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Research Progress on the Coupling Mechanism of Climate Change Mitigation and Carbon Footprint

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Abstract. The trend of global warming continues to intensify, and carbon emissions generated by human activities keep rising, which has become a key contradiction hindering the sustainable development of ecosystems. Carbon footprint can quantitatively describe the carbon emission intensity of human production and living activities and the resulting environmental pressure. This indicator has a two-way interactive and mutually restrictive coupling feedback relationship with climate change mitigation. Cumulative emissions measured by carbon footprint serve as an important driver of rising temperatures and frequent extreme climate events. In turn, various ecological risks derived from climate change constrain carbon emission behaviours of industrial sectors and push all sectors to carry out low-carbon transformation, forming a dynamically operating coupling system. This paper sorts out existing theoretical achievements concerning carbon footprint accounting systems and climate change mitigation. It analyses the internal logic of interactions between carbon footprint and climate change from four coupling dimensions: driving force, process, response and regulation. It summarises the objective rules of coordinated evolution between carbon footprint and climate responses at regional, industrial and product scales. It also identifies feasible coupling regulation paths including low-carbon emission reduction actions, carbon sink capacity improvement, industrial low-carbon upgrading, policy supervision and control. Meanwhile, this paper points out existing research deficiencies in this field at the current stage: insufficient depth in the analysis of coupling mechanisms, inconsistent standards for various quantitative models, an imperfect multi-party collaborative governance framework, and inadequate capacity for dynamic feedback simulation. Based on the practical demands of implementing China's "Dual Carbon" strategy and domestic climate governance, this paper puts forward future research directions from the perspectives of multi-dimensional coupled quantitative measurement, intelligent simulation, cross-industry and cross-regional collaborative emission reduction, and dynamically adaptive governance models. It aims to provide referable theoretical foundations and practical support for the coordinated advancement of climate change mitigation, socio-economic low-carbon transformation and the construction of a full-scope carbon governance system.

Keywords: climate change mitigation, carbon footprint, coupling mechanism, low-carbon transformation, Dual Carbon goal

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1. Introduction

1.1. Research background

After entering the 21st century, various ecological and environmental contradictions keep emerging. Global warming is no longer a simple rise in atmospheric temperature. Instead, it has evolved into a far-reaching ecological crisis that affects the survival and development of all humankind. Massive consumption of fossil fuels, continuous industrial production activities and changes in land use patterns keep releasing greenhouse gases into the atmosphere, directly driving the continuous rise of global temperatures. Glacier melting and sea level rise have gradually appeared, and the frequency of disasters such as extreme high temperature, heavy rainfall and drought has increased significantly. Warming breaks the original global energy balance and hydrological cycle. It also exerts holistic impacts on food security, ecosystem stability, residential environmental safety and the sustainable development of society and economy. How to govern climate change has become a major environmental issue shared by all countries around the world.

As the largest developing country worldwide and one of the top carbon emitters, China plays a vital role in global climate governance. In September 2020, China formally put forward the development goal of "striving to peak carbon dioxide emissions before 2030 and achieve carbon neutrality before 2060", namely the "Dual Carbon" goal [1]. This goal stands as a solemn commitment made by China to participate in global climate governance. It also acts as a critical starting point for the high-quality development of domestic economy, relief of resource and environmental constraints, and promotion of green modernisation. Against this historical background, how to accurately identify various carbon emission sources, quantify the stress effects of human social activities on the climate system, and formulate emission reduction plans consistent with the objective rules of climate response has become a key research topic to be solved in the interdisciplinary field of low-carbon science and climate science.

1.2. Research significance

Theoretically, this research can further improve the analytical framework of the carbon-climate coupling system. As an indicator, carbon footprint can measure the stress of anthropogenic greenhouse gas emissions on the atmospheric system at multiple scales including region, industry, enterprise and product. Compared with traditional single-dimensional carbon emission statistics, carbon footprint emphasises cumulative emissions from a life-cycle perspective and can reflect the comprehensive impacts of socio-economic activities on the climate and environment more comprehensively.

Practically, clarifying the coupling mechanism between the two can provide decision-making references matching real conditions for the implementation of China's "Dual Carbon" strategy. At present, many practical obstacles remain in the progress of domestic carbon emission reduction. Regions in China differ in resource endowments and economic development stages. Uniform emission reduction policies may easily widen inequities in regional development. Different high-carbon industries have accessible transformation paths and applicable technical solutions, so differentiated supporting policies need to be designed. The accounting of product carbon footprint itself is confronted with practical problems such as inconsistent accounting standards and poor quality of basic data [2]. Only by sorting out the evolution characteristics of carbon footprint at global, national, regional, industrial and product levels, together with its response features to various

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climate policies, can scientific support be provided for accurate, efficient and fair emission reduction policies.

1.3. Review of existing research branches

Existing literature related to the theme of this paper generally falls into three research branches. The first branch focuses on multi-scale quantitative accounting of carbon footprint. Its research objects have gradually shifted from national and regional scales in early studies to finer levels including cities, households, enterprises and products. At the urban scale, for example, Meng Fanxin et al. took Shenzhen as a case and built an urban carbon footprint accounting framework from the life-cycle perspective. Their results showed that Shenzhen's total carbon footprint reached 65.6619 million tonnes CO_2e in 2015. Scope 1 direct emissions accounted for 49.99%, Scope 2 indirect emissions from purchased electricity accounted for 18.89%, and Scope 3 cross-boundary indirect emissions accounted for 31.12% [3]. On this basis, they pointed out that urban carbon neutrality initiatives should not only control direct emission sources within administrative boundaries. Indirect emission reduction on the consumption side and along supply chains is equally important.

The second branch centres on emission reduction paths and the coupling relationship between energy and carbon emission systems. From the perspective of high-quality development, Huang Junxin et al. analysed the coupling relationship between energy consumption and carbon emissions and constructed a coupling degree measurement model. Their findings indicated that the two maintain a high level of coupling in the long run and cannot be fundamentally changed in a short period. High-quality economic development can adjust the degree of such coupling [4].

The third branch examines the quantitative relationship between carbon emissions and the responses of the climate system. Working Group I of the Sixth Assessment Report of the IPCC systematically assessed the physical science basis of climate change and provided authoritative evidence for understanding the link between anthropogenic carbon emissions and climate system responses [5]. In terms of emission accounting and observation, Friedlingstein et al. have released global carbon budget reports continuously to track annual changes in anthropogenic emissions such as fossil fuel combustion and land-use change, as well as various carbon sinks [6]. Deng et al. delivered the latest assessment of global carbon emissions and decarbonisation progress, and noted that a notable gap remains between current emission reduction progress and temperature control targets [7]. At the mechanism level, the near-linear relationship between transient climate response to cumulative carbon emissions (TCRE) underpins the carbon budget framework. Tachiiri et al. investigated the rise of TCRE [8], while Spafford et al. further quantified the probability distribution of TCRE to characterise its uncertainty [9]. Chinese scholars such as Zhou Tianjun et al. clarified key scientific issues in the estimation of future carbon emission space under the temperature targets of the *Paris Agreement*, and stressed that accurate estimation of the remaining carbon budget is essential for designing emission reduction roadmaps [10].

It can be seen from the three branches above: carbon footprint accounting studies supply quantitative methods at multiple scales; climate response studies describe the quantitative relation between cumulative carbon emissions and temperature rise; emission reduction path studies explore approaches for the low-carbon transition of energy and economic systems. Together, they form the theoretical foundation of this paper. Nevertheless, most existing studies stay confined within their own branches. Carbon footprint accounting is rarely directly connected with the response process of the climate system. Climate response research seldom goes down to specific emitters such as cities, industries and products. Emission reduction path analysis mostly adopts single-system frameworks. Few studies treat carbon footprint and climate change mitigation as an integrated coupling system

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and carry out comprehensive multi-dimensional and multi-scale investigations. In particular, there is ample room for research on the quantitative simulation of dynamic feedback effects and the construction of collaborative governance systems. This is the research gap that this paper intends to address.

2. Theoretical framework of carbon footprint and climate change mitigation

2.1. Concept, accounting boundaries and mainstream accounting methods of carbon footprint

Carbon footprint refers to the total direct and indirect greenhouse gas emissions generated by a research subject, industrial sector or a single product throughout its entire life cycle. All emissions are converted uniformly into carbon dioxide equivalents to measure the contribution of human activities to the greenhouse effect [11].

By research scale, carbon footprint can be classified into regional carbon footprint, industrial carbon footprint, corporate carbon footprint and product carbon footprint. By emission source, it falls into direct carbon footprint and indirect carbon footprint. Compared with conventional carbon emission statistics, carbon footprint highlights full-chain, whole-process and cumulative emission characteristics, which better match the scientific mechanism of long-term cumulative warming of the climate system [12].

At present, three mainstream accounting approaches are widely adopted in academia, as shown in Table 1. The first is the IPCC emission factor method. It relies on officially released emission factor datasets to rapidly calculate carbon emissions at regional and industrial levels. This method requires little data collection, covers wide application scenarios, and serves as the basic tool for macro-scale research. The second is the input-output method. It uses economic input-output matrices to analyse the correlation of indirect carbon emissions among industrial sectors, and is suitable for studying embodied carbon footprint in industrial transfer and cross-regional trade. The third is the life cycle assessment method, which strictly follows relevant *ISO* standards. It breaks down every stage of a product from raw material extraction to waste disposal, collects activity level data and emission factors for each link, and sums up the data to obtain the full-life-cycle carbon footprint of the product [13]. In addition, with advances in big data and intelligent simulation technologies, machine learning, remote sensing inversion and spatial econometric models have gradually been applied to simulate the spatial-temporal patterns of carbon footprint, further improving calculation accuracy and dynamic representation capacity.

Table 1. Comparison of three mainstream carbon footprint accounting methods

Method	Basic Principle	Applicable Scale	Major Advantages	Major Limitations
Life Cycle Assessment	Bottom-up; collect data by stages and sum the results	Product, enterprise	Fine granularity, high standardisation	Heavy data requirement; results sensitive to boundary selection
Input-Output Analysis	Calculate embodied carbon among sectors based on input-output tables	Nation, region, industry	Captures industrial linkages and carbon transfer	Slow data updates; coarse sector classification
Emission Factor Method	Activity data multiplied by emission factors	Macro inventories, corporate inventory checks	Simple operation, easy data access	Focuses mainly on direct emissions; results depend heavily on factor selection

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2.2. Core theories and technical system of climate change mitigation

Climate change mitigation is an integrated process that slows warming rates and reduces climate system risks through human intervention: cutting greenhouse gas emissions, enhancing ecological carbon sequestration, and regulating atmospheric greenhouse gas concentrations [14]. Its core theoretical foundation is built on the global carbon cycle balance theory, climate system radiative forcing theory and sustainable development theory. It emphasises the dynamic balance between anthropogenic carbon sources and natural carbon sinks, and pursues long-term stability of the climate system [15]. The carbon budget theory is a critical component: cumulative carbon emissions show an approximately linear correlation with global temperature rise. If warming is capped within a predefined target, the total allowable global carbon emissions will have a clear upper limit, namely the remaining carbon budget [10]. This theory translates abstract temperature control targets into quantifiable total emission constraints, providing quantitative support for countries to set emission reduction goals and allocate emission space.

In terms of technical implementation, the climate change mitigation system consists of three major directions: emission reduction, carbon sink enhancement and adaptive regulation. For emission reduction, anthropogenic carbon emissions are reduced by adjusting energy mix, upgrading industries, deploying energy-saving technologies, promoting green transport and guiding low-carbon lifestyles among residents. For carbon sink enhancement, ecological projects such as afforestation and reforestation are carried out to store carbon in vegetation and soil [5]. For adaptive regulation, climate risk early warning mechanisms, low-carbon policy supervision and cross-regional collaborative governance ensure dynamic matching between emission reduction progress and climate responses. Together, they form a complete mitigation technical framework: *source emission reduction – mid-term carbon sequestration – terminal regulation*.

2.3. Transmission and cumulative mechanism of carbon emissions in the climate system

Greenhouse gases do not dissipate immediately after entering the climate system; they go through a complete transmission chain: atmospheric retention followed by cumulative temperature rise.

In terms of atmospheric retention, only roughly half of the carbon dioxide released by human activities remains in the atmosphere. The rest is absorbed by ocean and terrestrial ecosystems. Oceans sequester carbon via physical dissolution and the biological pump effect. Terrestrial ecosystems fix carbon mainly through photosynthesis in forests and other vegetation. Ocean and land carbon sinks act as buffers and slow the rise of atmospheric carbon dioxide concentrations.

As for the cumulative mechanism, the best estimate from the IPCC Sixth Assessment Report is that every 1000 Gt CO_2 of cumulative emissions raises the global mean temperature by approximately 0.45 °C, with a probable range of 0.27 °C to 0.63 °C [5]. This linear relationship establishes a quantitative link between carbon emissions and temperature rise. To achieve the 1.5 °C or 2 °C temperature target, we can reversely calculate the remaining allowable global emissions, i.e., the remaining carbon budget. Essentially, carbon footprint quantifies human disturbance to the natural carbon cycle. Continuous cumulative emissions directly lift atmospheric greenhouse gas concentrations and further alter the climate system. In turn, climate change brings ecological degradation, frequent disasters and restricted industrial development, which constrain human carbon emission behaviours. This forms a closed-loop coupling system: *anthropogenic carbon disturbance – climate response feedback – low-carbon governance adjustment*. This is the underlying scientific logic behind the coupling relationship between carbon footprint and climate change mitigation.

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3. Bidirectional coupling mechanism between climate change and carbon footprint

3.1. Driving coupling: climate forcing effect of carbon emissions

The positive driving effect of carbon footprint on the climate system is mainly reflected in the radiative forcing effect induced by accumulated greenhouse gases. CO_2 molecules strongly absorb infrared radiation. When atmospheric CO_2 concentration rises, a large share of longwave radiation emitted from the land surface is trapped, which consequently warms the troposphere and cools the stratosphere. The cumulative carbon footprint emissions and the peak global temperature rise roughly follow a linear pattern. The TCRE framework condenses this complex physical process into a concise quantitative relationship: cumulative carbon emissions are approximately linearly correlated with the global mean temperature rise.

Two underlying reasons account for this pattern. First, CO_2 has a long atmospheric lifetime, so its radiative forcing depends more on total cumulative emissions rather than short-term emission rates. Second, the proportional relationship between ocean heat uptake and ocean carbon uptake remains generally stable under different emission scenarios [8]. Carbon budget estimation can be carried out based on this rule: once a temperature target is set, the upper limit of allowable cumulative emissions can be derived reversely.

Nevertheless, the linear TCRE relationship shows obvious nonlinear deviation under overshoot pathways. Tachiiri et al. revealed the physical mechanism behind such deviation [8]. In the early stage of CO_2 concentration decline, ocean heat uptake drops rapidly while ocean carbon uptake keeps increasing. Heat uptake and carbon uptake decouple temporarily, causing a transient TCRE rise of 10%–50%. This indicates that for overshoot pathways with excess early emissions offset by carbon removal later, the warming impact per unit carbon emission will exceed the prediction of linear models. For the 1.5 °C warming target, the remaining carbon budget may decrease by 16%–35% compared with estimates based on constant TCRE.

TCRE estimates carry multiple sources of uncertainty. For observational constraints, Spafford et al. used probability density functions to quantify the uncertainty in TCRE estimates and found that the TCRE probability distribution is strongly affected by the selection of historical emission datasets and ocean heat uptake estimation methods [9]. In terms of model structure, different Earth system models adopt inconsistent treatments for cloud feedbacks, indirect aerosol effects and carbon cycle feedbacks, which directly lead to substantial divergence in model outputs. These uncertainties are not merely technical issues. They affect the confidence interval of carbon budget results and the reliability of emission reduction pathways. Higher uncertainty requires larger safety buffers in policy design.

Carbon footprints at different scales exert distinctly different driving effects on the climate system. Carbon footprints generated by large-scale energy consumption and industrial activities at the regional scale are important drivers of local warming and intensified urban heat islands. Sustained carbon emissions from concentrated energy-intensive industries break the original regional energy balance and trigger local climate anomalies. The carbon footprint of a single product over its life cycle is limited in magnitude, yet the aggregated emissions from massive products across society can also create non-negligible macro climatic stress. Overall, the spatial agglomeration, temporal accumulation and internal structural differences of carbon footprints jointly determine the warming rate, temperature increment and regional divergence of climate change.

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3.2. Process coupling: reverse constraint of climate change on carbon footprint

Climate change does not only passively receive impacts from carbon emissions. Various ecological, economic and social risks triggered by climate change in turn constrain human carbon emission behaviours and form a negative feedback regulation mechanism. The rising frequency of climate disasters such as extreme heat, drought, flood and sea level rise weakens ecosystem stability, disrupts agricultural production, damages infrastructure and causes growing socio-economic losses. These pressures push societies to abandon high-carbon production modes, optimise energy supply structures and achieve low-carbon industrial transition.

At the physical level, extreme climate events can directly alter carbon emission patterns with clear internal logic. Heatwaves raise electricity demand for air conditioning. Relevant estimates show that global warming of 1 °C increases cooling electricity demand by 5%–10%. Droughts reduce hydropower output and force supplementary power generation from fossil fuels. Floods damage energy infrastructure, and additional carbon emissions are generated during post-disaster reconstruction [10]. As global warming intensifies, extreme events become stronger and more frequent, creating a vicious cycle: rising emissions → climate warming → more frequent extreme events → disturbance to energy systems → further emission growth. It should be noted that physical constraints are asymmetric. The positive climatic benefits of emission reduction often take decades to emerge, whereas the adverse impacts of extreme events on energy systems can break out within a short period.

At the ecological level, declining carbon sink capacity is the most direct reverse constraint imposed by climate change on carbon footprint, and it is also a positive feedback link that requires close attention. Climate warming imposes heat stress on forests, reduces net primary productivity, increases forest mortality under drought and raises wildfire risks, directly weakening forest carbon sinks [16]. Ocean carbon sinks face similar challenges: ocean acidification disturbs the growth of calcifying organisms and changes the carbon transport efficiency of the marine biological pump. Shifts in ocean circulation reduce deep-sea carbon sequestration and weaken ocean uptake of anthropogenic CO_2. Once such positive feedbacks are activated, natural processes can hardly achieve self-recovery.

At the macro governance level, rising global climate risks drive the update of the international climate governance system. Countries around the world have successively introduced emission reduction policies, carbon pricing mechanisms and low-carbon industrial standards to restrict the unregulated expansion of high-carbon industries. From the industrial perspective, climate risks raise production costs and environmental risks for high-carbon sectors, pushing enterprises to implement energy conservation, carbon reduction and technological upgrading. From the micro perspective, public science communication on climate risks improves people's risk perception, encourages low-carbon consumption and controls household carbon footprints, forming bottom-up constraining forces [17].

3.3. Response coupling: dynamic responses of carbon footprint to climate policies

Carbon pricing serves as a critical policy instrument and mainly includes carbon tax and emission trading systems. A carbon tax sets a fixed price for each unit of carbon emission. Enterprises pay more when they emit more, which motivates them to cut emissions. The emission trading system sets a cap on total emissions in advance and distributes emission allowances to the trading market. Carbon prices fluctuate with market supply and demand. Enterprises with low abatement costs achieve more emission reductions and sell surplus allowances to entities facing higher abatement

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costs [18]. Although they operate differently, both instruments internalise the external costs of carbon emissions and push firms and consumers to take carbon costs into account in their decisions. International practical experience shows that higher carbon prices and wider industry coverage deliver stronger restraining effects on carbon footprints. Policymakers also need to consider the competitiveness of local enterprises and assess the living impacts of policies on low-income groups.

Product carbon footprint labelling and certification systems are emerging as important channels for policy response. Labelled carbon footprint information allows consumers to learn the full-life-cycle emissions of products from raw material extraction to end-of-life disposal, making low-carbon goods more preferable. To sustain market competitiveness, enterprises voluntarily reduce emissions across their whole supply chains. This pathway can be summarised as "point-chain-area": starting from carbon footprint accounting for individual products, emission reduction pressure spreads upstream along supply chains to form constraints at the industrial chain level, and further expands to entire industries and the socio-economic system [19]. The European Union's Carbon Border Adjustment Mechanism (CBAM) is an outward extension of this logic. Imported products are required to bear corresponding carbon costs, forcing exporting enterprises to implement emission reduction measures.

Technological progress forms another major response pathway. Climate policies send clear price signals and market expectations, encouraging enterprises to develop and deploy low-carbon technologies such as clean energy substitution, energy efficiency improvement, process innovation and carbon capture and storage. Breakthroughs and cost reductions in technology in turn accelerate carbon footprint reduction, creating a virtuous cycle where policies drive technological innovation and technological innovation delivers emission reductions [20]. Nevertheless, technological responses feature time lags. It often takes a decade or longer for technologies to move from laboratory research to commercialisation and large-scale deployment. This calls for early, stable policies that convey clear long-term expectations to the market.

3.4. Regulation coupling: coordination between mitigation policies and carbon footprint governance

China's carbon emission governance adopts the "dual control of carbon emissions" as its core institutional framework. It controls both the total amount and intensity of energy use and carbon emissions, establishing a multi-level governance system covering regions, industries, enterprises, projects and products. The central government decomposes emission reduction targets layer by layer through territorial carbon assessment. It restricts the expansion of high-carbon industries via industrial access and emission standards, requires enterprises to conduct carbon inventories, controls new emissions through project carbon impact assessment, and realises full-life-cycle low-carbon management via product carbon footprints. This builds a connected, full-coverage governance network linking macro and micro levels [21]. The five levels — region, industry, enterprise, project and product — jointly form a relatively complete governance framework. Difficulties in collaborative governance still exist during implementation.

First, rebound effects and carbon leakage undermine actual abatement outcomes. Improved energy efficiency may stimulate greater market demand, while high-carbon production capacity shifts across regions, offsetting emission reductions achieved locally. This reveals the drawbacks of fragmented governance. Second, carbon policies bring uneven distributional effects. Tighter carbon constraints substantially raise operating costs for energy-intensive sectors and increase living burdens on low-income groups. Without supporting arrangements such as carbon revenue recycling and transitional employment security, governance may meet resistance and trigger conflicts over

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social equity [18]. Carbon emission governance must balance abatement efficiency and distributional equity, and rely on policy coordination to ensure a smooth low-carbon transition.

To clarify the complex feedback between carbon footprint and climate change mitigation, this paper develops a bidirectional coupling mechanism framework, as shown in Figure 1.

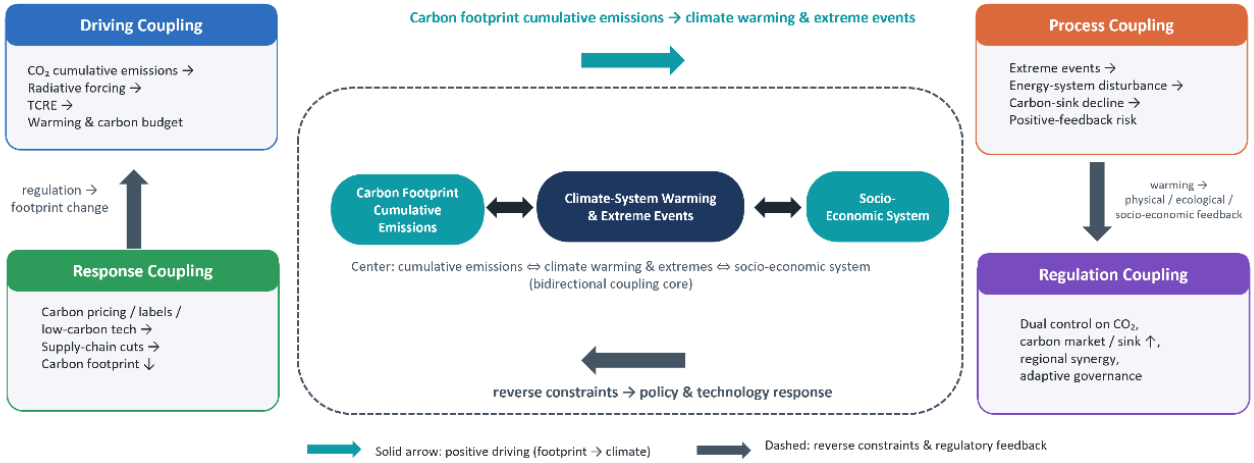


Figure 1. Bidirectional coupling mechanism framework between carbon footprint and climate change mitigation

4. Research progress on multi-scale coupling characteristics and low-carbon response rules

4.1. Carbon footprint and climate responses at global and national scales

Global carbon footprint generally shows a trend of initial growth followed by gradual stabilisation. According to the latest assessment from the Global Carbon Project, global fossil-fuel CO_2 emissions reached approximately 40 billion tonnes in 2025. The Asia-Pacific region accounts for nearly half of this total and stands as the world's largest emission source at present [6]. The global emission pattern can be roughly divided into three categories. Developed economies such as Europe, the United States and Japan underwent industrialisation earlier. Their emissions have peaked and declined steadily, yet per capita emissions remain relatively high. Countries including China and Russia are on a high plateau around peak emissions. Their total emissions are large, yet increments are minimal, and negative growth can be observed in certain periods. Emerging economies and less developed regions such as India, Southeast Asia and Africa are experiencing rapid industrialisation with rigidly rising carbon emissions, making them the main source of future global emission growth [7]. China aims to reach its carbon peak before 2030. Its emissions have entered a plateau phase, while installed capacity of non-fossil energy expands rapidly. Non-fossil power generation is expected to rise by 13% in 2025, corresponding to a reduction of roughly 3.3 billion tonnes of CO_2 emissions [7].

Historical records clearly reveal the linkage between global carbon footprint and temperature rise: larger cumulative emissions correspond to higher warming levels. Since 1850, cumulative net global CO_2 emissions have amounted to around 2400 Gt CO_2, pushing the global average temperature rise beyond 1.1 °C [6]. Future trajectories are assessed through scenario simulation. The IPCC combines different Shared Socioeconomic Pathways and Representative Concentration Pathways to generate multiple development scenarios ranging from 1.5 °C to above 4 °C. To achieve the 1.5 °C warming target, the world needs to reach net-zero CO_2 emissions around 2050. The time window is extended to roughly 2070 for the 2 °C target. C4MIP (Coupled Climate-Carbon Cycle

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Model Intercomparison Project) serves as an important simulation tool. It couples carbon cycle modules with climate systems to quantify carbon-climate feedback strength, namely the extent to which warming weakens carbon sinks and retains more carbon in the atmosphere [20].

4.2. Spatial-temporal differentiation of regional carbon footprint and its climate response features

The regional scale is a critical unit for carbon footprint-climate coupling research. China's regions differ greatly in resource endowments, industrial structures and economic development levels, leading to obvious spatial-temporal heterogeneity in carbon footprints. Eastern coastal regions enjoy advanced economic development and dense industrial agglomeration, accompanied by large total carbon footprints, high emission densities, and higher risks of local warming, urban heat islands and extreme heat events. Resource-based regions in central and western China rely heavily on energy industries and feature prominent high-carbon emissions. They face long-term climatic pressures including drought and ecosystem degradation. Different high-carbon industries respond unevenly to climate policies. The power sector has low abatement costs and mature supporting technologies, so it reacts sensitively to carbon price fluctuations. Carbon price hikes drive the expansion of wind and solar power installations. Industries such as steel and cement carry high abatement costs and lack mature technological reserves. They are highly vulnerable to carbon price volatility. Excessively high carbon prices may weaken corporate competitiveness and even trigger carbon leakage, where production capacity shifts to regions without carbon constraints while global total emissions see no real decline [18]. Therefore, when the carbon market expands to cover these sectors, allowance allocation should proceed step by step to reserve time and space for corporate transition.

From the temporal perspective, continuous urbanisation and industrialisation expand regional carbon footprints alongside intensified regional warming. As "Dual Carbon" policies are implemented and energy structures keep optimising, some economically developed regions witness slowing carbon footprint growth and falling emission intensity. The corresponding deterioration of regional climate is initially mitigated. This fully demonstrates the spatio-temporal consistency between the evolution of regional carbon footprints and climatic conditions.

4.3. Refined carbon footprint management at product and enterprise scales

Research at product and enterprise scales shifts carbon footprint management from aggregate statistics to refined accounting. Product carbon footprint accounting covers the whole life cycle of a product, from raw material extraction to end-of-life disposal, and is broken down into individual components and every production procedure. Practical application scenarios for such techniques keep expanding. In clean energy and power sectors, carbon footprint accounting frameworks for photovoltaic modules, wind turbine blades and power batteries are relatively mature. Accounting results have even become important access requirements in international trade. The EU CBAM explicitly demands imported products to declare carbon footprint data. Within the petrochemical industry, accounting for carbon footprints of traditional petroleum-based products is gradually extended to bio-based alternatives. Sinopec completed China's first carbon footprint accounting of bio-based benzene in 2026, and the results have been recognised by clients in Europe, Japan and South Korea [19]. Enterprise carbon footprint management is transforming from passive compliance to active strategic arrangement. Previously, firms conducted carbon footprint accounting mostly to meet regulatory inspections or customer audits. At present, an increasing number of enterprises integrate carbon footprint management into supply chain control, product design and even

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investment decision-making. Thirty-seven chemical enterprises including BASF jointly compiled and released the *Guidelines for Product Carbon Footprint in the Chemical Industry*, unifying internal calculation standards and enabling mutual comparison of carbon data along supply chains [19]. Nonetheless, multiple practical challenges persist at product and enterprise scales. It is difficult to obtain emission data from upstream supply chains, and small and medium-sized enterprises lack capacity for refined carbon accounting. Accounting methods vary across countries and industries, so results cannot be directly compared. Product carbon footprint calculations are built on baseline data from a specific period, while supply chains, energy mixes and production processes keep changing, creating barriers to dynamic updates of accounting outcomes.

5. Bottlenecks in coupling regulation and existing problems of low-carbon governance

5.1. Bottlenecks in coupling mechanism research and quantitative models

First, research on coupling mechanisms lacks sufficient depth. The interaction between carbon footprint and climate change forms a complex system with multiple links and feedback loops. Many existing studies remain confined to the unidirectional causal logic that rising carbon emissions drive climate warming. They fail to fully interpret intrinsic mechanisms such as bidirectional feedback, nonlinear responses and threshold effects. For instance, model outputs for the magnitude and timescale of permafrost carbon release under warming can differ by several times. Academia has not reached consistent conclusions about the temperature threshold at which forest carbon sinks shift from carbon uptake to carbon release [22]. Poor understanding of underlying mechanisms deprives regulation measures of solid scientific support.

Second, quantitative models lack unified standards. Most existing studies analyse carbon footprint characteristics and simulate climate trends separately. Quantitative models designed for their coupling relationship are still immature. Many coupling analyses rely merely on simple correlation and regression methods, which cannot capture cumulative lag effects of carbon footprints, time lags of climate feedback, or the evolutionary rules of dynamic mutual feedback. Static studies dominate while dynamic simulations remain scarce; linear analyses are common, yet interpretations of nonlinear coupling are inadequate, making it hard to uncover deep feedback mechanisms. Even for carbon footprint accounting in the same region, results derived from LCA and IOA can differ by 20% or more. Switching emission factor databases also leads to notable deviations [11]. Without consistent models, it is difficult to carry out policy simulation and effect evaluation on a shared platform.

Third, capacity for dynamic feedback simulation is insufficient. Most current coupling models are static or quasi-static and do not fully incorporate dynamic interactions between carbon emissions and climate change. Many models fail to reflect positive feedback loops: rising carbon prices encourage firms to invest in low-carbon technologies, and technological progress cuts abatement costs and further promotes emission reduction. Dynamic simulation of process coupling is also missing for pathways in which warming raises the probability of extreme events, and extreme events disrupt energy systems and agricultural production to indirectly alter carbon emission levels [23].

5.2. Problems within the low-carbon governance system and policy coordination

Carbon emission reduction covers numerous sectors including energy, industry, transport, construction, agriculture, science and technology, finance and fiscal administration. In practice, however, departments often work in isolation with poor policy coordination. For example,

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renewable energy promoted by energy authorities may face absorption difficulties if power grid planning cannot keep pace. Low-carbon technologies funded by science and technology departments struggle to move out of laboratories without timely supporting industrial and financial policies. Reports from the Ministry of Ecology and Environment also note that coordination among policies on carbon accounting, carbon footprint, green certificates and carbon markets needs further improvement [24].

The second challenge lies in uneven regional development and the difficulty of collaborative governance. China has a vast territory, and regions vary substantially in development stage, industrial structure and resource endowments. Eastern coastal regions boast advanced economies and relatively light industries, making emission reduction less demanding. Central and western regions host dense resource-based industries and a large share of heavy chemical sectors. They face heavy emission reduction pressure with limited capacity. Uniform, one-size-fits-all emission reduction targets may impose excessive costs on less developed regions and even threaten energy security and people's livelihoods. Excessively differentiated policies, on the other hand, may trigger carbon leakage: high-carbon industries shift from strictly regulated regions to loosely regulated ones without cutting national total emissions. Mature frameworks for fairly allocating emission reduction responsibilities across regions and building cross-regional collaborative governance mechanisms are still lacking [24].

Third, market mechanisms remain imperfect. The carbon trading market is the core market-based instrument for emission reduction, yet the national carbon market currently covers only the power sector. High-carbon sectors such as steel, cement and chemical industry have not yet been fully included, resulting in narrow coverage. Carbon prices fluctuate sharply and fail to deliver stable long-term price signals, undermining firms' confidence for long-term investment. Institutional design questions are still under exploration, including how carbon tax and carbon trading can coordinate, how carbon markets connect with green certificate markets, and how product carbon footprint accounting results align with carbon border tariffs. Imperfect market mechanisms and blocked transmission of price signals naturally weaken firms' intrinsic motivation for decarbonisation [11].

5.3. Deficiencies in data foundation and technical support

All governance activities rely on data, yet data infrastructure stands out as a prominent weakness at present. The primary concern lies in the uneven quality of data used for carbon footprint accounting. Product carbon footprint accounting requires activity data and emission factors covering the whole supply chain, from raw material extraction, manufacturing and logistics to product usage and end-of-life disposal. Data from upstream suppliers are often difficult to access, and small and medium-sized enterprises lack the capacity for refined carbon inventory. For emission factors, many studies directly adopt overseas databases or IPCC default values, while locally and regionally calibrated emission factor datasets remain insufficient. This makes accounting outcomes poorly adapted to domestic contexts. Without reliable baseline data, carbon footprint accounting loses practical value, and policies formulated based on such results may deviate from real-world conditions [11].

Second, carbon emission monitoring capacity needs strengthening. At present, domestic carbon emission data are mainly obtained through corporate self-reporting and statistical accounting, with limited coverage of real-time online monitoring. CEMS (Continuous Emission Monitoring Systems) have been deployed in parts of the power sector, yet process emission monitoring in steel, cement and chemical industries remains inadequate. Monitoring capacity is particularly weak in agriculture, transport and building sectors. Insufficient monitoring undermines the timeliness and accuracy of

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carbon emission data, leaving allowance allocation and compliance verification in the carbon market without solid data support [24].

Third, technologies for deep decarbonisation are not yet fully mature. Power supply technologies such as wind and solar power are well developed. However, industrial deep decarbonisation technologies including hydrogen metallurgy, low-carbon cement, green ammonia and CCUS mostly remain at the demonstration stage. They carry high construction and operational costs with limited industrial scale and are far from large-scale commercial rollout. Enabling technologies for massive new energy integration, such as energy storage, power grid flexibility retrofitting and the full hydrogen industrial chain, also await technological breakthroughs. Restricted key technologies mean that even high-carbon industries with emission reduction intentions face implementation barriers or unaffordable mitigation costs [23].

6. Conclusion and prospect

6.1. Main conclusions

Focusing on the coupling mechanism between carbon footprint and climate change mitigation, this paper sorts out relevant theoretical foundations, internal interaction mechanisms and multi-scale evolutionary characteristics, and identifies practical bottlenecks for coupling regulation. The relationship between carbon footprint and climate change is not a simple unidirectional causal link, but a complex system characterised by bidirectional interactions and dynamic feedback. Cumulative carbon footprints amplify the greenhouse effect and drive global warming. In turn, climate change reshapes human emission patterns through physical shocks, ecological feedback and socio-economic pressures. The two are closely connected across four dimensions: driving coupling, process coupling, response coupling and regulation coupling.

Furthermore, the approximately linear TCRE relationship between cumulative emissions and global warming provides quantitative support for carbon budget management and temperature target delivery. Nevertheless, this linear relationship breaks down near climate tipping points. Positive feedbacks such as permafrost carbon release and reversed forest carbon sink functions carry risks of nonlinear accelerated warming, which deserve high attention.

Among carbon footprint accounting methods, LCA, IOA and the emission factor method each have strengths and limitations. Integrated application of multiple methods will represent a future research direction. Climate change mitigation requires simultaneous progress in low-carbon energy transition, end-use electrification, industrial process innovation and ecological carbon sink enhancement; no single technology can deliver emission reduction targets. Current coupling regulation is constrained by inadequate mechanistic understanding, inconsistent quantitative model standards, missing dynamic feedback simulations, poor policy coordination, unbalanced regional development, imperfect market mechanisms, weak baseline data and immature deep decarbonisation technologies. Systematic solutions are needed from scientific research, institutional governance and technological development.

6.2. Limitations and prospects

Future research may prioritise the following directions. First, conduct multi-dimensional quantitative coupling analysis by deeply integrating carbon footprint accounting models, climate system models and socio-economic models, to build a unified, dynamic, multi-scale coupling simulation platform and improve the scientific validity and reliability of policy assessment. Second,

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adopt intelligent simulation technologies based on big data, artificial intelligence and digital twins to raise the real-time performance and accuracy of carbon emission monitoring, and strengthen prediction and early warning for complex coupled systems. Third, promote cross-sector coordinated emission reduction by breaking administrative and regional barriers, establishing a governance system linking energy, industry, transport, construction and agriculture with coordinated actions across eastern, central and western China, so as to realise synergistic benefits of policy packages. Fourth, develop dynamically adaptive governance frameworks with mechanisms for continuous monitoring, regular evaluation and timely adjustment, to optimise policy instruments and mitigation pathways in response to evolving realities.

Overall, research on the coupling mechanism between carbon footprint and climate change mitigation is interdisciplinary. It requires joint efforts from climate science, environmental science, economics, management science and engineering. With the continuous advancement of China's "Dual Carbon" strategy and global climate governance, research outcomes in this field will grow in both theoretical value and practical significance.

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