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Analyzing long-term dynamics of agricultural greenhouse gas emissions in Austria, 1830–2018

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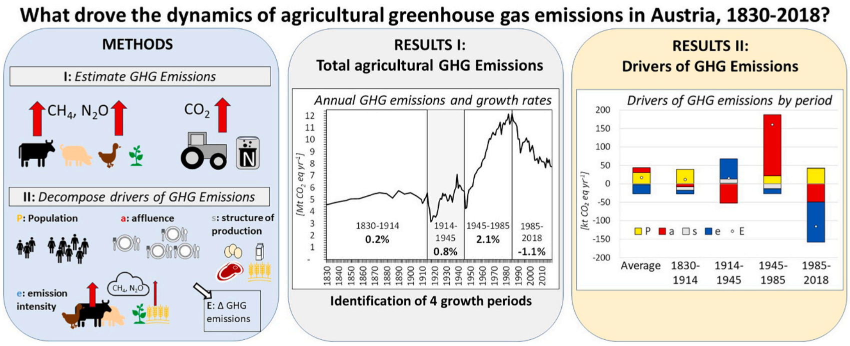
HIGHLIGHTS

- Agricultural GHG emissions increased by overall 69 % from 1830 to 2018.
- Highest mean annual growth rate (+2.1 %/yr) in the period 1945–1985
- GHG emissions peaked in 1985 and decreased by −1.1 %/yr in average afterwards.
- Emission growth driven by population growth and affluence (production per capita)
- Emission growth partly counterbalanced by decreases in emission intensities.

GRAPHICAL ABSTRACT



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ABSTRACT

Agriculture is an important contributor to greenhouse gas (GHG) emissions. While the development of agricultural GHG emissions on national and global scales is well studied for the last three to six decades, little is known about their trajectory and drivers over longer periods. In this article, we address this research gap by calculating and analyzing GHG emissions related to agriculture in Austria from 1830 to 2018. We calculate territorial emissions on an annual basis and include all GHG emissions from the processes directly involved in agricultural production. Based on this time series, we quantify the relative importance of major drivers of changes in GHG emissions across time and agricultural product categories, applying a structural decomposition analysis. We find that agricultural GHG emissions in Austria increased by 69 % over the total study period, from 4.6 Mt. CO_2e/yr in 1830 to 7.7 Mt. CO_2e/yr in 2018. While emissions increased only moderately from 1830 to 1945 (+22 % overall), with strong fluctuations between 1914 and 1945, they doubled from 1945 to 1985. In the most recent period from 1985 to 2018, emissions fell by one third, with decreases leveling off over time. Our decomposition analysis reveals that increases in agricultural production per capita most importantly contributed to the high growth in GHG emissions from 1945 to 1985. Conversely, decreasing emission intensities of products and a more climate friendly product mix were key drivers in the emissions reduction observed after 1985. We

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also contribute to the discussion around the global warming potential star (GWP*), by calculating GHG emissions based on this alternative metric, and contextualize our data within total socio-economic GHG emission trends. By providing insights into the historical trends and drivers of agricultural GHG emissions, our findings enhance the understanding of their long-term historical dynamics and adds to the knowledge base for future mitigation efforts.

1. Introduction

Agriculture is an important contributor to global greenhouse gas (GHG) emissions. In 2020, methane (CH_4) and nitrous oxide (N_2O) emitted on-farm by agricultural activities accounted for around 13 % of global GHG emissions, excluding emissions by Land Use, Land Use Change and Forestry (LULUCF) or forestry and other land use (FOLU) (FAO, 2021a; JRC/PBL, 2021; Tubiello et al., 2013). Upstream and on-farm emissions from fossil fuel use add to emissions ultimately induced by agriculture: the production of nitrogen (N) fertilizers and on-farm use of energy contributed another 2 % to global GHG emissions in 2020 (FAO, 2021a; Menegat et al., 2022). While agriculture's global contribution to total emissions has shown a decline over the past decades (Crippa et al., 2021), it is anticipated that this trend will be reversed in the future. This is due to the inherent challenges in mitigating N_2O and CH_4 emissions from agriculture, particularly from livestock breeding, using technological interventions alone. In line with this, the emission pathway outlined in the European Union's GHG emission development strategy anticipates that agricultural emissions will comprise a substantial portion of the remaining emissions in 2050 (European Commission, 2018). Furthermore, if unmitigated, agricultural GHG emissions alone could preclude achieving the 1.5 °C and 2 °C emission target (Clark et al., 2020). Improving our knowledge about the historical development of agricultural GHG emissions and their underlying drivers can inform viable future options for GHG mitigation in agriculture.

While there is a wealth of studies exploring future scenarios of agricultural GHG emissions (Frank et al., 2017; Röös et al., 2017; Theurl et al., 2020; Wiebe et al., 2015), as well as historical developments of fossil fuel related GHG emissions (Andres et al., 1999; Andrew and Peters, 2021; Boden et al., 2017), relatively little is known about long-term historical trends of agricultural GHG emissions, especially on sub-global scale. Research available for the period since 1960 shows that increased agricultural emissions went along with declining emissions per unit of agricultural product globally, with strong variations across regions (Bennetzen et al., 2016; Hong et al., 2021). However, the period before 1960 has only rarely been investigated. Garnier et al. (2019) presented a comprehensive dataset on all agricultural GHG emissions for France from 1852 to 2014, and Parton et al. (2015) included all emissions from agriculture except manure management in their assessment on the US Great Planes from 1870 to 2000. On the global scale, Jones et al. (2023) recently presented an assessment of all GHG emissions since 1850, including estimates for agricultural emissions. Publications with long time series on GHG emissions related to specific sectors of agriculture are more numerous and include Aguilera et al. (2019a, b, 2021) for the carbon footprint of traction, irrigation and N fertilization in Spain from 1900 to 2014, Kuhla and Viereck (2022) for enteric CH_4 emissions in Germany in 1883 and 1892 and Zhang et al. (2022) and Dangal et al. (2017) for global CH_4 emissions from livestock from 1830 to 2014/2019. While these studies suggest that with the green revolution, the mid-20th century marked a turning point in the quantity and composition of agricultural emissions, the dynamics in drivers of agricultural emissions across the period remain largely elusive.

A key question that arises is in what way intensification and industrialization of agriculture affected the associated GHG emissions in different time periods. On the one hand, inputs used in industrial agriculture cause additional emissions, including the production and use of synthetic fertilizers and tractors (Aguilera et al., 2019a, 2019b; Garnier et al., 2019). On the other hand, efficiency improvements in some sectors led to lower emissions per unit produced (Bennetzen et al., 2016). This is particularly true in the emissions-intensive livestock sector, which became increasingly efficient at converting feed into products as agriculture evolved by eliminating the labor function of livestock, the development of new livestock breeds, improvements in feed quality and a shift from ruminant to monogastric products (Dangal et al., 2017; Zhang et al., 2022). Such efficiency gains are generally associated with fewer emissions per unit of animal product produced (Connor, 2015; Herrero et al., 2016).

Against this background, the aim of our study is to quantify GHG emissions caused by agricultural activities in Austria in 1830–2018 and to assess the roles of major drivers across time and agricultural product categories. In addition, we calculate annual and cumulative emissions based on the alternative global warming potential metric GWP*. Based on these results, we discuss data limitations, contextualize our results by emissions from historical industrialization dynamics, including fossil energy emissions and ecosystem carbon sinks derived from existing studies. We conclude by drawing conclusions for current climate change mitigation challenges.

2. Methods

We employ methodologies outlined in IPCC (2006, 2019a), Hutchings et al. (2013), FAO (2017) and Gingrich et al. (2021), using datasets on short-term (BMLFUW, various years; Statistik Austria, 2015, 2018; UBA, various years) and long-term trends in land use and agricultural production (Gingrich et al., 2016; Gingrich and Krausmann, 2018; Krausmann, 2001a; Krausmann and Haberl, 2007), to generate a time series of agricultural GHG emissions on the current territory of Austria in the period 1830–2018 with annual resolution. Within this time series, we identify major drivers of change by a decomposition analysis. Our results cover all agricultural $CH_{4,}$ N_2O and CO_2 emissions, including CO_2 emissions during the use of tractors. In our calculation, we include and differentiate three categories of ruminant livestock (non-dairy cattle, dairy cattle, sheep and goats), three categories of monogastric livestock (pigs, poultry, horses), three types of livestock feed (food crops, fodder crops and grass, residues and litter) and 33 types of crops and grassland. For the decomposition analysis, we express all emissions in tons of CO_2 equivalents per year (t CO_2 eq/yr), using Global Warming Potentials (GWPs) with a 100-year time horizon according to the IPCC AR6 (N2O 273, CH4 27, IPCC, 2019b). The alternative time series of annual and cumulative GHG emissions, using GWP*, is based on the formula described in Section 2.4.

The dataset on historical land use, agricultural production and population relies on previous data compilations from domestic and international statistical sources (Gingrich et al., 2016; Gingrich and Krausmann, 2018; Krausmann, 2001a; Krausmann and Haberl, 2007), which we updated to the year 2018 using data from FAO (2021b) and national statistics (BMLFUW, various years; Statistik Austria, 2015, 2018; UBA, various years). The dataset enables us to quantify emissions at the detailed level required to decompose aggregate trends into different drivers.

Our analysis follows a territorial approach, i.e. it covers emissions generated by agricultural activities performed within the current territory of Austria in a given year, while excluding emissions from e.g. imports of food or feed, but including emissions related to exported goods produced in Austria. For the period prior to 1910, our source data did not include the province of Burgenland, whose area covers 4.7 % of Austria. We therefore added data for the period before 1910 by applying the ratio between agricultural production, areas and feed use in Burgenland and Austria in 1910 to all previous years.

2.1. GHG emissions: calculation procedures and data sources

Fig. 1 displays processes and associated GHG fluxes considered in our analysis. The description below gives an overview on calculation methods and data sources for the calculation of the GHG emission time series. A more detailed description of the emission calculation and an overview of the applied coefficients is provided in the supplementary material.

CH_4 *emissions from enteric fermentation (1)* are calculated as a function of feed energy intake and a methane conversion rate, defined as the share of feed energy converted into methane during enteric fermentation. This corresponds to the tier 2 method according to IPCC (2019a). The methane conversion rate is calculated as a function of feed digestibility according to values from INRA et al. (2020) and livestock category specific coefficients, applying equations from FAO (2017). Feed intake is calculated from feed supply according to Krausmann (2001b), BMLRT (2020), Statistik Austria (2015, 2018) and FAO (2021b), which is allocated to livestock categories according to basic principles, e.g. roughage is primarily allocated to ruminant livestock (see Section 1.1 in the supplementary material for details). For roughage and fodder crops, we applied loss factors for harvest and storage according to BMLRT (2020), which we hold constant over time, as data on historical changes was not available.

N_2O *and* CH_4 *emissions from manure management (2)* are calculated according to the tier 2 method from IPCC (2019a). CH_4 emissions from manure management are calculated for each livestock category from volatile solids excreted, shares of manure management systems and pasture management, multiplied by manure and pasture management specific CH_4 emission factors. N_2O emissions from manure management are calculated for each livestock category as a function of excreted N, manure management system shares, the fraction of N volatilizing or leaching and N_2O emission factors for direct and indirect emissions.

N_2O *emissions from soils (3)* include all N_2O emissions caused by the application/dropping of livestock manure and the application of synthetic fertilizers (3). They are also calculated using a tier 2 method (IPCC2019a). N_2O emissions from organic N application to soils and manure dropped on pastures are calculated as a function of N inputs to soils in the form of manure, residues and synthetic fertilizers, fractions of N volatilizing or leaching and N_2O emission factors for direct and indirect emissions. N inputs from above- and belowground residues returned to soils are calculated from data on biomass production, the ratio between above- and belowground biomass and N content of below- and aboveground residues. The excretion of volatile solids and N by livestock category is calculated from the livestock metabolism model described in Gingrich et al. (2021). For the share of manure management systems and pasture management, we use data from Austria's National Inventory Report for the period after 1990. Before this year, due to a lack of empirical data, we developed plausible assumptions for 1830 for all livestock categories and interpolated values linearly between these years (see Section 1.1 of the supplementary material for details).

We also included GHGs emitted during the use of agricultural machinery (tractors). They are derived from annual stocks of tractors according to Sieferle et al. (2006), multiplied by factors for average annual fuel use per power class and tractor hours according to Nemecek and Kägi (2007), Lips (2017) and ÖKL (2022). Fuel use was converted into GHG emissions, using emission factors from IPCC (2019a).

2.2. Attribution of GHG emissions

We present our results aggregated in t CO_2 eq/yr, as well as disaggregated into the three GHGs and into the ten processes causing emissions, as displayed in Fig. 1. In a second step, we attribute all emissions to three categories of agricultural products: ruminant products (cattle meat, meat from sheep and goats and dairy products),

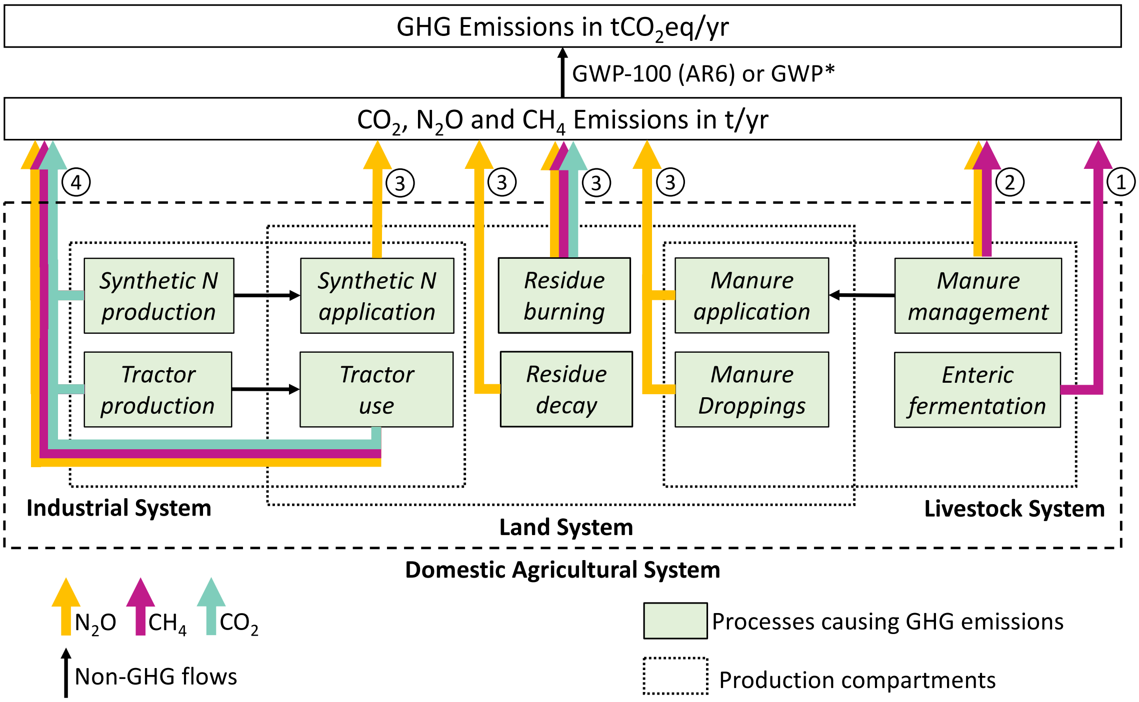

Fig. 1. Diagram showing considered processes and associated GHG emissions in Austrian agriculture. N_2O emissions from N application include indirect emissions via leaching/runoff and atmospheric deposition. The numbering of GHG fluxes links to the description in the text. Note that GHG emissions from the production of synthetic N fertilizers and tractors (compartments with dashed lines) are only shown in Fig. 2a, but not considered for further analysis, as it would be inconsistent with the chosen territorial system boundary.

monogastric products (pork, poultry, horse meat and eggs), and food/energy crops (all crops used as food, as energy or for export, i.e. not as domestic feed). In a best guess approach (attribution a), we attribute emissions as follows: Emissions occurring during animal husbandry, i.e. CH_4 emissions from enteric fermentation and N_2O emissions from manure management and deposition of manure on pastures, are fully attributed to the livestock category linked to these emissions (monogastric or ruminant products). Emissions from N flows on cropland, i.e. N_2O emissions from application of livestock manure, synthetic fertilizers and the decay of residues, as well as GHG emissions from tractor use, are attributed according to the share of dry matter from cropland used by each category. Thus, GHG emissions occurring during the production of monogastric/ruminant feed from cropland are attributed to monogastrics/ruminants. This approach follows a counterfactual thinking in the sense that the emissions associated with feed from cropland would not occur without livestock husbandry.

However, the attribution of emissions to products is to some degree arbitrary and may sensitively affect results. To test the sensitivity of our results to the assumptions described above, we therefore applied an alternative approach (attribution b), in which we only attribute those emissions to ruminants/monogastrics and the according products, which occur during livestock husbandry, i.e. CH_4 emissions from enteric fermentation and N_2O emissions from manure management and manure deposition on pastures. All other GHG emissions, i.e. N_2O emissions from the application of manure and synthetic fertilizers, residue decay, as well as GHG emissions from tractor use, are fully attributed to feed/energy crops. While in the results section we present data from our best guess (attribution a), we compare the results for attribution a and b in the supplementary material.

2.3. Decomposition analysis

To quantify the relative importance of major drivers of GHG emissions, we conducted several variants of structural decomposition analyses. The chosen method (log mean divisia index decomposition analysis) allows to attribute changes in a variable (in our case, annual GHG emissions) to changes in pre-defined underlying drivers through a formula that describes a so-called "identity" (Ang, 2015). Based on Hong et al. (2021), we developed an identity between changes in overall emissions E [CO_2 eq] and the following anticipated drivers: Population (P) in capita [cap]; total agricultural production per capita ($Prod_{cap}$) in [tDM/cap]; product mix (PM), i.e. the fraction of food/energy crops, monogastric products, and ruminant products ($Prod_i/Prod$), in [tDM_i/tDM]; and emission intensity of the product (EI_{prod}), i.e. emissions per unit of agricultural product ($E_i/Prod_i$), in [tCO_2 eq/tDM]:

$$E = \sum_i P \times \frac{Prod}{P} \times \frac{Prod_i}{Prod} \times \frac{E_i}{Prod_i} = P \times Prod_{cap} \times PM \times EI_{prod}$$

We derived population data, the only additional input data here, from Krausmann and Haberl (2007) and updated it for the period since 1952 based on Statistik Austria (2021). With this identity we disentangled the role of major drivers of cumulative agricultural emissions in the entire time period, as well as in the periods 1830–1914, 1914–1945, 1945–1985 and 1985–2018. The time periods were based on the periodization proposed by Jepsen et al. (2015) and represent fairly homogenous emission trends (Fig. 2), with the exception of 1914–1945,

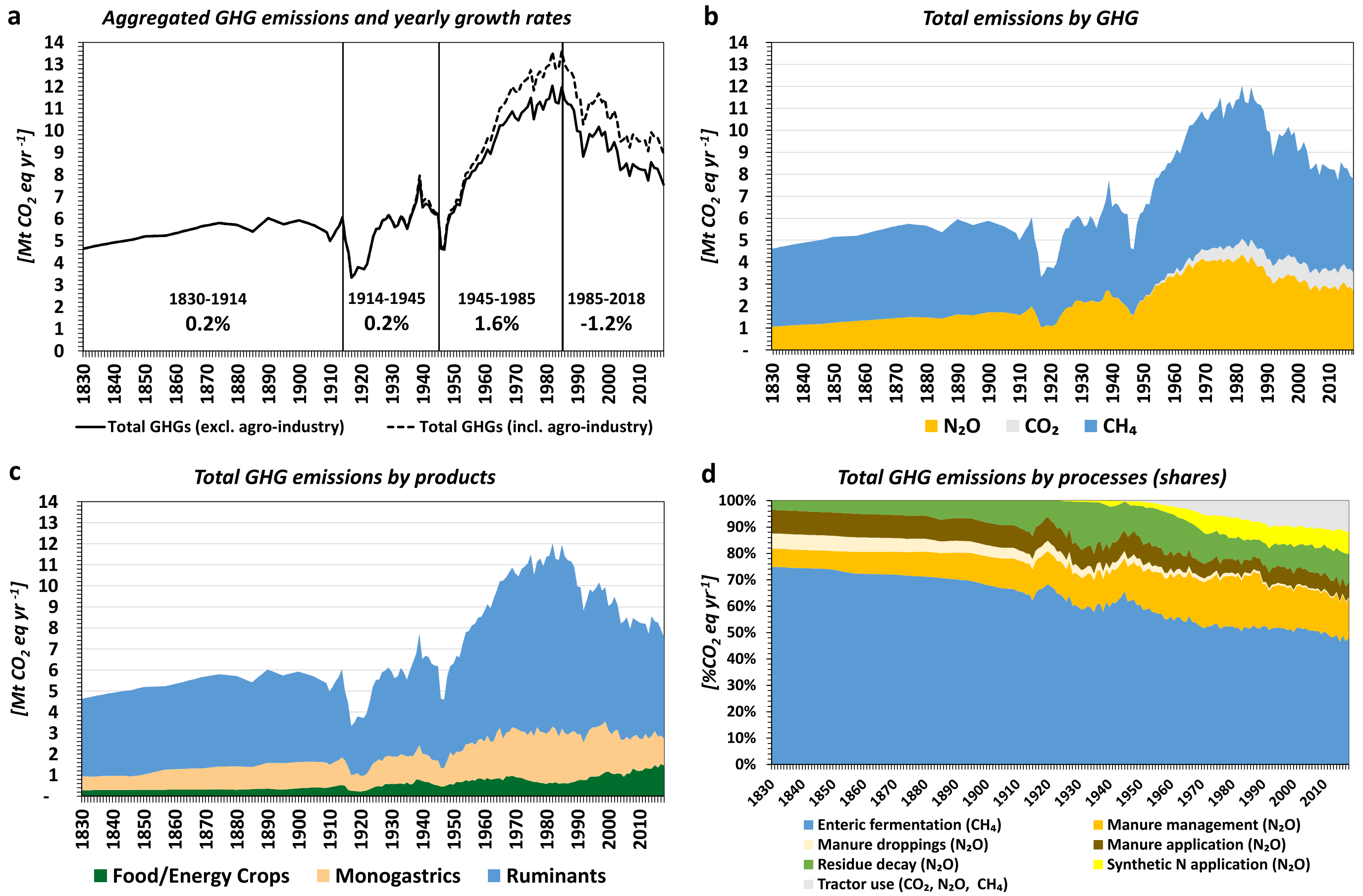

Fig. 2. Agricultural emissions per year from 1830 to 2018 on the current territory of Austria by **a**) total aggregated emissions, additionally showing emissions incl. production of fertilizers and tractors as dashed line and compound annual growth rates of GHG emissions for four periods **b**) GHGs **c**) products and **d**) processes as shares of total. **a-c**) in Mt. CO_2 eq/yr, **d**) in % CO_2 eq/yr. Figures b-d do not include GHG emissions from the production of fertilizers and tractors. The period shaded in grey is subject to relatively high data uncertainties.

where dynamics are high and data quality is poor. In addition to the analysis of individual time periods, we used the same identity to quantify the drivers of cumulative emissions stemming from the production of food crops, ruminant products, and monogastric products.

We developed additional identities to investigate temporal dynamics for the same periods in the drivers of cropping and livestock systems in more detail. Compared to the identities for total agricultural emissions, they merge population (P) and agricultural production per capita ($Prod_{cap}$) into total production (P_i) of the respective agricultural product but differentiate emission intensities of products into resource intensities of products (i.e. area or livestock units per product unit) and emission intensities of resources (i.e. emissions per area or livestock unit):

$$E_i = Prod_i \times \frac{R_i}{Prod_i} \times \frac{E_i}{R_i} = Prod_i \times RI_i \times EI_{r,i}$$

where E_i [CO_2 eq] are the GHG emissions attributed to the production of food/energy crops, ruminant and monogastric production, respectively; $Prod_i$ is the production of the respective product, in [tDM]; RI_i is the resource intensity, i.e. area or livestock units used per unit of product ($R_i/Prod_i$), in [ha/tDM] or [LSU/tDM] as detailed below; and $EI_{r,i}$ is the emissions intensity of the respective resource, i.e. emissions per area or livestock unit for the respective product (E_i/R_i), in [tCO_2 eq/ha] or [tCO_2 eq/LSU].

For emissions from the production of food/energy crops (E_c), the variable for resource intensity RI_c thus describes the area intensity of the production food/energy crops ($RI_c = R_c/Prod_c$) in [ha/tDM] and $EI_{r,c}$ the emission intensity of the production of crops for food/energy ($EI_{R,c} = E_c/R_c$) in [tCO_2 eq/ha]. The identity then reads as follows:

$$E_c = Prod_c \times \frac{R_c}{Prod_c} \times \frac{E_c}{R_c} = Prod_c \times RI_c \times EI_{r,c}$$

Emissions from ruminant (E_{ru}) and monogastric (E_{mo}) production, respectively, in [tCO_2 eq], were analyzed as a function of livestock production of meat, milk and eggs ($Prod_{mo/ru}$) in [tDM], the resource intensity of production RI_c, which is here defines as input of livestock units per output of livestock product ($LSU_{mo/ru}/Prod_{mo/ru}$) in [LSU/tDM] and emissions intensity $EI_{r,mo/ru}$, i.e. emissions per livestock unit ($E_{mo/ru}/LSU_{mo/ru}$) in [tCO_2 eq/LSU], with livestock units (LSU) referring to a standardized livestock unit of 500 kg. LSU were quantified as the number of animals multiplied by a species and time-specific live weight [kg] and divided by 500. The identity for ruminant products then reads as follows:

$$E_{ru} = Prod_{ru} \times \frac{R_{ru}}{Prod_{ru}} \times \frac{E_{ru}}{R_{ru}} = Prod_{ru} \times RI_{ru} \times EI_{r,ru}$$

The identity for monogastric products in analogy reads as:

$$E_{mo} = Prod_{mo} \times \frac{R_{mo}}{Prod_{mo}} \times \frac{E_{mo}}{R_{mo}} = Prod_{mo} \times RI_{mo} \times EI_{r,mo}$$

2.4. *GHG emissions applying global warming potential GWP**

GWP*, in contrast to GWP100, quantifies a warming potential (in CO_2 equivalents) that aims to quantify more closely the actual (additional) warming or cooling effect of CH_4 emissions in a given year. As CH_4 dissolves relatively quickly in the atmosphere, a cooling effect of CH_4 in a given year can occur, in the case a higher amount of CH_4 emissions accumulated in the atmosphere dissolve than new CH4 emissions are emitted in the given year. Therefore, the formula for GWP* involves the difference between current and past CH4 emissions. We quantified GWP*, applying the equation developed by Smith et al. (2021):

$$E^{*}(t) = 128{*}E_{CH4}(t) - 120{*}E_{CH4}(t-20)$$

where E*(t) are annual CH_4 emissions GWP* in [CO_2 eq/yr] in year t and E_{CH4}(t) or E_{CH4}(t-20) are CH_4 emissions measured as GWP_{100} CO_2 equivalents at year t or t-20, respectively.

Using GWP* for CH_4, we additionally show aggregate agricultural GHG emissions from 1830 to 2018, corresponding to cumulative climate impacts of agricultural emissions over time.

3. Results

3.1. *Long-term trajectories of agricultural GHG emissions*

Fig. 2 shows Austrian agricultural GHG emissions from 1830 to 2018. We identify 4 distinct phases in the trajectory of aggregated emissions, defined by their average annual growth rates (Fig. 2a).

Between 1830 and 1914 (period 1, annual growth rate 0.3 %), emissions increased moderately, from 4.6 MtCO_2 eq/yr in 1830 to 6.0 MtCO_2 eq/yr in 1914. From the beginning of World War I (WWI) over the interwar period until the end of World War II (WWII), agricultural GHGs fluctuated strongly, but the average annual growth rate remained positive at 0.7 %. Aggregated emissions reached their lowest value of the entire observed period in 1917 at 3.3 MtCO_2 eq/yr. In only about 2 decades, they more than doubled and reached 7.7 MtCO_2 eq/yr in 1939. It is important to note, however, that data quality during the two World Wars and the interwar period is subject to large uncertainties. After WWII, emissions fell to 4.6 MtCO_2 eq/yr in 1947. For the next 38 years, aggregated emissions grew constantly, at an average annual growth rate of 1.9 %. After peaking in 1982 and 1985 at 12.0 MtCO_2 eq/yr, aggregated GHG emissions declined again, to 7.6 MtCO_2 eq/yr in 2018, corresponding to a negative growth rate of −1.1 % in period 4.

As Fig. 2c shows, ruminant products were the largest contributor to agricultural GHG emissions throughout the studied time period and were mainly responsible for the large increase in period 3 as well as the decline in period 4. Accordingly, CH_4 was the most important agricultural GHG in Austria throughout the observed period (Fig. 2b). Enteric fermentation (mostly by cattle) was the single most important process emitting CH_4 (Fig. 2d), though with the fraction declining from 75 % in 1830 to 47 % in 2018. After the 1920s and especially post WWII, the increase in agricultural emissions coincided with a diversification of GHG emissions and processes, caused by increasing mechanization and intensification of agriculture. The relative shares of emissions from the application of synthetic N fertilizers to soils (N_2O), as well as the use of agricultural machinery (CO_2, N_2O, CH_4) increased strongly during periods 3 and 4. Conversely, the share of N_2O emissions from manure deposited on pastures decreased strongly since the 1960s, as livestock feeding partially changed from pasture grazing to all year barn feeding.

3.2. *Major drivers of agricultural GHG emissions*

Across the period 1830–2018, growth in agricultural emissions was driven first by population growth (P), closely followed by growth in per-capita production ($Prod_{cap}$), especially of ruminant products (Fig. 3a). This increase was partly counterbalanced by a reduction in emissions intensity of both ruminant and monogastric products (EI_{prod}). The production mix (PM) had only a minor effect on GHG emissions over the whole period, however with important differences between time periods (Fig. 3b).

Over time, not only the dynamics of emissions changed (Fig. 2), but also their drivers (Fig. 3b). In 1830–1914, the increase in agricultural production in absolute terms was less pronounced than population growth (Fig. 3f). These dynamics coincided with modest annual emissions increases (+11.1 ktCO_2 eq/yr on average). In the decomposition analysis, these trends translate into population growth (P) driving agricultural emissions increase, while a decrease in production per capita ($Prod_{cap}$) and the emission intensity of products (EI_{prod}) partly counterbalanced this driver. The effect of a change in production mix on GHG emissions was negligible in this first period.

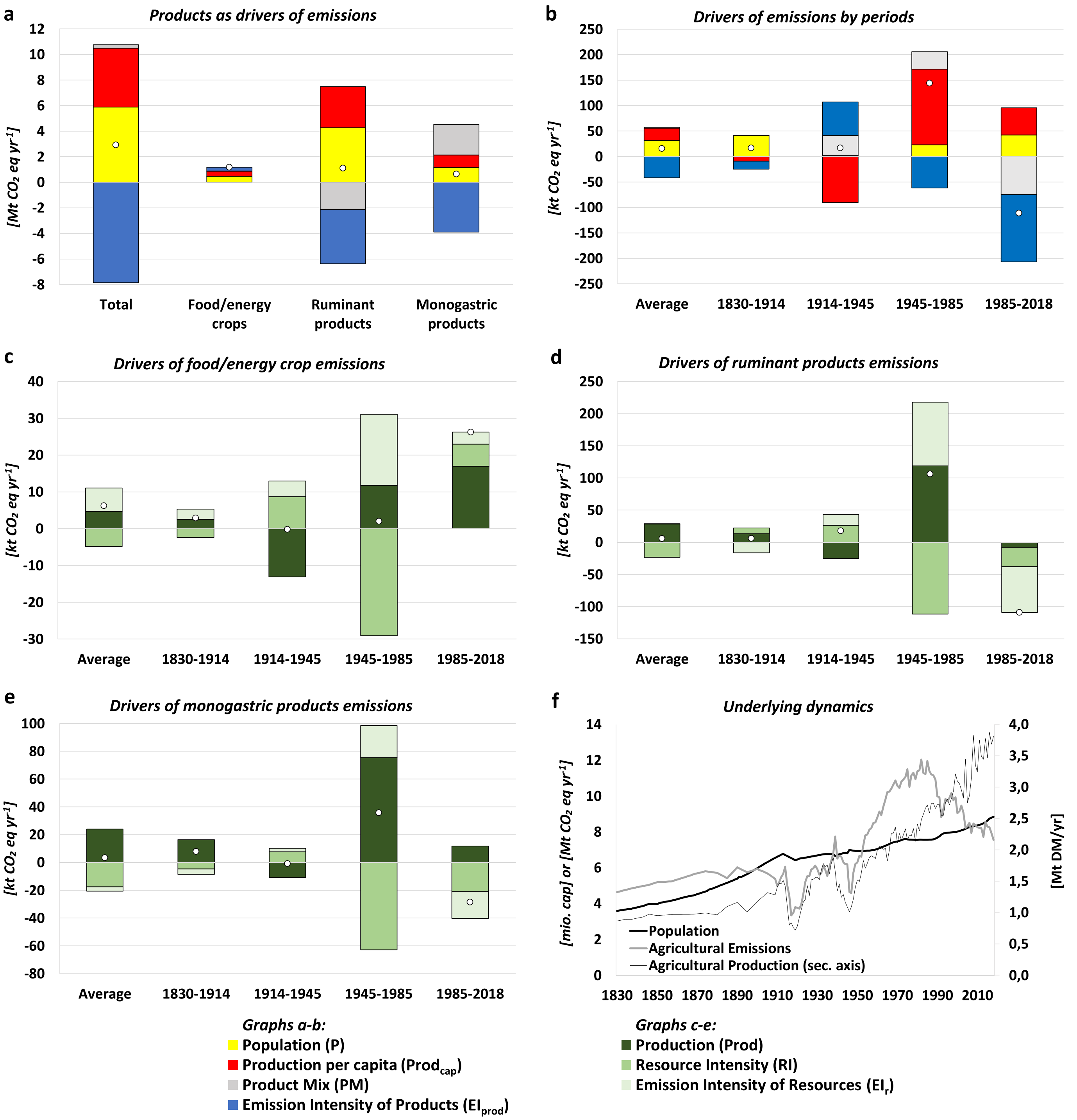

Fig. 3. Decomposed drivers of agricultural GHG emissions, applying emissions attribution a (for b, see supplementary fig. S2). Parameters refer to the definitions and equations in section 2.3. Emission intensities refer either to products, such as meat and milk for ruminants (EI_{prod}) or to resources, i.e. areas for crops and livestock units for animals (EI_r). Resources refer to areas for food/energy crops and livestock units for monogastric and ruminant products.

The period 1914–1945 was characterized by dumps in production and emissions during the two world wars (Fig. 3f), but on average agricultural emissions continued to grow slowly (3.0 $ktCO_2$ eq/yr on average), driven by changes in the production mix (PM), i.e. a shift towards more ruminant products, and increased emission intensity (positive EI_{prod}, Fig. 3b) due to dynamics in ruminant production towards more emissions per ruminant LSU and an increase in ruminant LSU required per unit of ruminant product (positive $EI_{r,ru}$ and RI_{ru}, Fig. 3d). At the same time, production (Prod) declined slightly for ruminant and monogastric products and more strongly for food/energy crops (negative Prod, Fig. 3c–e), which compensated for most of the emission increase (Fig. 3b).

The strongest annual increase in emissions can be observed in the period 1945–1985, at 162 $ktCO_2$ eq/yr on average. The major driver in this period was increased production per capita ($Prod_{cap}$), resulting from production increases across all product categories, which outpaced population growth (Fig. 3f). Population growth (P) was an additional minor driver of increases in emissions, while the effects of changes in the production mix (PM) and the emission intensity of production (EI_{prod}) slightly counteracted emission increases. Underlying this modest reduction of emissions intensity were the strong dynamics within all agricultural production processes: In this period, all agricultural products experienced major decreases in production intensity, i.e. declining area demand per unit of crops (negative RI_c, Fig. 3c) and declining LSU input per unit of livestock product for both ruminants and monogastrics (negative RI_{ru}, Fig. 3d; RI_{mo}, Fig. 3e).

Finally, the period from 1985 to 2018 saw a marked reduction of agricultural emissions (−134 ktCO$_2$ eq/yr on average) despite population growth. The decline was enabled by reduced emissions intensity of production (EI_{prod}, Fig. 3b), a shift towards monogastric products (PM), and a reduction in production per capita ($Prod_{cap}$), resulting in particular from declining food crop ($Prod_c$, Fig. 3c) and ruminant production ($Prod_{ru}$, Fig. 3d). The decline of emissions intensity (EI) in this period, particularly in ruminant production, enabled the very recent trend of increased agricultural production coinciding with declining total emissions.

3.3. *Annual and accumulated agricultural GHG emissions applying GWP**

Fig. 4a shows annual agricultural GHG emissions in comparison, when using either GWP-100 or GWP* for the conversion of CH_4 into CO_2 equivalents. The application of GWP* instead of GWP-100 results in much larger annual fluctuations of agricultural GHG emissions and a larger global warming effect in the periods 1936–1944, 1951–1958 and 1960–1982, but a lower effect in all other periods. In some years, notably 1915–1923 and most years after 2000, cumulative agricultural emissions even had a net cooling effect, owing to a decrease in CH_4 emissions, resulting in a net reduction of CH_4 from Austrian agriculture in the atmosphere. These results are in line with Hörtenhuber et al. (2022) who found similar results for the period 2005–2019.

Fig. 4b shows cumulated agricultural GHG emissions after 1850, using GWP* for CH_4, which can be approximated to the total net warming effect of agricultural emissions in each year relative to 1849. It shows that although in some years, CH_4 had a net cooling effect relative to the previous year (Fig. 4a), it remains a contributor to global warming in all years, when taking all (current and past) emissions into consideration. Fig. 4b also illustrates that there remains a large potential to reduce rather quickly the warming effect of CH_4 in the atmosphere by further reducing CH_4 emissions, as most CH_4 emissions breaks down into water and CO_2 with much less warming effect after about one decade.

4. Discussion

4.1. *Uncertainties of the analysis*

Uncertainties in our results pertain to (1) the data quality, as well as to (2) the underlying assumptions and system boundaries applied. Regarding the input data (1), two types of uncertainties prevail: (i) the input data derived from statistical records on agricultural production, and (ii) the input data for coefficients, such as emission factors, to quantify their associated GHG emissions. While we judge (i) recent agricultural statistics, particularly since the mid-20th century, to be fairly robust, the data pertaining to the 19th and early 20th centuries are more uncertain: less so for crop production, for which authorities strived for improving and harmonizing assessment procedures already in the early and mid-19th century, but more so for data on livestock numbers and production (Sandgruber, 1978), responsible for a high fraction of emissions in this period. Because livestock numbers were assessed with different methods and in different seasons throughout the 19th century, fluctuations in livestock emissions and total agricultural emissions during this period are not to be overinterpreted, while the general level and trends appear rather robust. Regarding (ii), studies using similar data and procedures point to an uncertainty of 25 %–35 % for the period since the 1960s (Crippa et al., 2021; Tubiello et al., 2013). For earlier periods, we assume an even higher uncertainty due to the data uncertainties described above, as well as rough estimates performed to quantify manure management system shares.

The underlying assumptions applied in our study (2) constrain the scope of our findings in two major ways: (i) By adopting a territorial approach on agricultural emissions in Austria, we exclude all emissions abroad which are induced by Austrian consumption. 64 % of emissions embodied in Austrian consumption of food products were estimated to occur outside the domestic territory in 2013 (Frey and Bruckner, 2021), including emissions both from agricultural practices and from so-called "forest risk commodities", which cause emissions due to deforestation abroad (Henders et al., 2015). In the context of our analysis, this means that from a global perspective, we underestimate GHG emissions related to the production of livestock fed from imported feed, in particular monogastrics. On the other hand, during the last period from 1986 to 2018, Austria also increasingly exported emission intensive ruminant products, in particular beef and dairy products.

(ii) Our choice of attributing emissions to agricultural products does not affect total emissions or their temporal trends but impacts the relative contribution of different products. Our best guess (attribution a) attributes emissions related to the production of feed from cropland to monogastric or ruminant livestock. In a sensitivity analysis, we tested the effect of alternatively attributing all emissions occurring during the

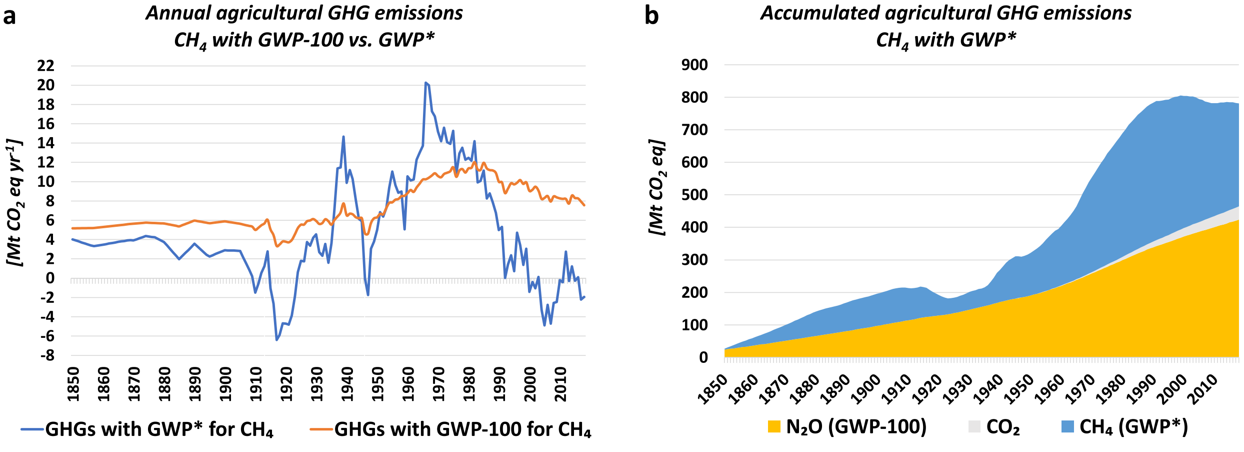

Fig. 4. Agricultural GHG emissions 1850–2018 in CO_2 eq/yr, with different GWP metrics in comparison: (a) Yearly GHGs, using GWP-100 or GWP* for CH_4; (b) cumulated GHGs, using GWP* for CH_4, with 1850 as base year. The period shaded in grey is subject to relatively high data uncertainties.

production of cropland products to food/energy crops (attribution b). It shows that attribution b mainly results in considerably more emissions attributed food/energy crops and accordingly less emissions attributed to monogastric products (supplementary fig. S2).

4.2. *Agricultural emissions as part of Austria's total GHG budget*

Across the period investigated, the role of emissions from agricultural activities in the total GHG budget changed fundamentally (Fig. 5). We derived data on other GHG emissions in Austria in the period 1850–2010 from Gingrich et al. (2016), including emissions from the combustion of fossil energy carriers (coal, oil, and gas), emissions from cement production, as well as net emissions from changes in ecosystem carbon stocks (“forestry and other land use”, FOLU) and carbon stocks in long-lived products (“harvested wood products”, HWP). Following the discussion about different GWPs, Fig. 4 shows both GHG emissions using GWP-100 (Fig. 5a) and GWP* (Fig. 5b) for CH_4.

GHG emissions from agriculture were dominant until the mid-19th century, however, while agricultural emissions remained relatively stable, fossil energy emissions increased quickly in the second half of the 19th century and surpassed agricultural emissions in 1875 when applying GWP* and 1878 when applying GWP-100 for CH_4. In contrast to the emissions from fossil fuel combustion, which were introduced by novel industrial practices in 19th century Austria (Sieferle et al., 2006), the emissions from agricultural activities have a much longer history. In fact, the introduction of agricultural emissions coincided with the first livestock-rearing settlers in the region several thousand years ago (Bätzing, 2003). Such traditions need to be taken into consideration when searching for climate-change mitigation options, including the reduction of livestock production and consumption. However, the recent dynamics of livestock efficiency increase (see also Kuhla and Viereck, 2022), in combination with agroecological practices, provide insights into potentials for further reducing agricultural emissions without compromising rural livelihoods.

Fig. 5 also illustrates that the application of GWP* can have a considerable effect on Austria's overall GHG budget, notably during periods with increasing or decreasing CH_4 emissions. In the 1960s, when CH_4 emissions strongly increased, Austria's total GHG budget was up to 22 % higher, if GWP* instead of GWP-100 is applied for CH_4. On the other hand, in the more recent period, the total GHG budget could have been up to −20 % lower with this al, owing to the decrease of CH_4 emissions from agriculture. This underlines the fact that a decrease in CH_4 emissions could play an important role in reducing GHG emissions and meeting climate targets (Reisinger et al., 2021).

4.3. *Comparison to other studies*

To the best of our knowledge, only two other studies present comprehensive data on the long-term historical development of agricultural GHG emissions on a national or regional scale. Only for the last decades, data becomes more abundant, with notably FAOSTAT providing data on agricultural GHG emissions for all countries after 1961 (Tubiello et al., 2013) and EDGAR-FOOD providing data on GHG emissions related to food systems, including agriculture, after 1990 (Crippa et al., 2021). Similar to our study, Garnier et al. (2019) show a trend of increasing agricultural GHG emissions between 1852 and 1981 for France, including an increase of GHG emission growth rates from 1950 until the end of the 1970's. Another similarity is a reversal of this trend in the beginning/middle of the 1980s, when emissions remain about constant in the case of France or even start to decrease in the case of Austria. This trend reversal can also be observed for the EU-27 as a whole, where agricultural GHG emissions start to decline in 1985 (FAO, 2021a). Interestingly, however, this decline seems to be particularly pronounced for Austria, possibly due to the high share of CH_4 from ruminants, which have a particularly large effect on emission reductions. It's also interesting to note that also in many Eastern European countries, the decline of agricultural GHG emissions already starts around the mid-1980s and thus precedes the final collapse of the Soviet Union. In the US Great Planes, agricultural GHG emissions rose quickly already in the last decades of the 19th century, even though from a very low level (Parton et al., 2015). This development was linked to an increasing number of settlers, which started to plough up the extensive grasslands and to keep livestock, promoted by the homestead act of 1862. Furthermore, other than in Austria, France and the EU-27, agricultural GHG emissions in the US Great Planes already start to plateau after the 1960s, mostly as tractors, adopted earlier, already become more efficient. For the USA as well, a trend reversal in the mid-1980s cannot be observed, but slightly fluctuating agricultural GHG emissions after 1961, with a slight peak in 1976 (FAO, 2021a). The difference in agricultural GHG emissions between the USA on the one hand and the EU-27 and many of its countries on the other hand is an interesting fact, which warrants further analysis.

More specifically, CH_4 emissions from livestock can be compared to a

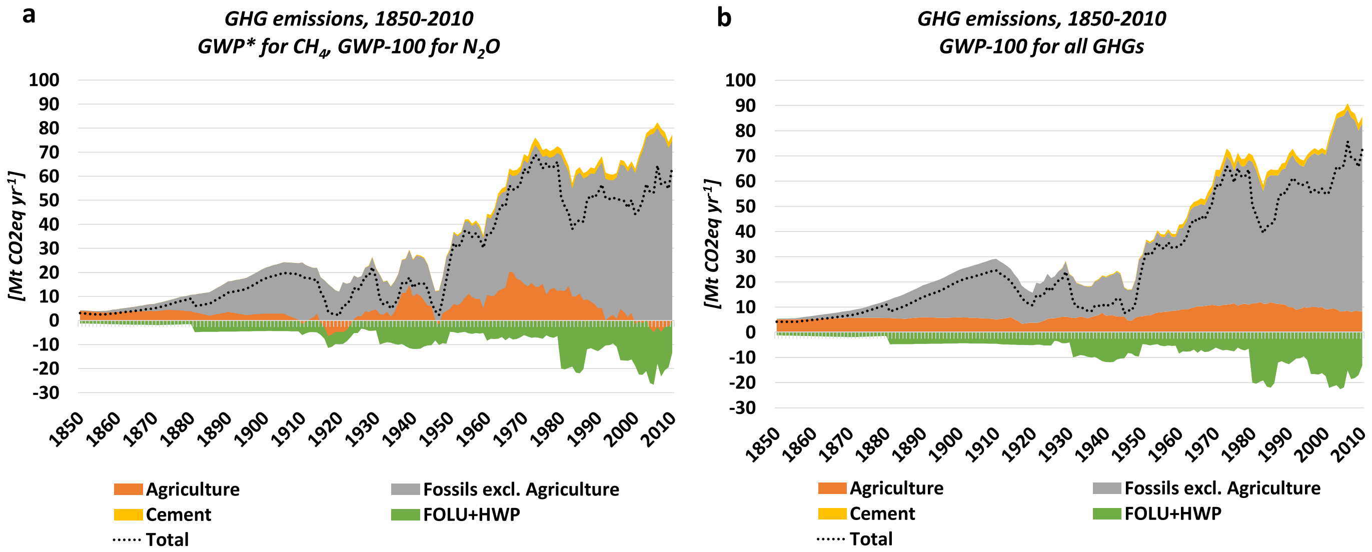

Fig. 5. Agricultural GHG emissions from 1850 to 2010 in Mt. CO_2eq/r, compared to GHG emissions from other sources, with a) applying GWP-100 for all GHGs and b) applying GWP* in the case of CH_4. FOLU: forestry and other land use; HWP: harvested wood products. The period shaded in grey is subject to relatively high data uncertainties.

study by Kuhla and Viereck (2022). They report an increase of livestock (enteric fermentation and manure management) related CH4 emissions by a total of 6 % throughout the period between 1883 and 2018 in Germany, which is not far from our estimate for Austria, showing an increase by 14 % during the same time period. In contrast, CH_4 emissions from enteric fermentation and manure management in France increased by a factor of 2.7 during the period 1852–2014 according to Garnier et al. (2019), compared to an increase by merely 1.1 in Austria according to this study. This stronger increase of CH_4 emissions in France might be explained partly by a larger increase in bovine meat and milk production in France compared to Austria throughout the study period (Krausmann, 2001b; Le Noë et al., 2018). The trajectory of enteric CH4 emissions both in Austria and France follow a – more or less strong – growth until the mid-1980s, followed by a stabilization in France or a decline in Austria. Chang et al. (2021) shows that this trend of decreasing CH4 emissions after the mid-1980s is characteristic for both Western and Eastern Europe, with a much more pronounced decrease for Eastern Europe after the collapse of the Soviet Union. As CH_4 contributes a large part to overall agricultural GHG emissions, this decline is the most important factor for the decline in agricultural GHG emissions in Austria and the EU-27 in general.

The trajectories of N_2O emissions from fertilization by synthetic fertilizers and livestock manure bear a high similarity in France (Garnier et al., 2019), Spain (Aguilera et al., 2021) and Austria (this study): They increase with small growth rates until WWII, as they are constrained by the livestock generating the manure linked to N_2O emissions. After WWII, they grow strongly until about 1980, mostly due to the availability and increasing application of synthetic nitrogen fertilizers. In the period after around 1980, they slightly decrease in France and Austria or continue to increase slowly in Spain according to Aguilera et al. (2021). This trend of stagnating of slightly decreasing N2O emissions after around 1980 can be observed for many other European countries and the EU-27 according to FAOSTAT data.

Aguilera et al. (2019a) published very detailed assessments of GHG emissions related to traction in agriculture in Spain after 1900 and how these changed during mechanization. However, as we do not differentiate livestock according to its function (e.g. food, nutrient transfer, labor), we can't directly compare our data to this study. Nonetheless, detailed data on GHG emissions shows that the mechanization of agriculture, particularly the replacement of working animals by tractors, occurred at different times in currently industrialized countries. In the US Great Plains (Parton et al., 2015) but also the region around Paris (Garnier et al., 2019), GHG emissions related to the use of tractors started to grow as early as between 1910 and 1920. In Austria, Spain and other regions of France, tractors only were introduced in relevant numbers after WWII, in particular during the 1950s and 1960s. Interestingly, the abandonment of work animals not always took place in parallel: While in Austria, working animals were abandoned in parallel to the rise of tractors from 1950 to 1970, in Portugal, this transition occurred delayed by 20 years, from around 1970 to 1990, with according implications for related GHG emissions.

4.4. *Implications for the mitigation of agricultural emissions*

If applying GWP-100 for CH_4 (Fig. 5a), changes in agricultural GHG emissions over the studied period were relatively modest when compared with changes in CO_2 emissions from fossil fuels. This might be explained by two fundamental reasons: On the supply-side, although the throughput of biomass through livestock increased, agriculture and the emission it causes are more constrained by the availability of land and natural primary production than the fossil fuel driven growth of industrial production. On the demand-side, the factor of food consumption shows a stronger saturation effect over time than the demand for industrially produced non-food products. However, the application of GWP* for CH_4 (Fig. 5b) changes this picture, as the short-lived nature of CH_4 results in a much more dynamic change of GHG emissions, especially in periods of changing CH_4 emissions.

The particularity of agricultural emissions is also reflected in future GHG emission pathways aimed at Austrian and European Climate Policies. For example, according to the study underlying the long-term strategy for climate-neutrality by 2050 of the European Union, GHG emissions in 2050 still remain at around 50 % of the agricultural emissions in 2014 and at this time will constitute the majority of all remaining GHG emissions (European Commission, 2018). Reaching this target would require an accelerated reduction of agricultural emissions by −1.6 %/yr, compared to −1.1 %/yr in the period 1985–2018.

In terms of effectiveness of different levers to mitigate agricultural GHG emissions, Fig. 3b shows that during the last period (1985–2018), a decrease in the emission intensity of agricultural production had the largest negative effect on agricultural GHG emissions. However, it is questionable whether this trend can be extrapolated into the next decades. Improved livestock feeding efficiencies and prolonging productive lifespans in dairy cows are linked to lower CH_4 emissions from enteric fermentation and contributed strongly to these efficiency increases, but are increasingly exploited (Bryngelsson et al., 2016; Siegel, 2014) and subject to animal welfare trade-offs (Herzog et al., 2018; Llonch et al., 2017). Further production-related mitigation potentials include the use of feed additives to reduce enteric CH_4 emissions (Kelly and Kebreab, 2023), further increases in N use efficiencies (Winiwarter et al., 2018) and changes in manure management and application (Höglund-Isaksson, 2012). In a modelling study for Austria, Le Noë et al. (2023) estimate the combined potential of these technical measures at only 11 %. On the other hand, our findings confirm that a change in the product mix, in particular towards less ruminant products, has a high potential to reduce GHG emissions while providing healthier diets (Theurl et al., 2020).

Concerning the application of GWP*, our results revealed interesting insights, showing more closely the actual annual and accumulated warming effect of CH_4 emissions. However, some authors argue that the use of GWP* in official GHG emission accountings should be fostered, as it better shows the actual contribution of CH_4 to global warming (Cain et al., 2021a, 2021b; Lynch et al., 2020; Mitloehner, 2020; Ridoutt, 2021). This argument has been welcomed by the beef and dairy industry, as it claims that "new methane math could take the heat off cows" (National Farmers Unions and others, 2020). Other authors stated that the application of the GWP* metric in the context of emission targets would disadvantage countries with low but growing CH_4 emissions against those with high but currently decreasing CH_4 emissions (Rogelj and Schleussner, 2019). Schleussner et al. (2019) further cautioned that the replacement of the internationally agreed GWP-100 by the new GWP* metric could even undermine the integrity of the Paris Agreement mitigation target, as it "can lead to profound inconsistencies in the mitigation architecture of the agreement". Although we here do not suggest to replace GWP-100 by GWP* in official reporting, our results on long-term agricultural emissions in Austria contribute to this debate by (1) showing that in a cumulative way, Austrian CH_4 emissions still contribute to global warming, but that (2) reductions in CH_4 emissions would have a high potential to rapidly reduce climate impacts from agriculture.

5. Conclusions

Our study showed that compared to GHG emissions from fossil fuels, agricultural emissions in Austria showed lower growth rates and thus became relatively less important within the total GHG budget over time. Moreover, while GHGs emissions from fossil fuels continued to grow until the end of the study period, agricultural emissions started to decline already in 1986 or even 1967, when using the metric GWP* for CH_4. This is an encouraging development, but it's important to understand the underlying drivers of this trend and to question under which conditions these can be extrapolated into the future. Our decomposition analysis reveals that in the latest period (1985–2018), decreasing agricultural production per capita and emission intensities per product both contributed to decreasing agricultural GHG emissions, with production per capita driven by domestic consumption and net exports. While there already have been strong advances in terms of decreasing emission intensities, with decreasing marginal benefits and trade-offs concerning animal welfare, there remain large potentials on the demand side, particularly by reducing the consumption of animal products, in particular from ruminants. As the assessment with the alternative metric GWP* shows, the land use sector could become increasingly important to deliver urgently needed negative GHG emissions, not only by the sequestration of carbon in soils and vegetation, but also a reduction in CH_4 emissions.

CRediT authorship contribution statement

Christian Lauk: Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft, Writing – review & editing, Visualization. **Andreas Magerl:** Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft, Writing – review & editing, Visualization. **Julia le Noë:** Conceptualization, Methodology, Formal analysis, Writing – review & editing. **Michaela C. Theurl:** Conceptualization, Formal analysis, Writing – review & editing. **Simone Gingrich:** Conceptualization, Methodology, Formal analysis, Writing – original draft, Writing – review & editing, Visualization, Supervision, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2023.168667.

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