Observed carbon decoupling of subnational production insufficient for net-zero goal by 2050

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Historically, economic growth has been closely coupled to carbon emissions responsible for climate change, but to stabilize global mean temperature, net-zero carbon emissions are necessary. Some economies have begun to reduce emissions while continuing to grow, but this decoupling is not fast enough to achieve global climate targets. Subnational climate actions seem to be crucial for the achievement of these targets. Here, we uncover the effectiveness of subnational efforts by estimating decoupling rates and CO2 emission intensities over the last three decades for over 1,500 subnational regions, encompassing 85% of global emissions, using global data on reported economic output and gridded production-based emissions. Thirty percent of regions with available data have fully decoupled, with higher-income and historically carbon-intensive regions exhibiting higher rates of decoupling and declining emission intensity. Countries of the Organization for Economic Co-operation and Development with greater spending on subnational climate actions show higher decoupling rates, as do subnational regions in EU countries where climate policies have been implemented, highlighting the effectiveness of subnational policies. Moreover, subnational analysis reveals greater variance of decoupling rates within national boundaries than between them and that countries with weaker governance typically show higher variance of decoupling within their borders. If recent rates of production-based carbon decoupling continue, less than half of subnational regions would reach net-zero before 2050, even when accounting for observed acceleration via socioeconomic development and assuming no interregional carbon leakage.

emissions decoupling | economic growth | green growth

Significance

Decoupling economic growth from greenhouse gas emissions is an important scientific and political framework underlying most mitigation efforts. With subnational entities increasingly setting climate policy and mitigation targets, an understanding of decoupling at subnational scales is a crucial foundation for these efforts. Here, we combine gridded data on CO2 emissions with data on reported subnational economic output to present the global pattern of subnational production-based emissions decoupling. We find that differences in decoupling are typically larger within national boundaries than between them, as well as being higher in wealthier economies. If recent rates of decoupling continue, less than half of observed subnational regions would reach net-zero before 2050, even if these rates increase with growing wealth as observed historically.

The expansion of the economy has been an important factor of increasing emissions (1, 2), leading to increases in global temperatures and human-induced climate change (3). Reducing these emissions, in accordance with recent international agreements to reach net-zero emissions by the middle of the 21st century (3), is a complex endeavor (4).

In the face of global goals to limit climate change, the concept of green growth has emerged as an answer to the challenge of continuing economic expansion while reducing negative impacts on the environment (5–7). Green growth is already central to many mitigation scenarios (1, 3, 8–10), among which most project increasing gross domestic product (GDP) while reducing emissions. These scenarios posit that the global economy could decouple from CO2 emissions, propelled by advancements in emission-free energy production or negative emissions in particular (11).

Economic development has already started to decouple to some degree from production- or consumption-based emissions (12–17), although with rates not fast enough to reach mitigation goals (18), fueling discussion on the feasibility of global-scale green growth with strong arguments for exploring scenarios with constant or even declining GDP in order to achieve such goals (19–21). In line with this shift, certain cities are prioritizing social and environmental well-being over economic growth (22, 23).

Typically, studies on decoupling describe such developments at a global-scale using national data or focus on data from cities in specific countries. However, along with national commitments for climate mitigation, subnational climate action seems to be crucial for its success, with recent work in the US suggesting that subnational action alone could reduce total national emissions by between one quarter to a third (24). Notably, certain cities and subnational regions have already set independent climate mitigation or net-zero emission targets (25–27). The advent of global data on subnational economic output (28, 29) and carbon emissions (30, 31) presents the opportunity for a global-scale analysis of emission decoupling with high granularity on a subnational level.

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In this article, we combine data on reported economic output at the subnational level with production-based CO2 emissions on a 0.1° by 0.1° grid derived from human activities. On this basis, we present the global pattern of decoupling economic output from production-based CO2 emissions on a subnational level for the last three decades. This approach reveals regional disparities in the degree of decoupling of economic growth from emissions within countries as well as between them and allows us to track their changes over time. Moreover, we explore these regional disparities in relation to contributing socioeconomic factors as well as subnational climate policy. Additionally, we examine the implications of recent declines in emission intensities for the feasibility of reaching the internationally recognized goals of net-zero emissions by 2050.

Results

Subnational CO2 Emission Intensities across the World. The combination of granular data on emissions and economic output reveals global patterns of regional emission intensity of economic output at high levels of detail, as depicted in Fig. 1. It is evident that specific geographical areas, namely Europe, South America, and Australia, have consistently maintained relatively lower emission intensities. Globally, the historical average emission intensity stands at 0.46 kg per US$ 2015 PPP, with Russia, South Africa, and China demonstrating elevated historical levels (*SI Appendix*, Table S1). Further disparities within countries are clear (Fig. 1), for example, with lower intensities in coastal US and Chinese regions. Deviations within countries are particularly large for South Africa, Kenya, Egypt, and Russia, and surprisingly are on average more substantial within countries than between them (*SI Appendix*, Table S1). This highlights the importance of accounting for details within national borders which provides a crucial backdrop for effective policy and intervention, particularly those targeted at the subnational level (24).

Furthermore, the temporal evolution across the past three decades suggests a consistent global decline in emission intensity. Specifically, during the decade 1990 to 2000, the average emission intensity was 0.68 kg per US$ 2015 PPP. The analogous intensities for the subsequent decades, 2000 to 2010 and 2010 to 2020, were 0.52 and 0.39, respectively. This declining trend in emission intensities indicates improved efficiency in resource use and production processes within regional economies. But have these declining trends been enough to offset rates of economic growth?

Subnational Decoupling of Emissions and Economic Growth. The concept of decoupling is used to analyze the trade-off between economic expansion and environmental pressure. In particular, the decoupling between economic development and growth in CO2 emissions is one of the indicators for green growth, as suggested by the Organization for Economic Co-operation and Development (OECD) (5). This indicator can have three outcomes: absolute decoupling, relative decoupling, and no decoupling. Absolute decoupling indicates economic expansion while carbon emissions remain stable or decrease. Relative decoupling, on the other hand, occurs when emissions grow at a positive but slower pace than economic output. Finally, no decoupling means that emissions grow at a higher pace.

The relative speed of emissions and economic growth is indicated by a decoupling measure, for example, the ratio of percentage change in emissions and percentage change in economic output, as suggested by Tapio (32). Here, we determine the global pattern of decoupling rates using a similar measure which has been transformed such that higher values indicate a greater degree of decoupling (*Materials and Methods*). Several regions with declining gross regional product (GRP) in specific decades are excluded from this analysis for ease of interpretation (32).

Our analysis reveals the global pattern of decoupling between economic growth and emissions at the subnational level (Fig. 2). Notably, Europe consistently outperforms other regions with a significant number of its regions sustaining a continuous decoupling trajectory, especially for the last two decades, while North America and Asia exhibit fluctuating decoupling patterns over the decades with a trend of improvement in the last decade in particular. Historical decoupling rates (over the whole period 1990 to 2020) are calculated for a total of 1,494 regions where the observed per capita GRP was increasing (*SI Appendix*, Table S2). Among these regions, 29% achieved absolute decoupling, accounting for 44 and 38% of historical CO2 emissions and GRP, respectively, while 52% accomplished relative decoupling.

We explore whether climate policies can explain regional discrepancies in decoupling rates. National analysis reveals higher average decoupling rates in OECD and EU countries with higher spending on subnational climate action as a proportion of the GDP (Fig. 3*A* and *SI Appendix*, Table S3A). Furthermore, subnational analysis within the EU indicates that regions where cities have implemented or announced any type of local climate mitigation plans typically exhibit higher levels of decoupling (*SI Appendix*, Table S4), with comprehensive stand-alone plans dedicated to climate change mitigation having a significant effect compared to those that partially address mitigation (Fig. 3*C* and *SI Appendix*, Table S5). Additionally, nationally mandated local plans are more effective than those autonomously developed by urban authorities (Fig. 3*C* and *SI Appendix*, Table S5). These findings highlight the important role of climate policy in driving decoupling, in particular at the subnational level.

Deviations in decoupling rates within countries are found to be typically larger than differences between them (*SI Appendix*, Table S2). Particularly large variations within countries are seen in Egypt, South Africa, and Brazil, while European countries exhibit low variability (*SI Appendix*, Table S2). In fact, higher deviations of decoupling within countries are generally observed in countries characterized by weaker governance (Fig. 3*B* and *SI Appendix*, Table S3B), as measured by the World Bank's government effectiveness index which reflects the development, quality, implementation, and commitment of the government to policies. This implies that effective governance is an important factor for making emission reductions nationally comprehensive.

Comparing decoupling rates across decades reveals evidence of an increasing number of regions achieving absolute decoupling of economic development from carbon emissions over the last three decades. Specifically, during the decade 1990 to 2000 27% (199) of regions with available data achieved absolute decoupling, while 33% (403) and 38% (476) of regions achieved it during the decades 2000 to 2010 and 2010 to 2020, respectively.

While these trends indicate positive developments in the goals of achieving green growth, whether they are sufficient to achieve the mitigation targets of the international community remains uncertain. We extrapolate recent trends in emission intensity with trends in population and GRP growth to assess their implication for reaching net-zero. Declining emission intensities are closely equivalent to relative decoupling, but provide a more suitable metric to project future changes given their independence of the rates of GDP growth. This approach does not aim to predict future CO2 emissions but simply explores the implications of historical rates of declining emission intensities for meeting future emission targets. See the *Materials and Methods* section for a detailed description of this projection method.

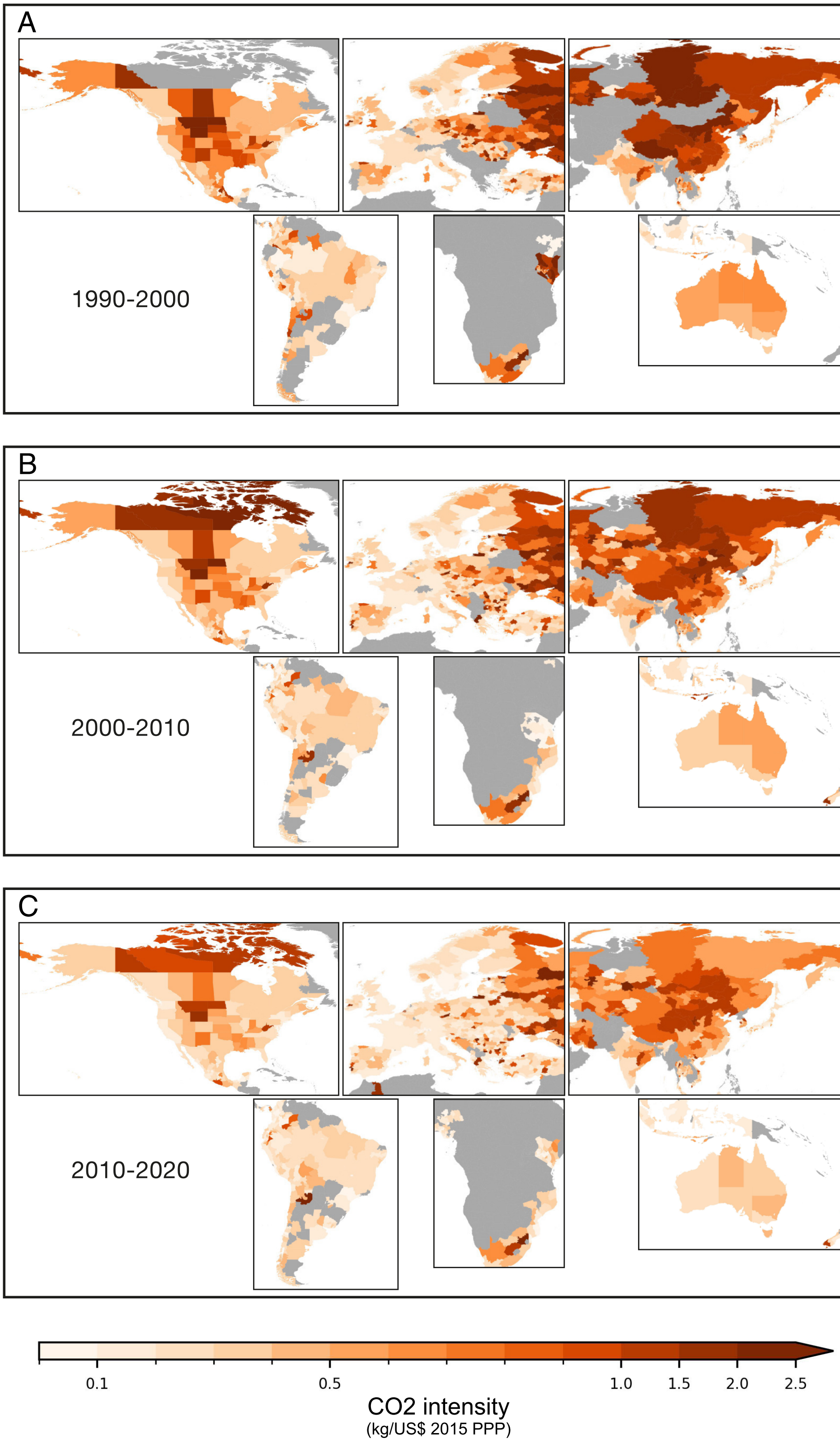

Fig. 1. CO2 emission intensities of GRP across the world. Integrating global data on reported economic output and gridded production-based emissions reveals the pattern of CO2 emission intensities at the subnational level for the last three decades: 1990 to 2000 (*A*), 2000 to 2010 (*B*), and 2010 to 2020 (*C*). These intensities are measured in kilograms of CO2 emitted from human activities (excluding land-use, land-use change and forestry) per unit of GRP measured in US dollars in 2015, adjusted for purchasing power parities (PPP). The depicted regions for each decade have a minimum of 5 y worth of data specific to that decade, while those shown in gray lack sufficient data for the corresponding period.

Using a Monte-Carlo simulation procedure to propagate errors from the different sources in our projections gives a 90% confidence range for the fraction of regions reaching net-zero by 2050 of 37 to 40%, covering 35% of global historical CO2 emissions on average, and an average net-zero year of 2107 to 2111. These findings demonstrate that recent trends are inadequate for achieving the net-zero by 2050 targets in most regions. Illustrated in Fig. 4*A*, the timelines for achieving net-zero vary strongly across

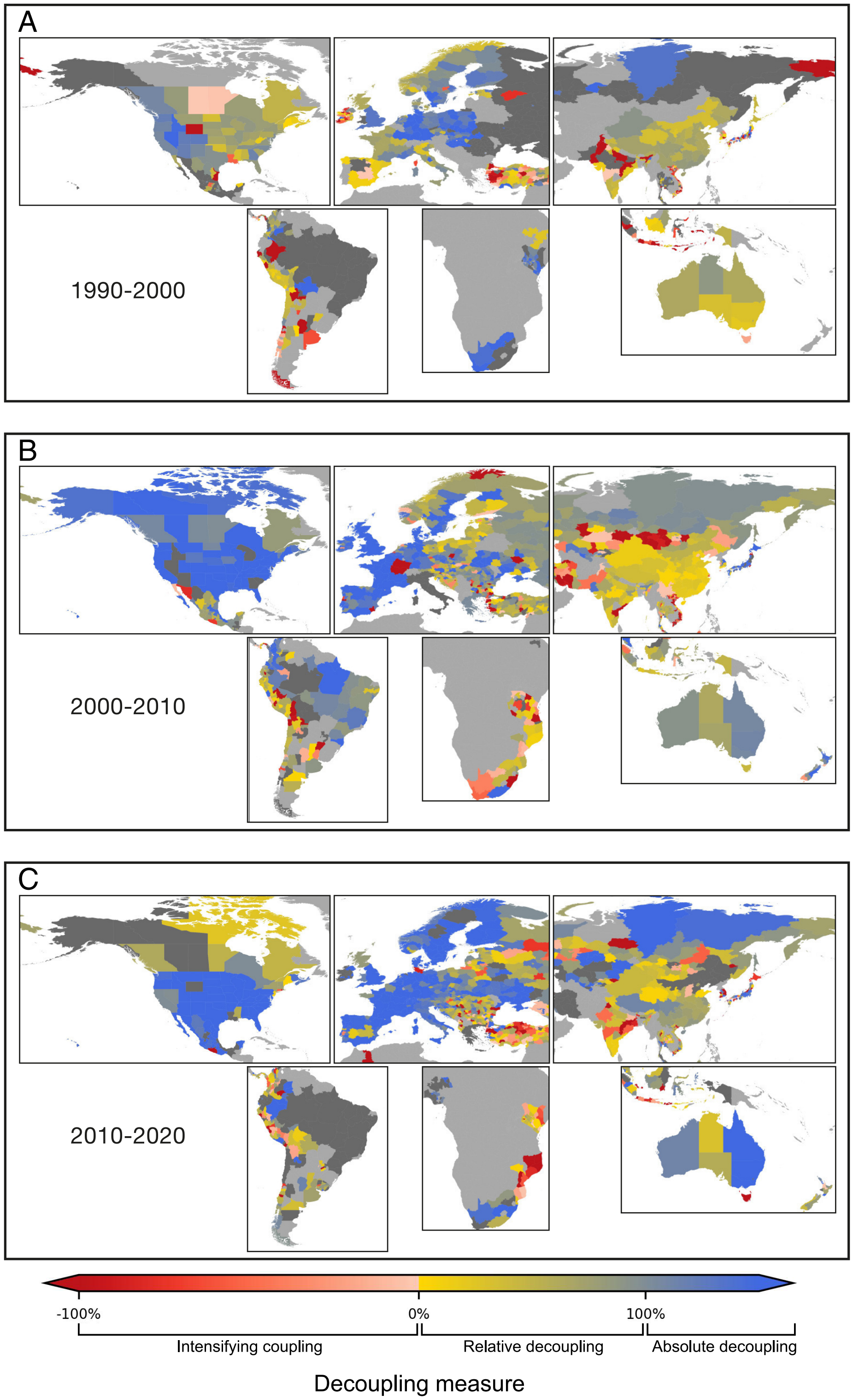

Fig. 2. Decoupling rates between CO2 emissions and GRP across the world. Each map illustrates decadal regional decoupling rates for the periods 1990 to 2000 (*A*), 2000 to 2010 (*B*), and 2010 to 2020 (*C*). These rates are calculated by subtracting from one the ratio of the average decadal percentage change in production-based CO2 emissions (measured in kilograms) to the average decadal percentage change in per capita economic growth (PPP-adjusted GRP in US dollars in 2015) and then transforming these values to percentages. The interpretation of decoupling rates is as follows: A value above 100% shows absolute decoupling, values between 0 and 100% show relative decoupling, and values below 0% show no decoupling (or "intensifying coupling"). Light gray regions lack sufficient data (less than 5 y) for the decade, while dark gray regions, characterized by negative economic growth, are excluded from the analysis.

regions, with developed countries appearing likely to fulfill these targets ahead of others. This prompts questions regarding the potential influence of historical levels of socioeconomic development on rates of decoupling and whether accounting for future socioeconomic development could have further important implications for the net-zero timelines.

The Role of Socioeconomic Development. The extensive spatial granularity and large number of observations in the global economic output and emissions data we employ facilitate a detailed analysis of historical decoupling trends and their underlying determinants. Here, we utilize a multivariable regression model to highlight statistically significant cross-sectional relationships between

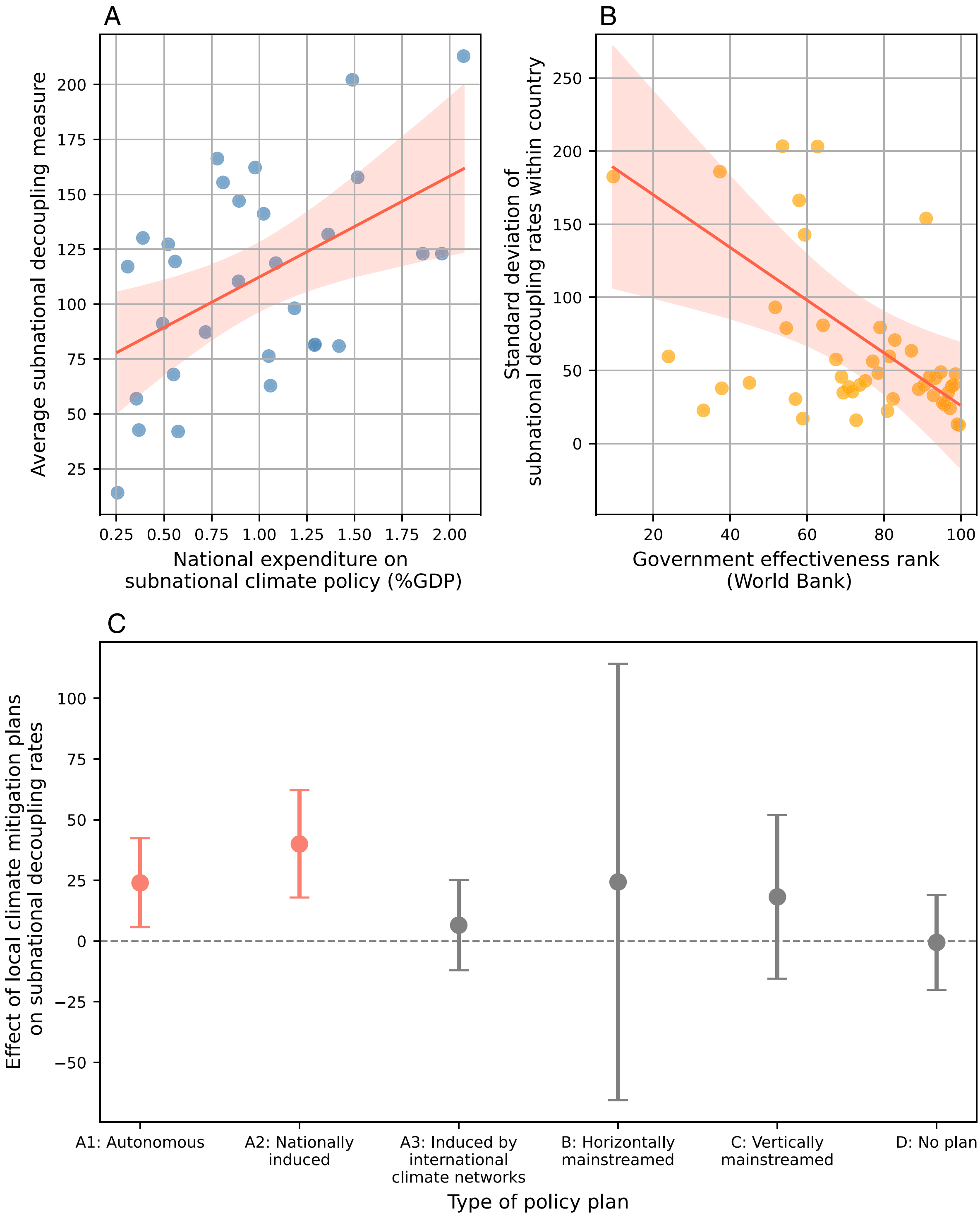

Fig. 3. Effectiveness of subnational climate actions and policies on decoupling rates. Results from multiple regression analyses, conducted on both a national and subnational level, explore the influence of subnational climate-related expenditure on nationally averaged subnational decoupling (*A*), government effectiveness on its variation within each country (*B*), and the effect of city-level policies on the respective subnational decoupling (*C*). The datapoints illustrating the nationally averaged subnational decoupling measure and national expenditure on subnational climate policy (*A*), measured as the percentage of GDP, in OECD and EU countries, are shown in blue. Similarly, the datapoints representing the SD of subnational decoupling measure within each country and the government effectiveness rank (*B*), as measured by the World Bank, are shown in orange color. Red lines represent the regression lines for the respective relationships. In (*B*), the regression line is shown with the other independent variable, CCPI, set at its mean, using the estimated coefficients from the regression analysis. Red shaded areas around the regression lines represent the 95% CI. All relationships are statistically significant with *P*-value of less than 0.01 (*SI Appendix*, Table S3). At the subnational level, the effect of climate policies in cities on the decoupling rates of their respective subnational regions is illustrated by dots (*C*), with bars indicating the 95% CI for the value of the coefficient (*SI Appendix*, Table S5), for the following types of mitigation plans: A1: autonomously developed by the authority or administration, A2: nationally mandated for the city, A3: induced by international organizations, particularly municipal climate networks, B: other types of municipal plans which include climate change aspects, C: vertically integrated plans partially addressing climate change concerning particular sectors, and D: no plan. Statistically significant relationships are indicated by red bars, while insignificant relationships are shown in gray (*SI Appendix*, Table S5).

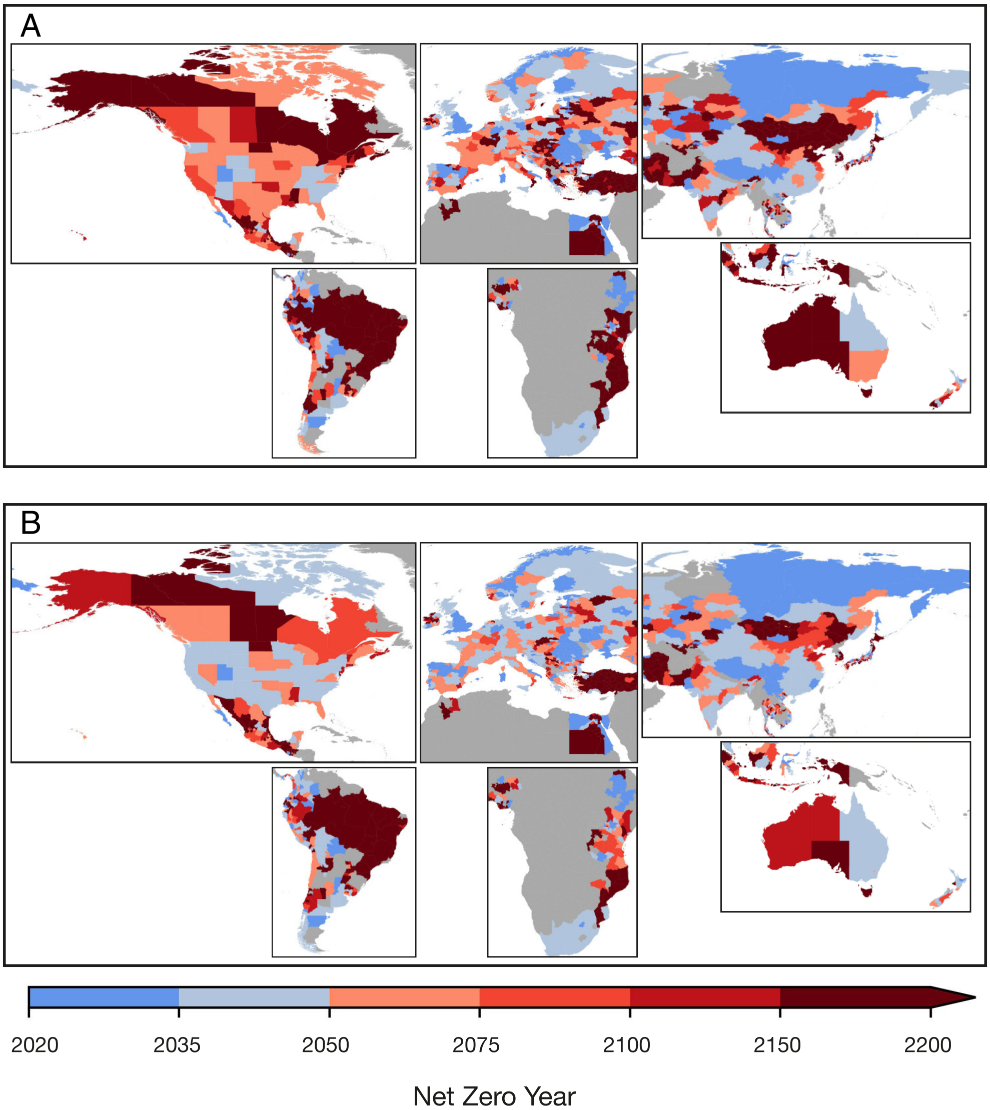

Fig. 4. Estimated net-zero times for subnational regions based on recent rates of declining emission intensity. The estimated year that each region would achieve net-zero CO2 emissions assuming continued rates of economic and population growth, as well as recent (using the last 5 y of available data) rates of declining emission intensity (*A*), and assuming accelerated rates of emission intensity declines driven by the influence of economic growth and cumulative CO2 emissions as observed historically (*B*).

historical socioeconomic factors and the observed decoupling rates in regions displaying a historical increase in GRP. We find that regions with more developed economies, characterized with higher income and accumulated CO2 emissions, exhibit a greater level of decoupling between economic growth and emissions, in addition to economies with a greater share in the service and manufacturing sector (*SI Appendix*, Table S6A).

A plausible avenue for understanding these relationships lies in the development and deployment of low carbon technologies and their infrastructure, as well as the replacement of obsolete technologies. The pursuit of technologies with lower emission levels necessitates investment which is typically linked to higher levels of income (33). Additionally, climate action initiatives from subnational actors are located mostly in developed countries (34). Furthermore, these correlations align with the principles of the Environmental Kuznets Curve (EKC) (35), which suggests a theoretical link between environmental degradation and per capita income. According to this hypothesis, environmental pressure first increases with economic development, primarily due to resource-intensive industrialization. However, as regions become wealthier, there is a shift in focus toward, and increasing capacity for, environmental preservation, resulting in a decrease in degradation despite ongoing economic development. EKC has been observed empirically in other contexts, but there is no agreement on the threshold level of income after which environmental pressure may start to decline (35).

Considering the influences of these historical factors on the extent of decoupling and, consequently, on emission intensity trends, we assess their implications for the timeline for achieving the net-zero target. Here, we again use trends in emission intensity rather than decoupling rates, which also show significant correlations between stronger declines in emission intensity and higher levels of per capita economic growth and cumulative emissions (*SI Appendix*, Table S6B). As with the decoupling rates, this confirms that countries with greater levels of economic development have greater capacity to increase climate change mitigation actions and green technology investments. Building upon these results, we extrapolate recent emission intensity trends while assuming accelerated rates of decline driven by growth in both GRP and cumulative emissions. Given the challenges of predicting the composition of sectors in the future, the acceleration is only based on these two variables without accounting for changing sectoral composition. For a detailed description of this method, refer to the *Materials and Methods* section.

Fig. 4*B* demonstrates the estimated net-zero year for each region when future rates of change in emission intensity are accelerated by socioeconomic development as observed historically. Propagating errors from different sources using a Monte-Carlo simulation procedure gives a 90% confidence range for the fraction of regions reaching net-zero by 2050 of 39 to 47%, which covers on average 53% of global historical CO2 emissions, and for the average net-zero year of 2104 to 2121. These results indicate that accounting for the accelerated rates of emission decoupling through economic growth and increasing cumulative emissions increases the number of regions likely to achieve net-zero prior to 2050, but only marginally.

Discussion

Subnational emission intensities have been globally declining over the period 1990 to 2020 (Fig. 1), with 30% of the regions experiencing positive economic growth fully decoupling production-based emissions from their economic output. Differences in decoupling rates between regions can be explained by a number of factors. Regions with high per capita wealth and cumulative emissions, as well as those with significant shares of service and manufacturing sectors, tend to achieve a higher degree of decoupling. This finding is consistent with the EKC theory but also may reflect inter- or intranational trade, where pollution-intensive production is transferred to less developed economies while developed economies focus in developing their service sectors domestically. We further find that high decoupling rates are driven by subnational mitigation action. In particular, EU cities with climate mitigation plans typically exhibit higher decoupling rates, reflecting the effects of recent local mitigation efforts (26, 27). Similarly, OECD countries with higher subnational climate-significant expenditure also show higher decoupling rates. However, since the policy data we use are mostly from groups of developed economies, it might mostly account for the effects of policies on these economies.

Although most climate mitigation goals and policies are implemented at the national or higher level, we find that emission intensities and decoupling rates have been more heterogeneous within national boundaries than between them. Moreover, decoupling rates are particularly variable in countries with weak governance. These results highlight the importance of analyzing drivers of decoupling at the subnational level and further point out that governance is key to ensuring that the effects of mitigation policies transfer to all regions of a country.

Assessing the recent global state of subnational emission decoupling, our results indicate that recent declines in emission intensity of GRP are insufficient to reduce emissions fast enough to reach net-zero by 2050 in most regions (Fig. 4). This highlights the need for increased engagement and climate action from all levels of government. Climate policy targets may vary across countries if assessed on equity principles of the Paris Agreement (36, 37), such as using the "fair shares" concept as a yardstick to measure progress toward international targets (18). By estimating net-zero timelines implied from recent decoupling trends, we remain agnostic to the value judgments underlying such equity-based targets and allow for a comparison of the estimated timelines to a range of targets, whether equity-based or not.

Additionally, we uncover large disparities between the developed and developing world. In particular, recent trends across parts of Europe, China, the United States, Russia, and Australia appear sufficient to reach net-zero prior to 2050, but across most of the developing world including South America and India they appear insufficient to do so, even when accounting for acceleration driven by future socioeconomic development. These regional discrepancies emphasize the need for increased efforts and investment in the energy transition in the developing world in order to meet net-zero targets globally. This complements recent work suggesting that such investments are also necessary from an equity perspective (38). The continuing necessity of economic development in the global south for the pursuit of sustainable development goals such as poverty alleviation further compounds the importance of such investments to decouple development from emissions. Moreover, given that emissions mitigation actions by subnational entities are primarily concentrated in developed nations (34), such imbalances could be addressed by policies focusing on equipping and encouraging actors in developing countries (34).

One limitation of this analysis is the use of production-based emissions data which, as opposed to consumption-based emissions, do not reflect emissions as embodied along global supply chains (39). This limitation stems from the lack of available global data on consumption-based emissions at the subnational level, although recent efforts are providing new insights within individual countries (40, 41). Consequently, the implications of inter- and intranational trade are not reflected in our results, with potential implications for the estimations of emission intensities, decoupling rates, and net-zero times, which do not account for changes in the distribution of CO2 emissions due to carbon leakage. Across countries, using production-based emissions to assess the decoupling rates likely leads to an overestimation of decoupling rates in developed countries in which international trade often facilitates the transfer of pollution-intensive production to other trade partners (42). Compared to estimates using consumption-based emissions, this approach may therefore also result in an underestimation of decoupling rates in developing countries or regions with high exports of carbon-intensive goods. Similarly, within national borders, the trade of carbon-intensive goods can shift emissions between consumers and producers in different regions. For example in China, highly developed coastal provinces outsource much of their consumption-based emissions to central provinces (43), a likely contributing factor to the lower emission intensities of coastal provinces in Fig. 1. Developing robust global data on consumption-based emissions at the subnational level is therefore an important avenue for future work. While these data are lacking, our analysis provides fundamental information on the patterns of production-based emission decoupling at the subnational level, which is likely of high relevance for the setting of targeted and effective climate policy.

Limitations arising from the lack of data in Africa and other developing regions, where reported subnational output data are not available at all or for a very low number of years (28), also have implications for our results. This scarcity of data could lead to underrepresentation issues, thus distorting the perspective at a global-scale. Since we find decoupling rates to be most insufficient for reaching net-zero targets in developing regions of the global south where data coverage is poorest, our results are likely optimistic with regard to the proportion of regions reaching net-zero before 2050.

The recent trends used for projecting the net-zero timelines are based on the most recent 5 y worth of data available for each region. These years are likely to be representative of the ongoing mitigation efforts spurred by the signing of the Paris Agreement in 2015. Moreover, conducting the analysis utilizing data from the past decade indicates very similar main results (*SI Appendix*, Fig. S1). These estimates of future net-zero times are based on extrapolation of recent trends and should be considered as an exploration of the implications of recent decoupling trends, rather than as detailed predictions of future emission trajectories (18). Important potential developments which could alter these estimates include technological "leapfrogging" and diminishing marginal returns to mitigation investments. On the one hand, developing countries may adopt renewable technologies at rates faster than those expected based on the historically observed acceleration of emission decoupling via socioeconomic development. However, empirical work suggests limited evidence for such leapfrogging effects (44). On the other hand, recent declines in emission intensities may reflect the results of low-hanging fruits and continued mitigation efforts may face increasing challenges as they move into sectors with fewer substitutes. Indeed, empirical evidence from firms supports the existence of diminishing marginal returns to investments in mitigation (45).

Materials and Methods

Subnational Economic and Population Data. We analyze economic development at the subnational level by utilizing GRP data sourced from DOSE, the MCC-PIK Global Database of reported Subnational Economic Output (28, 29). This comprehensive dataset covers 1,661 subnational regions in 83 countries and over the period 1960 to 2020 with varying temporal coverage by region. The subnational regions correspond to the highest administrative division within national boundaries. This database is based on reported data from sources such as statistical agencies, yearbooks, and academic literature and avoids the use of temporal or spatial interpolation to infer values at the subnational level as typically used in other global datasets (28). We use per capita GRP measured in US dollars at 2015 market prices and adjusted to the Purchasing Power Parity (PPP) by using the PPP exchange rate provided by the DOSE dataset, to facilitate meaningful cross-temporal and cross-sectional comparisons.

We also extract sector-specific economic data for agriculture, manufacturing, and services from the same dataset, which are then employed to calculate sectoral shares. The sectoral shares are calculated by dividing the economic output of each sector by the combined economic outcome of all sectors. Additionally, we utilize population data from the dataset to convert other measurements, such as emissions, into per capita values.

Production-Based Carbon Dioxide Emissions Data. The main source of data on global anthropogenic carbon dioxide (CO2) emissions is the Emissions Database for Global Atmospheric Research (EDGAR v7.0) (30, 31) which provides production-based, area-weighted, annual CO2 emissions data on a spatial grid with 0.1° by 0.1° grid cells, covering the years from 1970 to 2021. This database is used due its global coverage and spatial detail. The methodology used to calculate the CO2 data, derived from human activities (such as fossil fuel combustion, nonmetallic mineral processes, urea production, agricultural liming, and solvent use) apart from land-use, land-use change, and forestry sectors, is based on a combination of activity data, emission factors, and spatial allocation, by using proxy datasets, of the emissions to their respective grid cells (46). We use the Climate Data Operators provided from the Max-Planch-Institute for Meteorology (47) and the shapefiles provided by the DOSE dataset (29) to aggregate the emissions data from grid cells to the respective subnational level described in the economic data section. This results in subnational CO2 emissions time series.

In addition to the time series derived from the EDGAR database, we use carbon emissions data from the National Fossil Carbon Emissions 2022 v.1.0 provided by the Global Carbon Budget 2022 (48, 49) to obtain historical cumulative anthropogenic CO2 emissions data for each of the regions. This dataset contains carbon emissions by country in million tons of carbon per year from 1850 to 2021. To convert the data to million tons of carbon dioxide per year, we multiply by the ratio of the molecular weight of the carbon dioxide to the atomic weight of carbon. We then allocate emissions prior to 1970 to subnational regions based on their historical distribution within countries, using data from the oldest available historical decade from the EDGAR dataset and assuming that pre-1970 emissions had a similar pattern to the following decade after 1970. By aggregating the emissions data for each subnational region over the years 1850 to 2021, we obtain historical cumulative CO2 emissions.

The subnational CO2 emission time series and historical cumulative emissions are converted into per capita values using the historical population data and the recent population figures, respectively, provided by the DOSE dataset described in the preceding section.

Emission Intensity Analysis. Emission intensity refers to the amount of CO2 emitted per unit of economic output, typically measured with GDP. This metric provides insights into resource efficiency within production processes while the rate of change observed over time informs about the extent of relative decoupling between economic growth and emissions. In this context, we employ production-based CO2 emission intensity as a metric to evaluate the worldwide variations of the relationship between the economy and emissions across regions. This assessment includes both historical patterns and trends spanning the three preceding decades. We combine the two datasets described above, namely the timeseries data for subnational CO2 emissions and the GRP, which is the regional equivalent of GDP, for each region and its corresponding years. Both emissions and economic data are normalized to per capita values using the population data.

The historical emission intensity for each region is derived by dividing the annual per capita CO2 emission by the corresponding per capita GRP, subsequently calculating the average across the years for which data are available. To estimate the extent of variation between countries, the distinct subnational emission intensity values of the regions are used to obtain the average emission intensity at the country level, and from this average, the SD across all countries is calculated. Additionally, for each country, the SD of its constituent regions is computed to provide insights into the variations within the country's borders. Furthermore, we determine the average emission intensity on a decade-by-decade basis for the most recent three decades: 1990 to 2000, 2000 to 2010, and 2010 to 2020. Within each of these decades, we divide the average per capita CO2 emissions by the average per capita GRP.

Regions with less than 5 y of available data are excluded from this analysis. The number of observations of subnational emission intensity per decade for each region is detailed in *SI Appendix*, Fig. S2 and the number of regions with observations per country are presented in *SI Appendix*, Tables S1 and S2. Additionally, data coverage is sparse in Africa where reported values of GRP are not typically available at the subnational level. Nevertheless, our data comprise 1,597 subnational regions reflecting the developments which account for 84.8% of global emissions historically.

Decoupling Indicator and Analysis. Decoupling indicators are used in order to measure the degree of decoupling between economic growth and environmental pressure. We choose to use CO2 emissions and GRP, both measured per capita, as variables for measuring environmental pressure and economic activity, respectively. CO2 is the primary greenhouse gas emitted through human activities, making it a key indicator of the contribution to climate change from economic activity. Meanwhile, per capita GRP provides a good indication of economic activity measuring the average economic output per person in the region.

To measure the decoupling rate for each region, we subtract from one the average annual ratio of percentage change in per capita CO2 emissions and percentage change in per capita GRP over the span of a decade, and then transform this value to a percentage measure:

$$decoupling\ \ rate\,\% = \left(1 - \frac{\Delta pcCO_2\%}{\Delta pcGRP\%}\right) \cdot 100. \qquad [1]$$

Here, $\Delta pcCO_2\,\%$ is the percentage change of per capita CO2 emissions, and $\Delta pcGRP\,\%$ refers to the percentage change of per capita GRP.

Similarly as with the emission intensity analysis, the decoupling rates of the regions are used to obtain the deviations between and within the countries. Additionally, the decoupling rates for the decades 1990 to 2000, 2000 to 2010, and 2010 to 2020 are calculated by using the average percentage over the respective decades.

A decoupling rate value below 0% indicates that emissions are increasing at a faster rate than economic growth, during the specific time frame over which the percentage changes are averaged. A value ranging from 0 to 100% indicates a state of relative decoupling, where emissions' growth is lower than the growth of GRP. A decoupling rate value above 100% indicates decoupling, also referred to as absolute decoupling, where emissions decline despite ongoing economic growth.

Several regions with declining GRP within the specified time frame are excluded from this analysis for ease of interpretation. Additionally, this analysis is restricted to regions with data spanning a minimum of 5 y.

While the decoupling measure is valuable, its reliability can be affected by certain factors, such as the exclusion of regions experiencing negative economic growth or significant variations due to low but non-negative economic growth. Therefore, we use the decoupling measure as defined here for this analysis. However, to include a larger number of regions in our projections, described in the following sections, we use emission intensity rates, which are closely related to decoupling. In this context, positive values correspond to strong coupling between economic growth and emissions, whereas negative values indicate relative decoupling.

National and Subnational Climate Policy and Implementation Data. At the national-level, we employ data from the Organisation for Economic Co-operation and Development (OECD) for national expenditure on subnational economic activities that contribute to climate change mitigation and adaptation in OECD and EU countries (50), sourced from the Subnational Government Climate Finance Database. Furthermore, data from the World Bank, sourced from the Worldwide Governance Indicators for government effectiveness ranking (51), which includes measures of policy development, implementation, and commitment, are combined with the Climate Change Performance Index (CCPI) (52).

At the subnational level, we utilize data on the existence and type of climate mitigation plans for 327 cities in the EU (53, 54). These data were then allocated to the respective subnational regions used in our analysis.

Climate Policy Analysis. We utilize several linear regression models at both the national and subnational levels to explore the effects of policies and governance on decoupling rates and their variation within the country.

The first analysis at the national-level focuses on the relationship between national expenditure on subnational climate policy and average subnational decoupling and is defined as:

$$decoupling\ \ rate\%_c = \alpha_1 exp\_subnat\_clim\_pol_c + intercept, \qquad [2]$$

where $decoupling\ \ rate\%_c$ is the average decoupling rate for country c, calculated as the average historical decoupling rate across the subnational regions of the country, and $exp\_subnat\_clim\_pol$ represents the percentage of GDP spent on subnational climate policies, using data from the year 2015. The coefficient α_1 measures the effect of a one percentage point change in the percentage of GDP spent on climate policies on the average decoupling rate. The results from this analysis are presented in *SI Appendix*, Table S3A.

The second national-level analysis explores factors influencing the variability of subnational decoupling rates within the country. Specifically, it assesses how climate efforts, as reflected in the CCPI, and policy development, implementation, and commitment, measured by the effective governance rank from the World Bank, affect these variations in decoupling rates:

$$\sigma_{decoupling\ rate\%_c} = \alpha_1 gov\_eff\_rank_c + \alpha_2 CCPI_c + intercept, \qquad [3]$$

where $\sigma_{decoupling\ rate\%_c}$ represents the SD of subnational historical decoupling rates within country c, the variable gov_eff_rank denotes the government effectiveness rank issued by the World Bank, and $CCPI$ stands for the Climate Change Performance Index. Both the government effectiveness rank and the CCPI data are for the year 2010, which serves as a mid-point within the time period of this analysis. The coefficients α_1 and α_2 measure the impact of a one-unit change in rank of government effectiveness and CCPI, respectively, on the SD of the decoupling rate. The results from this analysis are shown in *SI Appendix*, Table S3B.

To assess the effect of subnational policies, specifically the presence of a city-level climate mitigation plan within a subnational region, we define the model:

$$decoupling\ \ rate\%_r = \alpha_1 ex\_mitig\_plan_r + intercept, \qquad [4]$$

where $decoupling\ \ rate\%_r$ represents the historical decoupling rate of subnational region r, and $ex\_mitig\_plan_r$ denotes the existence of mitigation plan in a city within region r. This variable is binary, taking the value 0 if no plan exists and 1 if a plan exists, regardless of the specific type of plan. The coefficient α_1 measures the change in the decoupling rate associated with the presence of a climate mitigation plan in a city within the region. If α_1 is positive and statistically significant, it suggests that such plans are effective and are associated with improvements in decoupling outcomes. The results from this analysis are presented in *SI Appendix*, Table S4i.

Additionally, we perform a similar regression accounting for the differences between the countries:

$$decoupling\ \ rate\%_{c,r} = \alpha_1 ex\_mitig\_plan_{c,r} + \alpha_c + intercept + \varepsilon_{c,r}, \qquad [5]$$

where $decoupling\ \ rate\%_{c,r}$ the decoupling rate for region r in country c and $ex\_mitig\_plan_{c,r}$ the existence of mitigation plan in region r in country c. The coefficient α_1 quantifies the impact of the existence of a mitigation plan on the decoupling rate. The country-specific fixed effects α_c control for unique characteristics of each country. The *intercept* provides the average baseline decoupling rate across all countries when $ex\_mitig\_plan_{c,r}$ is zero, after accounting these country fixed effects. Finally, the error term $\varepsilon_{c,r}$ captures any variation that is not explained. The results from this analysis are shown in *SI Appendix*, Table S4ii.

To quantify the effect of different policy types in a city-level mitigation plan on the decoupling rate of the respective subnational region, we perform a further analysis:

$$decoupling\ rate\%_r = \alpha_1 A_{1r} + \alpha_2 A_{2r} + \alpha_3 A_{3r} + \alpha_4 B_r + \alpha_5 C_r + \alpha_6 D_r + intercept, \qquad [6]$$

where $decoupling\ \ rate\%_r$ represents the historical decoupling rate of subnational region r. The categorical variables A_{1r}, A_{2r}, A_{3r}, B_r, C_r, and D_r represent different policy types announced for cities in the respective subnational region r and are essentially dummy variables with values 0 or 1, indicating the absence or presence of the respective policy type. The coefficients (α_1 to α_6) represent the effect of each categorical variable on the respective decoupling rate. The type of local plans for A are plans dedicated to climate change mitigation, which are comprehensive and stand-alone, autonomously developed by the urban authority or administration (A_1), nationally mandated for the city (A_2), and induced by international organizations, particularly municipal climate networks (A_3) (53). The type of local plans for B and C are mainstreamed mitigation plans: horizontally integrated plans (B) that incorporate other types of municipal plans, such as sustainability plans, development/master plans, or core strategies, which include climate change aspects; and vertically integrated plans (C) that partially address climate change concerning particular sectors, such as energy supply or transport, through stand-alone documents (53). The results from this analysis are presented in *SI Appendix*, Table S5.

Multilinear Regression Models. We apply multilinear regression to estimate relations between socioeconomic factors and the calculated historical decoupling rates. This involves utilizing averages of the historical data mentioned in the previous sections, in particular per capita GRP, per capita historical cumulative CO2 emissions, and sector-specific economic output shares for agriculture, manufacturing, and services. Prior to estimation of the regression model via ordinary least-squares, we standardized the independent variables by subtracting the mean and dividing by the SD. This step was found to alleviate otherwise excessively high condition numbers. The regression model is defined as:

$$Decoupling\ rate_r = \alpha_1 pc\_GRP_r + \alpha_2 pc\_cumulative\_CO2_r + \alpha_3 agriculture\_share_r + \alpha_4 manufacturing\_share_r + \alpha_5 services\_share_r + intercep, \qquad [7]$$

where pc_GRP_r represents the normalized average per capita GRP of the region, $pc\_cumulative\_CO2_r$ denotes the normalized per capita cumulative CO2 emissions of the region, and $agriculture\_share_r$, $manufacturing\_share_r$, and $services\_share_r$ refer to the respective normalized average sector share. In this equation, the coefficients (α_1 to α_5) signify the effect of a one-SD change in the corresponding independent variable on the decoupling rate. The results from this analysis are presented in *SI Appendix*, Table S6A.

For the second analysis, to calculate the historical rate of change in emission intensity of each region, we fit a linear trend to the emission intensity data. The model applied to each region is expressed as:

$$EI_y = \alpha_1 year + intercept, \quad [8]$$

where EI_y represents the emission intensity for the given year. The coefficient α_1 reflects the estimated rate of change in emission intensity per unit change in the year, providing insight into the temporal trend. The normalized emission intensity rate is calculated then for each region by dividing coefficient α_1 by the average emission intensity of that respective region. Subsequently, we repeat the multilinear regression analysis for the normalized average emission intensity rate while excluding the sector shares. This analysis is expressed as:

$$EI\_nornalized\_rate_r = \alpha_1 pc\_GRP_r + \alpha_2 pc\_cumulative\_CO2_r + intercept. \quad [9]$$

The results from this analysis are presented in *SI Appendix*, Table S6B.

CO2 Emissions Projections/Net-Zero Timelines Calculation. Our projection methodology focuses on subnational improvements on emission intensities representing recent subnational efforts that account also for regional circumstances based on recent trends and historical relationships with income and cumulative emissions, both indicating development of the economy and therefore capacity to increase climate actions. To project the year of net-zero transition for each region, we employ two distinct approaches based on recent trends and data. Both methods focus on projecting CO2 emissions by projecting emission intensity, using different assumptions for each approach. Additionally, both methods involve projecting per capita GRP, using historical observed exponential trends from the most recent 5-y period for each region, following a methodology similar to ref. 55. The second analysis further incorporates population projections, also based on historical exponential trends from the same 5-y period. This analysis includes only regions with a minimum of 5 y worth of data with which to estimate historical trends.

The first method for projection of future emissions assumes continuity of the observed emission intensity change trend (18) of each region as observed over the last 5 y. To calculate the recent emission intensity trend, we first perform a regression similar to Eq. **8** for each region. However, we exclusively utilize data from the most recent 5 y that are available for each region. This regression coefficient α_1 is an estimation of the change of emission intensity for each passing year and is then iteratively applied for calculating future emission intensity for all years following the last year of available data. The evolution for per capita CO2 emissions then is given by the product of the calculated emission intensity and the respective per capita GRP. This process is iterated until per capita emissions become negative or the iteration reaches the year 2200.

In the second method, we assume an accelerated emission intensity rate, driven by changes in regional per capita GRP and per capita cumulative CO2 emissions. To assess the effect of per capita GRP and per capita cumulative CO2 emissions on the rate of change of emission intensity, we repeat the second regression analysis shown in Eq. **9** but only using the data of the last 5 y with available data for each region. The results of this regression are presented in *SI Appendix*, Table S7. Then, for every year, we calculate the new level of per capita CO2 emissions by updating the normalized emission intensity rate using the per capita GRP and per capita cumulative CO2 emissions predictions derived from the most recent CO2 level, per capita GRP, and population predictions. The revised normalized emission intensity rate is then transformed to unnormalized units and is used to calculate the new emission intensity value, which subsequently informs the new per capita CO2 value. We iterate this process until the level of per capita CO2 emissions is below zero or the year reaches 2200.

We conduct a robustness check for the second analysis by using population growth projections based on the Shared Socioeconomic Pathways scenarios (SSPs). Specifically, we use annual gridded global population data at a 0.5-degree resolution for the years 2016 to 2100 (56), based on the middle-of-the-road SSP scenario (57). Using the shapefiles provided by the DOSE dataset (29), we calculate the population for each subnational region for the respective years. Repeating the analysis described in the previous paragraph, we obtain results (*SI Appendix*, Fig. S3) which are highly consistent with the main analysis (Fig. 4*B*). We continue to use exponential trends for both economic and population projections as our main specification primarily due to the lack of economic projections at the subnational level.

CO2 Emissions Projections/Net-Zero Timelines Sensitivity Test. To assess uncertainty in our projections of future emissions, we conduct Monte-Carlo simulations which sample from the sources of uncertainty in both of the approaches, each with 1,000 iterations from relevant parameter values. Perturbations are applied to each parameter based on the SE of each regression coefficient used to estimate the historical trends of GRP, population, emission intensity, and the dependence of emission intensity trends on socioeconomic development, and projections of future CO2 estimated under each perturbation. For both methods, we then calculate the 5th and 95th percentiles to establish a range of uncertainty within the 90% CI, representing a very likely outcome based on the IPCC classification of likelihoods.

Data, Materials, and Software Availability. Gridded carbon emissions data are publicly available from ref. 30. National-level emissions data are available from ref. 48. Data on subnational economic output are available from ref. 29. Data on national spending for subnational climate actions in OECD countries are available from https://data-explorer.oecd.org/vis?tenant=archive&df[ds]=DisseminateArchiveDMZ&df[id]=DF_SGCFD&df[ag]=OECD&dq=....&lom=LASTNPERIODS&lo=5&to[TIME_PERIOD]=false (50). Data on the government effectiveness ranking from the World Bank are available from https://www.govindicators.org (51). CCPI data are available from ref. 52. Data on existence and type of climate mitigation plans for EU cities are available from ref. 54. Gridded global population scenarios data are publicly available from https://www.isimip.org/gettingstarted/input-data-bias-adjustment/details/62/ (56). All code necessary for reproduction of the analysis is publicly available on Zenodo at https://zenodo.org/records/13756908 (58).

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