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Reducing Trade-Offs of Net Zero Carbon Transitions Through Entrepreneurship and Coordinated Innovation: A Spatially Disaggregated Analysis Across Countries and World Regions

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ABSTRACT

Transition processes towards a sustainable future benefit from historic perspectives, since feasible changes of socio-technological conditions and processes depend on a holistic assessment of how actors are embedded in existing institutions, routines, and structures. Building on the Income–Population–Affluence–Technology equation and utilizing comprehensive panel data spanning 155 countries globally from 1996 to 2020, we provide a disaggregated assessment of rates of technological progress and innovation in support of climate neutrality and biodiversity conservation across countries and world regions and relate this to entrepreneurial activity and development of innovative technologies. Employing multinomial logit regression analysis, we analyze the possibility of negative or positive spillover effects from pursuing greenhouse gas emission reductions to other grand challenges, and how this potentially depends on entrepreneurship and innovation activities and leads to variation across countries and world regions. Our findings show that trade-offs between climate change-related CO_2 emissions and indicators for biodiversity occur that can, however, be mitigated through entrepreneurial activities, technological innovation, and related policy choices.

1 | Introduction

With the Paris Agreement of 2015 and the Global Biodiversity Framework of Kunming and Montreal of 2022 (which has seen significant development through agreements reached during the COP16 in 2024), governments have created major milestones for combating climate change (SDG 13: Climate action) and preserving biodiversity (SDG 15: Life on land). While policies tackling climate change and biodiversity crises have largely been treated independently, recent evidence underscores that these planetary crises are interconnected and must be addressed through integrated strategies (IPBES 2021).

Studies have analyzed factors driving CO_2 emission reductions, with renewable energy expansion playing a pivotal role in achieving climate neutrality, public health and enhanced energy security (Chen et al. 2023; Aneja et al. 2024). Yet, there is growing evidence in the literature that the joint assessment of CO_2 emission reductions and biodiversity conservation poses additional challenges, and that climate neutrality could partly jeopardize the conservation of biodiversity if both are not integrated well. Studies show that renewable energy technologies can have a negative impact on biodiversity (Gasparatos et al. 2017; Trainer 2010). Without discounting the significant values of renewable energy technologies in achieving climate

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neutrality, this may become particularly problematic in the future if renewable energies are increasingly expanded as a solution towards carbon neutrality. To reduce the trade-offs between combating climate change and preserving biodiversity, innovative renewable energy solutions are needed that take the impacts of biodiversity into account. An example of how these trade-offs can be reduced is the "Energyfish" from the German startup "Energyminer", which aims to make energy generation from hydropower more benign to fish. The free-floating turbine uses the flow velocity of the water, and its design and the slow-turning turbine without sharp edges ensures that fish are not harmed (Energyminer 2024).

As this example shows, countries can choose between different energy transition pathways, with the question being how trade-offs between climate change related CO_2 reduction and biodiversity conservation can be reduced or even avoided. These transition processes towards more sustainable futures can benefit from historic perspectives that help identify trajectories realized in practice and feasible impact reductions. As a part of this, we also develop a regional perspective. Specifically, we identify when and for which countries trade-offs between reduction of CO_2 emissions and indicators for biodiversity occur, and how this varies across world regions.

The transformation into a climate-neutral society and industry while simultaneously preserving biodiversity entails enormous investment and innovations. Part of this is the development of new technologies, as technological progress is seen as one solution to the planetary crises humankind is currently facing. We therefore explore what role entrepreneurship and related (national) innovation activities play in avoiding trade-offs and tensions between targets in pursuit of net-zero carbon emissions and biodiversity conservation.

This is motivated by the possibility that both young and small startups and entrants, as well as large established incumbent firms, can equally be sources of technological improvements, which have been referred to as Schumpeter Mark I and Mark II (Nelson and Winter 1985). More recently, the notion of Schumpeter Mark II has also been extended to (coordinated) networks of firms or entrepreneurial ecosystems, with national governments or related public sector actors increasingly playing a role in guiding entrepreneurial and innovation activities (Mazzucato 2013; Obobisa 2024).

To analyze the effects of entrepreneurship and related (national) innovation in avoiding trade-offs, we build on the well-established "(Environmental) Impact–Population–Affluence–Technology" (IPAT) equation (Ehrlich and Holdren 1974; Commoner 1972; Chertow 2000). In a first step, we provide a comprehensive and disaggregated assessment of historic rates of technological change in different dimensions and relate this, in a second step, to entrepreneurial activity and to the development of innovative technologies.

As outlined above, the interaction between greenhouse gas emission reductions and other ecological targets prescribed by the UN SDGs, such as preserving biodiversity, necessitates an integrated approach (Fankhauser et al. 2022). Beyond global frameworks, net zero and biodiversity policies are typically detailed and implemented by means of national policies, where potential trade-offs between carbon neutrality and biodiversity policies can arise over time. Therefore, our first research question is:

In which countries and periods have trade-offs between CO_2 emissions reduction and measures of biodiversity impact arisen and can spatial and temporal patterns be inferred?

One potential remedy to such trade-offs is entrepreneurship and innovation, which can enable novel combinations and solutions that can address both the grand challenges of reducing greenhouse gas emissions (especially CO_2) and safeguarding biodiversity simultaneously. In this respect, Jay et al. (2017) propose different levels where tensions can arise and interact, and in doing so, create heterogeneity that requires nuanced assessment. Thus, the role of entrepreneurship and innovation for trade-offs becomes clearer when the IPAT equation is considered at a more disaggregated level, that is, for countries. As part of answering this research question, we also attempt to clarify if one of these two approaches (i.e., Schumpeter Mark I or Schumpeter Mark II) is empirically dominant in the data we analyze.

Consequently, our second research question to be addressed in the remainder of this paper is:

Can individual entrepreneurship and societally more coordinated innovation activities by large incumbents, national research initiatives, or cluster activities reduce trade-offs between carbon neutrality and biodiversity protection?

Our study makes several distinct contributions to the existing literature. First, advancing the methodology applied to date, we complement the assessment of rates of technological change for CO_2 emissions with rates of technological change for biodiversity impact (BDI) as a second important environmental impact. Changes in rates of technological change concerning CO_2 and BDI can be viewed as a reflection of technological progress (or decline) in these two dimensions. Second and building on our first contribution, we specifically explore the interdependence and trade-offs between efforts to reduce CO_2 emissions and those aimed at preserving biodiversity. As a third advancement over extant literature, we calculate rates of technological change at the country level and across multiple time periods, which enables a more detailed and spatially as well as temporally disaggregated assessment than was possible to date, especially with regard to the aforementioned trade-offs and in relation to our research questions. Fourth, we relate these insights to prior work with a similar overall approach (e.g., Cumming et al. 2014) by exploring the aforementioned aspects and by analyzing how innovation and entrepreneurship can help to avoid trade-offs and tensions between environmental impacts and targets in pursuit of net-zero carbon emissions. Fifth, we advance the IPAT methodology applied to date by integrating regional aspects in the assessment and by developing a categorical outcome framework that identifies four distinct efficiency trajectories (efficient, trade-off against biodiversity, trade-off against CO_2, inefficient), which allows for more nuanced policy recommendations.

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2 | Literature Review

2.1 | Absolute Decoupling for CO_2 and Trade-Offs Against Biodiversity in the IPAT Model

The IPAT equation, first proposed by Ehrlich and Holdren (1974) and Commoner (1972), has been extensively applied to analyze environmental impacts across various contexts (Silva et al. 2021). Studies have utilized IPAT and its extensions and variants to examine especially CO_2 emissions (Li et al. 2015; Pham et al. 2020; Ofori et al. 2023). However, these studies have predominantly focused on single environmental indicators, particularly CO_2 emissions, while the interaction of multiple environmental objectives remains understudied.

More recent work has begun to extend IPAT applications to other environmental dimensions. So far, only a few studies have expanded the use of the IPAT equation beyond examining CO_2 emission impacts. For example, Yilanci et al. (2023) used the IPAT model to analyze the role of affluence and urbanization as regards sustainable forest management in China. Further studies have explored the use of IPAT for assessing impacts on species diversity, water availability, and land use change (Engström and Kolk 2024; Krishnendu and Patra 2025; Marques et al. 2019). However, comprehensive IPAT-based analyzes that simultaneously assess trade-offs between CO_2 emissions and other impacts such as biodiversity decline remain scarce, representing a significant gap that our study addresses.

Finally, the application of IPAT at disaggregated spatial scales is also an area in need of development, since only a few analyzes at more disaggregated levels exist (Silva et al. 2021) which would allow for the identification of heterogeneous patterns in technological progress across different geographical contexts. Such spatial disaggregation is, however, particularly important for understanding how institutional, economic, and social factors shape environmental outcomes in different countries and world regions, and in doing so supports targeted policy interventions.

Relative decoupling describes the increase in efficiency for economic activities. This means using fewer resources per unit of an economic good and emitting smaller amounts of emissions per unit. Yet, even if resource use or emissions per unit might decrease relatively, when more people are able to consume, as it is a goal of the UN to end poverty, absolute emissions and resource use will rise. However, in order to meet global climate goals such as the Paris Agreement, absolute decoupling is necessary. This occurs when resource consumption or the emission of CO_2 needed to maintain economic growth is reduced in absolute terms (Jackson 2009).

A way of solving this global growth problem and the associated burden for the earth is to fully decouple economic growth from the consumption of naturally limited resources and problematic emissions. To ensure that growth does not exceed ecological limits or exhaust resources, economic output must be produced sufficiently more resource-efficiently (Jackson 2009). Thus, significantly more efficient technologies and processes are needed, also in order to mitigate rebound effects that can result from entrepreneurship, innovation, and technological progress in general (Li et al. 2021).

Building on the concerns raised in the introduction, there is increasing evidence in the literature that becoming climate neutral may detrimentally impact biodiversity, in turn leading to biodiversity loss. Biodiversity loss significantly reduces essential ecosystem services (Wendling et al. 2020). To counteract this development, the Aichi Biodiversity Targets (CBD 2011) and the SDGs have been implemented (UN 2020). However, the implementation of policies aiming to achieve the goals of the Paris Agreement for combating climate change and stopping global warming, if not integrated well with said biodiversity targets and the SDGs, may lead to biodiversity loss.

Specifically, Gasparatos et al. (2017) provide evidence that several different renewable energy technologies imply negative impacts on biodiversity if such potential impacts are not sufficiently considered when defining renewable energy and net zero policies in support of carbon neutrality. Furthermore, detrimental biodiversity effects of renewable energies increase with the scale of implementation (Trainer 2010). This can be aggravated by qualitative choices. For example, Harjanne and Korhonen (2019) point out that carbon net zero plans of many cities are based on the use of biomass-based energy, with potentially detrimental impacts on biodiversity. Similarly, ecosystem service provision levels can decline through hydro-electricity projects, especially if these are carried out at large scale, such as the Three-Gorges-Dam project in China (Moriarty and Honnery 2016).

2.2 | Solving Trade-Offs With Entrepreneurship and Innovation

The role of entrepreneurship and innovation for trade-offs becomes clearer when the IPAT equation is considered at a more disaggregated level, for example, for countries. In this respect, Jay et al. (2017) propose different levels where tensions can arise and interact, and in doing so, create heterogeneity that requires nuanced assessment. Amongst these levels are organizations (or more narrowly established (incumbent) and new (entrant) firms), countries, and the global in which the other levels are embedded. Schumpeter (1934, 1943) argued that creative destruction can be the result of entrepreneurial activities by small firms, but also by large established firms or (coordinated) firm networks, which later has been referred to as Schumpeter Mark I and II. Work awarded the Nobel Prize in Economics in 2025 has developed more formal notions of these arguments and has clarified their continued applicability up to date (Aghion and Howitt 1992; Aghion et al. 2021).

There has, however, been some debate as to which of the two mechanisms is more important. Scherer (1992), based on an evaluation of all relevant studies on the influence of firm size on innovation activities, argues more in favor of entrepreneurship of smaller firms. Similarly, Henrekson et al. (2022) argue that smaller firms tend to realize more radical innovations.

Opposed to this, Hemmelskamp (1999), Aghion et al. (2005) and Fang et al. (2021) support U-shaped relationships between innovation and firm size as well as competition, which confirms Schumpeter Mark I and II. More specifically, based on data from the Mannheim Innovation Panel survey, Hemmelskamp (1999) finds that the innovation level of large

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firms with around 33,000 employees is similar to the level found for startups and entrants. This size of the large firms suggests that their innovative potential is at least partly based on coordinated actions (e.g., along the supply chain) that have also been proposed more broadly in the context of national sustainability transitions.

In this respect, particularly the role of research and development (R&D) transfer has been highlighted. Studies show that R&D that leads to new commercial opportunities available to small and medium enterprises (SMEs) can significantly reduce environmental impacts (GEM 2024a). Similarly, national systems of innovation, which encompass the interactions between firms, universities, and government research institutions, crucially build on R&D transfer (Acs et al. 2017).

Specifically, Leyden (2016) and Mazzucato (2021) advocate that national governments should take a lead in (and potentially provide large-scale funding for) key technology projects, as well as ensure wide dissemination of the innovations resulting from such nationally funded research, since technological change is now considered endogenous (Romer 1990). In summary, nationally coordinated research should thus also be able to address potential trade-offs between technological improvements along different dimensions, such as reduction of CO_2 emissions and biodiversity protection. This motivates the empirical analysis in the remainder of this paper, which aims to clarify the role of both entrepreneurship of small firms, as well as coordinated innovation in large firm networks.

3 | Methods and Data

3.1 | Theoretical Framework

We base our theoretical framework on the IPAT equation, which in formal notation is as follows:

$$I = P \times A \times T \tag{1}$$

In this equation, an environmental impact I (e.g., the global emission of a certain amount of CO_2 in tons) is the multiplicative effect of human population P (in billions of humans), affluence A (in \$GDP[1]/capita), and a corresponding technology factor T (in gCO_2/\$GDP).

As described, the IPAT equation is historically calculated at the global level. To illustrate, the equation can be populated with numbers for the case of CO_2. In 1990, global emissions of CO_2 (I) amounted to 22 billion tons. At the same time, the world population (P) was 5.3 billion people who, on average, each had an income of \$4700 (A). At the time, 860 g of CO_2 were needed to create \$1 of that income in the global mean (T). In 2007, global emissions were at 30 billion tons, the world population amounted to 6.6 billion people, the per-capita income was \$5900 on average, and 760 g of CO_2 were needed to create \$1 of income globally (Jackson 2017). The trend that emerges from these figures continues until today: while firms and countries become more efficient, environmental damage increases at the global level. This, amongst other things, reveals that absolute decoupling has not been achieved and allows a disaggregation of the drivers of this failure. Specifically, the factors for population and affluence, P and A, have declined, while the technology factor T has improved.

As derived in the introduction and literature review, the absolute decoupling challenge just illustrated for CO_2 can lead to trade-offs against biodiversity, which is insufficiently addressed in extant literature. Specifically, no study to date uses the IPAT equation to identify trade-offs between two important sustainability goals, namely CO_2 emission reduction and simultaneous biodiversity conservation. Proceeding like this thus contributes novel insights, since several studies have pointed to the need to integrate biodiversity and climate aspects in the context of IPAT (Krishnendu and Patra 2025; Marques et al. 2019) yet did not explicitly measure trade-offs. While the most comprehensive study in this respect by Engström and Kolk (2024) integrates biodiversity and climate aspects in the analysis, it only does so based on annual historic changes (which cannot address trends in technological change in a sufficiently reliable manner) and does not consider trade-offs explicitly. Hence, our analysis provides a novel contribution in the context of IPAT by explicitly addressing trade-offs and by capturing longer-term trends in technological change more reliably through averaging across longer time spans and in a spatially more disaggregated manner.

As detailed in Section 3.2 based on publicly available data sources, we initially calculate rates of technological change for CO_2 and biodiversity impacts, which ultimately result in our dependent variable with four categories ("trade-off against biodiversity", "trade-off against CO_2 reduction", and "inefficient", and "efficient"). To further enable our empirical analysis, we then in Section 3.3 identify further (independent) variables in order to implement our analysis strategy. Our empirical analysis strategy is described in detail in Section 3.4.

3.2 | Dependent Variable

A simplified way to determine technological progress can be derived from the IPAT equation. By rearranging it, technology factors can be determined in a first step:

$$T = \frac{I}{P \times A} \tag{2}$$

In our analysis, this is done for CO_2 (resulting in the factor T_{CO2}) and for BDI (resulting in the factor T_{BDI}). Hence, Equation (2) is calculated for two different technology factors, which can also be referred to as carbon efficiency and biodiversity efficiency. T_{CO2} is an assessment of the amount CO_2 emitted for \$1 of value added, and T_{BDI} is an assessment of the impact on biodiversity for \$1 of value added. High values of T_{CO2} and T_{BDI} indicate inefficient technologies, which is why the aim is to simultaneously decrease T_{CO2} and T_{BDI}. Data for CO_2 is taken from the Global Carbon Project (Global Carbon Atlas 2020), and data for GDP is taken from the United Nations database (UNCTADSTAT 2020).

As explained in the introduction, by also estimating technology factors for BDI based on the IPAT equation, a novel and important extension of the analysis is achieved, which models the possible interaction of globally crucial environmental

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TABLE 1 | Overview and definitions of variables and data sources used.

Variable	Definition	Data source
CO_2 emissions	Territorial (production-based) emissions in $MtCO_2$	Global Carbon Atlas (2020)
Gross domestic product (GDP)	Total value of all goods and services produced within a country's economic territory during an accounting period in US dollars at constant prices (2015) in millions	United Nations Database UNCTADSTAT (2020)
Biodiversity Impact (BDI)	Inverted "Biodiversity and Habitat Issue Category" (BDH)[a]	Yale Center for Environmental Law & Policy (Wendling et al. 2020)
Total early-stage entrepreneurial activity rate (TEA)	Percentage of 18–64 population who are either a nascent entrepreneur or owner-manager of a new business	Global Entrepreneurship Monitor (GEM 2024b)
Research and development transfer (RDT)	The extent to which national research and development will lead to new commercial opportunities and is available to SMEs	Global Entrepreneurship Monitor (GEM 2024b)
Surface area (SA)	Country's total area in $1000\,m^2$	World Bank (2020)
Income groups	High-income group, middle income group (corresponding to World Bank upper-middle income group), Low income (combining World Bank lower-middle and lower income groups)	Word Bank (2020)
Time periods	1996–2000, 2000–2004, 2004–2008, 2008–2012, 2012–2016, 2016–2020	
World regions	The Americas, Eastern Europe and Central Asia, East and Southeast Asia, Europe, Middle East and Northern Africa (MENA), Pacific, South Asia, Sub-Saharan Asia, and the Rest of the World	"Earth for All" project of the Club of Rome

[a]The BDH comprises seven indicators, which are weighted and defined according to Yale Center for Environmental Law & Policy as follows: 20% Biome Protection national weights (TBN): Percent of a country's biomes in terrestrial protected areas, weighted by the prevalence of different biome types within that country; 20% Biome Protection global weights (TBG): Percent of a country's biomes in terrestrial protected areas weighted by the prevalence of different biome types around the world; 20% Marine Protected Areas (MPA): Percent of a country's Economic Exclusion Zone set aside as a marine protected area; 10% Species Habitat Index (SHI): Changes in the suitable habitats of species to provide aggregate estimates of potential population losses and extinction risk increases; 10% Protected Areas Representativeness Index (PAR): Extent to which a country's protected areas are ecologically representative; 10% Species Protection Index (SPI): Protected areas in relation to species distributions; 10% Biodiversity Habitat Index (BHV): Effects of habitat loss, degradation, and fragmentation on the expected retention of terrestrial biodiversity.

impacts and the possibility of trade-offs. A suitable index that covers the targets concerning biodiversity is the "Biodiversity and Habitat Issue Category" (BDH), which is part of the "Environmental Performance Index" (EPI) provided by the Yale Center for Environmental Law & Policy (Wendling et al. 2020). The BDH comprises seven indicators, namely Biome Protection national weights, Biome Protection global weights, Marine Protected Areas, Species Habitat Index, Protected Areas Representativeness Index, Species Protection Index, and Biodiversity Habitat Index, and ranges from 0 to 100 (see Table 1 for details). While prior studies only used individual and indirect biodiversity aspects, such as species decline or land use activities, usage of the BDH allows for a more comprehensive evaluation of biodiversity impacts, which is another reason why we chose to resort to this indicator, as compared to other alternatives.

In order to achieve the same directionality for CO_2 and BDH (higher values can be understood as disadvantageous, that is, they represent a higher BDI), the BDH was inverted (i.e., BDI = 100 − BDH). This transformation does not affect the calculation of percentual change in terms of both sign and order of magnitude.

In the second step of the analysis, average annual change rates of the technology factors per period can be determined, which represent the improvement or deterioration of carbon efficiency and biodiversity efficiency. This is formally calculated as a quantified measure of technological progress if the resulting figure is negative (or decline if the result is positive):

$$\Delta T = \left(\frac{T_2}{T_1}\right)^{\frac{1}{t}} - 1 \tag{3}$$

In Equation (3), T_1 represents the efficiency at the beginning of the period, T_2 the efficiency at the end of the period, and t the number of years in the period. An improvement in carbon efficiency or biodiversity efficiency in a period (i.e., less CO_2/\$GDP or less BDI/\$GDP at the beginning vs. at the end of the period) is illustrated by negative values of ΔT_{CO2} and ΔT_{BDI} and thus represents technical progress. Conversely, declines in terms of carbon efficiency or biodiversity efficiency are reflected by positive values of ΔT_{CO2} and ΔT_{BDI}. As our time period to calculate changes in T factors, we choose 5 years in order to strike a balance between reliably gauging average technological progress while simultaneously enabling an analysis of drivers

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for its temporal evolution. We examine the periods 1996–2000, 2000–2004, 2004–2008, 2008–2012, 2012–2016, and 2016–2020, respectively.

In a third step, technological progress (or decline) in terms of carbon efficiency and biodiversity efficiency can be combined and mapped. This results in four categories: "Efficient" ($\Delta T_{CO2} < 0$ and $\Delta T_{BDI} < 0$), "trade-off against biodiversity" ($\Delta T_{CO2} < 0$ and $\Delta T_{BDI} > 0$), "trade-off against CO_2 reduction" ($\Delta T_{CO2} > 0$ and $\Delta T_{BDI} < 0$), and "inefficient" ($\Delta T_{CO2} > 0$ and $\Delta T_{BDI} > 0$). In each of the aforementioned periods, countries are assigned to one of the four categories accordingly, which results in our dependent variable.

For the four categories the explicit definitions corresponding to the above formal notions are as follows: "Efficient" means that a country has achieved technological progress for CO_2 emissions and biodiversity impact in the respective period, representing the ideal of complementary improvements. "Trade-off against biodiversity" means that a country has achieved technological progress for CO_2 emissions but not for biodiversity impact, suggesting that climate mitigation efforts may be occurring at the expense of biodiversity conservation. "Trade-off against CO_2 reduction" means that a country has achieved technological progress for biodiversity impact, but not for CO_2 emissions. "Inefficient" is finally defined as the case where a country has not achieved technological progress in both CO_2 reduction and biodiversity impact. Such a country has worsened in both dimensions, representing the least desirable outcome.

3.3 | Independent Variables and Sample

The explanatory variables are calculated as an average value per period. The variables "total early-stage entrepreneurial activity rate" (TEA) and "R&D transfer" (RDT) are taken from the Global Entrepreneurship Monitor, where TEA is defined as the "percentage of 18–64 population who are either a nascent entrepreneur or owner–manager of a new business" (GEM 2024b) and RDT as "the extent to which national research and development will lead to new commercial opportunities and is available to SMEs" (GEM 2024b).

Furthermore, since large countries potentially show less trade-offs between biodiversity conservation and renewable energy expansion, as one important strategy to combat climate change (e.g., to a lesser degree in land use competition), we take data from the World Bank (2020) to control for surface area, which we measure in $1000\,m^2$. Due to the skewness of the data, we use the logarithm of this value as our variable SA. To account for income and development differences, countries are grouped into high-, middle-, and low-income groups based on how countries are categorized by the World Bank (2020). To test for regional geographical differences, we also control for world regions based on the Earth for All project of the Club of Rome, namely the Americas, Eastern Europe and Central Asia, East and Southeast Asia, Europe, Middle East and Northern Africa (MENA), Pacific, South Asia, Sub-Saharan Africa, and the Rest of the World.[2] Further, to control for temporal effects, we incorporate dummy variables for the six time periods considered in our analysis, namely 1996–2000, 2000–2004, 2004–2008, 2008–2012, 2012–2016, and 2016–2020. Table 1 summarizes all variables, definitions and data sources.

Merging all data results in 155 countries worldwide and a panel of 930 country-period observations for the descriptive analysis, which is the regionally most comprehensive dataset we could generate. After excluding observations with missing GEM (Global Entrepreneurship Monitor) data we arrive at a panel of 424 country-period observations that can be included in our regression analysis, which again represents the most comprehensive regional coverage to base inference on. Involving panel data in our analysis also enables us to control for time-invariant country-specific factors while capturing temporal dynamics in core relationships under study.

3.4 | Analysis Strategy

We initially provide a descriptive evaluation of the temporal and spatial patterns of our dependent variable, indicating in which periods countries had to cope with trade-offs or not between CO_2 reduction and simultaneous biodiversity conservation. In a second step, we perform multinomial logit regression analysis which is able to test the predictors for the country-level outcome categories "trade-off against biodiversity", "trade-off against CO_2 reduction", and "inefficient", with the category "efficient" being used as the omitted reference category.

Our approach differs from a STIRPAT (Stochastic Impacts by Regression on Population, Affluence, and Technology) framework which is frequently used when examining factors influencing environmental impacts (Li et al. 2015; Pham et al. 2020; Ofori et al. 2023). Unlike STIRPAT models that typically focus on singular environmental indicators (e.g., CO_2 emissions), our approach focuses on the simultaneous analysis of CO_2 emissions and biodiversity impacts and in doing so offers important advancements for environmental impact modeling. This methodological shift addresses a limitation in current models that insufficiently account for co-benefits or harms of other environmental aspects when evaluating CO_2 emissions. Integrating climate and biodiversity issues in this manner also responds to recent calls for models that further operationalize the climate–biodiversity nexus to achieve synergistic climate–biodiversity action (IPBES 2021).

Prior to the analysis, Table 2 shows the descriptive statistics and correlations of all our variables for the multivariate regression analysis sample. Furthermore, all variance inflation factors (VIFs) are below 3.5, as becomes clear from Table 3. This suggests that multicollinearity is not an issue for our analysis and that it is therefore feasible to proceed as indicated.

4 | Results

The four categories introduced earlier (namely "trade-off against biodiversity", "trade-off against CO_2 reduction", "inefficient", and "efficient") can be illustrated in a basic matrix for each time period, which is identically applied in Figures 1–3. It describes

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TABLE 2 | Descriptive statistics and correlations.

Variables	Obs.	Mean	Std. Dev.	Min	Max	(1)	(2)	(3)	(4)	(5)	(6)	(7)
(1) TEA	424	13.175	8.639	2.257	45.22	1						
(2) R&D transfer	424	3.957	0.741	2.38	6.55	−0.476***	1					
(3) Income group high	424	0.505	0.501	0	1	−0.511***	0.522***	1				
(4) Income group middle	424	0.316	0.465	0	1	0.155***	−0.284***	−0.686***	1			
(5) Income group low	424	0.179	0.384	0	1	0.478***	−0.336***	−0.472***	−0.318***	1		
(6) SA (log)	424	5.532	1.985	−0.844	9.747	0.116**	−0.032	−0.308***	0.232***	0.120**	1	
(7) Period 1996–2000	424	0.094	0.293	0	1	−0.081*	0.320***	0.126***	−0.046	−0.109**	0.042	1
(8) Period 2000–2004	424	0.132	0.339	0	1	−0.082*	0.029	0.052	0.020	−0.091*	0.047	−0.126***
(9) Period 2004–2008	424	0.184	0.388	0	1	−0.015	−0.049	−0.017	−0.009	0.032	0.015	−0.153***
(10) Period 2008–2012	424	0.212	0.409	0	1	0.026	−0.109**	−0.063	0.007	0.073	−0.038	−0.168***
(11) Period 2012–2016	424	0.215	0.411	0	1	0.081*	−0.099**	−0.057	0.003	0.070	−0.045	−0.169***
(12) Period 2016–2020	424	0.163	0.37	0	1	0.037	0.003	0.002	0.016	−0.023	0.000	−0.142***
(13) Americas	424	0.222	0.416	0	1	0.322***	−0.271***	−0.232***	0.358***	−0.131***	0.059	−0.017
(14) Eastern Europe and Central Asia	424	0.083	0.276	0	1	−0.189***	−0.175***	−0.200***	0.331***	−0.140***	0.024	−0.067
(15) East and Southeast Asia	424	0.068	0.253	0	1	0.030	0.117**	−0.180***	0.157***	0.044	−0.003	0.008
(16) Europe	424	0.307	0.462	0	1	−0.472***	0.442***	0.659***	−0.452***	−0.311***	−0.264***	0.118**
(17) MENA	424	0.108	0.311	0	1	−0.070	−0.060	−0.109**	0.040	0.094*	−0.012	−0.087*
(18) Pacific	424	0.064	0.244	0	1	−0.089*	0.145***	0.258***	−0.177***	−0.122**	0.193***	0.081*
(19) Rest of the World	424	0.007	0.084	0	1	−0.022	−0.020	0.084*	−0.057	−0.039	−0.141***	−0.027
(20) South Asia	424	0.028	0.166	0	1	−0.048	0.076	−0.172***	−0.116**	0.365***	0.136***	−0.006
(21) Sub-Saharan Africa	424	0.113	0.317	0	1	0.573***	−0.316***	−0.361***	−0.051	0.532***	0.117**	−0.064

Variables	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)	(19)	(22)	(21)
(1) TEA														
(2) R&D transfer														
(3) Income group high														
(4) Income group middle														

(Continues)

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TABLE 2 | (Continued)

Variables	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)	(19)	(22)	(21)
(5) Income group low														
(6) SA (log)														
(7) Period 1996–2000														
(8) Period 2000–2004	1													
(9) Period 2004–2008	−0.185***	1												
(10) Period 2008–2012	−0.202***	−0.246***	1											
(11) Period 2012–2016	−0.204***	−0.248***	−0.271***	1										
(12) Period 2016–2020	−0.172***	−0.209***	−0.229***	−0.230***	1									
(13) Americas	0.010	0.025	0.015	−0.016	−0.020	1								
(14) Eastern Europe and Central Asia	0.010	−0.032	−0.009	0.031	0.053	−0.160***	1							
(15) East and Southeast Asia	0.032	−0.008	−0.004	−0.005	−0.018	−0.145***	−0.081*	1						
(16) Europe	0.058	−0.012	−0.045	−0.061	−0.016	−0.355***	−0.199***	−0.180***	1					
(17) MENA	−0.046	−0.009	0.023	0.039	0.052	−0.186***	−0.105**	−0.095*	−0.232***	1				
(18) Pacific	0.041	0.001	−0.041	−0.042	−0.010	−0.139***	−0.078*	−0.071	−0.173***	−0.091*	1			
(19) Rest of the World	−0.033	−0.040	0.025	0.024	0.039	−0.045	−0.025	−0.023	−0.056	−0.029	−0.022	1		
(20) South Asia	−0.025	0.029	0.016	−0.020	0.002	−0.091*	−0.051	−0.046	−0.113**	−0.060	−0.045	−0.014	1	
(21) Sub-Saharan Africa	−0.095**	0.022	0.051	0.085*	−0.037	−0.191***	−0.107**	−0.097**	−0.238***	−0.125**	−0.093*	−0.030	−0.061	1

Note: Significance levels: *$p < 0.1$, **$p < 0.05$, ***$p < 0.01$.

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TABLE 3 | Variance inflation factors for independent variables included in the regression analysis.

Variable	VIF
TEA	2.72
R&D transfer	2.00
High income group	3.39
Low income group	2.35
SA (log)	1.29
2000–2004	2.23
2004–2008	2.66
2008–2012	2.90
2012–2016	2.90
2016–2020	2.48
Americas	2.90
Eastern Europe and Central Asia	1.69
East and Southeast Asia	1.87
MENA	1.72
Pacific	1.26
Rest of World	1.04
South Asia	1.68
Sub-Saharan Africa	3.44

the relationship between technological progress (or decline) for carbon efficiency and biodiversity efficiency based on the average annual change rates of carbon efficiency (ΔT_{CO2}, *X*-axis) and biodiversity efficiency (ΔT_{BDI}, *Y*-axis) at the country level for the six time periods under study.

Figures 1–3 present the data as six separate panels, one for each 5-year period (1996–2000, 2000–2004, 2004–2008, 2008–2012, 2012–2016, 2016–2020). Each panel is divided into four quadrants corresponding to the four categories of the dependent variable, with the same category always relating to the same quadrant. Countries are marked with different symbols and colors representing different world regions (namely 9 and 5, respectively, in Figures 1 and 2) or income groups (in Figure 3). This structure follows the approach of Cumming et al. (2014) and allows for clear visualization of how countries' positions evolve over time and how patterns differ across world regions and income groups.

As can be seen from Figures 1–3, the analysis reveals a nuanced picture indicating that some countries actually achieved technological progress with regard to carbon efficiency (even to the degree that they are trending towards becoming fully carbon neutral), biodiversity efficiency, or both, whereas other countries struggle in this respect. This provides evidence that trade-offs are not only possible but quite prevalent in the data.

Countries achieving technological progress in terms of carbon efficiency and biodiversity efficiency are assigned to the "efficient" category of our dependent variable and are accordingly always located in the lower left quadrant of the panels in Figures 1–3. Countries that have worsened in both factors are located in the upper right quadrant of all panels, that is, they are assigned to the "inefficient" category. All countries that were able to improve at least one environmental consumption factor—either technological progress in terms of carbon efficiency or in terms of biodiversity efficiency—are, in all panels, located in the upper left quadrant ("trade-off against biodiversity") or the lower right quadrant ("trade-off against CO_2 reduction"), respectively.

To illustrate the temporal and regional distribution and development, Table 4 provides a more disaggregated analysis by assigning countries to their respective world regions based on the most detailed classification applied in Figure 1. Analyzing the results presented in Table 4, it can be seen, that in the periods from 1996 to 2008, it was mainly countries in Latin America (Americas region) or Sub-Saharan Africa that had to grapple with trade-offs, that is, in particular carbon efficiency deteriorated in these countries during said time periods. This can be attributed to the sharp rise in CO_2 emissions in these countries resulting from development processes. With the adoption of binding CO_2 reduction targets in the Kyoto Protocol (starting with the period 2008–2012) and the Paris Climate Agreement (starting with the period 2016–2020), increasingly more countries are found in the "trade-off against biodiversity" and "inefficient" categories. This is especially the case for middle- and low-income countries, but also for some high income countries like those in Europe. One possible explanation for this pattern may be the strong expansion of renewable energies, which, as mentioned in the literature review, also can have a negative impact on biodiversity.

Having identified which countries had to cope with trade-offs in which periods, the next step in the analysis is to examine the association between entrepreneurial and other (especially nationally coordinated or supported) innovation activities and the likelihood of avoiding trade-offs. As hypothesized above, entrepreneurship and innovation can be important determinants of the heterogeneity identified at the country level and shall therefore be analyzed in more depth in the following. Table 5 shows the main results of the multinomial logit regression analysis, which indicate the relationship between entrepreneurial activities and the trade-offs in CO_2 reduction and biodiversity conservation. Specifically, we examine the role of entrepreneurial activities of mainly smaller firms (as measured by TEA), and the role of coordinated actions for national innovation transfers that typically involve larger firms (as measured by RDT).

We acknowledge that some regression coefficients for period and regional dummy variables are somewhat large. This pattern is indicative of certain periods or world regions having few or no observations in particular outcome categories, leading to larger parameter estimates. To address concerns about the robustness of our findings in this respect, we conducted several sensitivity checks. Firstly, we re-estimated the model collapsing adjacent time periods as summarized in Table 6. Secondly, we involved broader regional categories and combined these with collapsed adjacent time periods, as summarized in Tables 7 and 8.

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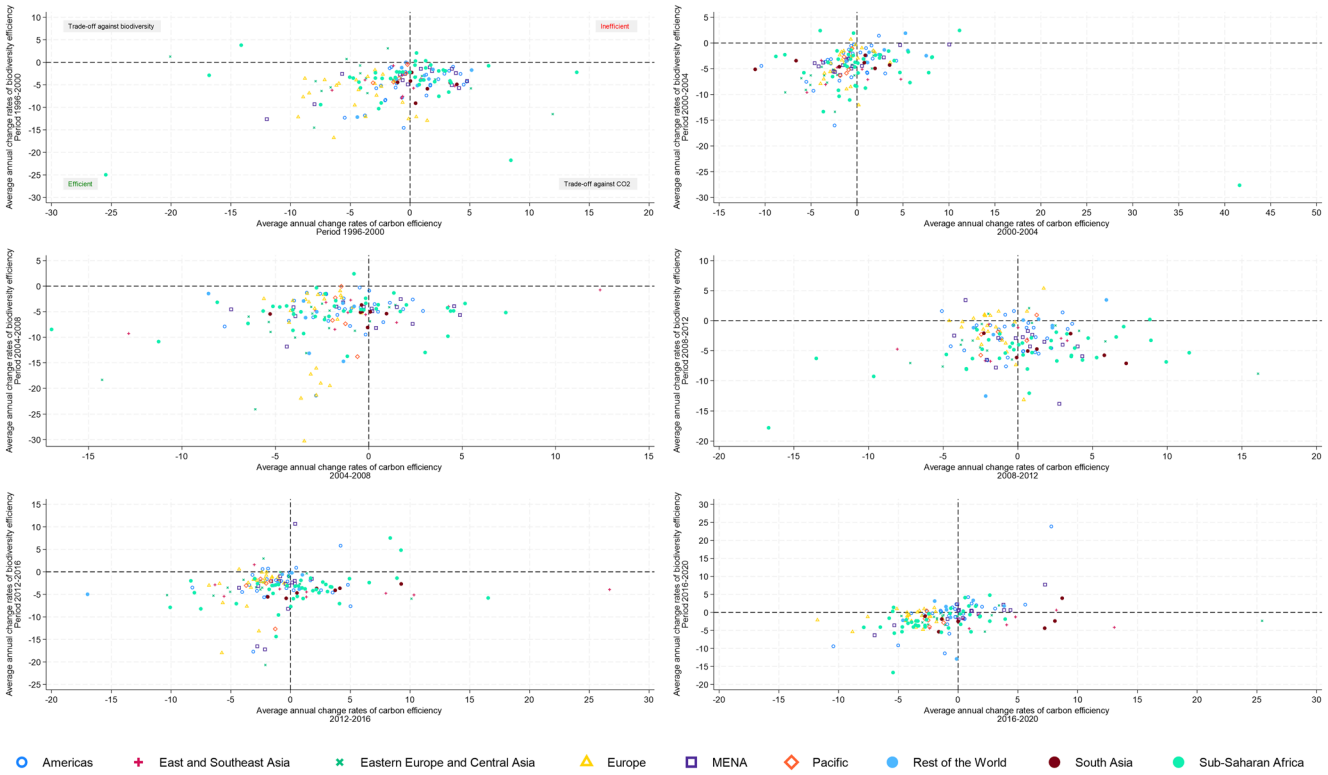


FIGURE 1 | Relationship between technological progress in terms of carbon efficiency and biodiversity efficiency (based on nine world regions).

Thirdly, for all estimations reported, we also involved the algorithmized surface area of the countries to further gauge sensitivity (results available upon request from the authors). All these robustness checks ascertained that our main results for TEA and RDT remain stable across these alternative specifications. The relationships under study therefore remain consistent across specifications, with the minor exception that the effect of RDT on the category "trade-off against CO_2 reduction" did not remain significant in all of the estimation variants. However, this effect was already only weakly significant in our initial model reported in Table 5. Given it remained so in some of the robustness checks and sensitivity analyzes we implemented and because the model in Table 5 has the highest R^2 value, we still include it in the interpretation for the remainder of the paper. Looking more closely at TEA reveals that the probability that a country falls into the category "trade-off against biodiversity" is negatively associated with TEA (−0.133; $p < 0.05$; relative risk ratio (RRR) = 0.875). In other words, higher levels of TEA are associated with a higher likelihood that a country falls into the reference group "efficient". Thus, increased entrepreneurial activities of small firms are associated with a reduced likelihood of trade-off between CO_2 reduction and biodiversity conservation.

Furthermore, higher levels of RDT are associated with a reduced probability that a country falls into the category "trade-off against biodiversity" (−1.498; $p < 0.01$; RRR = 0.223), the category "trade-off against CO_2 reduction" (−0,461; $p < 0.1$; RRR = 0.63) or the "inefficient" category, respectively (−1.969; $p < 0.05$; RRR = 0.140). In other words, higher levels of RDT are associated with the reference group "efficient" becoming more probable. Thus, increased national research and development activities as a basis for new commercial opportunities is associated with reduced trade-offs against biodiversity, trade-offs against CO_2 reduction and with reduced combined inefficiency in terms of CO_2 reduction and biodiversity conservation. Our analysis therefore shows that both entrepreneurial activities of small firms as well as national research activities are associated with lower likelihoods of trade-offs between CO_2 reduction and biodiversity conservation.

The question of whether entrepreneurial activities of small firms or national research and development transfers have a stronger association with avoiding trade-offs can be addressed by comparing the marginal effects of TEA and RDT, which are shown in Table 9. A comparison of the marginal effects of an increase of one unit of TEA with that of one unit of RDT shows that the marginal effects of RDT are around 10 times higher than those of TEA. This suggests that nationally coordinated innovation programs that involve larger firms have a stronger association with reduced trade-offs between CO_2 reduction and biodiversity conservation.

5 | Discussion

In this study, we assess the interaction of greenhouse gas emission reductions with other ecological targets prescribed by the UN SDGs, as exemplified for the case of biodiversity. Utilizing biodiversity conservation as another crucial ecological target, next to carbon neutrality and corresponding net zero CO_2(-equivalent) objectives, we evaluate the extent of complementary or substitutive effects between these two targets to expand on extant literature (Kanemoto et al. 2016), and clarify to what degree these can be influenced by means of entrepreneurship and innovation by answering two research questions derived from the literature. Our finding that trade-offs between climate and

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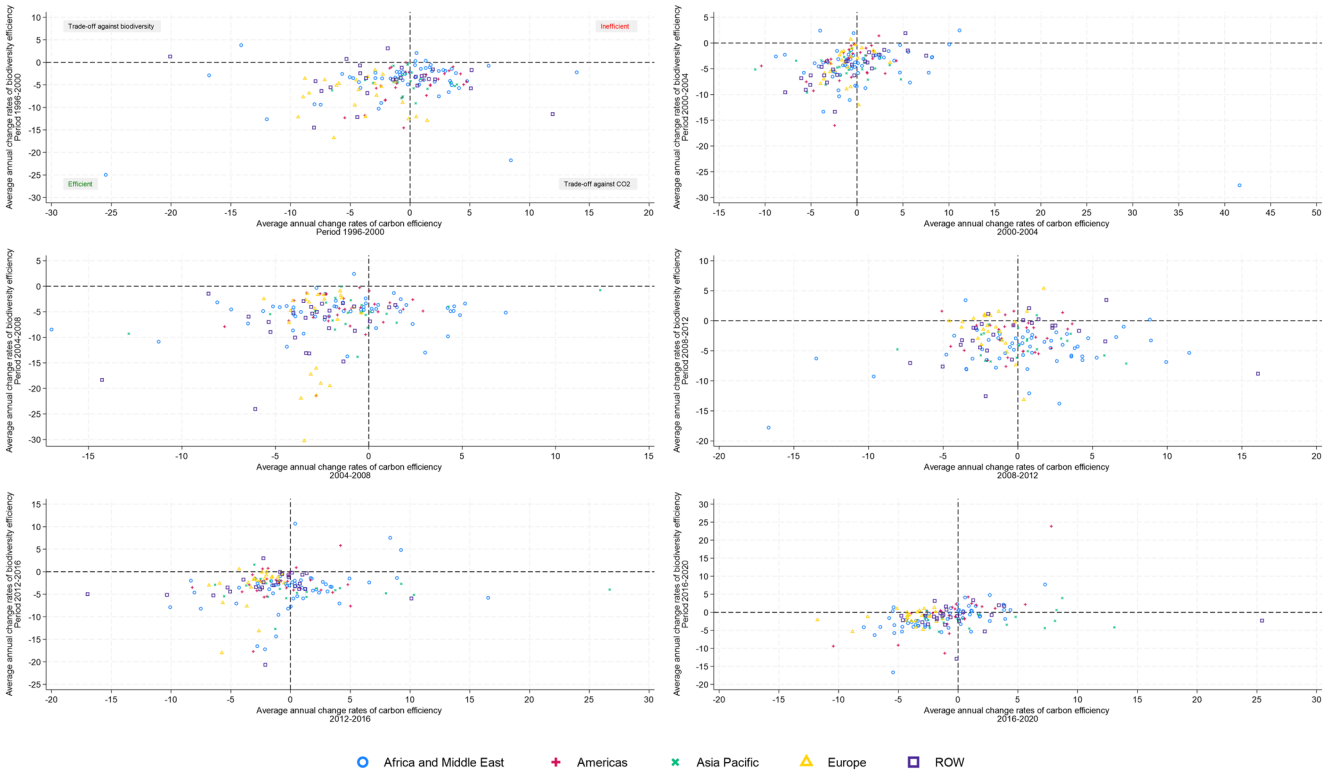


FIGURE 2 | Relationship between technological progress in terms of carbon efficiency and biodiversity efficiency (based on five world regions).

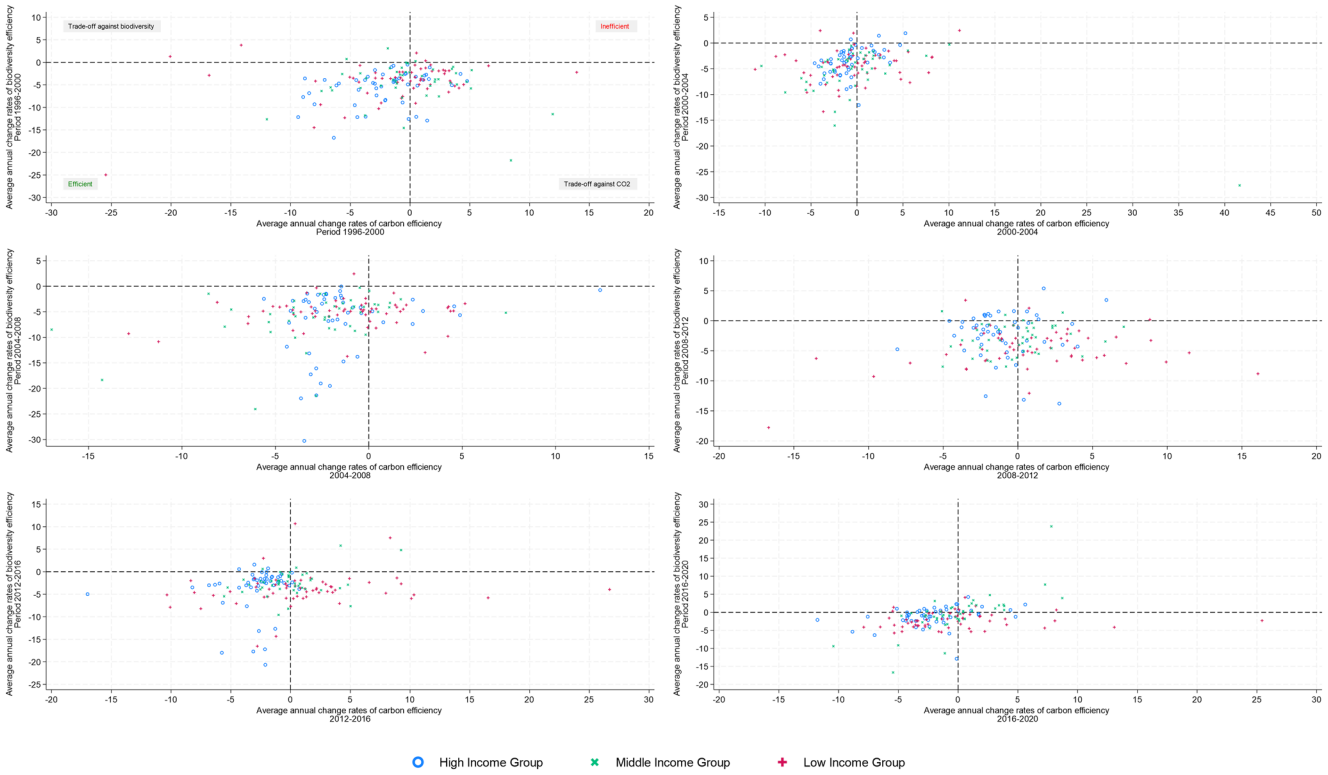


FIGURE 3 | Relationship between technological progress in terms of carbon efficiency and biodiversity efficiency (based on three income groups).

biodiversity objectives are prevalent aligns well with existing literature. Specifically, negative biodiversity impacts of renewable energy technologies have been found at larger scales of implementation (Gasparatos et al. 2017; Trainer 2010) and after the adoption of the Kyoto Protocol and Paris Agreement (Rehbein et al. 2020). Our spatially and temporally disaggregated analysis extends these works by generalizing these trade-offs at the national level across 155 countries over 24 years, and by revealing

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TABLE 4 | Trade-offs by period and world region.

	Trade-off against biodiversity	Trade-off against CO_2 reduction	Efficient	Inefficient	Total
Period 1996–2000	4	59	89	3	155
	2.58%	38.06%	57.42%	1.94%	
Americas	0	12	16	0	
Eastern Europe and Central Asia	3	5	10	0	
East and Southeast Asia	0	3	7	0	
Europe	0	2	22	0	
MENA	0	8	7	0	
Pacific	0	0	5	0	
Rest of the World	0	5	3	0	
South Asia	0	6	1	0	
Sub-Saharan Africa	1	18	18	3	
Period 2000–2004	3	54	95	3	155
	1.94%	34.84%	61.29%	1.94%	
Americas	0	10	17	1	
Eastern Europe and Central Asia	0	3	15	0	
East and Southeast Asia	0	5	5	0	
Europe	1	6	17	0	
MENA	0	4	11	0	
Pacific	0	0	5	0	
Rest of the World	0	6	1	1	
South Asia	0	4	3	0	
Sub-Saharan Africa	2	16	21	1	
Period 2004–2008	1	36	118	0	155
	0.65%	23.23%	76.13%	0.00%	
Americas	0	8	20	0	
Eastern Europe and Central Asia	0	3	15	0	
East and Southeast Asia	0	3	7	0	
Europe	0	0	24	0	
MENA	0	8	7	0	
Pacific	0	0	5	0	
Rest of the World	0	0	8	0	
South Asia	0	2	5	0	
Sub-Saharan Africa	1	12	27	0	
Period 2008–2012	11	63	72	9	155
	7.10%	40.65%	46.45%	5.81%	

(Continues)

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TABLE 4 | (Continued)

	Trade-off against biodiversity	Trade-off against CO_2 reduction	Efficient	Inefficient	Total
Americas	3	12	12	1	
Eastern Europe and Central Asia	1	5	11	1	
East and Southeast Asia	0	5	5	0	
Europe	6	1	15	2	
MENA	1	9	5	0	
Pacific	0	1	3	1	
Rest of the World	0	2	3	3	
South Asia	0	5	2	0	
Sub-Saharan Africa	0	23	16	1	
Period 2012–2016	5	52	93	5	155
	3.23%	33.55%	60.00%	3.23%	
Americas	2	7	17	2	
Eastern Europe and Central Asia	1	4	13	0	
East and Southeast Asia	1	5	4	0	
Europe	1	0	23	0	
MENA	0	4	10	1	
Pacific	0	0	5	0	
Rest of the World	0	4	4	0	
South Asia	0	5	2	0	
Sub-Saharan Africa	0	23	15	2	
Period 2016–2020	21	26	82	26	155
	13.55%	16.77%	52.90%	16.77%	
Americas	7	3	11	7	
Eastern Europe and Central Asia	0	4	12	2	
East and Southeast Asia	0	6	3	1	
Europe	6	0	18	0	
MENA	1	3	3	8	
Pacific	1	0	4	0	
Rest of the World	3	0	3	2	
South Asia	0	2	4	1	
Sub-Saharan Africa	3	8	24	5	
Total	45	290	549	46	930

heterogeneity at the climate–biodiversity nexus, with some countries successfully improving both carbon and biodiversity efficiency. Importantly, we can relate this heterogeneity to innovation capabilities in terms of entrepreneurship and R&D transfer.

Our findings on the role of entrepreneurship (i.e., Schumpeter Mark I) align with and extend research on sustainable entrepreneurship that documented how entrepreneurial ecosystems can support environmental goals based on qualitative case studies (Tiba et al. 2020) as well as quantitative

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TABLE 5 | Multinomial logistic regression analysis.

	"Trade-off against biodiversity" versus "efficient"			"Trade-off against CO_2 reduction" versus "efficient"			"Inefficient" versus "efficient"		
	Coefficient	**Std. error**	***p*>|z|**	**Coefficient**	**Std. error**	***p*>|z|**	**Coefficient**	**Std. error**	***p*>|z|**
TEA	−0.133	0.054	**	−0.012	0.022		−0.039	0.069	
R&D transfer	−1.498	0.571	***	−0.461	0.277	*	−1.969	0.786	**
Income group (reference category: middle)									
High	1.072	0.809		−0.237	0.458		1.316	0.940	
Low	0.355	1.044		0.024	0.441		−18.052	2547.332	
SA (log)	−0.215	0.133		−0.012	0.075		−0.094	0.168	
Period (reference category: 1996–2000)									
2000–2004	15.731	3111.302		−0.190	0.575		16.170	3685.925	
2004–2008	−0.550	3852.157		−0.999	0.567	*	−0.203	4357.910	
2008–2012	18.176	3111.302		0.130	0.532		17.049	3685.925	
2012–2016	16.500	3111.302		−0.466	0.537		15.214	3685.925	
2016–2020	19.220	3111.302		−1.321	0.650	**	18.531	3685.925	
World regions (reference category: Europe)									
Americas	1.323	0.882		1.298	0.589	**	1.412	1.291	
Eastern Europe and Central Asia	−2.173	1.296	*	0.757	0.689		−16.701	3105.281	
East and Southeast Asia	−15.906	3503.192		1.309	0.684	*	−13.897	3564.251	
MENA	−0.465	1.041		1.857	0.592	**	2.645	1.054	**
Pacific	−0.484	1.150		−0.660	1.105		1.012	1.367	
Rest of World	−19.317	12,076.090		1.639	1.363		−17.610	13,620.220	
South Asia	−17.265	4834.924		1.683	1.363	*	2.564	6445.484	
Sub-Saharan Africa	0.466	1.579		1.433	0.741	*	2.708	1.755	
Constant	−12.145	3111.302		0.006	1.447		−1.838	3685.926	

Note: Significance levels: *$p<0.1$, **$p<0.05$, ***$p<0.01$; observations = 424; LR $\chi^2(54) = 189.37$***; pseudo $R^2 = 0.255$; log likelihood = −276.812.

meso-level data (Leendertse and van Rijnsoever 2025). Our contribution lies in demonstrating that these effects extend to macro-level environmental outcomes measured by means of aggregate metrics.

The stronger associations we observe for R&D transfer (see Table 9) compared to entrepreneurial activity align with arguments by Mazzucato (2013, 2021) and Leyden (2016) regarding the importance of coordinated, large-scale innovation efforts (i.e., Schumpeter Mark II) for addressing complex sustainability challenges. This extends the debate between Schumpeter Mark I and Mark II by showing that coordinated innovation may be more effective than individual entrepreneurship when addressing complex, multi-faceted environmental challenges.

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TABLE 6 | Sensitivity analysis with nine world regions and three periods.

	"Trade-off against biodiversity" versus "efficient"			"Trade-off against CO_2 reduction" versus "efficient"			"Inefficient" versus "efficient"		
	Coefficient	Std. error	$p>\|z\|$	Coefficient	Std. error	$p>\|z\|$	Coefficient	Std. error	$p>\|z\|$
TEA	−0.089	0.048	*	0.013	0.022		0.003	0.056	
R&D transfer	−0.896	0.487	*	−0.454	0.271	*	−1.251	0.671	*
Income group (reference category: middle)									
High	0.582	0.738		−0.236	0.452		0.836	0.831	
Low	0.470	0.918		0.034	0.433		−16.059	1008.719	
SA (log)	−0.151	0.117		−0.015	0.0743		−0.036	0.151	
Period (reference category: 1996–2000)									
2004–20,012	1.838	1.073	*	−0.261	0.348		0.426	1.196	
2012–2020	2.602	1.068	**	−0.609	0.367	*	1.541	1.112	
World regions (reference category: Europe)									
Americas	0.846	1.073		1.263	0.582	**	1.022	1.183	
Eastern Europe and Central Asia	−14.285	1168.537		1.304	0.678	*	−12.620	1436.021	
East and Southeast Asia	−1.629	1.226		0.761	0.678		−14.281	1291.128	
MENA	−0.559	0.966		1.861	0.584	***	2.462	0.983	**
Pacific	−0.560	1.103		−0.657	1.101		0.840	1.318	
Rest of World	−16.300	4153.415		1.757	1.312		−15.232	5827.747	
South Asia	−14.804	1803.42		1.629	0.914	*	2.707	2870.625	
Sub-Saharan Africa	−0.326	1.484		1.456	0.727	**	1.972	1.580	
Constant	0.630	2.273		−0.120	1.316		−0.156	3.068	

Note: Significance levels: $*p<0.1$, $**p<0.05$, $***_p<0.01$; observations = 424; LR $\chi^2(54)=125.29$***; pseudo $R^2=0.167$; log likelihood = −308.853.

However, our results also indicate that both mechanisms can be complementary, since the significant association of TEA with reduced trade-offs, even after controlling for RDT, suggests that small-firm entrepreneurship contributes unique capabilities that complement larger-scale coordinated efforts. This aligns with the U-shaped relationship between firm size and innovation supported in extant literature (Hemmelskamp 1999; Aghion et al. 2005; Fang et al. 2021), which suggests that both small and large firms contribute to reducing trade-offs between environmental objectives.

6 | Conclusions and Policy Implications

Our study addresses associations between entrepreneurship, innovation activities, and the likelihood of countries avoiding trade-offs between CO_2 emissions reduction and biodiversity conservation. These results contribute to and extend the existing body of knowledge. Specifically, our analysis shows the possibility of negative spillover effects from pursuing greenhouse gas emission reductions, but also finds empirical evidence that these are reduced by entrepreneurship and (more pronounced) larger-scale innovation activities, even after controlling for important institutional and structural conditions and determinants at the national and regional levels.

Our findings also reveal the need for comprehensive but spatially differentiated analyzes of sustainability transitions to account for the role of entrepreneurship for economic development and structural change across countries and world regions.

Finally, our extension of the IPAT framework to incorporate biodiversity alongside CO_2 emissions represents an important methodological contribution. While previous applications of IPAT and STIRPAT have predominantly focused on single environmental indicators (Li et al. 2015; Pham et al. 2020; Ofori et al. 2023), our approach demonstrates the value of simultaneously considering multiple environmental dimensions.

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TABLE 7 | Sensitivity analysis with five world regions and six periods.

	"Trade-off against biodiversity" versus "efficient"			"Trade-off against CO_2 reduction" versus "efficient"			"Inefficient" versus "efficient"		
	Coefficient	**Std. error**	***p*>|*z*|**	**Coefficient**	**Std. error**	***p*>|*z*|**	**Coefficient**	**Std. error**	***p*>|*z*|**
TEA	−0.122	0.051	**	−0.002	0.019		−0.040	0.685	
R&D transfer	−1.528	0.560	***	−0.344	0.268		−2.003	0.773	**
Income group (reference category: middle)									
High	1.036	0.762		−0.597	0.408		1.368	0.867	
Low	0.170	0.994		0.177	0.402		−17.200	1701.681	
SA (log)	−0.198	0.128		−0.050	0.072		−0.089	0.162	
Period (reference category: 1996–2000)									
2000–2004	15.008	2228.588		−0.114	0.561		15.504	2723.88	
2004–2008	−0.579	2754.357		−0.923	0.557	*	−0.431	3291.84	
2008–2012	17.446	2228.587		0.221	0.525		16.365	2723.88	
2012–2016	15.769	2228.587		−0.375	0.525		14.480	2723.88	
2016–2020	18.446	2228.587		−1.199	0.640	*	17.867	2723.88	
World regions (reference category: Europe)									
Africa and Middle East	−2.673	0.924		1.481	0.570	***	2.627	1.0355	**
Americas	1.218	0.834		1.261	0.567	**	1.441	1.266	
Asia Pacific	−1.215	1.621		0.830	0.547		0.801	1.350	
Rest of World	−2.397	1.236	*	0.664	0.658		−16.196	2242.505	
Constant	−11.394	2228.588		0.039	1.426		−12.100	2723.881	

Note: Significance levels: *$p<0.1$, **$p<0.05$, ***$p<0.01$; observations = 424; LR $\chi^2(54) = 180.65$***; pseudo $R^2 = 0.243$; log likelihood = −281.173.

Our insights also contribute to deriving quantitative evidence to support policy in designing transition pathways for halting climate change while not jeopardizing biodiversity. In terms of specific recommendations, our results underscore the importance of integrating multiple sustainability dimensions in policy programs. Specifically, national policy measures should incentivize startups to address multiple environmental dimensions in their innovation activities. This would also imply linking conventional entrepreneurship policies more to environmental conditions, for example in relation to environmentally oriented public procurement or other regulation incentivizing innovation. Furthermore, specific policy measures for research cooperation are needed to further support such simultaneous environmental conditioning. This especially holds in the context of university–industry partnerships and with regard to technology transfer offices (Wagner et al. 2021), but also beyond individual countries in the context of global technology transfer (Audretsch et al. 2014).

Finally, to balance Schumpeter Mark I and Mark II mechanisms, concerted actions linking startups with large firms, coordinated networks, and government-supported R&D in the context of so-called mission-oriented innovation policy (Mazzucato 2021; Leyden 2016) may be particularly important for avoiding trade-offs between multiple environmental objectives.

As concerns limitations and future research, a number of aspects merit further exploration. Specifically, we could not address in greater detail policy variations and their role for avoiding trade-offs. In this respect, one important question for future research would be what specific configurations of national systems of innovation (Freeman 1987; Acs et al. 2017) are best suited to

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TABLE 8 | Sensitivity analysis with five world regions and three periods.

	"Trade-off against biodiversity" versus "efficient"			"Trade-off against CO_2 reduction" versus "efficient"			"Inefficient" versus "efficient"		
	Coefficient	**Std. error**	$p>\|z\|$	**Coefficient**	**Std. error**	$p>\|z\|$	**Coefficient**	**Std. error**	$p>\|z\|$
TEA	−0.0886	0.0447	**	−0.003	0.0183		−0.002	0.055	
R&D transfer	−0.951	0.481	**	−0.341	0.260		−1.265	0.669	*
Income group (reference category: middle)									
High	0.621	0.700		−0.589	0.403		0.969	0.767	
Low	0.3669	0.888		0.181	0.394		−15.118	610.318	
SA (log)	−1.392	0.114		−0.052	0.071		−0.036	0.146	
Period (reference category: 1996–2000)									
2004–2012	1.824	1.073	*	−0.225	0.343		0.395	1.192	
2012–2020	2.592	1.067	**	−0.556	0.363		1.539	1.109	
World regions (reference category: Europe)									
Africa and Middle East	−0.473	0.877		1.494	0.562	***	2.390	0.970	**
Americas	0.864	0.742		1.222	0.561	**	1.148	1.135	
Asia Pacific	−1.287	1.112		0.826	0.543		0.626	1.294	
Rest of World	−1.787	1.182		0.686	0.649		−13.656	913.835	
Constant	0.776	2.252		−0.038	1.294		−0.181	3.060	

Note: Significance levels: *$p<0.1$, **$p<0.05$, ***$p<0.01$; observations = 424; LR $\chi^2(54) = 116.74$***; pseudo $R^2 = 0.157$; log likelihood = −313.127.

TABLE 9 | Marginal effects of TEA and RDT.

	Average marginal effects (Std. error)
TEA	
"Trade-off against biodiversity"	−0.006 (0.002)**
"Trade-off against CO_2 reduction"	0.003 (0.003)
"Inefficient"	−0.0003 (0.001)
RDT	
"Trade-off against biodiversity"	−0.058 (0.026)**
"Trade-off against CO_2 reduction"	−0.043 (0.038)
"Inefficient"	−0.035 (0.017)**

Note: Significance levels: *$p<0.1$, **$p<0.05$, ***$p<0.01$; based on estimations reported in Table 5.

minimize or at least reduce trade-offs? As part of this question, it should be clarified what role national policies and institutions have on entrepreneurship in support of net zero carbon emissions. Formal and informal institutions such as regulations (e.g., on carbon emissions or property rights), cultural norms, and societal values are often nationally determined and are thus important for differences in trade-off conditions across countries. Specifically, the proper design of institutions by national governments can support the entrepreneurial creation of technologies supporting net zero carbon emissions that have no or only very limited detrimental effects on other sustainability targets, such as biodiversity.

Furthermore, we can only to a limited degree shed light on global technology transfer aspects which likely matter for the most efficient approach to avoiding trade-offs. Specifically, beyond the country level, future research should address more important international issues such as the tension between global technology transfer (Audretsch et al. 2014) and national competitiveness (Porter 1990). For example, already Marshall (1920) pointed to agglomeration mechanisms that can lead to regionally heightened technology transfer. Such spillovers again seem very crucial for widely diffusing technologies supporting net zero carbon emissions that have no or only very limited detrimental effects on other crucial sustainability targets, such as biodiversity. Therefore, future research is well advised to study further integration mechanisms and processes, as for example

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in the context of global climate negotiations (where already global technology transfer is considered an important means to halt climate change) or in other supranational initiatives aimed at addressing sustainability challenges, such as the recently instituted Global Biodiversity Framework.

Finally, we are aware that the standardization of biodiversity measurement is more limited as compared to that of greenhouse gas emissions. Future research should therefore explore further the robustness of our findings based on alternative biodiversity indicators. As well, the inferential statistical approaches applied in our study are limited to associational observations. Therefore, future research should attempt to clarify causal effects, for example by focusing on single countries or world regions that allow for involving natural experiments as they can emerge from changes in national or EU regulations.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Endnotes

[1] GDP: Gross Domestic Product.

[2] Personal communication by Ulrich Golüke (advisor to the Earth4All project), https://earth4all.life/who-we-are/the-team/.

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