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The history of a + 3 °C future: Global and regional drivers of greenhouse gas emissions (1820–2050)

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A B S T R A C T

Identifying the socio-economic drivers behind greenhouse gas emissions is crucial to design mitigation policies. Existing studies predominantly analyze short-term CO_2 emissions from fossil fuels, neglecting long-term trends and other GHGs. We examine the drivers of all greenhouse gas emissions between 1820–2050 globally and regionally. The Industrial Revolution triggered sustained emission growth worldwide—initially through fossil fuel use in industrialized economies but also as a result of agricultural expansion and deforestation. Globally, technological innovation and energy mix changes prevented 31 (17–42) Gt CO_2e emissions over two centuries. Yet these gains were dwarfed by 81 (64–97) Gt CO_2e resulting from economic expansion, with regional drivers diverging sharply: population growth dominated in Latin America and Sub-Saharan Africa, while rising affluence was the main driver of emissions elsewhere. Meeting climate targets now requires the carbon intensity of GDP to decline 3 times faster than the global best 30-year historical rate (–2.25 % per year), which has not improved over the past five decades. Failing such an unprecedented technological change or a substantial contraction of the global economy, by 2050 global mean surface temperatures will rise more than 3 °C above pre-industrial levels.

1. Introduction

Effectively implementing the Paris Agreement while sustaining present rates of economic growth is only possible with radical and urgent actions to drastically reduce the carbon intensity of the global economy, i.e. the greenhouse gas emissions (GHGe) per unit of economic output (IPCC, 2022; Riahi et al., 2017). This fall in carbon intensity can result from two main mechanisms. The first is the reduction of the energy intensity of GDP (i.e. the energy spent per unit of value added) via technological improvements, structural change in favour of less-polluting sectors of the economy, and changes in consumption patterns (Grubler et al., 2018b; Keyßer and Lenzen, 2021; Rogelj et al., 2015; Slameršak et al., 2022). The second is the reduction of the emission intensity of energy use (i.e. the carbon released per unit of energy consumed) through energy transition towards cleaner energy sources and the development of carbon removal strategies (Anderson and Peters, 2016; Budinis et al., 2018; Meinshausen et al., 2022; Minx et al., 2018; Smith et al., 2016).

A common approach to evaluate the feasibility of achieving climate agreements in contexts of economic growth is by analyzing recent experiences. Methodologically, the most usual way to do this is through decomposition analyses. These analyses quantify the impact of economic activity (population and average incomes) and technological change (usually disaggregated into energy intensity of GDP and carbon intensity of energy) on total GHGe. While model-based scenarios explore future emission trends under uncertain forces driving behavior (Van Vuuren et al., 2012), decomposition analyses are commonly used to examine the past evolution of those drivers in order to evaluate their contribution to GHGe.

There is a rich scientific literature deploying decomposition analyses to examine the drivers between GHGe variations in global perspective (Desai, 2018; Dong et al., 2020; Hubacek et al., 2021; Lamb et al., 2021; Malik et al., 2016; Xia et al., 2021), as well as for different regions (e.g., Western countries (Henriques and Borowiecki, 2017; Le Quere et al., 2019), Africa (Ayompe et al., 2020; Sun et al., 2022), Europe (Xiao et al., 2022), Asia (Li et al., 2020; Parker and Bhatti, 2020)); or national case studies (e.g. in China (Guan et al., 2008; Liu et al., 2021; Zheng et al., 2020; Zhu et al., 2018), USA (Feng et al., 2015), Colombia (Roman et al., 2018)). Overall, most of these studies have shown that the rising levels of emissions are the result of the emission-inducing impact of economic growth outpacing the savings, which have succeeded in reducing carbon intensity. These reductions were mostly due to falls in the carbon intensity of GDP as a result of technological and structural change in the economy (Dong et al., 2020; Lamb et al., 2021). Savings derived from

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improvements to the energy mix have been more limited, because while cleaner sources are gaining ground in some countries, others are still heavily reliant on dirtier energy carriers (Lamb et al., 2021; Schäfer, 2005).

Overall, the world has experienced over the last few decades a process of weak decoupling—that is, GDP has grown faster than emissions, while the latter have continued to increase (Friedlingstein et al., 2023). However, some studies have highlighted that, in recent years, a group of high-income nations have been experiencing absolute decoupling, i.e., combining GDP growth with a reduction in CO_2 emissions (Le Quere et al., 2019; Ritchie, 2024; Vogel and Hickel, 2023). This evidence encourages optimistic narratives about the feasibility of meeting climate targets. Nevertheless, other scholars argue that instances of absolute decoupling are geographically limited and insufficient to achieve climate agreements (Hickel and Kallis, 2020; Parrique et al., 2019; Vogel and Hickel, 2023).

Most of the literature on the socio-economic drivers of emissions presents two main limitations. First, studies are usually based on very limited historical evidence, covering short periods, usually from 1990 to the present. This lack of a deeper historical perspective is primarily due to data availability, as consumption-based accounting—that is, considering the carbon footprint of countries—is only available, at best, since 1990 (Friedlingstein et al., 2023). Nevertheless, there is another underlying reason why scholars work with data only since 1990: it was during the 1990s that the international community began to take institutional action on climate change. That is, it is implicitly assumed that significant improvements in the relationship between emissions and economic growth occurred only when active measures were taken.

The second limitation is that, with a few exceptions (Lamb et al., 2021; Liu et al., 2019; Sanchez and Stern, 2016), this literature tends to consider only CO_2 emissions from fossil fuels. Recent studies have shown that fossil fuels' CO_2 accounts for 68 % of global emissions today and for only 49 % of cumulative emissions since 1820 (Friedlingstein et al., 2022; Gütschow et al., 2021). The remaining emissions were generated by other activities, such as CO_2 released by land-use change, or are due to other gases, mainly CH_4 and N_2O. Not counting these emissions misrepresents the history of climate change, as it ignores the part played by economic activities which decisively contributed to rising temperatures (IPCC, 2021; Jones et al., 2023).

These limitations prevent us from properly understanding the drivers of GHGe, and more crucially they often lead to an inaccurate narrative of climate change history. Most historical narratives tend to associate climate change with the emergence of industrialization and the growing use of fossil fuels in manufacturing, overlooking other types of emissions and activities that have significantly contributed to changes in the climate. The unprecedented increase in global emissions that took place in the 19th century was undoubdtedly linked to the spread of the industrial revolution, but this owed as much to the expansion of the global agricultural frontier as it did to fossil fuels in factories (Barbier, 2012; Ellis et al., 2021).

In this paper, we aim to address these gaps by studying the *long-term* global evolution of GHGe and their drivers. This approach allows us to substantially expand, across both time and space, the existing evidence on socio-economic drivers of emissions, providing a bird's-eye view of the modern origins of anthropogenic climate change, and finally using history as a yardstick to assess the changes required by current climate agreements. How have the different types of GHG emissions evolved over time and space? What have been the main drivers behind the historical growth of GHGe? How have these drivers changed across regions and periods? Is there historical evidence of technological and productive changes that reduced carbon intensity at the pace needed for the next few decades? Or are we instead facing an unprecedented challenge in human history?

To address these issues, we trace GHGe and their socioeconomic drivers between 1820 and the present. Drawing upon different sources we construct a country-level database with annual series of emissions, energy use, GDP, and population (full details in Methods). The emissions series includes all GHGe (CO_2, CH_4, N_2O, and fluorinated gases), harmonizing different datasets which provide annual data at the national level (Friedlingstein et al., 2022; Gütschow et al., 2021; Hurtt et al., 2011; Jones et al., 2023). Energy consumption series are taken from Malanima (2022), which are the only ones to incorporate traditional energy carriers (including food and fodder for human and animal muscle energy) at the regional scale. GDP and population data are taken directly from the Maddison Project Database (Bolt and van Zanden, 2020) which offers global coverage since 1820 at the regional level (national-level estimates usually have a much shorter coverage). Thus, for our regional analyses we follow the 8 country groups defined by the Maddison Project. To systematically examine the drivers of variations in emissions we rely on the Kaya Identity to produce a decomposition analysis using the Logarithmic Mean Divisia Index method (Ang, 2005).

We distinguish five periods based on economic and environmental historiography. First, the initial spread of industrialization and globalization between 1820 and 1913 (Allen, 2017; O'Rourke and Williamson, 2001). Second, the World Wars and interwar period between 1914 and 1945, characterized by a global economic downturn, especially in Western countries. Thirdly, the decades of the 'Great Acceleration' (Steffen et al., 2015) of environmental impacts and economic growth between 1945 and the 1980 s, including the 'late industrialization' in much of the global periphery (O'Rourke and Williamson, 2017). Fourthly, we consider the period between 1990 and the present, characterized by a new expansion of international trade, the fast growth of large Asian economies (Baldwin, 2017), and the relative decline in emissions in some parts of the West (Le Quere et al., 2019). Finally, we analyse 2050 scenarios considering the requirements of the Paris Agreement and different projections of economic growth.

2. Materials and methods

2.1. Dataset

The GHGe series is derived from various previously published databases. Fossil-fuel and cement production CO_2 emissions are retrieved from the Global Carbon Project (CGB) (Andrew and Peters, 2021; Friedlingstein et al., 2022). This source provides yearly data at the national level of emissions produced by coal, gas, oil, and cement. Land use, land-use change, and forestry emissions are taken for the period 1850–2018 from the recent estimates by Jones et al. (2023). Their study offers annual series based on the average of three bookkeeping estimates also used by the GCB (Gasser et al., 2020; Hansis et al., 2015; Houghton and Nassikas, 2017). They include emissions caused by vegetation loss and soil organic carbon in processes of land-use change, as well as wood harvesting, peat burning, and drainage. To extend the series back to 1820, we rely on the Land Use Harmonization dataset (LUH2) (Hurtt et al., 2020), which offers gridded data on biomass C stocks since 850. We extracted yearly country stocks from this source and used the annual variation in these stocks to project Jones et al.'s back from 1850 to 1820. Emissions of CH_4, N_2O and fluorinated gases are taken directly from the dataset of the Postdam Realtime Integrated Model for probabilistic Assessment of emissions Paths (PRIMAP-hist) (Gütschow et al., 2021). The GHGe series are presented in CO_2-equivalent (CO_2-eq) terms using 100-year global warming potentials (GWP100) from IPCC AR6 (IPCC, 2021).

In this study, we incorporate uncertainty estimates following the IPCC AR6 guidelines (IPCC, 2022), which predominantly build on Minx et al. (2021). The latter combines multiple lines of evidence – including bottom-up inventories, top-down atmospheric constraints, and expert assessments – to derive uncertainty ranges for aggregated emission categories. We apply relative uncertainties at a 90 % confidence interval to major GHGe groups: carbon dioxide from fossil fuels and industry (CO_2-FFI, ±8 %), net carbon dioxide from land use, land-use change, and forestry (CO_2-LULUCF, ±70 %), methane (CH_4, ±30 %), nitrous oxide (N_2O, ±60 %), and fluorinated gases (F-gases, ±30 %). Total GHGe uncertainty in CO_2-equivalent terms, for each region and globally, is calculated as the square root of the sum of squared absolute uncertainties for individual gas categories (Minx et al., 2021; IPCC, 2022). This approach assumes statistical independence between uncertainties across gas categories to avoid overcomplicating error propagation. While other uncertainty sources exist – such as metric choice (GWP values) or the transient climate response to cumulative emissions (Jones et al., 2023) – we focus solely on emission estimation uncertainty to align with IPCC reporting conventions. This ensures consistency with global emissions budgets and facilitates policy-relevant comparisons. Our uncertainty calculation is strictly limited to GHG emissions.

The energy use series are taken from Malanima (2022). This database, following the approach in Kander et al. (2014), offers evidence for both modern and traditional energy sources. Modern sources include coal, oil, gas, primary electricity, and biofuels; traditional sources include food, fodder for working animals, and biomass fuel. All series are expressed in primary energy equivalents and calculated from a production-based perspective. This database offers yearly estimates for 8 world regions and national data every ten years.

Data on GDP and population are taken from the Maddison Project Database (MPD) (Bolt and van Zanden, 2020). This source offers estimates for almost every country in the world; the time coverage and the periodicity vary in each case. It is not possible, therefore, to produce a global series via the addition of national data. However, the MPD offers aggregate estimates for 8 world regions in 21 benchmark years between 1820 and 2018. To obtain an annual series for these 8 regions, we have recalculated the regional series from the national-level data. For years when the MPD provided estimates for countries which encompassed more than 85 % of a region's aggregate GDP, we added up the national values to arrive at the regional total. Given the uneven coverage across regions, this re-calculated annual series begins in different years in each region: for Western Europe, Western Offshoots, and South and South-East Asia, the annual regional series covers the entire period, starting in 1820; for East Asia, it begins in 1823; for Latin America in 1846; for the Middle East and North Africa in 1907; for Eastern Europe in 1910; for Sub-Saharan Africa in 1950. The years preceding these annual regional series are calculated by interpolating MPD's original regional benchmark estimates. Figure SM6 compares our estimated annual regional series with the original estimates in the MDP with missing values interpolated. The results are very similar, with the advantage for our method that we are able to capture yearly variations much better, which is crucial for the decomposition analysis by periods.

GHGe data is available annually at the national level. However, the energy use series are only available annually for 8 world regions, while MDP series only offer global coverage for 8 world regions. Unfortunately, the two latter databases do not share the same regional groupings. We have therefore recalculated Malanima's series to fit the regional categorization used in the Maddison Project Database. Both databases share the same regional composition for Western Europe, Eastern Europe, and Latin America (and the Caribbean). Malanima distinguishes between North America and Oceania, which in the MPD are aggregated as Western Offshoots. In this case we simply aggregate the energy consumption of North America and Oceania. Moreover, Malanima distinguishes between Africa and the Middle East, while the MPD considers Sub-Saharan Africa separate from the Middle East and North Africa. All the while, Malanima considers Asia a single region whereas the MPD differntiates between East Asia and South and South-East Asia. Using Malanima's national estimates (available every ten years) we recalculated the regional estimates to fit the regions defined by the MPD.

2.2. Decomposition analysis

For the analysis of drivers we follow the Kaya Identity (Kaya, 1989), which proposes to estimate the relative weight of different factors, generally population (P), affluence (A), and technological change (T), in the overall variation of emissions (C). Adding up the contribution of each factor, which can be positive or negative, is equivalent to the variation of emissions between two moments T and 0:

$$\Delta C = C^T - C^0 = \Delta P + \Delta A + \Delta T \quad (2)$$

In our study, we decompose technological change into two factors: the energy intensity of economic output, i.e. the amount of energy consumed per unit of GDP (Te), and the emissions per unit of energy (Tc). According to this model, ceteris paribus, the sum of the variations in each component will result in the total variation of GHGe. The main advantage of this model is that it transforms the variation of each factor, expressed in its own units of measure, into the unit of measure of the outcome variable (CO_2e). The resulting model is as follows:

$$\Delta C = C^T - C^0 = \Delta P + \Delta A + \Delta Te + \Delta Tc \quad (3)$$

To estimate our model we use an additive Logartithmic Media Divisia Index (LMDI)(Ang, 2005), the most widely used method in the literature on index decomposition analysis. We estimate the model at the global level as well as for each of the regions (r) under study. Its mathematical formulation is:

$$\Delta C = \frac{C^{t1} - C^{t0}}{lnC^{t1} - lnC^{t2}} \cdot ln\left(\frac{C^{t1}}{C^{t0}}\right) \quad (4)$$

We apply the model in three different ways: analyzing the percent contribution of each component to the absolute variation in emissions in each of the periods (Fig. 3); analyzing the variation of each year with respect to the 1820 levels (Fig. 2, Fig. 4a); and analyzing the annual rate of change within each period (Fig. 4b).

Since we only account for uncertainty in GHG emissions (ΔC) and not in other variables (P, A, Te, Tc), the decomposition results may exhibit asymmetric factor contributions when quantifying the uncertainty bounds of each component's effect. This arises because the LMDI method nonlinearly redistributes ΔC uncertainty across components, weighting their impact by their relative share in the Kaya identity. For instance, dominant drivers (e.g., ΔA in recent periods) amplify uncertainty ranges disproportionately, while others adjust asymmetrically to compensate. Consequently, uncertainty in decomposition components is presented as asymmetric ranges (e.g., +X/−Y) rather than symmetric intervals.

2.3. Scenarios

We analyze whether the historical trends of carbon intensity of GDP (i.e., greenhouse gas emissions per unit of GDP) are compatible with current climate agreements and future economic projections. To do so, we compare the historical evolution of carbon intensity with different future scenarios combining projections of economic growth and emissions. For economic growth, we rely on the OECD's long-term projections, which estimate that global GDP will nearly double by 2050 (OECD, 2023). For emissions, we use as benchmarks the C3 and C4 pathways assessed in the IPCC's Sixth Assessment Report (AR6) (IPCC, 2022), which correspond to global warming levels of approximately 2 °C and 3 °C by 2100 (>67 % likelihood), respectively. According to the IPCC, these scenarios project global greenhouse gas emissions (GHGe) in 2050 of approximately 20 $GtCO_2$-eq for C3 and 35 $GtCO_2$-eq for C4. Following the approach replicated in previous studies (e.g., Jackson et al., 2024), we estimate the current global carbon intensity and the level required in 2050 under each scenario. With this information, we calculate the implied annual reduction rate in carbon intensity (also referred to as the decoupling rate) that would be needed to meet the 2 °C and 3 °C scenarios, and we compare those rates with historical trends.

These benchmarks could be even more demanding for two reasons. First, recent research has calculated that the remaining carbon budget is smaller than the one reported by the AR6 of the IPCC (Lamboll et al., 2023). Second, some studies question the potential of new technologies for carbon sequestration, e.g., so-called biomass carbon capture and storage (BCSS) (Anderson and Peters, 2016; Fuss et al., 2018; Smith et al., 2016). As a result, some scholars argue that the impact of these technologies will be smaller than the one predicted by the models considered in the IPCC reports (Grubler et al., 2018a; Vogel and Hickel, 2023). If sequestration is indeed more limited, the decoupling rate would also need to be higher. Although for simplicity we do not include these two factors in the calculations, we address them in the discussion of the results.

With this exercise, we simply aim to reflect the scale of the future change required in the context of regional and global historical experiences.

3. Results

3.1. Historical trends in global GHG emissions

Since the early 19th century, anthropogenic GHGe have risen to ever-larger levels, from 3.1 ($\pm$1.4) Gt CO_2e in 1820 to 53.9 ($\pm$5.4) Gt CO_2e in 2018 (Fig. 1a). While this secular increase is often attributed primarily to CO_2 emissions resulting from the large-scale use of fossil fuels since the Industrial Revolution, these were not the main source of GHGe until 1969 and only represent 48 % of cumulative emissions since 1820. Even when considering the 'fugitive emissions' (N_2O and CH_4) from fossil fuels, their total cumulative contribution to overall emissions is still *only* 56 % (Fig. 1c). The rest are essentially due to the so-called Agriculture, Forestry, and Other Land Uses (AFOLU) emissions (hereafter referred to as land-based emissions) and, in much smaller measure, to other activities (e.g. cement production) and gases (e.g. fluorinated gases). Among land-based emissions, the most important is the CO_2 released as a result of land use and land-use change (LULUC) –mainly through deforestation-, representing 23 % of global cumulative emissions and remaining the single largest source until as late as 1965. Biogenic emissions of CH_4 and N_2O, generated primarily by agricultural activity, and to a lesser extent by waste management, accounted for 18 % of cumulative emissions.

The global geography of historical emissions has been extremely uneven (Fig. 1d–e). Western countries, accounting for only 15 % of world population, have produced 36 % of cumulative GHGe (and 47 % of fossil-fuel emissions). In the last few years, their total emissions have stabilized and, in some countries, even declined in absolute terms. Consequently, since c.1990 the relative contribution of other world regions has substantially increased, especially in the case of East Asia. Meanwhile, developing regions with large tropical forests contributed significantly to land-based emissions. Latin America and Sub-Saharan Africa jointly account for 39 % of cumulative LULUC emissions, whereas they contributed only 7 % of global fossil fuel emissions.

To better address historical responsibilities for climate change, we calculate cumulative per capita emissions by dividing total regional emissions by cumulative population, aligning with the concept of 'fair share.' Fig. 2 presents the average per capita emissions for regions and the world across the entire period, providing insights into disparities in

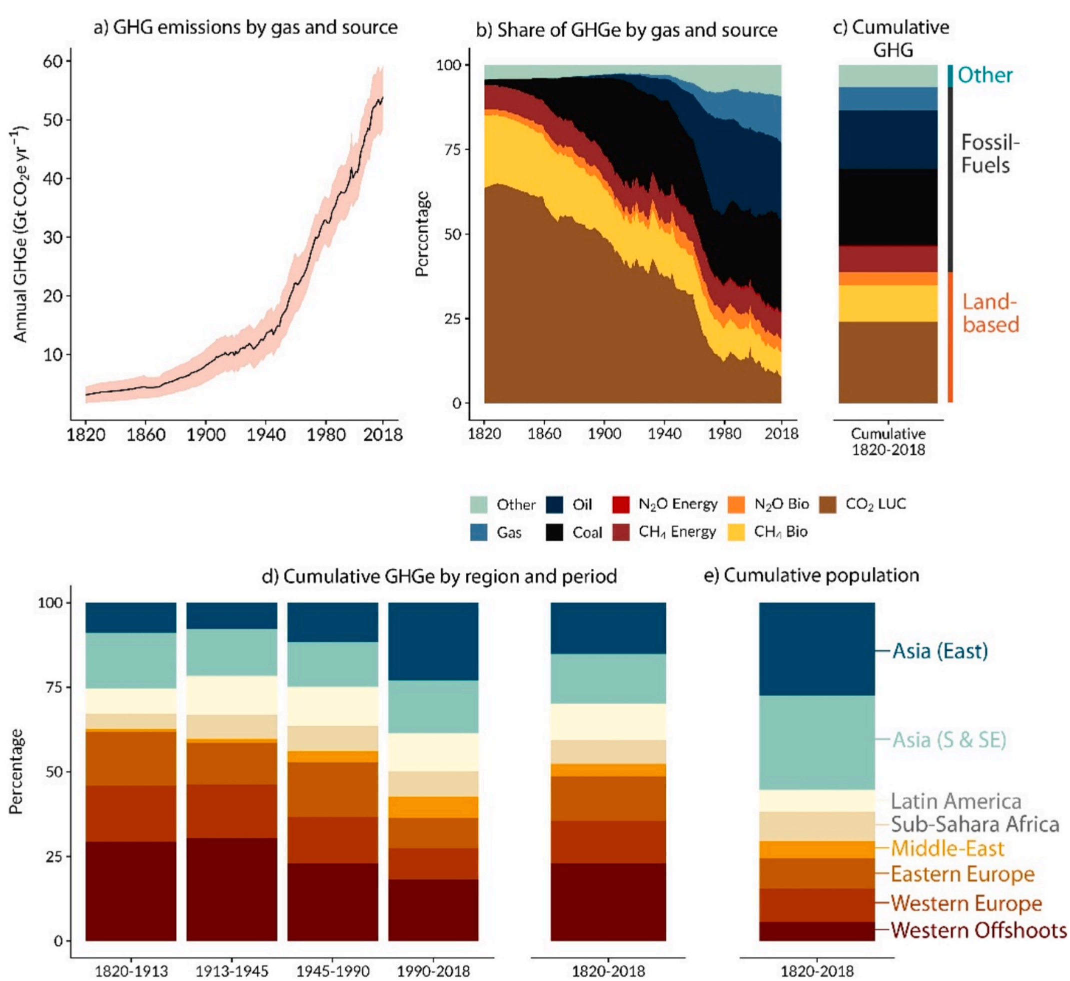

Fig. 1. Historical trends in greenhouse gas emissions (expressed as 100-year global warming potential) and population. Regional data on total greenhouse gas emissions uncertainty and emissions by type of gas can be found in Fig. SM1-SM3.

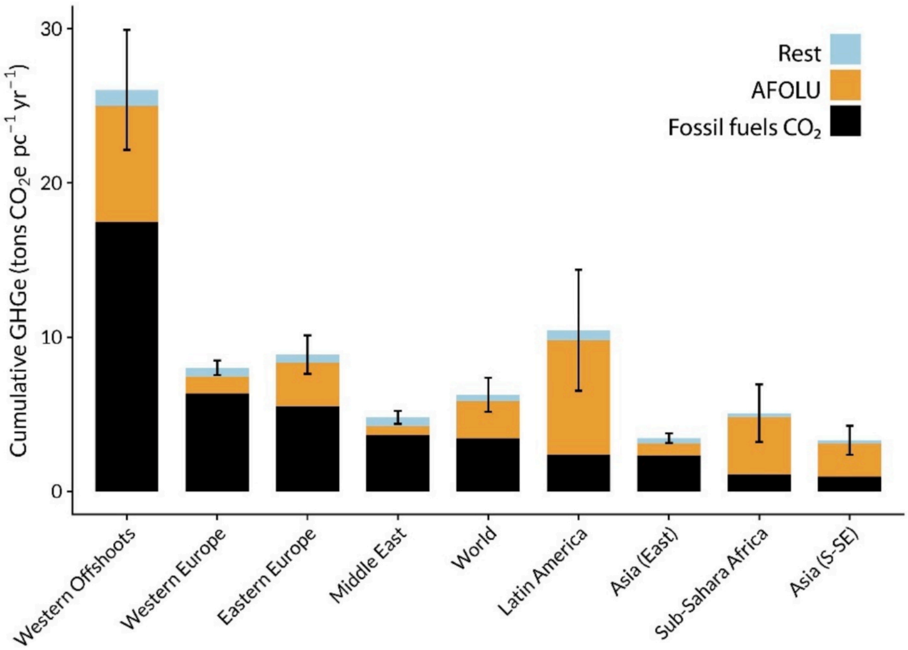

Fig. 2. Cumulative greenhouse gas emissions per capita. Emissions are expressed in CO_2e per capita, calculated as the cumulative annual emissions divided by the cumulative annual population between 1820 and 2018.

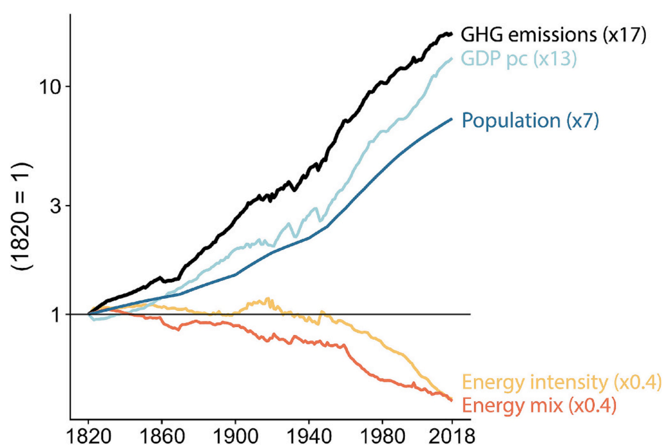

Fig. 3. Trends of GHG emissions and their socioeconomic drivers (1800 = 1). Regional data in Fig. SM4.

historical contributions to global emissions. If we focus solely on fossil fuel emissions, a familiar narrative emerges: Western countries exhibit values far above the global average and, in general, higher than those of any other region in the world. However, when we include all emissions, the picture changes. Some regions, such as Latin America and Eastern Europe, display higher cumulative per capita values than Western Europe, though they still fall short of the levels seen in the Western Offshoots. This is largely due to land-use-related emissions, which, as we have observed, are particularly significant in Latin America and Sub-Saharan Africa. In cumulative per capita terms, the land-based emissions from Latin America (7.4 tCO_2e/person) are comparable to fossil fuel emissions in Western Europe (5.7 tCO_2e/person), the cradle of the Industrial Revolution. In summary, when considering all emissions—not just those from fossil fuels—the narrative surrounding historical responsibilities shifts considerably. We will return to the potential explanations for this phenomenon in the discussion.

The historical trajectory of global emissions was far from linear, even if they almost always increased. During the initial spread of the Industrial Revolution in the West, between 1820 and 1913, global GHGe increased at an cumulative annual rate of 1.3 %, resulting in equal measure from increasing fossil fuel use and from the expansion of land-based emissions. Western countries (i.e. Western Europe and the 'Western Offshoots' in North America and Australasia) were responsible for 46 % of total emissions in this period and for 77 % of fossil-fuel emissions. Between 1914 and 1945, in the context of the World Wars and inter-war crises, emission growth slowed down, increasing only at a rate of 0.8 % per year globally. In this period most emissions (58 %) were land-based and concentrated in Asia, Africa, and Latin America, whereas in Western Europe—the main theater of war—total emissions decreased. After World War II, we find the fastest growth in global emissions of any period considered in our study: an annual growth rate of 2.4 %. This is partially explained by the recovery of fossil-fuel emissions, which had been fallen during the war, but also by a significant expansion of land-based emissions (39 % of all GHGe), led by CO_2 released in land-use change which reached its historical peak in this period. Since 1990, aggregate emissions have continued to grow but at a slower rate (1.3 % per annum). Over the last three decades Western countries have reduced their total emissions and, as a consequence, their overall contribution to cumulative emissions, although they still remain the largest contributors (with 28 % of the world historical total) (Fig. 1d). They are followed by East Asia (23 %) and South-East Asia (16 %), even if these regions have long been home to much larger populations than the West (Fig. 1e). However, in terms of per capita GHGe, the gap between the West and the rest of the world remains wide, particularly when considering only fossil fuels (Fig. 2).

3.2. Drivers of historical global emissions

Figs. 3–5 show the results of our decomposition analyses, both in absolute terms (Fig. 3, Fig. 4 and Fig. 5a) and in annual growth rates for selected periods (Fig. 4b). Over the last two centuries global emissions have increased by 51 Gt CO_2e. This expansion (x17) is the net result of the countervailing impact of different factors (Fig. 2). While population (x7) and per capita income (x13) also increased dramatically, the energy intensity of economic activity (x0.4) and the emissions per unit of energy consumed (x0.4) have fallen throughout most of the two centuries

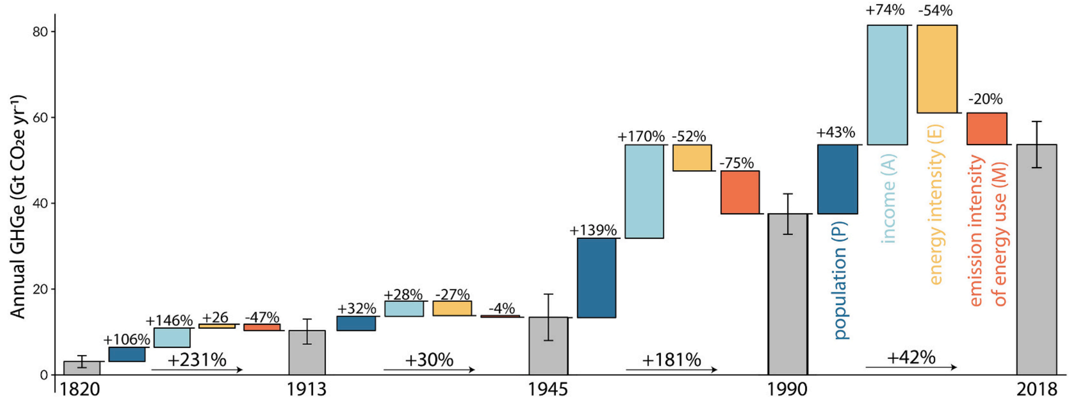

Fig. 4. Drivers of changes to annual greenhouse gas emissions (GHGe) globally in selected periods (NB: time in the x-axis is not to scale).

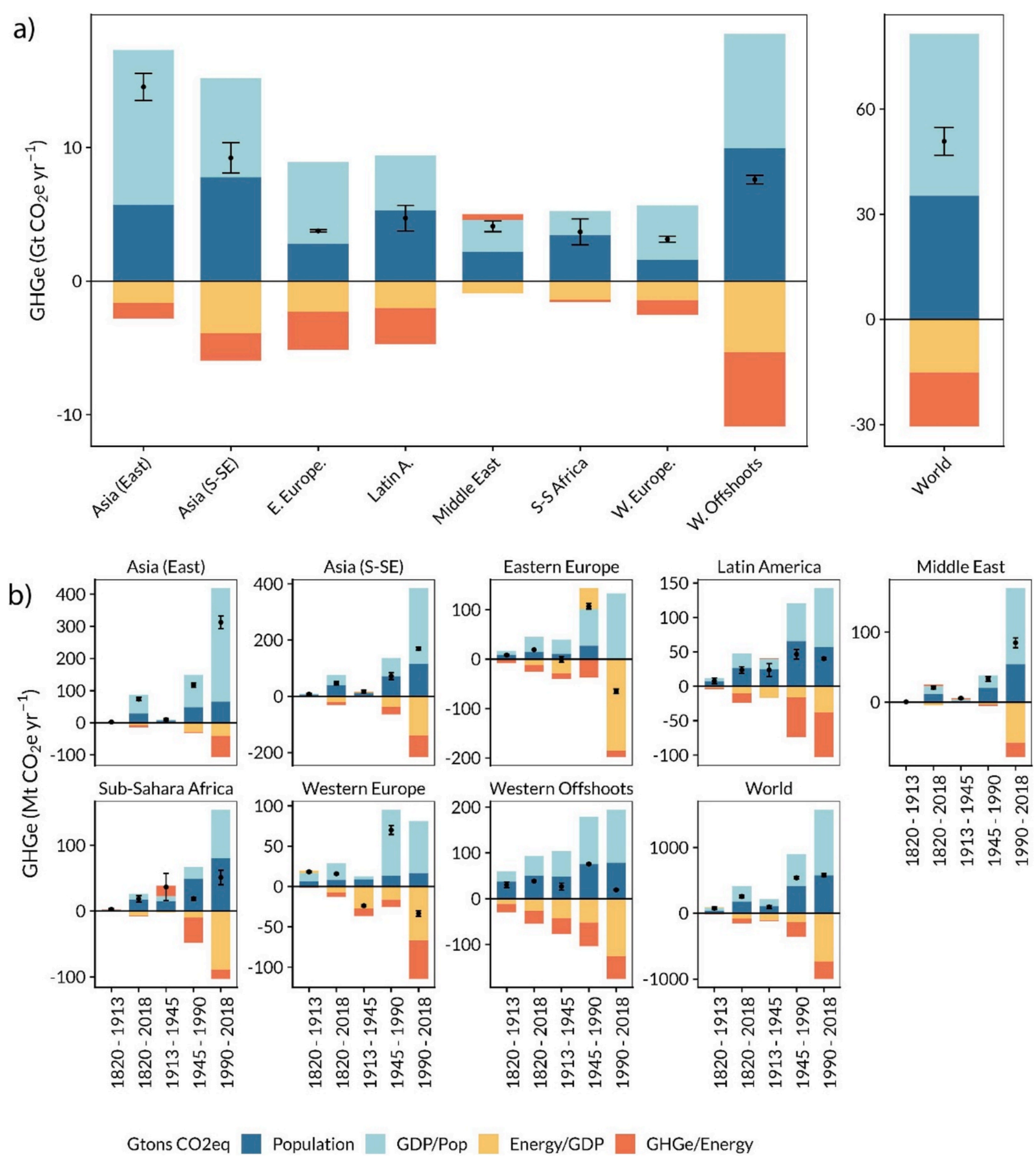

Fig. 5. Drivers of global and regional greenhouse gas emissions (GHGe). Black dots stands for annual total net change in GHGe between selected years. This variation is the result of changes in population, per capita income, (GDP/population), energy intensity (energy use/GDP), and the energy intenisty of energy use (CO_2e emissions/energy use). Panel (a) shows absolute variations for the entire analyzed period, while panel (b) shows absolute annual variations in selected periods.

following the Industrial Revolution, and especially so in the second half of the 20th century. These improvements in energy intensity and energy mix have produced savings of 15 (range: 12–18) and 15 (5–25) Gt CO_2e respectively (Figs. 4 and 5a). Thus, technological change, both in the productive structure and in the energy mix, has resulted in substantial savings in global emissions in the long-run. Indeed, the carbon intensity of the global economy has decreased from 2.6 to 0.5 kg CO_2e per dollar of GDP between 1820 and 2018: each unit of added value requires today, on average, 6 times fewer emissions than two centuries ago. However, the increases of both population and per capita income have by far overtaken these technological savings, as they drove emissions upwards to the tune of 35 (28–42) and 46 (36–55) Gt CO_2e respectively. In sum, the expansion of economic activity, fundamentally in terms of income increases (responsible for 57 % of GHGe increments) more than compensated the savings due to increased efficiency.

The relative contribution of each driver to changes in global emissions was different across periods (Figs. 4 and 5). The increase in emissions between 1820 and 1913 was extraordinary in relative terms and it was driven by demographic and economic growth (pushing emissions upwards 106 % and 146 %, respectively), without efficiency gains achieving significant savings. In the war and interwar period (1914–1945), economic activity once again pushed emissions upwards (per capita income + 28 % and population + 32 %), but this was partially compensated by a fall produced by energy intensity (−27 %), while emission intensity of energy use remained largely unchanged. During the 'Great Acceleration' of environmental impacts between 1945 and 1990 there were unprecedented savings due to both energy intensity (which pushed emissions down 52 %) and changes in the emission intensity of energy use (which reduced emissions by 75 %). Nevertheless, these savings were once again unable to counter the impact of historically exceptional rates of economic growth, resulting in the fastest pace of increase in GHGe of any period under consideration. Since 1990, economic activity (especially in terms of rising incomes) has continued to push emissions upwards, but over 60 % of this increase has been countered by the largest savings in modern history, due primarily to a substantial fall in energy intensity (decreasing total emissions by 54 % compared to a 20 % reduction derived from the emission intensity of energy use).

3.3. Regional drivers of historical emissions

Western countries were responsible for 46 % of total emissions and for 77 % of fossil-fuel emissions between 1820 and 1913, on the back of increasing affluence in Western Europe and rising populations in the 'Western Offshoots' (United States, Canada, Australia, and New Zealand) (Fig. 1d). Between 1914 and 1945, in the context of the World Wars and inter-war crises, emission growth slowed down. This fall was substantial in the countries most affected by World War II, such as Germany (−73 %), Poland (−54 %), and France (–33 %). After World War II, emissions grew at unprecedented rates in all world regions with the exception of Sub-Saharan Africa, where emission growth slowed down. This surprising deacceleration of emissions in Sub-Saharan Africa is explained by the substantial fall in deforestation rates, in a context where both incomes and population expanded significantly. Figure SM5 provides a decomposition analysis showing that during this period fossil-fuel CO_2 emission intensity of energy use did not significantly change in this region. Finally, since 1990, global emissions have continued to grow but at a slower rate (1.3 % per annum). In this final period, two aspects stand out. First, emissions have been growing more slowly in Western economies, and in the case of Western Europe in particular emissions have even declined in absolute terms, achieving (at least for a while) absolute decoupling. Secondly, as observed in Sub-Saharan Africa during the earlier period, emission growth in Latin America has also slowed down. Once again, this reduction is largely explained by trends in land-based emissions, particularly due to the slowing down of deforestation processes. However, when focusing exclusively on fossil fuels, we see that in Latin America emissions are growing faster, and the reduction in the carbon intensity of GDP is smaller (Figure SM5).

Regional contributions to changes in the drivers, and thus to variations in global emissions, were different across periods (Fig. 5). Looking at the last 200 years as a whole, all regions saw an expansion in economic activity (rising populations as well as per capita incomes) which far outpaced the savings brought about by efficiency gains (both in energy intensity of output and emission intensity of energy), thus leading to higher emissions the world over. In Western Offshoots, savings amounted to 10 Gt GHGe, without which, their total GHGe would have been 143 % higher. The increase in emissions without changes in efficiency would also have been very significant in Eastern Europe (137 %), Latin America (99 %), and Western Europe (81 %), while it would have been more modest in the Middle East (12 %) and East Asia (19 %). In terms of the forces behind emission reductions, in most regions the fall in energy intensity was the main driver, except in Latin America, Eastern Europe, and Western Offshoots, where changes in the emission intensity of energy use were the most important source of savings. Meanwhile, the relative contribution of demographic growth and affluence to GHG emissions was also different across regions (Fig. 5). In Latin America and Sub-Saharan Africa, as well as to a smaller degree in South and South-East Asia and Western Offshoots, the leading driver was population growth rather than per capita income, whereas in Europe, the Middle East, and East Asia it was the other way around.

3.4. The history of a 3 + degree future

According to the OCDE, global GDP will multiply by 1.9 (an annual growth rate of 2.6 %) by 2050. Meanwhile, to fulfill even the least ambitious aim of the Paris Agreement — keeping global mean surface temperature (GMST) below a 2 °C rise above pre-industrial levels —, total emissions would have to decrease by ~ 65 % between 2019 and 2050 (an annual growth rate of −3.4 %). Achieving both goals at the same time would require an amazingly rapid fall of the carbon intensity of the global economy (emissions per unit of GDP). Following these projections, carbon intensity would have to fall from the current 0.5 to 0.009 kg CO_2e per dollar of GDP by 2050, a cumulative yearly variation of −5.7 %. Are there historical precedents for such a reduction? How ambitious is that goal in the light of the preceding history of emission-mitigating technological change?

As shown above, the carbon intensity of economic output has fallen substantially over the last two centuries and has done so especially fast in the last few decades. Nevertheless, the annual rate of change between

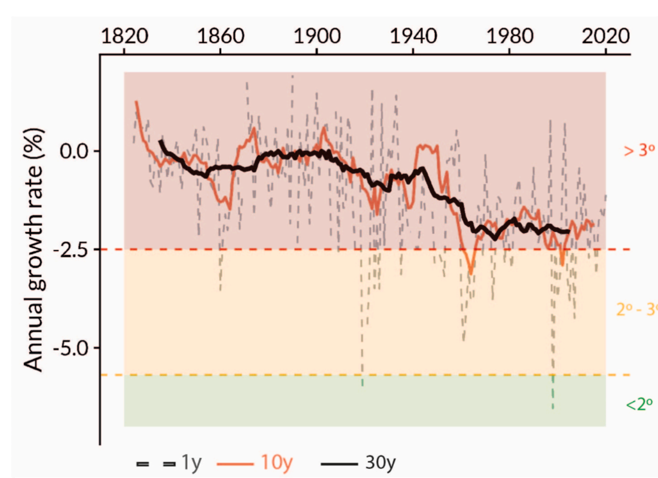

Fig. 6. Rates of growth of global carbon intensity, measured as GHGe (kg of CO_2e) per $ of GDP ($2011): annual (grey), 10-year moving average (red), 30-year moving average (black). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

1820 and 2018 (−0.9 %) is far from the levels required to meet economic projections and climate agreements by 2050 (Fig. 6). In recent decades, the pace of efficiency gains has been faster and more widespread than before, allowing for a yearly fall in global carbon intensity of −2.2 %. But even if these recent trends persist for the next three decades, carbon intensity by 2050 would be of 0.02 kg CO_2e per $ of GDP, which would still result in temperature increases over 3° above pre-industrial levels. As we show in Fig. 6, no 10-year period during the past two centuries has shown a fall in carbon intensity remotely compatible with both economic growth projections and the Paris Agreement climate targets. Even if the world were to replicate the best-performing regional trajectories in history for three consecutive decades, this would still fall short of the 2 °C pathway. Merely matching the best global historical performance would place us on a trajectory above 3 °C. Additionally, we also observe that the downward trend in carbon intensity has stabilized in recent decades. That is, while it continues to decline, the rate of decline has leveled off, and there are no signs that we are approaching the expected levels.

This lack of historical precedents also applies at the regional level. Although all world regions exhibit lower carbon intensity levels today than 200 years ago (Fig. SM7), the underlying drivers and trajectories vary widely. Fig. 7a illustrates this diversity by plotting the annual change in the energy intensity of GDP (vertical axis) against the annual change in the carbon intensity of energy use (horizontal axis), both for global and regional averages. For each region, we show historical averages and best performances over multidecadal periods. This reveals distinct historical paths to emission reduction across regions: in sub-Saharan Africa and Latin America, the most substantial gains have come from decarbonizing the energy mix (i.e., reducing the carbon intensity of energy), whereas in Eastern Europe, sharp reductions in energy intensity of GDP played a larger role—even if energy carriers themselves remained relatively carbon-intensive.

The fall in carbon intensity required to fulfill climate targets would be smaller if economic growth slowed down—and even more so under degrowth scenarios. Fig. 7b illustrates the combinations of economic growth and carbon intensity reductions that would be compatible with different GMST outcomes. Over the past two centuries, the world has averaged an annual GDP growth rate of 2.4 % and a carbon intensity decline of −0.9 %. Even if from now on the world replicated the best historical performances by any region, the emissions trajectory would still lead to warming levels well above the international targets. An especially revealing case is that of Eastern Europe. During its best-performing period (1985–2014), the region achieved a level of economic growth of 2.5 % –comparable to current global growth projections for 2050-, combined with the largest recorded regional decline in carbon intensity (–3.6 %). Yet even replicating this exceptional performance would fall significantly short of the 2 °C target.

As shown above, sustaining economic growth at the pace projected by the OECD would require unprecedented efficiency improvements in the carbon intensity of the global economy. Conversely, if carbon intensity were to continue declining at its current historical average, meeting climate goals would only be possible through a sustained global GDP contraction of around –1.4 % per year. Such a prolonged recession, however, has no regional or global precedent in modern global history.

4. Discussion

4.1. On the historical narratives of climate change

Modern economic development has allowed human societies to grow larger and richer than ever before. But it has also produced environmental impacts which threaten the future viability of those societies—as well as the planet's (Infante-Amate et al., 2024; Rockström et al., 2023). After centuries of economic stagnation, the use of fossil fuels enabled societies to escape the Malthusian trap, paving the way for sustained economic growth (Wrigley, 2016; Wrigley, 1990). Western countries, as pioneers of industrialization and energy transitions, embarked on a process of sustained economic growth that set them apart from the rest of the world, initiating the so-called "Great Divergence" (Pomeranz, 2000). This growth, heavily reliant on fossil fuels, led to high levels of CO_2 emissions, accelerating climate change. Consequently, these countries are the primary contributors to current accumulated emissions and, by extension, bear the greatest responsibility for climate change (Hickel, 2020; Wei et al., 2012).

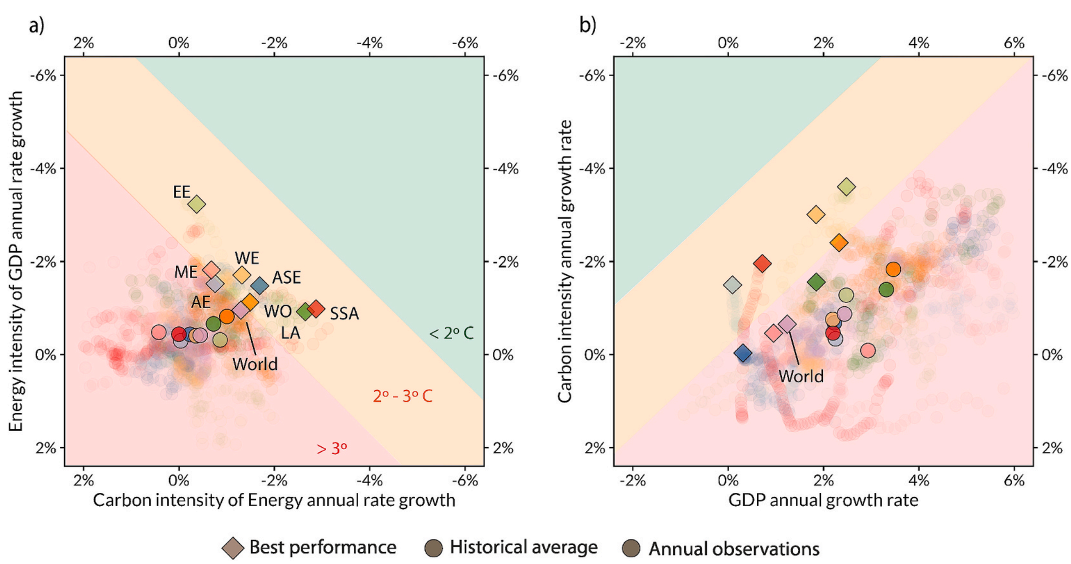

Fig. 7. Simulation of mean global surface temperature scenarios by 2050 replicating historical rates of growth. a) Annual growth of the energy intensity of GDP (y-axis) and annual growth of the emission intensity of energy (x-axis), 30-year moving averages. 'Best performance' refers to the year with the largest fall in the carbon intensity of GDP (as the combined effect of the variables in both axis). b) Annual growth of GDP (x-axis) and carbon intensity of the economy (y-axis). 'Best performance' refers to the year with the largest fall in GHGe (as the combined effect of the variables in both axis). In panels a) and b) colours in the background represent temperature outcomes by 2050 depending on the evolution of the variables considered. The red area implies global mean temperatures more than 3 °C above pre-industrial levels; the orange area refers to temperatures between 2 °C and 3 °C above pre-industrial levels; the green area represents outcomes below 2 °C. Light circles represent yearly observations; dark circles represent the historical mean; diamonds represent the largest reduction in history for each region. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

However, this narrative often overlooks emissions beyond fossil fuels. When incorporating what we refer to here as *land-based emissions*, new elements emerge that challenge this story. First, land-based emissions were the dominant source of emissions until well into the 20th century, with a significant share originating in Africa, Asia, and Latin America. As noted in the IPCC AR6, when CO_2 emissions from land-use change are included, Latin America exhibits cumulative emission levels comparable to those of Western countries (IPCC, 2022). Does this mean that the increase in emissions until the mid-20th century is not necessarily tied to industrialization and Western growth? Not quite: the Industrial Revolution in north-western Europe was global in its reach for materials, which generated high emissions directly or indirectly through deforestation processes (Barbier, 2012). Therefore, the increase in emissions was not only due to the use of coal in furnaces and cotton mills, but also to the growing demand for land-based products, both to supply factories with raw materials and to feed a growing and increasingly affluent population (Federico, 2010; Wrigley, 2016; Wrigley, 1990). Crucial fibers and ores often came from 'ghost acres' (Pomeranz, 2000; Theodoridis et al., 2018), i.e. lands beyond the industrial nations, as the Industrial Revolution opened up vast commodity frontiers in other world regions (Berg, 2021). These fundamental raw materials included cotton imported from Egypt, India, and the US South; wool from Argentina, Australia, New Zealand, and Uruguay; copper ores from Peru and Chile and tin ores from Malaysia and China (McNeill, 2019). The first industrial nations (beginning with Britain) imported also vast amounts of foodstuffs and beverage crops, which transformed landscapes and released GHGe in faraway places. These included sugar from the Caribbean, tea, cocoa, and coffee from tropical Africa and Latin America, and grains (and later beef and mutton) from temperate regions in the Americas and Australasia. In other words, European industrialization owes an ecological debt to the produce of other continents, including crucially agricultural produce in sub-tropical and tropical regions (Albritton Jonsson, 2012; Wrigley, 2015), which led to large-scale deforestation and land-based emissions.

4.2. On the lessons from history

A crucial aim of our study is to assess the targets of the international climate agreements through the lens of history beyond the narrow confines of the recent past. Models that posit the feasibility of current climate agreements in contexts of bussiness-as-usual economic growth assume accelerated improvements in technology and the energy mix, as well as the development of large-scale CO_2 removal methods (IPCC, 2022; Riahi et al., 2017; van Vuuren et al., 2017). That is, they assume it is essential to substantially reduce energy use per unit of GDP and, simultaneously, to lower emissions per unit of energy consumed. These assumptions have, however, come under heavy criticism from a range of recent studies (Hickel, 2019; Hickel and Kallis, 2020; Vogel and Hickel, 2023). Scholars have underlined both the limitations of proposed energy transition paths and the restrictions of carbon capture technologies (Anderson and Peters, 2016; Smith et al., 2016). Indeed, the progress made in the aftermath of the Paris Agreement was insufficient (Blok et al., 2012; den Elzen et al., 2022; Hausfather and Peters, 2020; Jackson et al., 2019) which forces us to a faster pace of change in the future (Höhne et al., 2020). However, recent evidence of absolute decoupling processes in high-income countries is being interpreted optimistically—that is, as proof that economic growth with absolute emission reductions is feasible, even though these reductions remain insufficient (Ritchie, 2024).

Looking back at history, the path of efficiency gains has been impressive and led to a secular fall in carbon intensity. Notwithstanding several discontinuities and significant variation between regions, this fall has been due to improvements in the energy intensity of GDP as well as in the emission intensity of energy use. In the case of energy intensity, historians suggest that structural change played a limited role. Throughout the 19th century, the transition from agrarian to industrial economies led, in fact, to a slight increase of the energy intensity of GDP (Malanima, 2021). The more recent transitions led by the service sector have not produced significant energy savings (Dong et al., 2019), partially because manufacturing production has relocated to less environmentally efficient sites (Kander, 2005; Schäfer, 2005). Therefore, the secular fall in global energy intensity is explained by persistent technological improvement across economic sectors. For example, the energy required to produce pig iron has fallen from 300 to 20 MJ kg^{-1} in the last 250 years (Smil, 1999). Improvements such as this, widespread across industries, have managed to substantially decrease energy requirements per unit of output.

Mitigation due to changes in the emission intensity of energy use have also contributed to significant emission savings. In the aftermath of the Industrial Revolution, coal (a comparatively 'dirty' energy carrier) was increasingly adopted, but during and since the 20th century, it was progressively substituted by sources with lower emission impacts: initially oil and eventually gas, nuclear, and renewables (Kander et al., 2014; Malanima, 2022; Smil, 2018). Nevertheless, these improvements to the emission intensity of energy use can be countered by rising land-based emissions. Until the mid-20th century, rapid deforestation produced land-use change CO_2 emissions which prevented emission intensity from falling more substantially. Since then, the pace of forest loss has slowed down in several regions. As a result of the 'forest transition' (Meyfroidt and Lambin, 2011) some countries have seen a net increase in forest cover, allowing for carbon sequestration in the biomass (Gingrich et al., 2022; Infante-Amate et al., 2022; Magerl et al., 2022). Meanwhile, in recent decades there have been widespread reductions in the emission intensity of agricultural output (Hong et al., 2021), contributing to the fall of emissions per unit of energy consumed.

Nevertheless, all these long-term energy and emission savings across world regions have been ultimately insufficient to counter the climate footprint of ever-richer and ever-larger populations. The 'rebound effect' seems to have prevailed everywhere over the last two centuries: efficiency gains have been absorbed and outpaced by the growing scale of the economy. If the best performances from the past were replicated in terms of reducing carbon intensity, we would only maintain current emission levels, and thus temperatures would exceed the 3° threshold by 2050. Even if future efficiency gains manage to outshine all historical precedent, further 'rebound effects' will remain a risk and require novel agreements and policies (Grubler et al., 2018b).

Given current uncertainty about the feasibility of technological solutions to reach climate agreements, some scholars and activists advocate for degrowth strategies (Hickel et al., 2022; Kallis et al., 2012). With a few exceptions (Keyßer and Lenzen, 2021; Li et al., 2023), integrated assessment models do not consider degrowth alternatives, which makes it difficult to technically assess their viability, beyond the very substantial political obstacles to their implementation. According to our results, if efficiency gains stay in a bussiness-as-usual path, the global economy would need to shrink substantially by 2050 in order to meet international climate targets. Such a protracted economic contraction also has no historical precedent.

Historical analysis is, by definition, the opposite of prediction, so historians are rightfully wary of speaking of the future (reconstructing past evidence is already hard enough). Indeed, no amount of historical data can prove whether the Paris Agreement's climate targets for 2050 are achievable. What historical analysis can do, however, is give us a higher vantage point from which to discern the contours and the magnitude of present challenges. Our reading of the long-term evidence, in line with the recent analysis by Smil (2024), is that our history does not look like the past of a 2° future.

4.3. Limitations of this study

The reliability of our analysis is limited by the uncertainty associated to the data we have used. In the case of GHG emissions, we provide an estimation of uncertainty ranges, which are particularly large in the case of land-based emissions. Therefore, adding land-based emissions adds more uncertainty to the assessment of the history of the anthropogenic contribution to climate change. However, we argue that it also provides a more realistic picture through the incorporation of the current knowledge on the causes of climate change.

Another important source of uncertainty is in the estimation of GDP, which requires many assumptions in the earlier decades, and also even in recent periods in some countries. Estimates are based on incomplete data, and economic historians must often make assumptions about the way in which the data represent actual economic activity in the past (Bolt and van Zanden, 2025: 635), and indeed some of those concerns also apply to present-day GDP data. In this case, the Maddison Project Database does not provide information on the error margins of income estimates, and therefore we were not able to compute this uncertainty, which is an additional limitation of our study.

Another limitation of our analysis is the Production-Based Accounting (PBA) methodology we have adopted to quantify GHG emissions at the regional level, which was necessary given the lack of bilateral trade datasets before the late-20th century. This approach does not take into account the transfer of commodities through international trade and thus it does not inform us on the emissions responsibilities in the studied regions. As discussed above, a substantial portion of the demand for land-based products in Western industrialized economies was met by agricultural frontiers in other world regions. An indeterminate share of the high emissions recorded in non-industrialized countries could be seen as environmental leakage from richer nations. Studies of more recent periods highlight that the transfer of land-based emissions is particularly significant today (Hong et al., 2022; Pendrill et al., 2019). Given that deforestation and agricultural expansion were even more pronounced in the mid-20th century than they are now (Houghton et al., 1991; Meyfroidt and Lambin, 2011; Williams, 2003), it is plausible that land-based emissions transfers from the Global South to the Global North were considerable. Nevertheless, as Kander et al. (2017) have shown, until relatively recently, Western countries were specialized in exporting energy- and CO_2-intensive manufactured goods. Much like China today, they were the "world's workshop." It is estimated that 20 % of UK energy consumption at the end of the 19th century was dedicated to exports. The extent to which these transfers offset those generated by imports of agricultural products remains uncertain, and this will likely remain unclear until historical carbon footprint estimates are available.

5. Conclusions

The Industrial Revolution inaugurated an era of sustained economic growth and uneven prosperity. It also transformed the global environment, including through the climate change which now threatens future development. These impacts were driven in roughly equal parts by expanding agricultural frontiers and by increased fossil fuel use.

The history of anthropogenic emissions over the last two centuries shows that, despite significant regional disparities, modern societies have managed to limit emissions through improved technology and a gradual shift to cleaner energy. Yet, these improvements have not been enough to offset the growth in economic activity. Moreover, the decline in carbon intensity has stagnated since the 1990s, when environmental awareness and policies became more widespread. The present pace of carbon intensity reduction is insufficient to meet climate targets under current economic growth projections.

This does not prove that these targets are unattainable. Historical analyses does not predict the future, but it provides the tools, knowledge, and context needed to confront it. In other words, a historical perspective does not question the possibility of a black swan; instead it tells us precisely how large black swans have been in the past, so that we can get a sense of the scale of the one needed now. Historical trajectories reveal that, when looking back, the changes required to sustain economic growth within safe climate limits demand transformations on an entirely unprecedented scale—transformations far greater than those seen in recent years despite widespread climate policies.

CRediT authorship contribution statement

Juan Infante-Amate: Writing – original draft, Methodology, Funding acquisition, Data curation, Conceptualization. **Emiliano Travieso:** Writing – review & editing, Writing – original draft, Supervision, Formal analysis. **Eduardo Aguilera:** Writing – review & editing, Validation, Methodology, Investigation, Data curation.

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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.gloenvcha.2025.103009.

Data availability

Data will be made available on request.

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