was enough information (as opposed to other GHG sources) provided the simplicity of the method to do this change.

GLEAM also calculates GHG emissions for the energy use along the entire supply chain. Production of fertilizers and the use of machinery for crop management, harvesting, processing and transport of feed crops generate GHG emissions, which are accounted as part of the emissions from feed production. Energy is also consumed on animal production site for ventilation, illumination, milking, cooling, etc. Finally, livestock commodities are processed, packed and transported to retail points, which involves further energy use.

### *EU-27 data sourcing*

Weiss & Leip (2012) comprehensively assessed GHG emissions, including emissions from land use and land use change (LULUC), from livestock systems in the EU27 for the year 2004. Boundaries include a cradle-to-gate life-cycle assessment and characterizes livestock systems from information drawn from European databases. They consider emissions on the farm as well as emissions related to the production of inputs, but not emissions from processing, transport, packaging, retail, consumption and waste of the products (Weiss & Leip, 2012). This study uses the CAPRI model (Britz & Witzke, 2008), which originally is an economic model to assess agricultural policies but, in this version, it incorporates GHG emissions via emission factors (Efs). Small ruminants' estimations are aggregated for both species, i.e. sheep and goats' systems, and disaggregated for meat and dairy commodities. For this study we only used the dairy systems. For details on the estimation of fluxes of nitrogen and GHGs, see Leip *et al.* (2010).

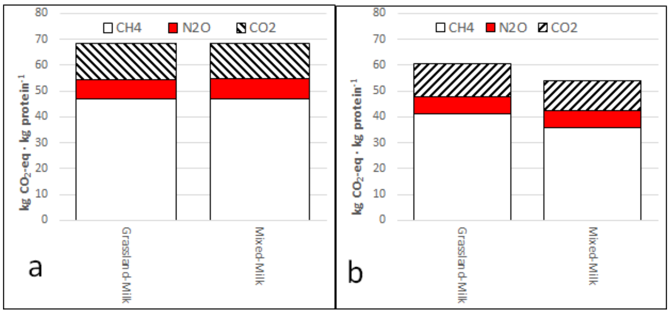
Generally, the quantification of GHG emissions follows the IPCC (2006) guidelines (Weiss & Leip, 2012). For example, calculation of $CH_4$ emissions from enteric fermentation and manure management follows a Tier 1 approach for small ruminants' systems. For our study, we updated $N_2O$ from manure application and grazing using Efs from IPCC (2019) as there was enough information (as opposed to other GHG sources), given the simplicity of the method to do this change.

Emissions from land use change (LUC) are included (including carbon sequestration in grassland soils) by looking at three scenarios relating to LUC. They differ in their assumption on the origin of required additional land for imported feed products, and reflect the uncertainty associated with estimates on LUC emissions. For our study, we only used one of the scenarios of LUC, which results in lower impact on CO2 emissions from LUC.

### *C footprints used as basis for Europe and EU-27*

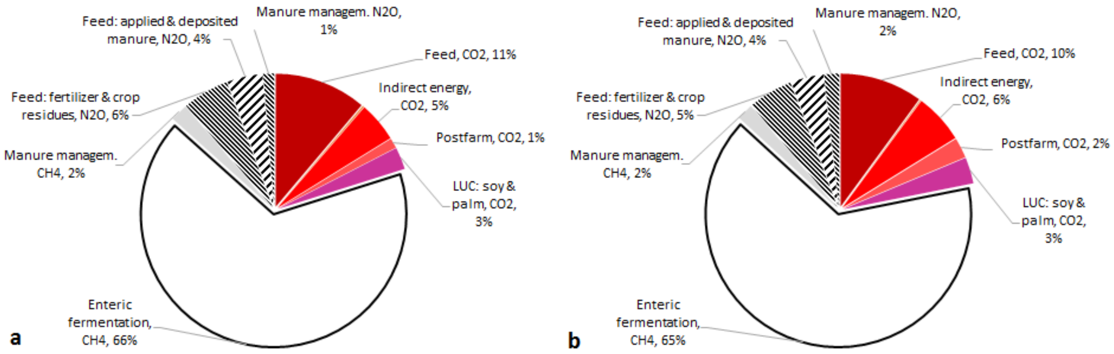
We used the basis of the emission sources from these two different studies and regions, each utilizing different models: Gerber *et al.* (2013) with the GLEAM model (MacLeod *et al*. 2018) (EUROPE) and Weiss & Leip (2012) with the CAPRI model (Britz & Witzke, 2008) (EU-27). Both approaches contain total emissions at the country level for C footprint values for livestock, including small ruminants' species (sheep and goat separated for Gerber et al. 2013 and aggregated in Weiss & Leip, 2012), commodities (milk, meat) and production systems (grassland-based, mixed systems) for Gerber *et al.* 2013. For both approaches, GHG emissions are only calculated for one specific year: 2010 and 2004 for Gerber *et al.* (2013) and Weiss & Leip (2012), respectively.

Suppl. Figure S1 shows the different gas sources that comprise the C footprint expressed as kg $CO_2$/kg protein milk for sheep (a) and goat (b) milk for the year 2010 as calculated by Gerber *et al.* (2013) for different production systems in Europe (FAO region). The largest proportion of the carbon footprint, over 60%, is associated with $CH_4$ emissions. Methane contribution to the C footprint ranges from 66% for goat milk from mixed-farming systems to any production system associated to sheep milk (69%). Species-wise, goat products result in lower emissions per kg of protein than that from sheep production.



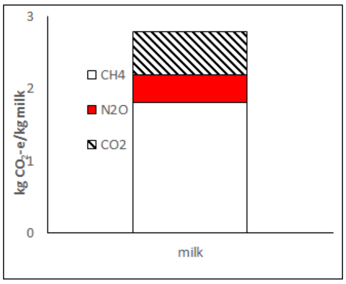
**Supplementary Figure S1.** Different gas sources that comprise the C footprint, expressed as kg $CO_2$-e per kg of protein for sheep (a) and goat (b) milk under different production systems (grassland vs. mixed systems) in Europe (year 2010). Based on Gerber *et al.* (2013)

Further dissagregation of emission by the different sources considered in the GLEAM model is shown in Suppl. Fig2.



**Supplementary Figure S2.** Relative contribution of the different emissions that comprise the C footprint, expressed as % for sheep (a) and goat (b) milk in Europe (year 2010). Based on Gerber *et al.* (2013)

For the EU-27 (Leip *et al.*, 2010) the C footprint of 1 kg of milk from small ruminant systems results in about 2.8 kg CO2-e/kg milk as calculated by Leip *et al.* (2010) for the year 2004. Methane contribution to the total C footprint ranges from about 65% for milk products from small ruminants. Carbon dioxide emissions from fossil fuel use and land use change represents the second source of GHG emissions with a contribution of about 20% of the total carbon footprint for Europe (Gerber *et al.*, 2013) and 21% for the EU-27 (Leip *et al.*, 2010) (Suppl. Figure S3).



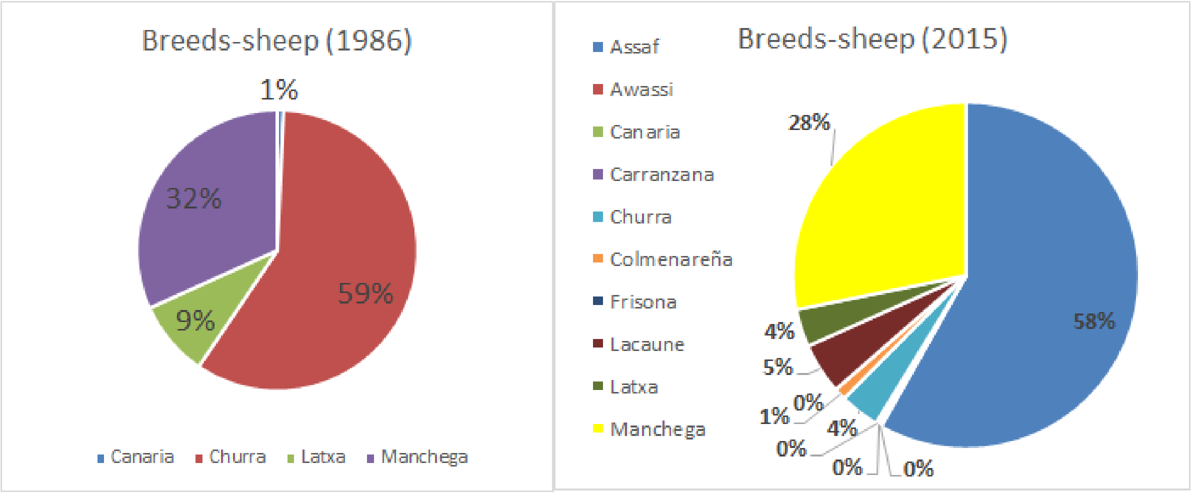
**Supplementary Figure S3.** Different gas sources that comprise the C footprint, expressed as kg $CO_2$-e per kg of milk from small ruminants in EU-27 (year 2004). Based on Leip et al. (2010)

## 3. Extrapolation of GHG emissions for Europe (FAO region and GLEAM model -2010 year) and EU-27 (CAPRI model-2004 year) to a full time series of GHG emissions (1961-2018)

In order to create a time-series of GHG emissions (1961-2018) we extrapolated 2010 and 2004 values to the different years based on:

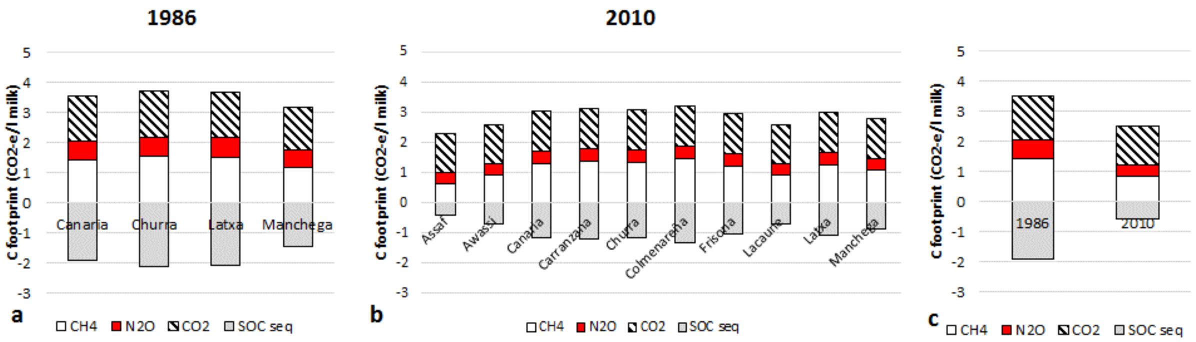
- Historical data on changes in Spanish sheep productivity parameters and breeds as a proxy of how European production systems may have changed in a relative way in the last decades
- LCA-based GHG emissions for different Spanish production systems and breeds.
- Annual values for sheep and goat milk production for Europe and EU-27 for the period 1961-2018 (based on FAOstat).

We used the changes in real commodity production for each country and year and multiplied these values with two assumptions of how C footprint values (as kg CO2-e/ kg product) have changed over time. In order to develop how C footprint values (as kg CO2-e/ kg product) have changed, in a relative way, over time, we used the existing C footprint values for different production dairy sheep systems in Spain (Assaf and Latxa breeds: Batalla *et al.*, *2015* and Churra breeds: Escribano *et al.*, 2019) and normalized these values depending on the different % of breed types and production levels for different years in Spain (based on Yañez-Ruiz, 2019) (Suppl. Figure S4).

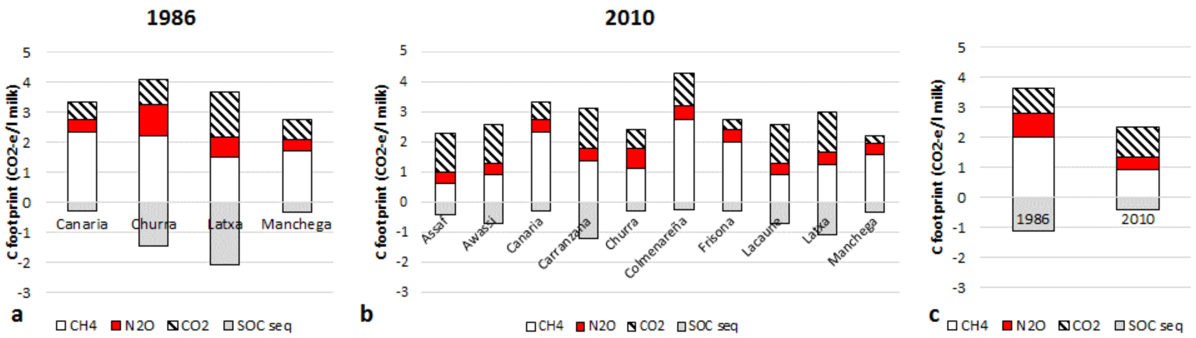


**Supplementary Figure S4.** Example for different breed types % in Spanish sheep production systems for 1986 and 2015.

We developed 2 different extrapolation methods based on two different LCA-based GHG studies: Batalla *et al.*, 2015 (EUR-1, EU-27 1) and Batalla *et al.*, 2015 and Escribano *et al.*, 2020 (EUR-2, EU-27 2). For both extrapolation methods we normalized LCA results for breeds and years considering the breed productivity data for different historical years based on Yañez-Ruiz (2019). The main differences of both extrapolation methods were the studies that were used a basis for LCA extrapolation. Whereas for EUR-1, EU-27 1 we only used the data from Assaf and Latxa breeds from Batalla *et al.* (2015) study as a basis for intensive and extensive systems, respectively. For EUR-2, EU-27 2 we additionally used the Churra breed results from Escribano *et al.* (2020). An example of results are shown for sheep EUR-1 (Suppl. Figure S5) and sheep EUR-2 (Suppl. Figure S6).



**Supplementary Figure S5.** Different gas sources that comprise the C footprint, expressed as kg $CO_2$-e per kg of milk from small ruminants for the different sheep breeds in (a) 1986 and (b) 2010 associated to production systems in Spain and their resulting estimated C footprint accounting for the relative importance of each breeds on these years (c). C footprint data are based on Batalla *et al.* (2015) and national statistical data is based on Yañez-Ruiz (2019).



**Supplementary Figure S6.** Different gas sources that comprise the C footprint, expressed as kg $CO_2$-e per kg of milk from small ruminants for the different sheep breeds in (a) 1986 and (b) 2010 associated to production systems in Spain and their resulting estimated C footprint accounting for the relative importance of each breeds on these years (c). C footprint data are based on Batalla *et al.* (2015) and Escribano et al. (2020) and national statistical data is based on Yañez-Ruiz (2019).

It must be noted that to our knowledge there is not any study that have produced a time series of GHG for small ruminants in Europe at the LCA level and this approach is just to be used as an example rather than a precise value.

## 4. GWP* as a metric for estimation of climate change impacts

In light of the shortcomings for $GWP_{100}$ to accurately describe real contribution to global warming, we compared its results with those from GWP*. For long lived climate pollutants (LLCPs) like $CO_2$ an $N_2O$, $GWP_{100}$ (i.e $CO_2$-e) is representing acceptably well the impact of these gases on climate change. For short lived climate pollutants (SLCPs) (i.e $CH_4$ emissions) we carried out GWP* calculations.

The following equation is used to calculate GWP* (called the $CO_2$ warming equivalent: $CO_{2\text{-}we}$) at a particular year:

$ECO_{2\text{-}we} = GWPH \times \{[0.75 \times (\Delta ESLCP/\Delta t) \times H] + [0.25 \times ESLCP]\}$

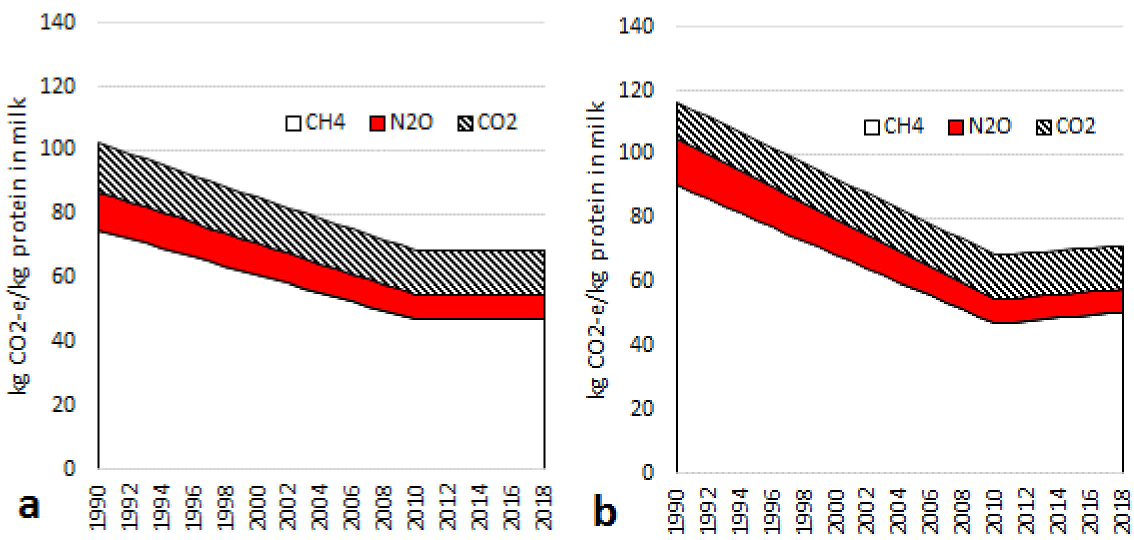
where $ECO_{2\text{-}we}$ is the estimated $CO_2$-we, GWPH is the conventional global warming for $CH_4$ over time-horizon H (100 years), ΔESLCP is the change in $CH_4$ emission rate over the preceding Δt (20) years, ESLCP is the $CH_4$ emissions for the objective study year (Cain *et al.*, 2019)

Values of $CO_2$-we from $CH_4$ emissions were then summed with $CO_2$-e values from $CO_2$ and $N_2O$ ($CO_2$e are equivalents to $CO_{2we}$ for LCPs in the 100 year time frame) and, in order to estimate the cumulative warming from the period studied, annual $CO_{2we}$ (from $CH_4$) and $CO_2$e (from $CO_2$ and $N_2O$) values were aggregated for an overall estimation of GHG emissions.

A simple coefficient known as TRCE (Transient climate Response to cumulative Carbon Emissions) can be multiplied by cumulative $CO_{2\text{-}we}$ to obtain an approximate estimate of temperature change due to the change in $CO_{2\text{-}we}$ burden experienced. The TRCE coefficient for $CO_2$ is 0.4 K°/Tt $CO_2$ (Lynch *et al*, 2020).

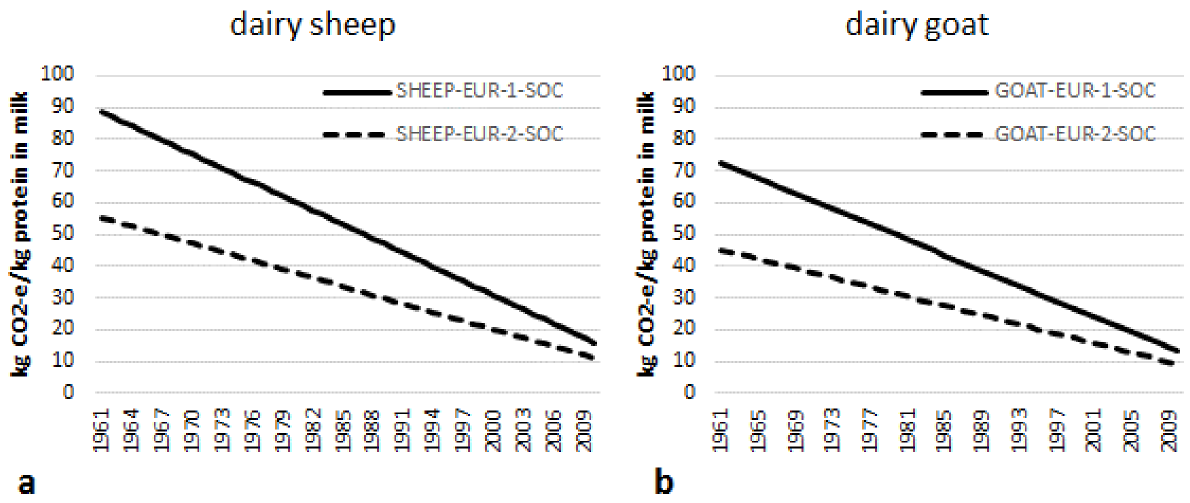
## 5. European trends in GHG emissions from small ruminant systems during 1961-2018: results

Suppl. Figure S7 shows as an example how sheep C footprint is estimated during the period 1990-2018 to have changed for the two different extrapolations EUR-1 (a) and EUR-2 (b).



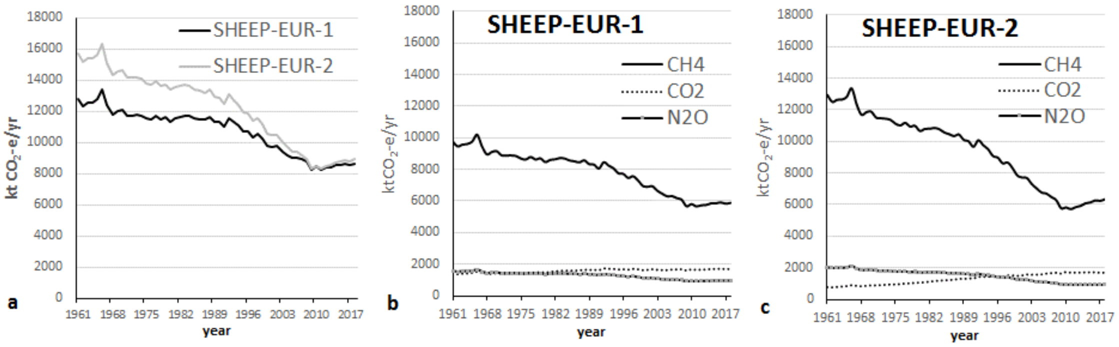
**Supplementary Figure S7.** Evolution of the different gas sources that comprise the C footprint, expressed as kg $CO_2$-e per kg of protein for European sheep milk estimated for extrapolation EUR-1 (a) and EUR-2 (b) Based on Gerber *et al.* (2013) and extrapolations based on Yañez-Ruiz (2019) and (a) : Batalla *et al.* 2015 and (b): Batalla *et al.* 2015 + Escribano *et al.*, 2020.

Suppl. Figure S8 shows SOC sequestration as estimated for the period 1961-2010 for European sheep (a) and (b)goat systems and the two different extrapolations EUR-1 (a) and EUR-2 (b).

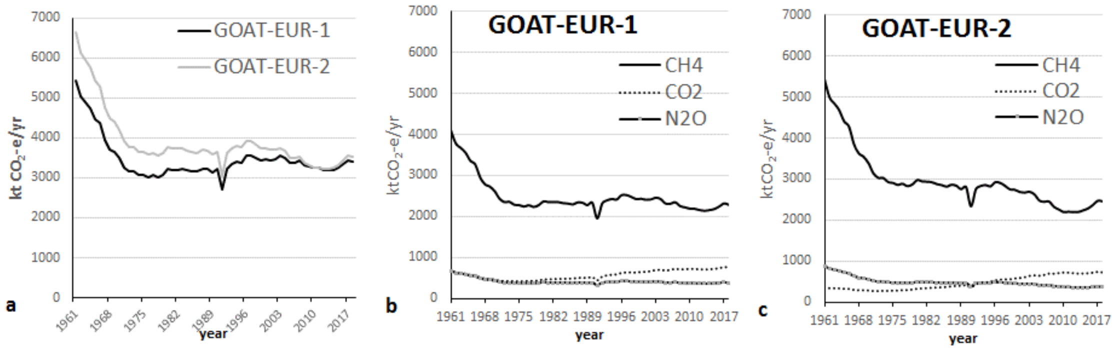


**Supplementary Figure S8.** Evolution of the estimated SOC sequestration (1961-2010), expressed as kg $CO_2$-e per kg of protein for European sheep (a) and (b) milk estimated for extrapolation EUR-1 and EUR-2 Based on extrapolations based on Yañez-Ruiz (2019) and (a) : Batalla *et al.* 2015 and (b): Batalla *et al.* 2015 + Escribano *et al.*, 2020.

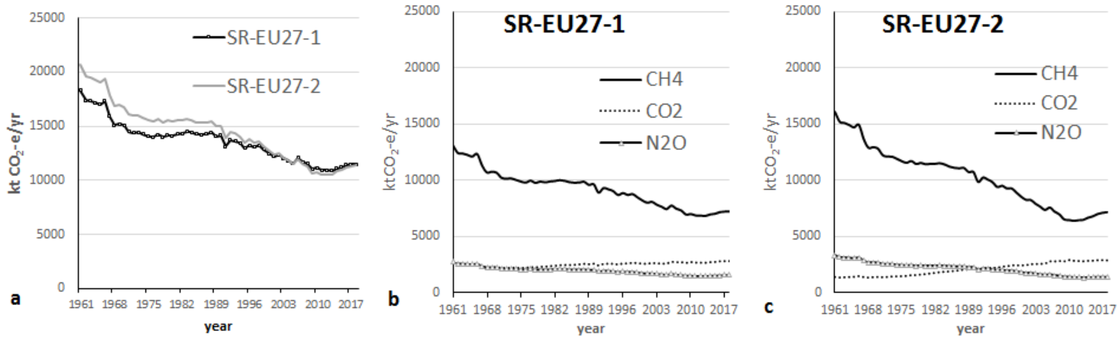
Suppl. Figure S9 and S10 show the total GHG emissions for European (FAO region) dairy sheep and goat production systems (as estimated by GLEAM for 2010 + extrapolations), respectively. Suppl. Figure S11 shows the GHG emissions for EU-27 European GHG emissions from small ruminant production systems (as estimated by CAPRI model for 2004 + extrapolations). Figure S12 shows the evolution of potential SOC sequestration for European sheep and goat production systems as estimated using changes in real commodity production for each country and year and multiplied these values with two assumptions of how SOC sequestration potential in footprint values (expressed as kg $CO_2$-e/ kg product) have changed over time. In order to develop how SOC sequestration potential in footprint values (as kg CO2-e/ kg product) have changed, in a relative way, over time, we used the existing SOC sequestration potential values for different production dairy sheep systems in Spain (Assaf and Latxa breeds: Batalla *et al.*, 2015 and Churra breeds: Escribano *et al.*, 2019) and normalized these values depending on the different % of breed types and production levels for different years in Spain (based on Yañez-Ruiz, 2019) (Suppl. Figure S4).



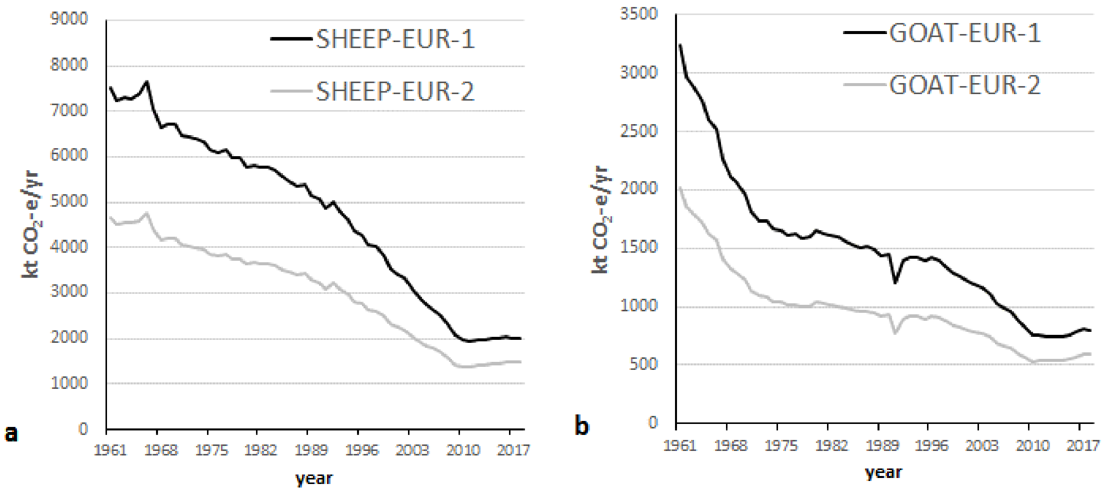
**Supplementary Figure S9.** Evolution of GHG emissions for the years 1961-2018 for milk from European (West Europe + East Europe FAO regions) sheep systems as calculated using LCA values by Gerber *et al* (2013), FAOstat production numbers and assuming 2 different extrapolations of how C footprint has changed in time (based on 1: Batalla *et al.* 2015 and 2: Batalla *et al.* 2015 + Escribano *et al.*, 2020).



**Supplementary Figure S10.** Evolution of GHG emissions for the years 1961-2018 for milk from European (West Europe + East Europe FAO regions) goat systems as calculated using LCA values by Gerber *et al.* (2013), FAOstat production numbers and assuming 2 different extrapolations of how C footprint has changed in time (based on 1: Batalla *et al.* 2015 and 2: Batalla *et al.* 2015 + Escribano *et al.* 2020).



**Supplementary Figure S11.** Evolution of total (a) GHG emissions from EU-27 dairy small ruminants, (b) $CO_2$-edisaggregated by GHG species for extrapolation 1 (based on Batalla *et al.* 2015) and (c) $CO_2$-e disaggregated by GHG species for scenario 2 (based on Batalla *et al.* 2015 + Escribano *et al.*, 2020). Calculations are based on FAOstat production numbers and assuming 2 different extrapolations of how C footprint has changed in time (based on 1: Batalla *et al.* 2015 and 2: Batalla *et al.* 2015 + Escribano *et al.*, 2020).

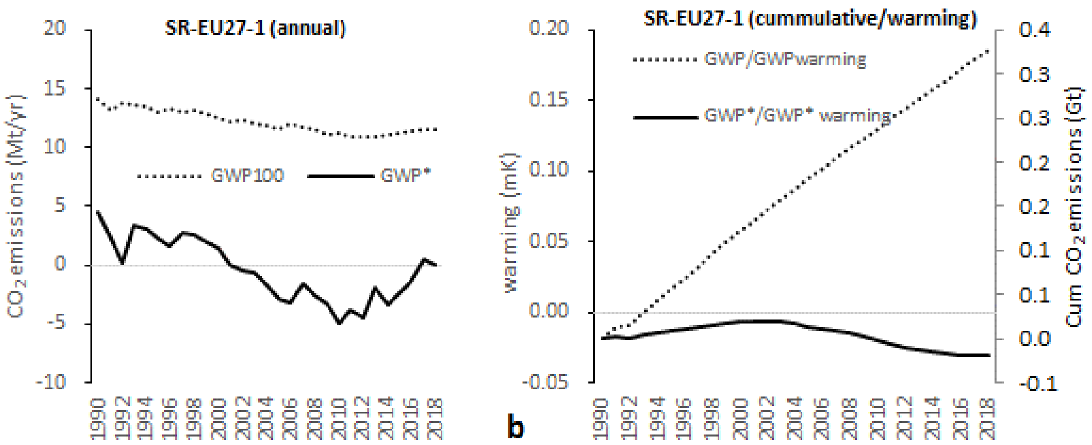


**Supplementary Figure S12.** Evolution of potential offsetting by SOC sequestration potential (in $CO_2$-e) for the years 1961-2018 for milk from European (West Europe + East Europe FAO regions) sheep (a) goat (b) systems as estimated using FAOstat production numbers and assuming 2 different extrapolations of how SOC sequestration potential has changed over time (based on 1: Batalla *et al.* 2015 and 2: Batalla *et al.* 2015 + Escribano *et al.*, 2020).

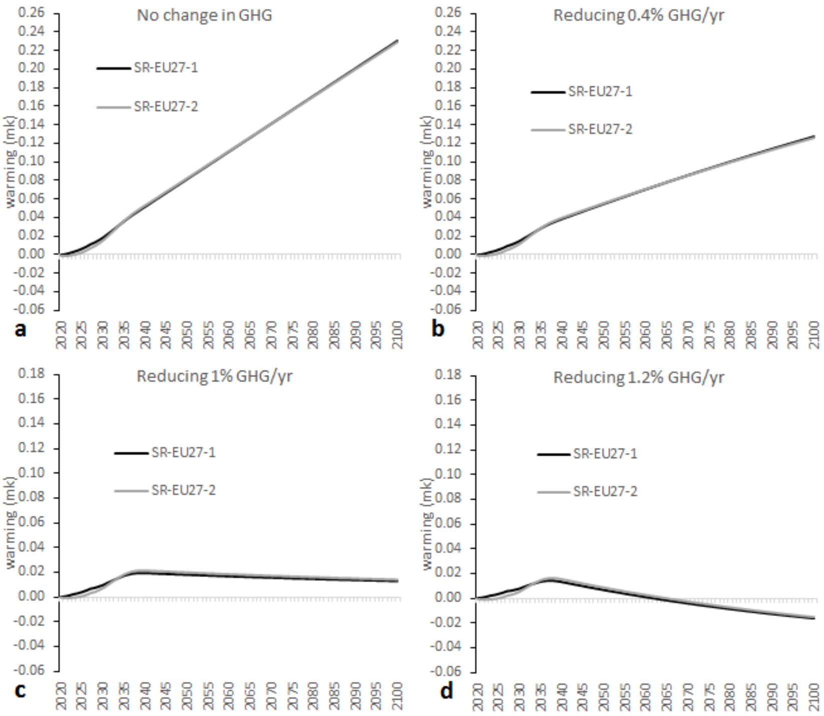
To sum these graphs up, European GHG emissions from small ruminant production systems dairy production as calculated using an LCA approach, have overall been reduced in the period 1961-2018 for both extrapolation methods considered. Whereas for sheep dairy systems reductions have occurred until 2010 and then have not changed much, for goat dairy systems GHG emissions seem to have sharply decreased during the first years (1961-1973) but remained fairly unchanged since.  For the EU-27, integrated sheep and goat dairy systems seem to have reduced their GHG emissions until about year 2010 and slightly increased since then.
Both extrapolation methods indicate that there has been a considerable reduction in annual $CH_4$ emission rates, slight reduction in $N_2O$ emissions, a moderate increase in $CO_2$ emissions and a large decrease in SOC sequestration potential.

## 6. Historical and scenario warming estimate for small ruminant systems in EU-27: results

Suppl. Figure S13 and Suppl. Figure S14 show the historical (1990-2018) and future scenarios testing (2020-2100) for warming of small ruminant production systems in the EU-27.



**Supplementary Figure S13.** Corresponding annual $CO_2$-equivalent emissions from small ruminant dairy systems in the EU-27 using $GWP_{100}$ or GWP* (a), followed by (b) the warming resulting from those GHG emissions overlaid with cumulative $GWP_{100}$ and GWP* $CO_2$-equivalent emissions. Values use extrapolation of GHG emissions based on Batalla *et al.* (2015) (SR-EU27-1)



**Supplementary Figure S14**. Warming resulting from different GHG emission reductions pathways considering the full life cycle analysis for small ruminants milk in the EU-27 in the period 2020-2100 for no change (a), 0.4% (b), 1% (c) and 1.2% (d) annual reduction in total

GHG emissions. Values use extrapolation of GHG emissions based on Batalla *et al.* (2015) (SR-EU27-1) and Batalla *et al.* (2015) and Escribano *et al.* (2020) (SR-EU27-2).

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