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Nonlinear and weak interactions among Sustainable Development Goals (SDGs) drive China's SDGs growth rate below expectations

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Abstract

Despite substantial efforts dedicated to achieving the Sustainable Development Goals (SDGs) by 2030, there remains a critical lack of focus on how the nonlinear interactions between the SDGs affect their progress. To fill this pressing knowledge gap, we conducted a comprehensive analysis of SDG interactions and progress in China, from 2000 to 2021, with a focus on assessing nonlinear interactions and their effects on compound annual growth rates of SDGs at both national and provincial scales. Our results show that unless its current trajectory improves, China will not fully achieve all SDGs by 2030, with actual growth rates of some of the goals falling short of desired targets. Crucially, nonlinear interactions among SDGs are more prevalent than linear ones, calling into question the conventional assumption of predominantly linear interactions. While linear synergies do exert the strongest positive influence on SDG progress, the unclassified interactions emerge as the most critical factor inhibiting it. Our findings emphasize the importance of adopting more tailored policy approaches that leverage beneficial nonlinear dynamics and tackle obstacles posed by isolated actions or trade-offs, thus offering valuable insights for both China and the global community in navigating the complexities of the timely achievement of the SDGs.

Keywords: Sustainable Development Goals, growth rates, nonlinear interactions, synergies, trade-offs

1. Introduction

The launching of the 17 Sustainable Development Goals (SDGs) by the United Nations in 2015 has provided a critical framework for guiding global sustainable development efforts (UN, 2015). But recent assessments have revealed that progress in over half of the global SDG targets is either stagnant or regressing, with only 17% of them currently on track (UN, 2024). Furthermore, the progress towards different SDGs varies considerably across countries (Sachs et al., 2024). Therefore, identifying the key challenges hindering the realization of SDGs and exploring effective pathways to implement them not only has important implications for accelerating SDG progress, but can also yield valuable insights for shaping the post-2030 agenda (Biermann et al., 2023; IGSSG, 2023; Malekpour et al., 2023).

To expedite SDG realization, substantial efforts have been dedicated to localizing SDG indicators and measuring progress towards SDGs (Allen et al., 2021; Zhang et al., 2022a). Moreover, elucidating the synergies (where progress in one goal can enable progress in another) and trade-offs (where progress in one goal may hinder progress in another) between the SDGs is deemed crucial for exploring the mutually beneficial achievement of these goals and constructing reliable predictive models (Kroll et al., 2019; Anderson et al., 2022). A previous study analyzed SDG indicator data for 227 countries and found that synergies largely outweigh trade-offs in most countries, with SDG1 (No poverty) showing synergistic relationships with most other goals in 80%–90% of the data pairs (Pradhan et al., 2017). In contrast, SDG12 (Responsible consumption and production) exhibited trade-offs with 10 goals (SDGs 1–7, 9, 10, 17) in 50%–90% of the data pairs (Pradhan et al., 2017).

Moreover, several studies highlight that synergies and trade-offs between SDGs are not static but evolve dynamically over time, with significant implications for policy prioritization and resource allocation (Kroll et al., 2019; Cao et al., 2023). For instance, Kroll et al. (2019) employed Spearman correlation analysis on global data from 2010–2018, identifying that

SDG1 exhibited synergies with 70% of other SDGs, while SDG11 (Sustainable Cities and Communities) and SDG13 (Climate Action) showed trade-offs in 60% of interactions. Importantly, projected trends until 2030 indicate persistent challenges: SDGs 11, 13, 14, 16, and 17 are expected to retain >50% trade-offs, whereas SDGs 1, 3, 7, 8, and 9 may sustain synergies across 65–80% of interactions (Kroll et al., 2019). Additionally, a China-specific study analyzing 1,302 directed networks from 2000–2020 found 27% of trade-off pairs transitioning to synergies, while 25% of synergistic pairs shifted to trade-offs (Cao et al., 2023).

Recent research has increasingly adopted systemic approaches to understand SDG interactions, moving beyond static, pairwise correlations to dynamic analyses of causal drivers and feedback mechanisms. Moallemi et al. (2022) introduced eight archetypes of SDG synergies and trade-offs, such as 'Fixes That Fail' and 'Tragedy of the Commons', which generalize recurring interaction patterns and link causal drivers like delayed feedback and path dependency to dynamic behaviors and policy implications. Luttikhuis and Wiebe (2023) advanced methodological frameworks for technology-specific SDG interaction analysis, integrating expert elicitation, literature triangulation, and focus groups to identify context-dependent trade-offs and synergies. These approaches address data-driven method limitations by incorporating qualitative insights and stakeholder perspectives. Yet most research has predominantly focused on linear interactions, leaving nonlinear interactions largely overlooked (Warchold et al., 2021; Kostetckaia and Hametner, 2022). Particularly, how nonlinear interactions influence SDG progress constitutes a critical research gap.

Nonlinearity describes a scenario where the relationship between two variables is neither proportional nor constant, and instead shows curved patterns (Skene, 2024). Regarding possible SDG synergies and trade-offs, the impact of one goal on another is likely not static; it can change dynamically as their targets evolve. Preliminary analyses by some scholars using global-scale SDG indicator data have uncovered vital insights (Warchold et al., 2021). Yet our understanding of nonlinearity dynamics in SDGs is still nascent (Kostetckaia and Hametner, 2022). For instance, nonlinear synergies can take an array of forms, such as starting strong but later weakening, or starting weak but later strengthening. The same applies to nonlinear trade-offs. Most importantly, the patterns of non-monotonic nonlinear interactions between SDGs can have a U-shape (where trade-offs change into synergies) or an inverted U-shape (where synergies change into trade-offs), neither yet adequately explored.

Filling this pivotal knowledge gap is crucial, since it underpins a better understanding of how to harness the benefits of nonlinear interactions while avoiding their adverse impacts. To address this issue, we assessed the progress and growth rates of the SDG Indices in China, as well as the nonlinear features of the interactions between differing SDGs at national and provincial scales. China presents an ideal case study for several compelling reasons. As the world's largest developing country, China has made enormous efforts and achieved considerable progress in constructing its SDG indicator framework, assessing progress towards SDGs, and analyzing their interactions (Xu et al., 2020; Zhang et al., 2022b). Additionally, the relationship between China's SDG achievements and various topics such as ecological civilization (Zhang and Fu, 2023), human well-being (Yu et al., 2025), the construction of a beautiful China (Guan et al., 2024), and planetary boundaries (Chen et al., 2024) has garnered great attention. Key solutions have been identified on how to promote synergetic and balanced development between regions and various SDGs (Liu et al., 2021; Zhang et al., 2022b).

However, China simultaneously faces ongoing difficulties with the slow progress of many SDGs (Yu et al., 2025). In particular, the nonlinear dynamics between various SDGs and how such interactions may influence SDG changes have not been thoroughly examined. The geographic, economic, and social diversity across China's provinces provides a rich field laboratory for examining how nonlinear interactions manifest under various development contexts (Sachs et al., 2024; Yu et al., 2025). Meanwhile, China's increasingly sophisticated

SDG monitoring framework can supply high-quality, consistent data, which is undoubtedly essential for quantitatively analyzing complex nonlinear interactions (Guo et al., 2022; Luo et al., 2024). This combination of factors makes China a prime study subject for comprehensive SDG-related investigations.

Our study aims to answer three key questions: (1) What are the progress and growth rates of SDGs across Chinese provinces from 2000 to 2021? (2) What are the spatial patterns of the nonlinear synergies and trade-offs between different SDGs? (3) How do these nonlinear interactions affect the realization of SDGs in China? Tackling these questions will enhance our understanding of the complex dynamics underlying SDG implementation; inform more effective policy interventions that explicitly account for nonlinear interactions; and provide timely insights for optimizing resource allocation in SDG efforts. China's experience could also provide a model framework and findings to guide studies in other parts of the world, particularly in those developing countries facing similar sustainable development challenges.

2. Methods

2.1. Indicator framework and data sources

This study extends the time series of indicators based on the framework established recently by Zhang et al. (2022a) and refines that framework further given the available data. At the provincial scale, a total of 91 indicators were developed, corresponding to 71 targets and 16 goals (Table S1). It is important to note that 20 inland provinces in China do not have indicators related to SDG14 (Life below Water). Given the need for comparability across indicators (Lafortune et al., 2018), this study does not assess SDG14 and focuses exclusively on the remaining 16 goals.

To enhance the robustness of the analysis of interactions among SDGs, we collected long-term historical data for various SDG indicators. Since the availability of statistical yearbooks from most departments ended in 2022 or 2021, historical data for each indicator were collected from 2000 to 2021 (i.e., the study period). The available data per indicator varies to some extent, as detailed in Table S1. Generally, from an indicator perspective, SDG15 (38.64%), SDG17 (35.23%), and SDG1 (31.17%) exhibit the highest proportions of missing data, while SDG7 (0%), SDG12 (6.82%), and SDG5 (7.58%) show the lowest proportions (Fig. S1). From a temporal perspective, with the exception of the period from 2015 to 2017, data are missing to varying degrees in other years. The largest gaps are observed in 2000, with a missing rate of 71.43%. This missing rate gradually decreased, reaching its lowest point in 2014 (1.1%), but then increased again, rising to 9.89% in 2021 (Fig. S2).

To deal with such missing data, the 'mice' package in R was utilized to perform multiple imputations, thereby generating multiple complete datasets. Each of these complete datasets was then analyzed using the same statistical methods to obtain more accurate parameter estimates and more reliable statistical inferences (Austin et al., 2021). This approach boosts statistical power while also substantially enhancing the robustness of our results by quantifying the uncertainty associated with the imputation (Austin et al., 2021). Our compilation revealed that the SDG Index for the nation and provinces was assessable from 2000 to 2021. Importantly, despite the lack of a formal SDG framework between 2000 and 2015, China had already started implementing policies strongly aligned with SDGs, including reducing poverty, improving the quality of education and promoting conservation (Zhang and Fu, 2023). Therefore, data from this period provides valuable historical context for understanding the implementation of the SDGs after 2015.

2.2. Assessment of SDG progress and growth rates

To measure progress towards the SDGs in China, we borrowed methodologies from previous research to compile aggregated indices for the SDG Index and SDG scores, at both the national and provincial scales, from 2000 to 2021 (Zhang et al., 2022b). Initially, the raw data were preprocessed to minimize the influence of outliers by replacing values exceeding the 97.5th percentile and below the 2.5th percentile with their corresponding percentile values. Based on the characteristics of the indicators, the SDG indicators were categorized into three types: positive, negative, and intermediate. Normalization of these indicators was then performed using the method outlined by Zhang et al. (2022b), in accordance with the target and baseline values for each SDG provided in Table S2.

After calculating the SDG Index and SDG scores, the compound annual growth rate (CAGR) of score changes was derived using formula (1), where X_t denotes the SDG Index or SDG scores for year t, and X_{t0} that for the initial year (Allen et al., 2020). This method let us determine the rate of change for each score over time using formula (2). Our study evaluates the observed compound annual growth rate ($CAGR_O$) and the desired compound annual growth rate ($CAGR_D$). For $CAGR_O$, t corresponds to 2021, and t_0 stands for year 2000, with X_t being the SDG Index or SDG scores in 2021. For $CAGR_D$, t is 2030, while t_0 is also 2000, and X_t is the target score of 100 points. By comparing the $CAGR_O$ with the $CAGR_D$ needed to achieve the target score by 2030, our study calculated their ratio, $CAGR_{(O/D)}$. It is important to note that this study performs calculations at both the national and provincial scales: the national scale $CAGR_{(O/D)}$ is derived from national SDG Index data, while the provincial scale $CAGR_{(O/D)}$ are based on the corresponding regional SDG Index data. Additionally, the $CAGR_{(O/D)}$ for each individual SDG is computed using the scores specific to that goal.

$$CAGR = \left(\frac{X_t}{X_{to}}\right)^{\frac{1}{t-t0}} - 1 \tag{1}$$

$$CAGR_{(O/D)} = \frac{CAGR_O}{CAGR_D} \tag{2}$$

We analyzed changes to $CAGR_{(O/D)}$ across provinces differing in their mean income levels. Following the methodology described by Xu et al. (2020), 31 provinces of China's mainland—excluding Hong Kong, Macau, and Taiwan—were categorized according to their per capita

GDP values from 2000 to 2021. The five provinces with the highest per capita GDP (ranging from 57,457 to 87,807 RMB during this period) were classified as high-income ones. Conversely, those five provinces with the lowest per capita GDP (from 18,567 to 23,639 RMB) were classified as low-income ones. Provinces ranked 6th to 15th (per capita GDP of 29,851–50,367 RMB) were categorized as upper-middle-income, and those ranked 16th to 26th (per capita GDP of 26,530–29,712 RMB) were categorized as lower-middle-income ones (Table S3).

2.3. Synergies, trade-offs and nonlinearities

Building on the work of Warchold et al. (2020), SDG interactions were categorized into six types by using Spearman and Pearson correlation coefficients and the Maximal Information Coefficient (Reshef et al., 2011). These types are synergy monotone interactions (Sml); trade-off monotone linear interactions (Tml); unclassified interactions (Un); synergy monotone nonlinear interactions (Smnl); trade-off monotone nonlinear interactions (Tmnl); and unclassified non-monotone nonlinear interactions (Unnmnl). Furthermore, we conducted polynomial regression analyses of the three types of nonlinear interactions and used the sign of the resulting quadratic term's coefficient to determine the type of nonlinearity involved. A positive quadratic term coefficient indicates a Type I nonlinear relationship, while a negative coefficient signifies a Type II nonlinear relationship. The corresponding methodology is detailed in the supplementary information (Fig. S3). This approach provides a more in-depth analysis than reported in previous studies, which only examined six types of SDG interactions.

The interactions between SDGs could then be quantified into nine categories: synergy monotone interactions (Sml); trade-off monotone linear interactions (Tml); unclassified interactions (Un); Type I synergy monotone nonlinear interactions (Smnl1); Type I trade-off monotone nonlinear interactions (Tmnl1); Type I unclassified non-monotone nonlinear interactions (Unnmnl1); Type II synergy monotone nonlinear interactions (Smnl2); Type II trade-off monotone nonlinear interactions (Tmnl2); and second-type unclassified non-monotone nonlinear interactions (Unnmnl2). We then grouped Smnl1, Tmnl1, and Unnmnl1 as Type I nonlinear interactions, and Smnl2, Tmnl2, and Unnmnl2 as Type II nonlinear interactions. For detailed definitions of the different SDG interactions, please refer to Table 1.

To evaluate the impact of different interactions on SDG progress, we first calculated the respective proportions of the nine relationship types for each province and each SDG. These proportions were analyzed alongside their corresponding $CAGR_{(O/D)}$ values. Next, linear regressions were fitted, to examine the relationships between the proportions of the nine relationship types for each SDG and the SDG Index, and their respective $CAGR_{(O/D)}$ values. The sign of regression coefficients would indicate the direction of the impact, with positive coefficients suggesting positive impacts and negative coefficients indicating negative impacts. Finally, the absolute values of these coefficients can be employed to gauge the relative magnitude of these impacts. Applying this approach ensures a systematic and quantitative assessment of all potential interactions, providing greater insight into how they could influence SDG progress.

3. Results

3.1. Progress and growth rates of SDGs in China

Our findings indicate that, at its current pace, China is unlikely to achieve all the SDGs by 2030. While China's SDG Index did rise from 54.46 in 2000 to 72.44 in 2021 (Fig. S4), the observed compound annual growth rate ($CAGR_O$) of the SDG Index during this period was about 1.37%, which is only two-thirds (67%) of the desired compound annual growth rate ($CAGR_D$) (Fig. 1a). In terms of progress toward individual SDGs, only SDG 11 (Sustainable Cities and Communities) and SDG 13 (Climate Action) achieved the $CAGR_D$. This progress can be attributed to the Chinese government's prioritization of ecological civilization, embedding "carbon peaking and carbon neutrality" goals into its national development strategy, and advancing sustainable urban development and climate change mitigation under its "14th Five-Year Plan". Six other goals had growth rates that exceeded the national average of the SDG Index, namely SDG1 (No Poverty), SDG3 (Good Health and Well-being), SDG5 (Gender Equality), SDG6 (Clean Water and Sanitation), SDG7 (Affordable and Clean Energy), SDG11 (Sustainable Cities and Communities), and SDG13 (Climate Action).

Unfortunately, progress in achieving the remaining goals has been comparatively slow, with notable challenges faced with respect to SDG9 (Industry, Innovation, and Infrastructure), SDG10 (Reduced Inequalities), and SDG15 (Life on Land). Their $CAGR_O$ values were particularly low, at 0.32%, 0.29%, and 0.13%, respectively, these corresponding to just 17.6%, 19.3%, and 5.5% of their $CAGR_D$ values (Fig. S5). The slow progress in SDG9 (Industry, Innovation, and Infrastructure), SDG10 (Reduced Inequalities), and SDG15 (Life on Land) can be attributed to economic restructuring, income inequality, environmental degradation, and competing land-use pressures. While advancements have been made in certain areas, these challenges highlight the difficult complexities of balancing economic growth with sustainable development.

At the provincial scale, we also found that no province has yet made sufficient progress to achieve all SDGs under China's current trajectory. Our results indicated relatively slower progress in high-income provinces in particular, whose $CAGR_{(O/D)}$ values mainly ranged from 30% to 60%; this range represents the lowest distribution of $CAGR_{(O/D)}$ values among all four income categories. For middle-high and middle-low income provinces, more than half of the $CAGR_{(O/D)}$ values fell within the 30% to 60% range, with a smaller proportion between 60% and 80%. In stark contrast, low-income provinces had the highest proportion of $CAGR_{(O/D)}$ values exceeding 60%, with some provinces even surpassing 80% (Fig. 1b). For example, two high-income provinces, Zhejiang and Tianjin, have only achieved their expected targets in two SDGs, while low-income Guizhou has achieved its targets in six SDGs (Fig. 1c). This suggested that high-income provinces are encountering developmental bottlenecks, potentially slowing their SDG progress, while low-income provinces may have played a key role in driving national SDG trends.

3.2. Nonlinear synergies and trade-offs between SDGs in China

Some differences were found in how SDGs interacted at the national versus provincial scale. At the national scale, no trade-offs were identified, whereas at the provincial scale, a low proportion of trade-offs (4.4%) was observed. This suggested that although local conditions at the provincial scale may lead to some trade-offs, these effects were offset at the national scale, resulting in no significant trade-off effects at the latter scale. At both scales, however, nonlinear interactions were more common than linear interactions. At the national scale, Sml (32.8%) slightly outweighed Smnl (28.2%, the sum of Smnl1 and Smnl2). Nevertheless, with 11% of interactions classified as Unnmnl, the overall proportion of nonlinear interactions (39.2%) exceeded that of linear interactions (32.8%). Similarly, at the provincial scale, nonlinear interactions were dominant, at 37.2% compared to 33.7% for linear interactions (Fig. 2a).

Figure 2b illustrates the nine types of SDG interactions. For example, Smnl1 exhibits a promotional effect that starts weak but later strengthens. In Gansu Province, before eradicating poverty, residents had to endure a low quality of life. Following comprehensive poverty alleviation (SDG1) there in 2020, an improved rural infrastructure led to enhanced living standards (SDG3). Conversely, Smnl2 reflects a promotional effect that starts strong but later weakens. For instance, bolstering gender equality (SDG5) facilitates more equitable resource allocation and empowers women’s access to engage in projects aimed at improving water and sanitation facilities (SDG6). Yet further progress may encounter cultural, policy, or structural economic barriers, leading to a deceleration in this aspect of development.

The Tmnl interactions can also exhibit nuanced patterns. Tmnl1 represents a trade-off effect that weakens after reaching a threshold. In Qinghai Province, for example, the development of clean energy (SDG7) initially limited the expansion of information infrastructure (SDG17). However, as clean energy objectives are gradually met, additional resources become available for investments in technology and internet accessibility. In contrast, Tmnl2 refers to a trade-off effect that intensifies after crossing a threshold. For instance, the heavy reliance on coal in Shanxi Province means that substantial resources are needed for transitioning to clean energy (SDG7), which further constrains the development of its technology and internet infrastructure (SDG17).

The Unnmnl interactions often involve transitions between trade-offs and synergies. Unnmnl1 exemplifies a shift from a trade-off to a synergistic relationship. For example, in Qinghai Province, the short-term development of clean energy (SDG7) may negatively impact infrastructure and the ecological environment, thus affecting climate action (SDG13). But in the long term, Qinghai's abundant clean energy resources enable it to reduce fossil fuel use and carbon emissions, ultimately hastening progress in climate action (SDG13). Conversely, Unnmnl2 represents a shift from a synergy to a trade-off. In Sichuan Province, hydropower initially supports local economic growth (SDG8) that also enables more efficient resource use (SDG12). Over time, however, sustained economic expansion often involves intensive resource consumption, increasing the risk of natural resource depletion.

3.3. Spatial variation in the nonlinear interactions between SDGs in China

Our results indicated that, at the national scale, Smnl interactions (Smnl1 and Smnl2) occur widely among all SDGs, with the highest proportion (68.75%) observed between SDG10 and other goals (Fig. 3a). Hence, SDG10, which addresses inequalities in income, social security, education, and employment, has a positive influence on other SDGs. Meanwhile, the Unnmnl interactions (Unnmnl1 and Unnmnl2) were chiefly observed for SDG9, SDG12, and SDG17 vis-à-vis other goals, with respective proportions of 25%, 31.25%, and 31.13% (Fig. 3a). This suggested that the impacts of SDG9, SDG12, and SDG17 are more indirect and may vary depending on regional contexts and implementation strategies.

At the provincial scale, SDG6, SDG7, and SDG11 were each characterized by a relatively higher proportion of Smnl interactions (Smnl1 and Smnl2) with other goals, at 9.08%, 8.75%, and 8.21%, respectively (Fig. 3a). This suggested that improvements in infrastructure and social resources at the local scale are more likely to generate widespread positive effects in meeting the SDGs. Meanwhile, SDG17 had the highest proportion of Unnmnl interactions (Unnmnl1 and Unnmnl2) with other goals, at 10.9%. Concerning the Tmnl interactions (Tmnl1 and Tmnl2), these were mainly observed in SDG12 and SDG17, at 14.77% and 30.11%, respectively (Fig. 3a), probably reflecting potential tensions between local development priorities and regional cooperation.

Moreover, nonlinear interactions among SDGs exhibited spatial variation at the provincial scale. Those provinces with high, upper-middle, and lower-middle income levels had higher proportions (8.33%, 4.58%, and 2.78%, respectively) of Type I nonlinear interactions than Type II nonlinear interactions (Fig. 3b). The opposite trend characterized low-income provinces: as their income levels rose, the proportions of Tmnl1 and Tmnl2 fell. However, in high- and upper-middle-income provinces, the proportion of Tmnl1 (0.52% and 2.45%, respectively) surpassed that of Tmnl2 (0% and 1.07%, respectively); but the opposite was true for low- and lower-middle-income provinces. The proportion of Smnl1 consistently exceeded that of Smnl2 (6.97%) across all income levels, with the difference being most pronounced in high-income provinces. Additionally, in low-income provinces, the proportion of Unnmnl1 (4.47%) was lower than that of Unnmnl2 (7.18%). By contrast, in other provinces with greater income levels, the proportion of Unnmnl1 surpasses that of Unnmnl2 (Fig. 3b). Altogether, these findings suggested that Type I nonlinear interactions play a more essential role in promoting China's provincial development than Type II nonlinear interactions.

3.4. Impact of nonlinear interactions on the progress of SDGs in China

We observed that, as the $CAGR_{(O/D)}$ of the SDG Index increases, so too does the proportion of Sml interactions across Chinese provinces; however, the proportion of Un interactions decreases, while that of Tml interactions initially falls but then rises (Fig. 4a). For example, in provinces whose $CAGR_{(O/D)}$ of the SDG Index is lower (between 30% and 60%), Un interactions reach 30% in proportion, whereas Sml interactions are under 30%. At the other end of the spectrum, for provinces having a higher $CAGR_{(O/D)}$ of the SDG Index (between 80% and 100%), their proportion of Sml interactions increases to 40%, while Un interactions decline to below 20%, with that of Tml interactions falling from 2.48% to 1.89% before rising to 2.35%. These findings suggest the isolation of individual goals may be a pivotal factor inhibiting overall progress in the SDG Index. Furthermore, the role of Tml interactions in potentially advancing the SDG Index warrants further investigation. This trend was also corroborated in Fig. 4b, with one key difference: when the $CAGR_{(O/D)}$ of individual SDGs reach their expected values, the proportion of Sml interactions slightly decreases, while that of Un interactions slightly increases. This discrepancy could imply that, once the $CAGR_D$ is achieved, subsequent advancements could encounter diminishing returns in progress.

The linear regression results further clarified the impacts of the nine types of interactions on SDG progress (Fig. 5). Overall, we found that synergistic interactions exhibit stronger positive effects on SDG targets compared to non-monotonic and trade-off interactions. Moreover, linear interactions exhibited greater positive effects than did nonlinear ones. Among nonlinear interactions, the suppressive effects of Type I nonlinear interactions are relatively less severe than those of Type II nonlinear interactions. For instance, Sml interactions were able to positively influence 15 goals, whereas Smnl1 and Smnl2 interactions contributed to the progress of 14 and 10 goals, respectively. Conversely, Un interactions hindered progress across all 15 goals, representing the most suppressive relationship type. Likewise, Unnmnl1 and Unnmnl2 interactions negatively impacted more than half of the goals, affecting 8 and 9 goals (out of 16), respectively.

Nonlinear trade-offs, in contrast, had a more detrimental effect on SDGs than did linear trade-offs (Fig. 5). Specifically, we found that Tmnl1 and Tmnl2 interactions negatively impact 10 and 11 goals, respectively, while Tml negatively affects 6 goals. Despite their predominantly negative effects, trade-offs (Tml, Tmnl1, and Tmnl2) also had positive effects on certain SDGs, such as SDG7 and SDG8. This could arise when inhibiting one goal facilitates the advancement of other goals via trade-offs. An example is SDG17, whose trade-offs with other SDGs (Fig. S6 and Fig. S7) may indirectly augment the development of goals (e.g., SDG7 and SDG8) in mutual suppression with it. This indicates that when the development of information infrastructure (SDG17) is curtailed, more resources may be allocated to clean energy (SDG7) and employment (SDG8), thereby fostering their progress.

4. Discussion

4.1 Nonlinear interactions among SDGs

Our analysis reveals several critical insights about the nature of nonlinear interactions among SDGs in China and their implications for sustainable development's implementation. The paramount finding is that nonlinear interactions, including synergies and trade-offs, as well as non-monotone nonlinear interactions, are more prevalent than linear ones. This challenges the traditional linear perspectives that have long dominated SDG research and policy discussions (Warchold et al., 2021; Luttikhuis and Wiebe, 2023). Importantly, our findings underscore the differential impacts of these nonlinear synergies and trade-offs upon SDG progress, an aspect often overlooked in previous studies.

Another key finding of our study is that China's current trajectory is insufficient for fulfilling all SDGs by 2030, with actual growth rates falling short of the desired targets. Other research has highlighted the slow pace of SDG achievement in many countries, particularly due to economic disparities across regions (Sachs et al., 2024). However, our study provides deeper insight into how interactions among SDGs—especially nonlinear interactions—can influence overall progress. Specifically, we find that provinces with faster progress in attaining their SDG indices, as indicated by higher $CAGR_O$ values, are distinguished by a more balanced distribution of linear synergies (Sml). Nonetheless, in those provinces, the prevalence of negative interactions (Tml) fluctuates, initially declining before rising again.

By contrast, provinces with slower SDG progress, as characterized by lower $CAGR_O$ values, tend to show a higher proportion of unclassified interactions (Un). This means there is weak interaction between the SDGs, in that advancement towards one goal has a minimal impact on others. Previous analyses have largely focused on correlation coefficients between SDGs, which typically range from –0.5 to 0.5, indicating weak negative or positive interactions (Kroll et al., 2019; Warchold et al., 2021). Our results, however, suggest that the lack of strong synergies and trade-offs—manifested in the high levels of Un—poses a major barrier to achieving the SDGs. This highlights the critical importance of enhancing potential synergies among various SDGs to accelerate their comprehensive progress (Malekpour et al., 2023). Further, this preponderance of Un interactions may be evidence that the isolated implementation of SDGs remains common, or that past policy actions have not yet achieved their desired effects (Glass and Newig, 2019; Berrone et al., 2023).

The emergence of nonlinear interactions among the SDGs could be influenced by various factors, both known and unknown, that shape the complex dynamics of sustainable development. Interdependencies and feedback loops inherent in SDGs contribute to this nonlinearity (Dawes, 2022); for example, while greater access to clean energy (SDG7) may initially boost economic growth (SDG8), it can eventually lead to resource depletion or environmental degradation, adversely affecting the realization of other goals. Also, the socio-economic and political contexts of different regions can profoundly shape such interactions (Nerland et al., 2023). Variations in governance, economic policies, and cultural norms will affect the provinces' capacities to address multiple SDGs, resulting in divergent progress trajectories (Skene, 2022). High-income regions could face development bottlenecks, while low-income areas may achieve rapid improvements due to targeted interventions. The stage of development and initial conditions also predetermine, to some degree, how SDGs interact. Early development stages often entail strong synergies as basic needs are increasingly met, but as economies grow, trade-offs become more pronounced, particularly between poverty reduction (SDG1) and environmental protection (SDG15) (Zhang et al., 2022b). External shocks, such as economic crises and climate events, will introduce further nonlinearities, disrupting progress in one goal while creating new opportunities for others (Skene, 2022).

4.2 Policy implications

Our findings go beyond previous research by demonstrating that the impact of nonlinear interactions on SDG progress is not uniform, but rather varies greatly across different development stages and contexts. Compared with a previous study (Warchold et al., 2021), we identified six distinct types of nonlinear interactions: synergistic nonlinear (Smnl1 and 2), trade-off nonlinear (Tmnl1 and 2), and non-monotonic nonlinear (Unnml1 and 2). These variations have significant implications for transforming policy-making, suggesting that successful SDG implementation requires both understanding and leveraging these nonlinear interactions rather than presupposing simple linear progressions (Skene, 2021; Allen and Malekpour, 2023).

For example, in those regions with relatively high economic growth, achieving certain SDGs, such as poverty reduction (SDG1) or clean energy use (SDG7), appears to accelerate the realization of other related SDGs. Still, the non-monotonic nature of these interactions, such as

U-shaped and inverted U-shaped patterns, suggests that synergies are not always sustained and may in fact reverse depending on the stage of development or specific regional challenges. Additionally, the transition from trade-offs to synergies (Unnmnl1) during Qinghai's shift towards clean energy (SDG7), and its impact on climate action (SDG13), illustrates the potential for nonlinear interactions to evolve. Policymakers can leverage this facet by investing in initiatives that not only tackle immediate challenges but also proactively prepare for long-term synergies. Conversely, nonlinear trade-offs, especially those that intensify beyond a threshold (Tmnl2), could pose substantial challenges, as seen for the relationship between SDG7 and SDG17 in Shanxi. Hence, these dynamics demand a detailed understanding of SDG interactions and call for adaptive management strategies that can quickly respond to changing conditions and interactions (Fu et al., 2020; Scoones et al., 2020).

Building on our analysis of nonlinear interactions among SDGs, policymakers in China could prioritize goals with key synergistic and trade-off dynamics. For instance, SDG1 (No Poverty), and SDG7 (Affordable and Clean Energy) have shown strong synergies in China, indicating that integrated policies in these areas could drive broader SDG achievement. Conversely, SDG9 (Industry, Innovation, and Infrastructure), SDG10 (Reduced Inequalities), SDG12 (Responsible Consumption and Production), and SDG15 (Life on Land) also require urgent attention due to their slow progress and complex nonlinear interactions. The choice of which goals to prioritize should be flexible and context-dependent, reflecting the dynamic nature of SDG interactions and the need to adapt to changing conditions and regional challenges (Fu et al., 2020; Allen et al., 2021).

These insights extend beyond China, offering critical lessons for regions navigating similar development complexities, particularly in reconciling SDG interdependencies shaped by divergent developmental stages. In early stages, strong synergies emerge as basic needs (e.g., availability of food and water) are met, but as economies grow, salient trade-offs arise (Zhang et al., 2022b). For example, rapidly urbanizing regions, particularly in developing or underdeveloped countries, often face trade-offs between SDG11 (Sustainable Cities and Communities) and SDG13 (Climate Action), as urban expansion can lead to increased carbon emissions and resource consumption (Kroll et al., 2019). Addressing these challenges requires coordinated policies that balance urban development with climate resilience, such as investing in green infrastructure and climate-adaptive planning (Mirasgedis et al., 2024). By recognizing the interconnected nature of SDGs and adopting adaptive governance strategies, policymakers can navigate nonlinear dynamics and achieve more resilient and sustainable outcomes.

4.3 Limitations and prospects

Our study provides critical insights into the nonlinear dynamics of SDG interactions, yet several limitations must be acknowledged. Firstly, the robustness of our assessment method and the uncertainty surrounding nonlinear interactions require further enhancement. While we employed rigorous scientific methods to address missing data, such as multiple imputations using the 'mice' package in R, these approaches inherently carry limitations. The assumptions underlying the imputation process may introduce uncertainties, particularly when extrapolating trends or interpreting dynamic interactions. Additionally, the sensitivity of nonlinear interactions to contextual factors such as policy shifts, economic conditions, or environmental events was not explicitly quantified in this study. Future research could incorporate sensitivity analyses or scenario modeling to better understand how these factors influence SDG interactions and outcomes.

Secondly, the temporal dynamics of nonlinear interactions were not fully explored in this study. Although our analysis spans the period from 2000 to 2021, the long-term nature of the dataset precludes a detailed examination of time-dependent effects. Rolling-window analyses (e.g., 5-year intervals) could provide valuable insights into how SDG interactions evolve over time and how their nonlinear characteristics might shift in response to policy changes or external shocks. However, such analyses were not feasible in this study due to data constraints, particularly the limited availability of granular data for certain provinces and SDGs. As more official data become available in the future, it will be possible to conduct segmented analyses to explore how interactions evolve over time and under different contextual conditions. Such analyses could offer critical insights into the adaptive management of SDG interactions and inform more resilient policy strategies.

5. Conclusion

Our study enhances the comprehension of SDG interactions by elucidating the pivotal role of nonlinear dynamics in influencing sustainable development progress. Employing China as a case study, we illustrate that nonlinear synergies, trade-offs, and non-monotonic interactions are more common than linear relationships and significantly affect SDG outcomes in diverse contexts. These insights contest the conventional linear assumptions prevalent in SDG research and policy, underscoring the necessity for systems-based approaches that consider complexity and interconnectedness. Our work unveils the widespread nature of nonlinearity in SDG interactions, offering researchers a framework to investigate comparable dynamics in various regions, especially where development challenges are intricate and context-dependent. Nonlinear dynamics necessitate a transition from isolated actions to comprehensive, context-sensitive strategies, as advancement in one goal can either enhance or impede others based on developmental phases and regional circumstances. Our findings, by acknowledging the dynamic and interconnected nature of SDG interactions, provide a pathway for accelerating sustainable development in a manner that is both resilient and equitable, delivering practical insights for researchers and practitioners globally.

Data availability

Data will be made available on request.

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Table

Table 1 The nine types of SDG interactions defined in this study.

	Type of SDG interactions	Abbreviation	Meaning
1	Synergy monotone linear interactions	Sml	Linear growth with a promoting effect.
2	Type I synergy monotone nonlinear interactions	Smnl1	A promotional effect that starts weak but strengthens over time.
3	Type II synergy monotone nonlinear interactions	Smnl2	A promotional effect that starts strong but weakens over time.
4	Trade-off monotone linear interactions	Tml	Linear growth with a negative effect.
5	Type I trade-off monotone nonlinear interactions	Tmnl1	A negative effect that starts strong but weakens over time.
6	Type II trade-off monotone nonlinear interactions	Tmnl2	A negative effect that starts weak but strengthens over time.
7	Unclassified interactions	Un	Weak interaction or unclear classification.
8	Type I unclassified non-monotone nonlinear interactions	Unnmnl1	Transition from a trade-off to a synergistic relationship.
9	Type II unclassified non-monotone nonlinear interactions	Unnmnl2	Transition from a synergistic to a trade-off relationship.

Figure legends

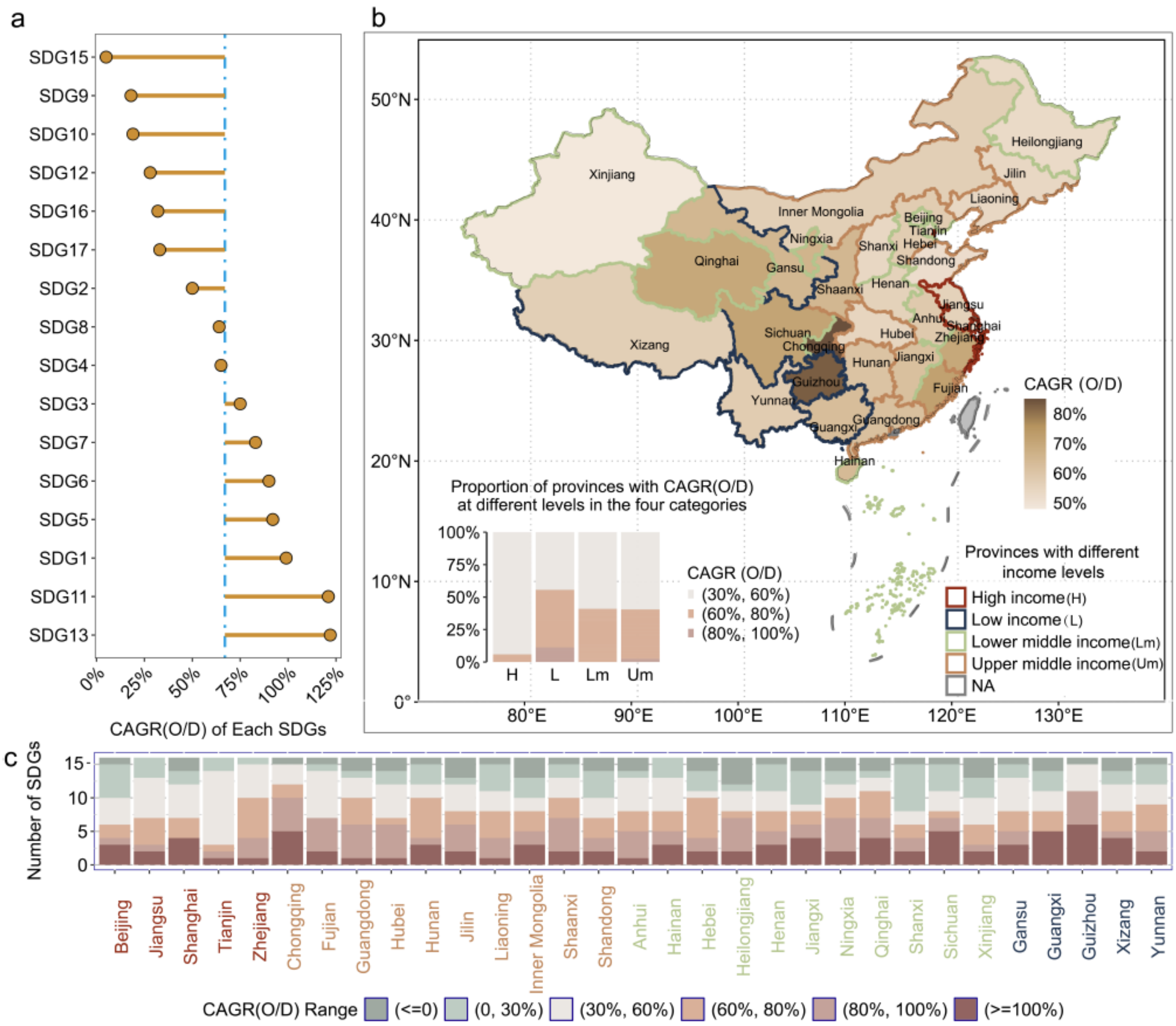

Fig. 1. The ratio of the observed compound annual growth rate to the desired compound annual growth rate ($CAGR_{(O/D)}$) for the SDGs, from 2000 to 2021, and its spatial distribution in China. (**a**) $CAGR_{(O/D)}$ values for China's SDGs. The dashed blue line represents the $CAGR_{(O/D)}$ values of the SDG Index at the national scale. (**b**) $CAGR_{(O/D)}$ values for the SDG Index across 31 provinces of mainland China. In the map, the borders of each province are highlighted with colors to indicate their income classifications based on per capita GDP from 2000 to 2021 (Table S3). (**c**) Distribution of the number of SDGs at different bins of $CAGR_{(O/D)}$ values across China's provinces.

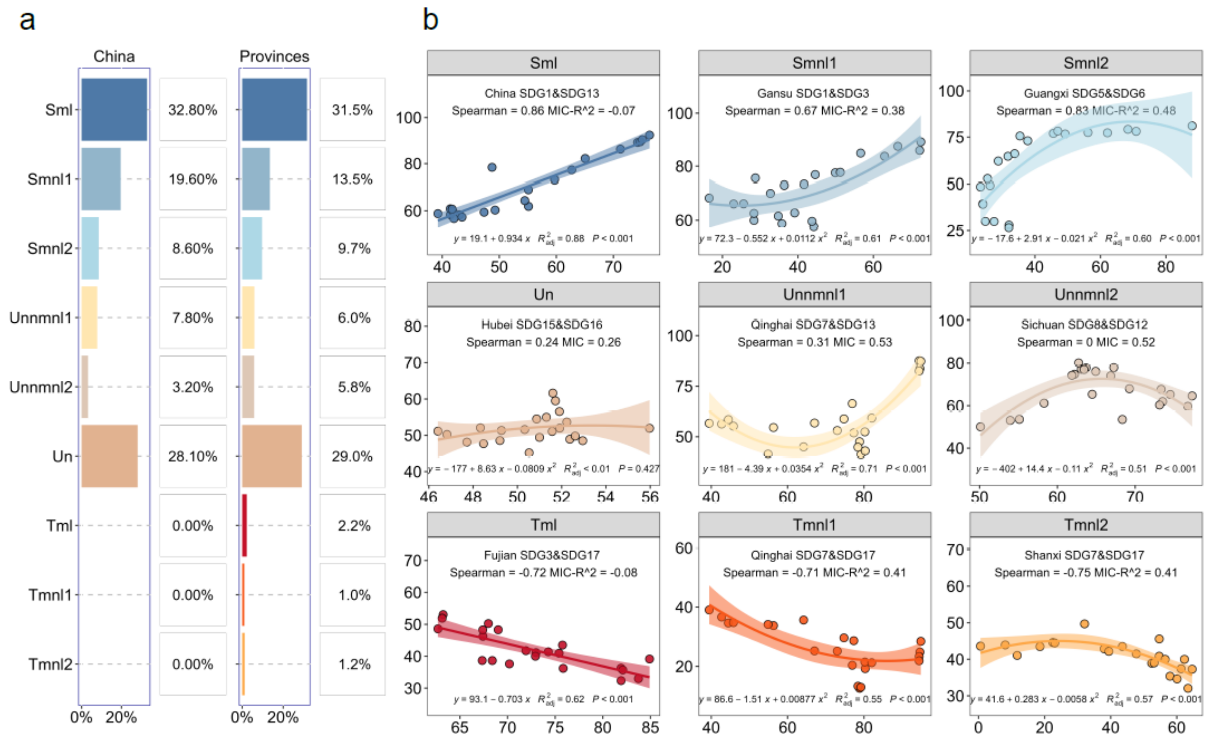

Fig. 2. Characteristics of the nine types of interactions between SDGs at the national and provincial scales in China. (a) Proportions of the nine interactions between SDGs at either spatial scale. (b) Illustrations of the nine interactions between SDGs. In Fig. 2b, the score of SDG (left) and SDG (right) represent the horizontal and vertical axes, respectively, indicating how SDG (right) changes in response to variations in SDG (left). The relevant parameters (R^2, P-values, etc.) for polynomial regression on the nonlinear relationships between different SDGs at both the national scale (China) and the provincial scale (across mainland China's 31 provinces) can be found in Table S4. The full names of the nine abbreviated SDG interactions are as follows: synergy monotone linear interactions (Sml), trade-off monotone linear interactions (Tml), unclassified interactions (Un), Type I synergy monotone nonlinear interactions (Smnl1), Type I trade-off monotone nonlinear interactions (Tmnl1), Type I unclassified non-monotone nonlinear interactions (Unnmnl1), Type II synergy monotone nonlinear interactions (Smnl2), Type II trade-off monotone nonlinear interactions (Tmnl2), and Type II unclassified non-monotone nonlinear interactions (Unnmnl2). For detailed definitions of these different SDG interactions, please refer to Table 1.

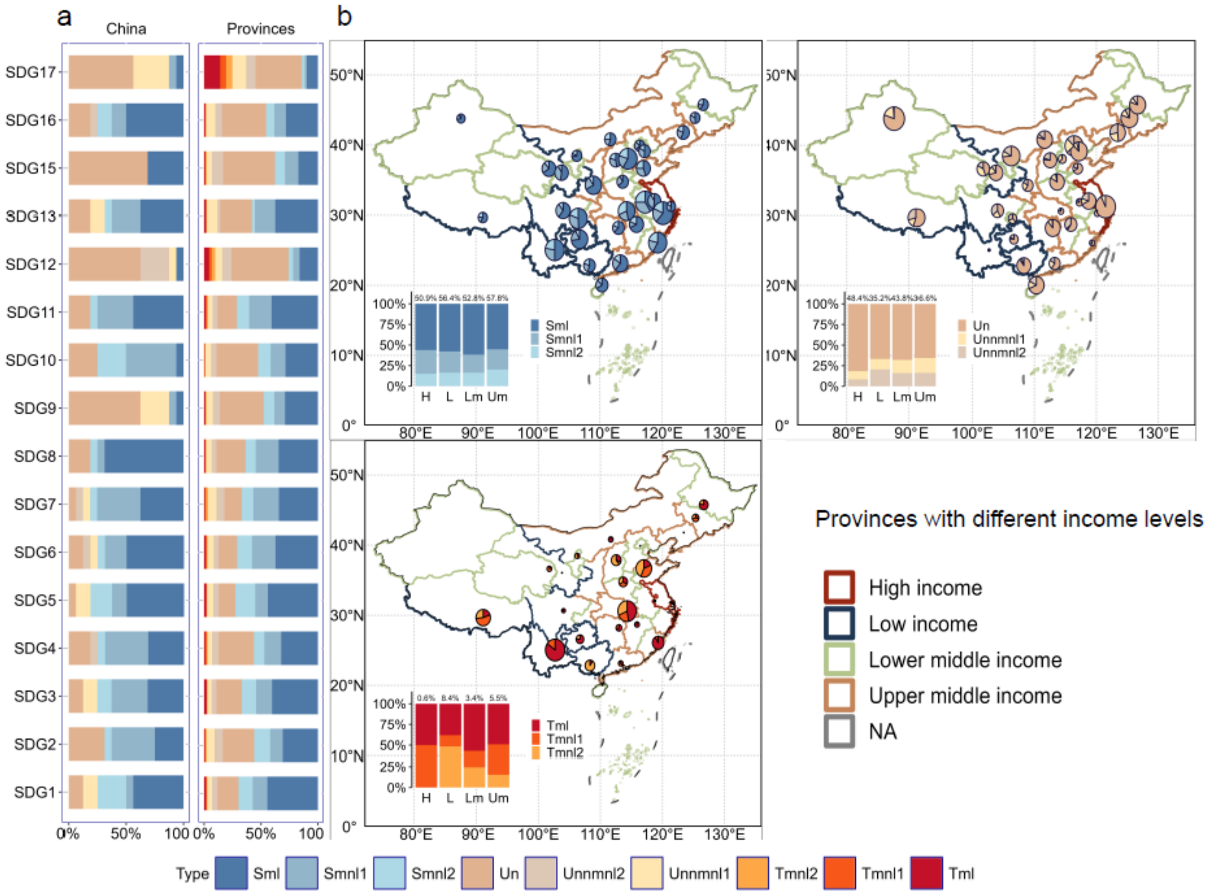

Fig. 3. Distribution of the nine types of SDG interactions. (**a**) Relative distribution of the nine types of interactions across SDGs at the national or provincial scale in China. (**b**) Spatial distribution of the nine types of interactions across China. The bar chart represents the proportions of each relationship type in provinces categorized by four different income levels (classified in Table S3). The full names of the nine abbreviated SDG interactions are as follows: synergy monotone linear interactions (Sml), trade-off monotone linear interactions (Tml), unclassified interactions (Un), Type I synergy monotone nonlinear interactions (Smnl1), Type I trade-off monotone nonlinear interactions (Tmnl1), Type I unclassified non-monotone nonlinear interactions (Unnmnl1), Type II synergy monotone nonlinear interactions (Smnl2), Type II trade-off monotone nonlinear interactions (Tmnl2), and Type II unclassified non-monotone nonlinear interactions (Unnmnl2). For detailed definitions of these different SDG interactions, please refer to Table 1.

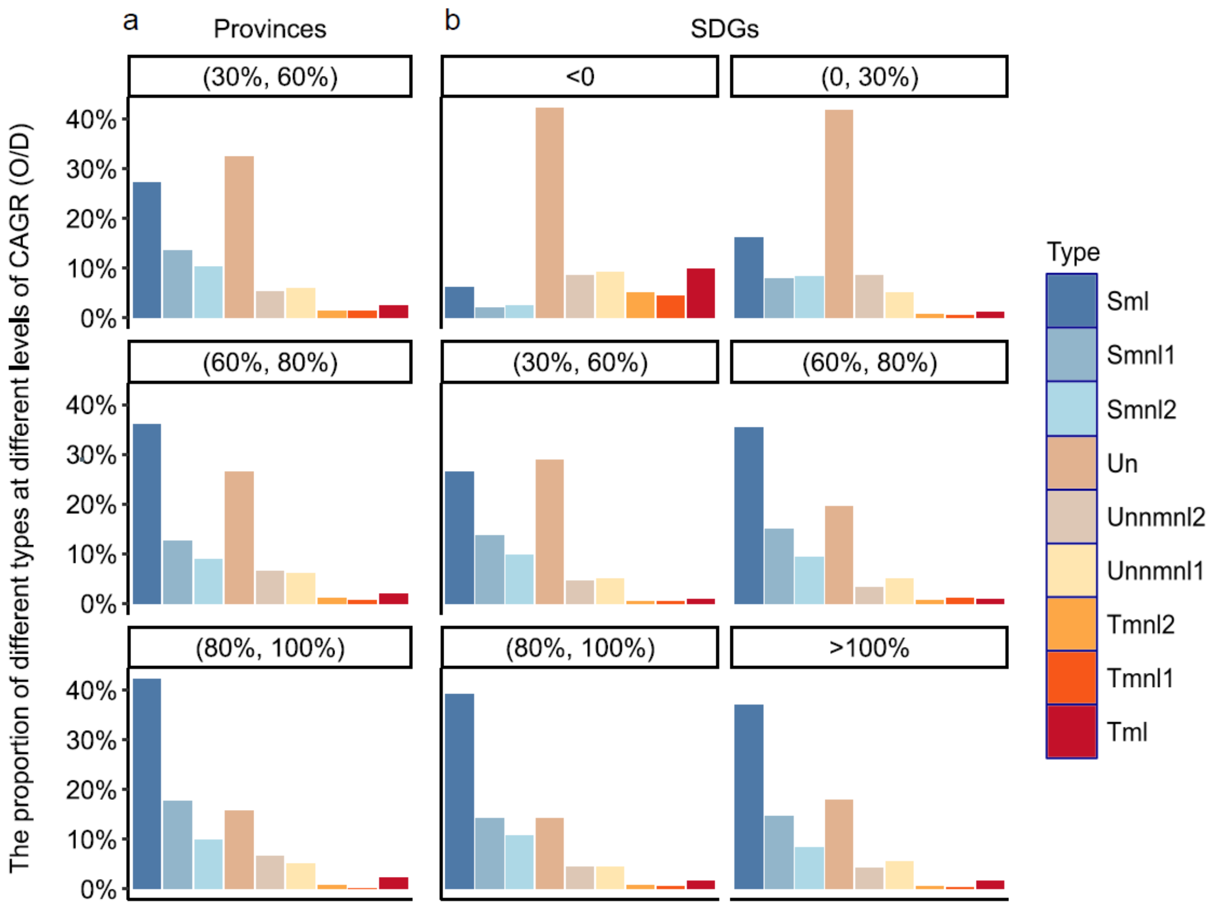

Fig. 4. Proportion histograms for the ratio of the observed compound annual growth rate to the desired compound annual growth rate ($CAGR_{(O/D)}$) for provinces and individual SDGs. (**a**) Probability distribution of the ratios of $CAGR_{(O/D)}$ across provinces for the SDG Index (first column of panels on the left). (**b**) Proportion distribution of the ratios of $CAGR_{(O/D)}$ for individual SDGs (next two columns of panels to the right). The full names of the nine abbreviated SDG interactions are as follows: synergy monotone linear interactions (Sml), trade-off monotone linear interactions (Tml), unclassified interactions (Un), Type I synergy monotone nonlinear interactions (Smnl1), Type I trade-off monotone nonlinear interactions (Tmnl1), Type I unclassified non-monotone nonlinear interactions (Unnmnl1), Type II synergy monotone nonlinear interactions (Smnl2), Type II trade-off monotone nonlinear interactions (Tmnl2), and Type II unclassified non-monotone nonlinear interactions (Unnmnl2). For detailed definitions of these different SDG interactions, please refer to Table 1.

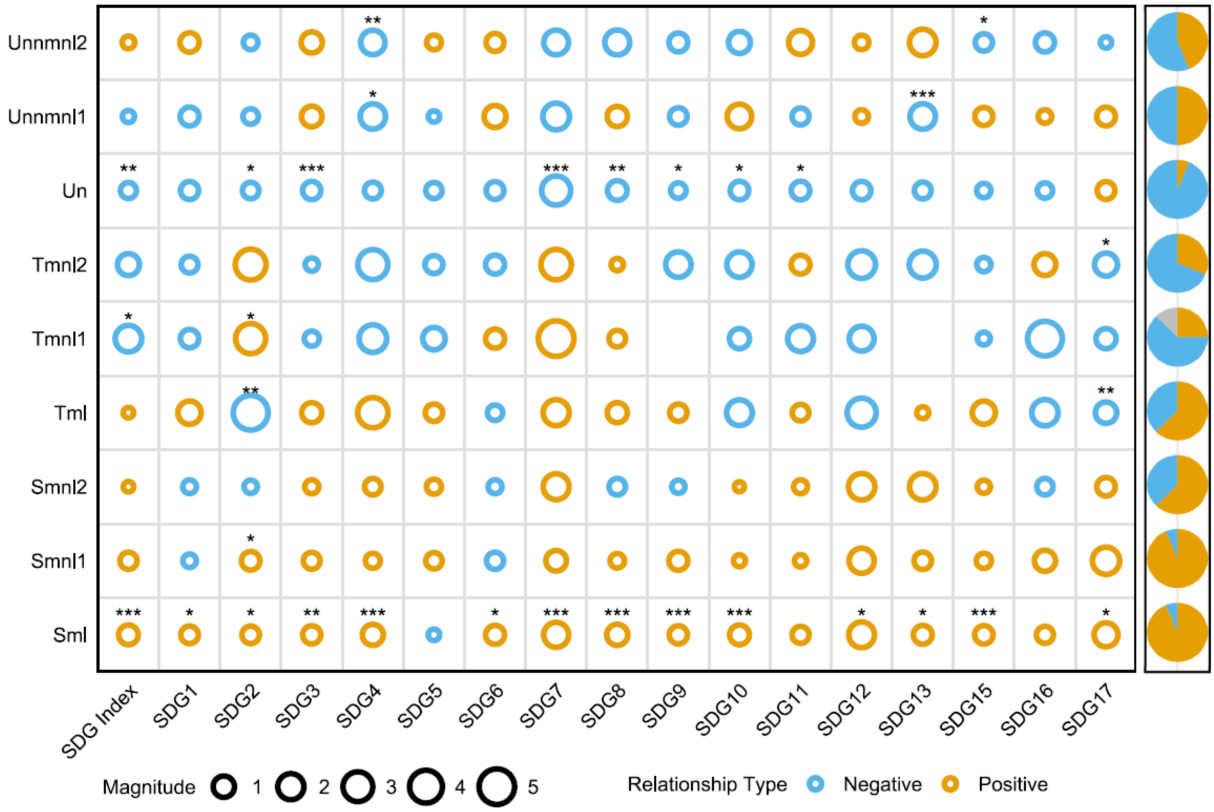

Fig. 5. Results of the linear regression analysis between different SDG interactions and the ratio of the observed compound annual growth rate to the desired compound annual growth rate ($CAGR_{(O/D)}$) for each SDG. It shows how each interaction contributes to or hinders the goals. The pie charts on the right show the percentage of each relationship type that helps or hinders in achieving the goals. The color of circular symbols indicates the sign of the regression slope: orange for a positive slope and blue for a negative slope. The size of each symbol is proportional to the absolute slope value, with larger points indicating greater absolute values. Significance levels are as follows: *** $p < 0.001$, ** $p < 0.01$, and * $p < 0.05$ (Table S5). The full names of the nine abbreviated SDG interactions are as follows: synergy monotone linear interactions (Sml), trade-off monotone linear interactions (Tml), unclassified interactions (Un), Type I synergy monotone nonlinear interactions (Smnl1), Type I trade-off monotone nonlinear interactions (Tmnl1), Type I unclassified non-monotone nonlinear interactions (Unnmnl1), Type II synergy monotone nonlinear interactions (Smnl2), Type II trade-off monotone nonlinear interactions (Tmnl2), and Type II unclassified non-monotone nonlinear interactions (Unnmnl2). For detailed definitions of these different SDG interactions, please refer to Table 1.