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Carbon Emission Rights as a New Form of Usufructuary Right

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Received: 19 June 2025; Accepted: 3 September 2025; Available online: 17 September 2025

ABSTRACT: The debate surrounding the legal nature of carbon emission rights arises from the tension between their dual characteristics of public and private law, which challenges traditional property rights theory. This tension has led to conflicts regarding the effectiveness of legal frameworks, fragmented regulations, and a crisis of institutional trust within the carbon market. Carbon emission rights should be redefined as a novel form of usufructuary right, with ecological capacity resources—owned by the state—serving as the object. These rights are realized through digitalization and specificity enabled by blockchain technology. Their powers and functions can be understood as twofold: the power of quota control, which falls under public law constraints, and the power of ecological benefits, which exists within private law autonomy. The former limits the boundaries of private rights by ecological thresholds, while the latter translates ecological value into non-possession benefits. To address these issues, a "two-stage governance" system can be established through a dynamic interpretation of Article 329 of the Civil Code of the People's Republic of China (2020), creating a registration system and enacting specialized legislation for Carbon Emission Rights Trading. By conceptualizing carbon emission rights as a new type of usufructuary right, the contradictions between public and private law can be reconciled, enabling the transition of the carbon market from a policy-driven to a rights- and law-based operation.

Keywords: Carbon emission rights; Usufructuary rights; Ecological capacity resources; Quota control rights; Ecological benefit rights

Terminology Explanation

Usufruct: Refers to a limited real right where the holder is entitled to possess, use, and derive benefits from property owned by another, without altering its essential nature or disposing of its ownership. Traditional usufruct typically applies to tangible assets such as land and buildings; this article extends its application to intangible ecological capacity resources, emphasizing "non-possessory" and "functional control" characteristics [1].

Blockchain: A distributed ledger technology that employs cryptographic algorithms, timestamps, and consensus mechanisms to ensure that data, once recorded, becomes virtually tamper-proof. It enables full traceability and decentralized verification. In this context, blockchain leverages its "unique coding + smart contract" functionality to transform carbon emission quotas into specific, publicly verifiable digital objects, thereby addressing the challenge of rights confirmation for intangible resources [2].

1. Problem Identification

As a critical mechanism for achieving the "dual carbon" goals, carbon emission trading has expanded from regional pilot programs to nationwide implementation [3]. Despite the growing scale of transactions and the increasing number of participants, the inadequate development of legal norms has led to systemic risks, resulting in three major structural contradictions regarding the nature of carbon emission rights.

First, there exists a conflict concerning the boundary between public and private law at the legal level. Carbon emission rights are imbued with dual characteristics: obligations governed by public law and disposal powers rooted in private law. This results in a complex structure of "regulatory empowerment—autonomous exercise of rights". However, the current legal system has failed to establish a unified framework to reconcile these two aspects, leading to boundary

https://doi.org/10.70322/ecolciviliz.2025.10015

disputes between public law intervention and private autonomy. This conflict arises from the paradigm differences between "command-and-control" environmental regulation and the market-driven property rights system [4]. It not only weakens the role of carbon emission rights in balancing public and private interests, but also hinders the coordinated optimization of resource allocation and ecological objectives within a legal framework for carbon markets [5].

Second, fragmentation and disconnection arise at the local regulatory level. Some local legislation assigns quasi-property rights to carbon emission rights based on market logic, while others adhere to an administrative control perspective, limiting the rights to mere expressions of environmental interests. In China's administrative legislation at both central and local levels, the definition of "carbon emission rights" or "carbon emission quotas" varies significantly. While regions such as Beijing and Chongqing characterize it as "the right to emit greenhouse gases" or an "entitlement", provinces like Guangdong and Hubei define it merely as a "quantified indicator allocated by the government". Meanwhile, jurisdictions such as Shanghai and Shenzhen avoid attributing a specific legal nature to their provisions, referring directly to "quotas" as the subject of trading. Such textual discrepancies not only reflect the academic divergences—such as the property rights theory and the administrative permit theory—projected in local legislation, but also result in inconsistent supporting systems regarding whether quotas can be mortgaged, inherited, or dealt with in bankruptcy proceedings. The fragmentation of local regulations has resulted in divergent standards for ownership determination, eroded the liquidity of carbon emission rights, and created legal challenges for cross-regional transactions [6].

Finally, judicial decision-making reveals a divergence in legal reasoning. There is ambiguity in judicial practice regarding the classification of carbon emission rights. If viewed as private property, the logic of autonomy would grant right holders complete disposal rights and compensation priorities. Conversely, if public law regulatory attributes are emphasized, the exercise of private rights must be constrained by the public interest. This dilemma exacerbates the market's trust crisis regarding the system's stability, undermining the expected functionality of a law-based carbon market [7].

The core issue is that carbon emission rights neither fully conform to the private law framework of rights nor entirely comply with the constraints imposed by public law regulations. This results in a "four-nothings" situation concerning their legal attributes.

2. Literature Review: From the "Public-Private Debate" to the "Absence of Technology"

2.1. The Path Dilemma in Existing Doctrines

2.1.1. Administrative Permit Theory: Normative Conflict between Public Law Authorization and Private Autonomy

This theory defines carbon emission rights as administrative licenses granted by authorities under the Administrative Licensing Law [8]. While it aligns with public law logic, it neglects the need for private law autonomy.

Wang Mingyuan [9] argues that carbon emission rights should be characterized as having quasi-property attributes. Zheng Shuang [10] contends that defining carbon emission rights as property rights would render the setting or adjustment of carbon allowances a substantial intervention into the content of property rights. Li Wei [11] posits that carbon emission quotas, "administered by the ecological and environmental authorities" and "established based on administrative permits for the use of atmospheric environmental capacity", reflect a "strong administrative dominance" and a public law nature. Chen Yilong [12] views carbon emission rights as a "non-transferable" franchise under Article 9 of China's Administrative License Law, emphasizing their public law attributes. Meanwhile, Ren Zhuoran and Liu Shiqi [13] argue that carbon emission quotas are essentially administrative permits issued by authorities under a cap-and-trade system, whereas tradable products must possess property attributes—the two should not be conflated. Button J [14] suggests that within trading systems, carbon emissions manifest as a "sui generis right", it has the dual attributes of both commodities and currency. However, treating them merely as homogeneous goods may lead to an "equivalence dilemma" due to divergent regulatory standards across jurisdictions. Drawing on the U.S. SO_2 trading experience, Reisch M S [15] advocates treating allowances as "limited property rights" that can be freely traded. Yet Shittu I & Abdul Latiff A R [16] promptly note that propertization creates a "property lock-in", wherein governments must compensate holders if they reduce the cap ex post. To resolve this, Godwin K & Ntayi J M [17] propose the concept of "regulatory license", framing allowances as revocable administrative privileges that can be reclaimed without compensation in the public interest. To transcend the property–regulation dichotomy, Capretto M & Ceresa M [18] designed a "Carbon Currency" model, which was later refined by Ding K & Fan L [19].

This article argues that the fundamental flaw of the administrative permit theory lies in its use of a static public law framework to dissect the "disposition gene" of carbon emission rights. Blockchain-based registration can technically solidify the boundaries of "limited disposition", thereby resolving the normative conflict between "prohibition on transfer" and market circulation.

2.1.2. The Property Theory and the New Rights Theory: The Triple Dilemma of Definitude of Object, Rules of Alteration, and Public-Private Interface

The Property Theory suggests that carbon emission rights should be recognized as a new form of property right, with "ecological capacity resources" as the object. It seeks to endow them with exclusive control through the property rights section of the Civil Code [20]. However, this theory is inconsistent with the current legal situation. Article 114 of the Civil Code requires property rights to be "specific". Yet, carbon emission rights are intangible, relating to the "atmospheric environmental capacity", which conflicts with traditional property rights theory that emphasizes physical control. The "Interim Regulations on the Administration of Carbon Emission Rights Trading" stipulate that these rights are "transferable". Still, they fail to establish clear rules for altering property rights, leaving carbon emission rights without stable support in the context of property law. Moreover, conflicts arise from public law interventions, wherein administrative authorities possess regulatory powers such as freezing or revoking quotas in accordance with the law. These actions directly undermine the exclusivity characteristic of property rights, revealing a fundamental value disconnect between the logic of "private rights primacy" and public law regulation.

Pan Xiaobin [21] points out that the legislative gap concerning carbon credits has perpetuated the debate over the legal nature of carbon emission rights. Nie Zhihai [22] advocates for the inclusion of carbon emission rights in the Property Section of the Civil Code, albeit only under the classification of "quasi-property" or "property-like" rights. Zhou Xu [23] observes that the current Civil Code has not yet provided a definitive characterization of such rights. Wang Wenxi [24] further notes that the "atmospheric environmental capacity" resists specific delineation, thereby preventing it from breaking the traditional constraint that usufructuary rights apply only to immovable property.Burgoyne M T & Olexiuk P [25] argue that in the absence of a unified and cross-border enforceable definition of rights, carbon credits suffer from weakened liquidity and pledgeability as financial assets. Laoli E & Alamsyah A [26] propose that ownership, transferability, and enforceability of carbon credits should be encoded into self-executing smart contracts. Saeed N [27] suggests that a "unified meta-registry" built on Distributed Ledger Technology (DLT) could resolve the difficulties in specifying environmental capacity within traditional property frameworks. Michels J D & Millard C [28] provide a paradigm for upgrading carbon emission rights from "quasi-property" to a digital usufruct that is "registrable, pledgeable, and traceable".

The claim of the new rights theory is that carbon emission rights are a "mixed" or "environmental" right, blending public law regulation and private law autonomy. This approach attempts to transcend the traditional dichotomy by categorizing carbon emission rights as "public-private hybrids" [6]. However, the power structure within this theory remains ambiguous. It fails to define the boundaries of the exercise of rights due to regulatory obligations or to clarify the hierarchy of effects when the exercise of disposal rights conflicts with public interests, leading to a vague conception of rights.

Chen Jinglin [29] contends that carbon emission rights constitute a form of property rights, analogous to the right to use environmental capacity. Jiang Chaofu [30] observes that carbon emission rights possess a dual nature, combining characteristics of both an "administrative permit" and "property rights". Tang Tang [31] argues that environmental rights can be normatively articulated through property rights provisions within the Civil Code. Ye Yongfei [32] proposes a dual hybrid model of "environmental rights–property rights".Lähteenmäki-Uutela A [33] notes that, in international law, carbon emission rights are often defined as a "new type of property right", given their attributes of exclusive use, economic value, and incentive effects. Nie S [34] & Khurshid A [35] advance a "multiple interests–rights juxtaposition" framework for conceptualizing carbon emission rights. Lecuyer O & Quirion P [36] further emphasize the necessity of a clear definition of the legal attributes of carbon emission rights.

Although the traditional usufructuary right takes "controlling tangible objects" as its typical model, it is not completely impossible to accept the legal recognition of the disposition relationship of environmental resources [37]. Carbon emission rights, which take intangible ecological capacity as their object, achieve digital specification and exclusivity through blockchain technology, fully aligning with the modern evolution of usufructuary rights toward "non-possessory disposition". Incorporating carbon emission rights into the usufructuary system can clarify the structure of rights and powers, establish a public-private law coordination mechanism, and leverage technological empowerment to

legitimize the system, thereby dispelling traditional doctrinal skepticism regarding the "transferability" of usufructuary rights [38].

2.2. Practical Technological and Legal Challenges

2.2.1. Gaps in Technological Pathway Research

Existing scholarship remains predominantly focused on legal characterization, with insufficient attention paid to rights-affirming technologies. Domestically, Wang Shekun [39] was the first to propose the concept of "digital property rights"; Ren Hongtao [40] argues that carbon emission rights should be legally defined as "data property rights". Zhao Lei [41] suggests that although Article 127 of the Civil Code currently offers data protection that could provide technical support for carbon emission rights, Li Li [42] focuses on the security and efficiency of blockchain consensus algorithms, while Wu Peng [43] explores the systemic transformation of the Civil Code in the digital age. Together, their work provides the technological and jurisprudential foundation for this article's deep integration of blockchain-based rights affirmation and the specification of usufructuary objects.

The international academic community has also begun engaging with this interdisciplinary issue: SUKARDI A J & HERTANTO A W [44] note that English courts have recognized carbon emission rights as "other types of intangible property" through case law; Bassan F & Rabitti M [45] lay a theoretical foundation for the automatic enforcement of compliance obligations via smart contracts; Christodoulou P & Psillaki M [46] and Stöckel M [47] demonstrate the value of blockchain in green financial governance from the perspectives of central bank digital currency and environmental policy, respectively; Bellaj B & Ouaddah A [48] further point out that the timestamp feature of distributed ledgers directly meets the specificity requirements for "electronic records" under the Draft European Property Code. Additionally, Ofoeda I [49] and Abiodun T P [50] provide technical migration experience for the global tokenization of carbon emission rights on-chain from the perspectives of cross-chain interoperability and copyright governance.

2.2.2. Dilemmas in Current Legislation

Carbon emission rights, characterized by their dual nature of public law regulation and private law autonomy, give rise to multiple legal dilemmas in practice. First, public law interventions can directly invalidate private law acts. For instance, in 2020, Shanghai A Certain Industrial Company v. Beijing A certain Computing Technology Company (Case 1) [51] in Beijing, the court ruled an entrustment contract invalid because Bitcoin "mining" violated national industrial policy and the "green principle" under the Civil Code. This reflects a fundamental intrusion of public policy objectives into private autonomy, resulting in significant legal uncertainty regarding the validity of market behaviors. Second, the overlap between public and private law liabilities creates challenges of accumulation and coordination. As seen in the 2017–2019 Deqing County People's Procuratorate v. Deqing, a certain insulation materials company (Case 2)[51] in Zhejiang Deqing, the same corporate act simultaneously triggered administrative penalties, criminal liability, and civil public interest compensation. Although offsetting was attempted in practice (e.g., administrative fines deducted from criminal fines), the relationship between ecological damage compensation and administrative/criminal penalties remains unclear, potentially leading to overlapping liabilities or inadequate remediation. Finally, potential conflicts exist between administrative supervision and judicial enforcement. In the 2021 case involving Agricultural Bank of China, a branch of a certain county v. Fujian: A certain chemical company (Case 8) [51] in Fujian, the court enforced carbon emission quotas as a new form of property. While innovative, such quotas are essentially publicly allocated emission permits. Compulsory disposition may impair a company's compliance capabilities, creating tension between judicial enforcement power and administrative regulatory authority.

These challenges highlight systemic issues in the current legal system when addressing carbon emission rights as a novel type of right, including insufficient coordination between public and private law rules, poor liability coordination, and ambiguous legal characterization. There is an urgent need to clarify the attributes of such rights through legislation, refine judicial application standards, and establish inter-agency collaborative mechanisms to resolve these conflicts systematically [51].

2.2.3. Legal-Economic Challenges of Financialization and Market Evolution

Due to the interdisciplinary nature of carbon assets and institutional differences across countries, a unified theoretical consensus has yet to emerge regarding their legal characterization, market mechanisms, and regulatory frameworks. Button J [14] notes that financialization has transformed carbon emission rights from "administrative

quotas" into "currency-like" assets. Burtraw D & Mansur E [52] emphasize that the U.S. SO_2 trading experience demonstrates that defining allowances as "limited property rights" enhances liquidity but also triggers "asset lock-in" risks in bankruptcy proceedings. Kim Jong Woo [53] argues that if IFRS 9 treats carbon emission rights as "derivative instruments", fair value measurement could lead to significant volatility in corporate income statements. Ekardt F [54] argues that the current Emissions Trading Systems (ETS 1 and ETS 2) provide the central economic incentive for phasing out fossil fuels through progressively tightening cap-and-trade mechanisms and linear reduction factors; nevertheless, their present mitigation ambition remains insufficient to achieve the 1.5 °C target enshrined in the Paris Agreement. Munoz J C [55] finds that carbon price disparities under different regulatory standards have spurred cross-border regulatory arbitrage, exacerbating adverse selection akin to "bad money driving out good". Parhamfar M, Sadeghkhani I, & Adeli A M [56] propose that timestamp and zero-knowledge proof technologies in distributed ledgers can encode exchange rates and clearing rules for "carbon currency" into on-chain smart contracts. Similarly, Gong Weifeng [57] calls for clarifying the financial attributes of carbon emission rights through State Council regulations.

These developments indicate that, both internationally and within the Chinese context, scholars are increasingly exploring the deep integration of blockchain technology with carbon market behaviors, seeking to resolve the paradigmatic challenges in carbon asset research within a tripartite "technology-institution-market" framework.

3. Object Justification: The Ecological Capacity Resource Object of Carbon Emission Rights

3.1. Object Breakthrough in the Context of Paradigm Shift

The traditional concept of usufructuary rights, rooted in the classical theory of real rights, emerged from the cognitive inertia of Roman law, which held that "things must have a form". This historical perspective rigidly confines the scope of real rights to movable or immovable property that can be physically possessed. However, when applied to carbon emission rights, this paradigm faces a significant doctrinal crisis. The traditional emphasis on "physical reality" fosters cognitive biases that equate "possessability" with "disposability", neglecting the practical trend of non-possessable rights facilitating resource utilization through abstract disposal. This exclusionary approach disregards intangible ecological resources, such as atmospheric environmental capacity, as potential property rights objects.

The essence of this paradigm shift under the concept of ecological civilization lies in overcoming the institutional exclusion of ecological capacity resources by "object-centric" approaches. It advocates for the establishment of a functional rights system that caters to environmental governance needs. As a scarce asset integral to achieving the "dual carbon" goals, the market-based allocation of environmental capacity must be underpinned by clear ownership. Without adherence to the traditional paradigm, ecological capacity risks falling into a "tragedy of the commons" due to a lack of defined ownership. Such an absence undermines the capacity to foster technological innovation in emission reduction through private law frameworks or to enforce rigid constraints through public law mechanisms [58]. The key to overcoming this impasse is the reconstruction of the value core of traditional usufructuary rights: shifting from resource allocation to ecological governance. This shift emphasizes functional control rather than physical dominance as the foundational principle for rights construction. Blockchain technology provides an avenue for endowing intangible resources with digital and specific capabilities through unique codes and smart contracts (e.g., the traceability of quotas in the China Carbon Dioxide Registration System), thereby granting ecological capacity the exclusivity and publicizability required of usufructuary objects. Blockchain eliminates traditional theories' doubts about the "liquidity" of intangible resources, offering not just a rule adjustment but a necessary evolution in property rights law, in response to the green principles embedded in the Civil Code. Only by incorporating ecological capacity resources into the object scope of usufructuary rights can their transition from a policy instrument to a legal right be achieved, thereby providing a stable rights foundation for the legalization of carbon markets.

This paradigm shift reflects a transcendence of the traditional physical domination model, moving toward an ecological governance logic centered on functional control. The legitimacy of this shift is underpinned by two factors: First, the construction of ecological civilization necessitates that environmental capacity resources be legally elevated from public goods to objects of legal rights, thus clarifying ownership and fostering emission reductions. Second, the empowerment of digital technologies facilitates the specification and publicization of intangible resources, breaking free from the traditional dependence on physical form. As a usufructuary right, the carbon emission right must be viewed through the lens of functional control as the substantive criterion for real property rights. When legal control over specific resources is achievable through technological means (e.g., blockchain coding) and institutional design (e.g., registration and public disclosure), the right status of ecological capacity should be recognized regardless of its physical form [59]. Currently, ecological capacity resources have met the essential criteria of usufructuary rights—specifiability,

disposability, and public attestability. Incorporating them into the object category of usufructuary rights is not only consistent with normative logic but also represents a deep integration of technological rationality and legal value. Recognizing ecological capacity resources as a property object allows the law to create a coordinated public-private law mechanism within the constitutional framework. This not only offers a usufructuary solution to disputes over the legal nature of carbon emission rights but also advances the transition of the carbon market from policy-driven to rights-based, law-based operation, contributing a Chinese model of institutional innovation to global ecological governance.

3.2. Object Specificity Empowered by Technology

The traditional usufructuary rights paradigm, with its emphasis on the physical form of objects, struggles to address the challenges posed by the intangibility of ecological capacity resources. However, blockchain technology offers a potential solution for the digital affirmation of rights. By utilizing unique codes and distributed ledgers, blockchain technology reconfigures the specific logic of usufructuary rights, transforming intangible ecological capacity resources into digital carriers that are traceable, divisible, and publicizable [60]. Carbon emission quotas are generated as unalterable digital fingerprints through hash algorithms, and their entire lifecycle (allocation, trading, and settlement) is automatically tracked and verified via smart contracts. This process imparts the exclusivity and specificity required by legal rights to the abstract concept of atmospheric environmental capacity.

Blockchain technology provides technical support for the recognition of carbon emission rights as usufructuary rights [61]. When blockchain technology, through unique coding and smart contracts, enables the digital specification of ecological capacity resources, the legal identification of objects ceases to depend on physical tangibility and instead focuses on the functional realization of disposition—that is, whether exclusive control and public attestation of resources can be achieved through technological rationality and institutional design. Specifically, blockchain employs distributed ledger and timestamp technologies to solidify relationships of dominance over ecological capacity into traceable and verifiable legal facts. This shifts traditional usufructuary rights from a static logic of "dominance as right" to a dynamic framework of "disposition as effect". For example, Zhang Yi et al. applied quantum blockchain technology to construct a model for carbon quota allocation and trading to enhance both the fairness of initial quota distribution and the efficiency of market transactions [62].

Meanwhile, Patel D et al. explored using blockchain tokens for issuing and tracking carbon emission permits to promote transparency and decentralization in carbon trading processes [63]. Under this framework, administrative authorities uphold ecological public interests through cap control, while civil actors exercise dispositional powers based on registered publicity, forming a public-private collaborative governance structure. The profound significance of blockchain technology for carbon emission rights lies not only in its potential to resolve the longstanding ambiguity regarding their legal nature but also in its support for the functional evolution of property law from a safeguard of private rights to an instrument of ecological governance.

The innovation in the specificity of usufructuary rights objects facilitated by blockchain technology relies on the registration system to legally confirm the effect of public notice. Traditional public displays of usufructuary rights are limited by time and space, whereas blockchain-driven systems enable real-time synchronization and distributed node consensus, endowing ecological capacity resources with credibility. As Article 208 of the Civil Code specifies, property rights changes must be publicly registered or delivered. Blockchain registries meet this requirement by recording each quota transfer with a timestamp, creating a hash-linked ownership chain. This allows for real-time third-party verification, ensuring the absolute authenticity of records. This logic of publicity not only endows carbon emission rights with erga omnes effect against third parties, but also enables the automatic execution of public law directives—such as compliance surrender and freezing—through smart contracts, thereby achieving seamless integration of administrative intervention and private autonomy.

3.3. The Deep Impact of Blockchain and Digital Technology on the Structure and Legal Framework of Carbon Markets

Blockchain technology not only resolves the challenge of specifying the object of carbon emission rights but also reshapes the underlying logic of carbon markets across three dimensions: transaction structures, regulatory paradigms, and legal applicability. First, transaction structures can evolve from "centralized matching" to "on-chain peer-to-peer" trading: the traditional centralized exchange model is replaced by distributed ledgers. The national carbon emission rights registry system utilizes smart contracts to integrate matching, clearing, and settlement, thereby reducing transaction costs and enhancing transparency. Second, the regulatory paradigm shifts from "ex-post review" to "real-

time penetration": regulators can directly access on-chain data through node permissions and use zero-knowledge proof technology to verify transaction compliance without exposing commercial privacy. Third, the legal framework evolves from "text-based rules" to "code-based rules": smart contracts compile legal provisions—such as cap control, intertemporal banking, and penalty clauses for non-compliance—directly into executable code logic. Once conditions are met, actions are automatically executed, reducing the need for human intervention and interpretive discretion [64].

Through blockchain and digitalization, carbon emission trading markets now exhibit new characteristics of "decentralization, real-time supervision, and code-based governance", driving the legal framework toward a governance transition where "technology becomes the rule".

3.4. Normative Basis and Judicial Support

At the regulatory level, the open interpretation of existing laws can provide a solid foundation for recognizing carbon emission rights as usufructuary rights. Article 329 of the Civil Code offers a normative interface for including intangible resources such as atmospheric environmental capacity within the property rights framework. This aligns with the academic interpretation of natural resources, which encompasses not only traditional physical assets like land and minerals but also newer resources with ecological value [39]. The state ownership of natural resources, as established in Article 9 of the Constitution, can be translated into the limited right of enterprises to use ecological capacity through total quantity control and quota allocation, embodying "the right to use natural resources" [65]. Although the "Interim Regulations on the Administration of Carbon Emission Rights Trading" (2024) do not explicitly define the nature of carbon emission rights, their provision that "quotas are transferable" effectively acknowledges their property rights characteristics. This provision aligns with the right of disposition inherent in usufructuary rights as outlined in Article 326 of the Civil Code. Moreover, the green principles embedded in the Civil Code further substantiate the utilization of ecological capacity resources, legitimizing their inclusion within the property rights system via blockchain technology.

The open-textured interpretation of legal norms creates a doctrinal foundation for the propertization of carbon emission rights, while the synergy between judicial practice and technological empowerment enables its practical realization. Article 18 of the Guidelines on Fully and Accurately Implementing the New Development Philosophy and Providing Judicial Services for the Prudent Advancement of Carbon Peaking and Carbon Neutrality, which addresses the "adjudication of disputes over security interests in carbon emission quotas and certified voluntary emission reductions", substantively reflects a judicial stance protective of carbon emission rights as collateral. By upholding the validity of security contracts and recognizing pledgees' priority in compensation—as evidenced by phrases such as "upholding contract validity to the greatest extent permitted by law" and "supporting pledgees' claims for priority compensation against carbon emission quotas in registered accounts"—the judiciary engages in gap-filling amid legislative silence. Rather than explicitly defining the nature of these rights, judicial authorities indirectly confer erga omnes effect against third parties by recognizing the public credibility of blockchain—such as the timestamp-based immutability and tamper-resistance of quota ownership—thus forming an adjudicative logic where "technology serves as evidence". Here, technology fulfills a dual function: first, the National Carbon Emission Rights Registry employs smart contracts and distributed ledger technology to transform abstract rights into verifiable and traceable legal facts, providing an objective basis for judicial decisions; second, blockchain's publicity system addresses traditional doubts about the "transferability" of intangible resources in usufructuary rights, enabling courts to focus on the substance of disposition relationships rather than physical form [66]. This collaborative mechanism not only operationalizes the "green principle" of the Civil Code but also facilitates the transformation of carbon emission rights from policy instruments into legally enforceable rights. Ultimately, it establishes a progressive rights-affirmation pathway characterized by "normative interpretation—technological support—judicial recognition".

4. Empowerment Deconstruction: The Dual Empowerment of Carbon Emission Rights

To avoid conceptual ambiguity, this article distinguishes between the following two sets of notions: ① "Rights" refer to the overall novel usufructuary right held by carbon emitters over ecological capacity resources owned by the state; ② "Entitlements" denote the quantified emission quotas (unit: tCO_2e) allocated to specific right-holders upon registration.

4.1. Quota Allocation: The Limited Power of Disposition within the Constraints of Public Law

Traditional property rights theory faces a fundamental contradiction in the context of ecological governance, particularly when the object of rights is an indivisible and non-exclusive ecological capacity resource. Exclusive control over such resources is neither physically feasible nor consistent with the public nature of ecosystems [67]. The

institutional design of carbon emission rights is a creative response to this dilemma, transforming the inherent characteristics of natural systems into a rigid legal framework for the operation of rights [68]. This tension gives rise to the unique authority of carbon emission rights—the power of quota allocation. The emission threshold, set by public law based on ecological carrying capacity, defines the absolute upper limit for the exercise of private rights. Within this threshold, quota allocation and transactions rely on private law principles to achieve optimal resource allocation. The freedom to dispose of emission quotas is neither infinite nor entirely restricted; rather, it is reconstructed through a dynamic balance between ecological security and market rationality. In other words, carbon emission quota trading not only embodies the freedom of contract and transactional autonomy inherent in private law, but also embeds ecological responsibilities—in the form of precise numerical values—into the very definition of each right and obligation. Supported by blockchain technology, smart monitoring systems provide continuous real-time data feedback, promptly translating the nonlinear fluctuations of natural systems—driven by climate tipping points—into dynamic signals for adjusting the exercise of legal rights and the performance of obligations [69]. Thus, the legal capacity of carbon emission rights is neither a purely private law instrument nor a mere appendage of public law control. Instead, it embeds ecological principles into market behavior through institutional flexibility, forming a governance paradigm characterized by "bounded autonomy and calibrated intervention" [70].

The "quota control" power of carbon emission rights arises from the legal system's response to the nonlinear characteristics of ecosystems [71]. Traditional environmental governance tends to rely on linear thinking, setting fixed standards, and implementing static rules. However, such approaches are ill-equipped to address the sudden and irreversible changes in ecosystems (such as climate tipping points). Carbon emission rights reconstruct governance logic through a threshold response mechanism: the total emissions figure is not fixed, but rather a dynamic variable that is deeply connected to ecological feedback. When market transaction data is linked to climate monitoring information, preset algorithms can trigger threshold calibration programs, enabling legal rules to adapt in real-time, much like an ecosystem. For example, if satellite remote sensing detects a sudden decline in the carbon sink capacity of forests, the system can automatically suggest a reduction in quotas. After confirmation through legal procedures, a new governance benchmark can be established [72]. Such a design elevates the law beyond a merely reactive instrument for addressing crises, enabling it to emulate the self-regulatory mechanisms of natural systems—constraining human activities within the Earth's ecological boundaries through negative feedback loops.

The "quota control" power of carbon emission rights enables the integration of ecological dynamics with the stability of the law, forming a governance structure characterized by "rigid thresholds and elastic autonomy" [73]. In traditional legal frameworks, public law control and private law autonomy are often in conflict. Environmental regulations enforce market behavior through administrative orders, and property law promotes market autonomy through the freedom to dispose of rights. Carbon emission rights quantify ecological capacity as dynamically adjusted composite parameters (such as total annual emissions). The threshold, however, is not a static administrative directive but one that is flexibly adjusted based on scientific models and ecological feedback. Within this framework, the "elasticity" of private law autonomy remains nested within the "rigidity" of public law boundaries. Although enterprises may freely trade and pledge quotas, their actions are consistently subject to the implicit regulation of ecological thresholds. Market price fluctuations reflect not only supply and demand but also real-time ecological feedback signals. This "threshold response" autonomous mechanism allows the law to indirectly regulate transactions by resonating with market dynamics. It transforms ecological laws into institutional levers, guiding market entities to align with environmental capacity through price signals. Ultimately, a self-adjusting governance ecosystem is established through balancing freedom and restraint.

4.2. Ecological Benefit: The Expression of the Right to Non-Possessive Use

In addition to the power of quota allocation under public law constraints, carbon emission rights extend further into private law autonomy, with the power of ecological benefits. When the emission threshold defines the ecological security boundary through legal design, ecological beneficiary rights can create non-possessive benefits within this boundary. These benefits transform the service functions of ecosystems into quantifiable property rights. Enterprises do not need to physically control the atmospheric environment to internalize the positive externalities of emission reduction (e.g., regional air quality improvements) into tradable economic assets. This can be achieved simply through the compliance management and market circulation of emission quotas. The key innovation in this design is that it shifts the focus of disposal from the physical occupation of resources to the ecological contribution at the institutional level. Quota management represents the functional maintenance of environmental capacity, while market transactions convert

this maintenance behavior into economic incentives through price signals. Thus, the income derived from usufructuary rights is extended to the capitalization of ecological value: carbon emission rights not only safeguard the economic interests of private rights holders but also embed ecological security goals within market rationality, transforming environmental protection from passive compliance into active value creation [74].

The ecological beneficiary rights of carbon emission rights embed the dynamic balance of ecosystems into the normative logic of market behavior through "institutional flexibility". The market circulation of carbon emission rights no longer serves solely the efficient allocation of resources. Instead, it reveals the scarcity of ecological capacity through a price discovery mechanism, driving market entities to internalize environmental costs into their decision-making processes [75]. For example, the market premium on carbon quotas reflects the marginal cost of ecological restoration, incentivizing enterprises to reduce emissions through technological innovation. Green financial derivatives, such as carbon futures and carbon pledges, convert long-term ecological value into immediate financing capacity, creating a cross-period incentive structure of "expected returns—actual investment".

Through the "dynamic equilibrium" mechanism, ecological beneficiary rights embed the ecosystem's self-repair capacity into the institutional framework of market behavior, achieving a deep coupling of legal rules and natural laws. The ecological benefit function, through legal fiction, transforms the dynamics of ecosystems—such as carbon cycles and climate feedback—into operable institutional variables. For instance, the market circulation of carbon quotas not only reflects current supply and demand relationships but also, through price fluctuations, mirrors real-time changes in ecological capacity, thereby forming an adaptive cycle of "natural signals → market response → regulatory adaptation".

Under this logic, property law shifts from "post-event relief" to "process regulation", evolving from a passive "rights confirmer" to an active "system coordinator". This governance paradigm, built on the trinity of "rights—nature—technology", integrates ecological laws and market mechanisms into a cohesive framework.

4.3. Dual Rights Distinct from Traditional Usufructuary Rights

The authority to control carbon emission quotas transcends the doctrinal framework of traditional usufructuary rights, achieving a structural embedding of public law intervention into private autonomy [76]. Traditional usufructuary rights allow holders to exclusively utilize tangible objects through physical control, with their right of disposition restricted only by private agreements [77]. However, the allocation of carbon emission quotas is based on the threshold characteristics of ecological capacity resources, defining a rigid boundary: the total emissions figure, established by administrative authorities in accordance with constitutional and environmental law principles, represents the absolute upper limit of such rights. This limited disposition is reflected not only in the dynamic adjustment of total quotas (e.g., reductions triggered by climate tipping points) but also in the internalization of public law constraints into technical rules via blockchain smart contracts (e.g., automatic execution of quota freeze instructions) [78]. Hence, the structure of authority in carbon emission rights is not one where private autonomy takes precedence, but rather one where public-interest constraints hold primacy.

Ecological beneficiary rights further deconstruct traditional usufructuary rights by transforming the object of real rights into non-possessive usufructuary rights [79]. In traditional usufructuary rights, the generation of benefits presupposes the physical consumption of the object—for instance, mining requires the removal of ore from mineral deposits, and farming entails extracting produce from the land. In contrast, the ecological benefit function of carbon emission rights is entirely detached from the domination of a physical object: enterprises need not physically occupy atmospheric space; rather, by lawfully obtaining and transferring emission quotas, they can quantify positive outcomes—such as increased carbon sequestration and improved air quality resulting from emission reduction measures—into attributable property value and transform them into tradable economic benefits. The innovativeness of this design of rights and powers lies in its use of legal fiction to transform the service functions of ecosystems into substantive rights content, thereby elevating benefit generation from direct physical domination to the abstract utilization of ecological value. For example, the market premium of carbon quotas reflects not only economic supply and demand but also implicitly incorporates the marginal cost of ecological restoration; The essence of its benefits is the privatized expression of environmental public interests. Simultaneously, the ecological benefit function of carbon emission rights remains constrained by the green principle under Article 9 of the Civil Code, which mandates that the acquisition of benefits must uphold ecological security as a baseline [80]. Leveraging blockchain-based registry systems, environmental data—such as forest carbon sinks—are updated in real time. Should excess emissions be detected, smart contracts automatically trigger profit adjustment mechanisms, obligating non-compliant entities to provide financial

remediation [81]. This design transforms the function of property rights from resource allocation to ecological governance, ultimately achieving a dialectical unity between private autonomy and public-interest constraints.

It is evident that the fundamental distinction between carbon emission rights and traditional usufructuary rights lies in the public-interest constraints inherent in "quota control" and the innovative departure from conventional property logic through "ecological benefit" realized without physical possession [82]. The "ecological benefit" function completely abandons reliance on physical domination, employing legal fiction to internalize the positive externalities of intangible resources—such as atmospheric environmental capacity—into quantifiable and tradable property interests. It elevates benefit generation from consumptive use of objects to the abstract preservation of ecological value.

4.4. A Three-Dimensional Comparison between the EU ETS and China's Usufructuary Approach

4.4.1. Nature of Quota Rights

EU ETS allowances have been characterized by the Court of Justice of the EU as "tradable administrative authorizations" (Case C-127/07), which may be revoked at any time for public interest reasons, resulting in weak stability of property rights. They may be used to establish pledges either through fixed or floating charges [54]. In contrast, China anchors carbon emission rights in ecological capacity owned by the public and establishes them as usufructuary rights under Article 329 ("right to use natural resources") of the Civil Code of the People's Republic of China (2020). The existence of these rights is not subject to unilateral administrative discretion and enjoys exclusivity and erga omnes effect [83].

4.4.2. Effectiveness of Security Interests

Whether EU Allowances (EUAs) can be pledged depends on whether member states include them in the list of "pledgable assets", leading to regulatory fragmentation [84]. SUKARDI & HERTANTO (2023), in a comparative study of Indonesia and England, note that pledges of EU ETS quotas are influenced by divergent national legislations and lack unified rules [44]. In China's usufructuary model, carbon emission rights can directly apply to pledge rules under Article 440 of the Civil Code and receive priority over ordinary claims in bankruptcy proceedings, providing financial institutions with uniform expectations. For example, Hou Guoyue (2023) demonstrates that carbon emission rights are eligible for pledge rules and enjoy priority in bankruptcy compensation [85].

4.4.3. Public Law Intervention

The EU ETS allows the Commission to temporarily cancel allowances under Article 29a of the Directive, without providing a compensation mechanism [86]. China's approach internalizes cap reductions through the "quota control function" by encoding adjustment thresholds into smart contracts. Any quota modification must undergo proportionality review and trigger compensation clauses, achieving a balance between public-interest constraints and private rights protection. Yang Jiejun (2024) argues that dynamic quota adjustments under a cap-and-trade system must comply with the principle of proportionality and be accompanied by compensation mechanisms [87].

In summary, the usufructuary approach demonstrates stronger institutional advantages over the EU ETS in terms of rights stability, financing facilitation, and predictability of intervention, offering a Chinese paradigm for the legalization of global carbon markets.

5. Realization of Rights: The Normative Path for Incorporating Carbon Emission Rights into the Usufructuary Rights System

5.1. Dynamic System Interpretation of Article 329 of the Civil Code

The normative meaning of "the right to use natural resources" in Article 329 of the Civil Code must transcend the physical constraints of traditional property rights objects through a dynamic system interpretation approach. This interpretation provides doctrinal support for recognizing the usufructuary nature of carbon emission rights. From a purposive perspective, the legislative value of this provision lies not only in confirming existing types of natural resource rights but also in responding to the legal recognition of ecological capacity resource utilization in the context of ecological civilization.

From an analogical perspective, although traditional usufructuary rights, such as exploration and water withdrawal rights, superficially involve physical objects, their essence lies in the non-possessive control of resource functions. Similarly, the power structure of carbon emission rights, characterized by "quota control + ecological benefit", shares

functional homogeneity with these traditional rights. Both transform abstract resource utilization relationships into exclusive rights through legal mechanisms. The primary difference lies in the fact that the intangibility of ecological capacity resources can be digitized and specified through blockchain technology. Consequently, carbon emission rights fully align with the regulatory framework of "natural resource use rights" under Article 329 of the Civil Code. Their inclusion in the usufructuary rights system represents a natural extension of legal doctrine.

Furthermore, the openness of dynamic system interpretation allows judicial interpretations and market practices to fill the gaps left by written laws. The Supreme People's Court could incorporate established trading practices, such as quota pledges and intertemporal carryovers in the carbon market, into the scope of usufructuary rights. This would clarify the real rights status of ecological capacity resources through judicial interpretation.

From a system interpretation perspective, Article 329 of the Civil Code forms a normative synergy with the green principle under Article 9, collectively establishing the institutional foundation for the propertization of ecological capacity resources. The open-textured formulation of the "right to use natural resources" in Article 329 precisely provides interpretative space for such new types of rights. A systematic interpretation requires that the definition of "natural resources" be understood within the framework of Article 9 of the Constitution, which establishes state ownership of natural resources. As an environmental public good owned by the state, the allocation of usage rights over ecological capacity necessitates the clarification of rights and responsibilities through propertization. The usufructuary nature of carbon emission rights serves precisely this purpose. Consequently, the meaning of "usage rights" under Article 329 should transcend a narrow physical conception and incorporate ecological capacity resources into its normative scope, ensuring the substantive unity of the Civil Code's system with the values of ecological civilization [88]. The Supreme People's Court may employ judicial interpretation to conduct a purposive expansion of Article 329 of the Civil Code, explicitly affirming the legality of carbon emission rights, and incorporating stable rules formed in carbon market practices—such as quota pledging and intertemporal banking—as sources of customary law. This approach maintains the stability of the numerus clausus principle of property rights while dynamically adapting to the practical needs of carbon markets, achieving an organic balance between institutional innovation and normative constraints within the dogmatic framework.

5.2. Technologically Empowered Publicity of Property Rights: A Digital Implementation Path for Blockchain Registry Systems within the Framework of the Civil Code

Having established the usufructuary nature of carbon emission rights through dynamic system interpretation, it is crucial to construct a corresponding registration system to standardize the implementation of legal interpretation through technical means. The blockchain-driven national carbon emission rights registration and filing system utilizes distributed ledger technology and timestamps to convert the digitization and specification of ecological capacity resources into verifiable property rights public notices. Its technical core forms a logical loop with the open interpretation of "natural resource use rights" in Article 329 of the Civil Code. According to Article 208 of the Civil Code, the public announcement of property rights must involve registration as the central requirement, and blockchain's characteristics of immutability and temporality precisely meet this requirement. Under this framework, Article 14 of the Electronic Signature Law endows smart contracts with legal effect, enabling automated processes that trigger property rights changes, such as quota freezing and cross-period carryover, as stipulated in Article 143 of the Civil Code. This addresses the dynamic balance between public law intervention and private autonomy inherent in the "quota control" power mentioned earlier, while also reducing risks associated with human intervention in traditional registration systems through technological rationality. The registration system serves not only as technical support for the usufructuary nature of carbon emission rights but also as an inevitable extension of dynamic system interpretation from theory to practice.

The ultimate goal of the registration system is to contribute to a globally compatible carbon governance framework. Relying on the cross-border data flow rules of the Data Security Law, the domestic blockchain registration system can facilitate ownership chain communication with international carbon markets (e.g., the EU ETS) through mutual recognition of hash values [89]. Furthermore, the introduction of zero-knowledge proof technology helps balance market transparency with commercial privacy protection, ensuring that the registration system remains credible while respecting enterprises' core interests [90]. Through the governance paradigm of "technology as rule", the carbon emission rights registration and credibility system has ultimately become the institutional hub linking the interpretative logic of the Civil Code with global carbon market practices.

The regulatory significance of the registration system lies in its ability to practically implement the dynamic system interpretation of Article 329 of the Civil Code through technological means. Blockchain registration converts the non-possessive control of ecological capacity resources into verifiable legal facts via an immutable ownership chain and automated smart contract execution. As a result, the usufructuary attribute of carbon emission rights moves beyond theoretical deduction to an operational starting point through the credibility of registration, creating a closed-loop governance logic of "legal interpretation—technological empowerment—global collaboration".

5.3. Special Legislative Design for Matching Carbon Emission Rights

Building on the dynamic system interpretation and registration system construction of Article 329 of the Civil Code, it is necessary to bridge regulatory gaps through special legislation—the Carbon Emission Rights Trading Law—and create a carbon emission rights system framework that coordinates public and private laws. The primary objective of the "Carbon Emission Rights Trading Act" is to clarify the usufructuary nature of carbon emission rights while transforming the registration rules and market practices enabled by technology into stable legal expectations. Legislation should begin by defining carbon emission rights as "usufructuary rights that take ecological capacity resources owned by the state as the object and confer rights of possession, use, income, and disposal". This would resolve academic disputes and eliminate uncertainty in judicial determinations. Furthermore, a collaborative mechanism between public and private laws should be designed. On one hand, administrative agencies should be authorized to implement dynamic regulation of total ecological capacity based on Article 9 of the Constitution to ensure public law intervention aligns with the principle of proportionality. On the other hand, the ownership status recorded in the blockchain registration system should have a presumptive effect, creating a closed-loop system between the public notice requirements of Article 208 of the Civil Code and the technical rules of the Electronic Signature Law. The theoretical core of the "Carbon Emission Rights Trading Act" is to reconstruct the "two-stage governance" logic between public and private laws. The first stage, grounded in Article 9 of the Constitution, establishes state ownership of ecological capacity resources and grants administrative organs the authority to implement total quantity control based on "ecological security" (as defined in Article 44 of the Environmental Protection Law). The second stage, based on the Property section of the Civil Code, converts the right to use ecological capacity into tradable private rights via usufructuary rights, thus activating the market's resource allocation function. These two levels are dynamically connected through the blockchain registration system: administrative authorities embed quota adjustment instructions into smart contracts (e.g., triggering reductions due to climate tipping points), while market entities exercise their right of disposition based on registration and public announcement, forming a closed-loop system of "public interest constraints—private autonomy".

The regulatory framework of the "Carbon Emission Rights Trading Act" should be built upon the logical starting point of "public-private complexity", and through the synergy of legal formulation and technological empowerment, resolve the structural tension between the values of public and private laws. In the private law dimension, the Carbon Emission Trading Law should establish a theoretical framework for "ecological property rights": Firstly, it must clarify the legal effect of transactional rules such as quota pledging and intertemporal banking. By referencing Article 440 ("pledge of rights") of the Civil Code, carbon emission rights should be incorporated into the category of pledgeable assets. The publicity and credibility of blockchain registry systems should replace the traditional requirement of possession transfer for pledge effectiveness, achieving a technologically reconstructed validity of security rights. Secondly, invoking Article 113 of the Enterprise Bankruptcy Law, the law should establish the priority of carbon emission rights over ordinary claims in bankruptcy proceedings. The legitimacy of this priority stems from the public goods nature of ecological capacity: carbon emission rights essentially constitute a limited right to use state-owned resources. Their preferential treatment in bankruptcy not only protects market actors' property interests but also reflects a value preference for ecological security—a higher-order legal interest.The technological empowerment of the Carbon Emission Trading Law is built on blockchain technology, enabling a paradigm shift in carbon emission rights from "public-private antagonism" to "collaborative symbiosis" through dual legal-technological authorization. Therefore, the Carbon Emission Trading Law must introduce a "principle of technological adaptability", requiring that public law interventions—such as quota recall or cap reduction—be encoded into smart contracts. This ensures transparency (through open-source code auditing) and non-retroactivity (via timestamp-based enforcement), preventing technological black boxes from undermining legal predictability. When administrative authorities trigger quota adjustments through smart contracts, they are essentially using technological rationality to achieve self-limiting public law intervention. When market entities engage in free trading based on the registry system, they are exercising boundary-conscious private autonomy through code-based consensus.

6. Conclusions

6.1. Final Determination of Legal Nature

Carbon emission rights should be conclusively defined as a novel category of usufructuary rights over state-owned ecological capacity resources, digitally specified through blockchain technology. This right incorporates a dual structure of "quota control authority" and "ecological benefit authority": the former empowers the holder, within the publicly established cap threshold, with the rights to possess, use, benefit from, and dispose of quotas; the latter transforms the ecological value derived from emission reduction activities—through non-possessory usufruct—into tradable, pledgeable, and inheritable property interests. Thereby, this legal framework unifies the rigidity of ecological security with the flexibility of market autonomy.

6.2. Theoretical Contributions

Through an in-depth exploration of the legal attributes of carbon emission rights, this paper proposes an innovative theoretical framework that defines carbon emission rights as a new type of usufructuary right. This contribution offers significant academic and practical value in several respects.

First, this paper transcends the limitations of traditional property rights theory by shifting the legal characterization of carbon emission rights from a strictly public or private law perspective to a more dynamic "public-private compound" framework. Furthermore, the dual structure of "quota allocation power" and "ecological benefit power" proposed herein not only addresses the constraints imposed by public law on carbon emission rights but also safeguards the autonomy of private law, achieving a dynamic balance between public welfare and private interests.

Second, this article provides a dynamic system interpretation of Article 329 of the Civil Code, offering a solid legal foundation for incorporating carbon emission rights into the usufructuary rights system. This approach presents a technology-empowered example for the modernization of property rights law, integrating "legal interpretation" and "technological empowerment" as a novel methodology to bridge the gap between traditional legal theories and emerging technologies.

Lastly, the "two-stage governance" normative system proposed in this paper provides a comprehensive institutional framework for the legal regulation of carbon emission rights. By establishing a governance mechanism that integrates both public and private laws, this paper resolves disputes regarding the legal status of carbon emission rights while offering a systematic solution for the legal operation of the carbon market.

In summary, this study, through an in-depth examination of the legal nature of carbon emission rights, proposes a theoretical framework defining them as a novel form of usufructuary right and constructs a corresponding normative system. This research not only offers a new perspective for resolving legal controversies surrounding carbon emission rights but also provides an advanced paradigm of "rights-technology-ecology" synergy for global ecological governance.However, this study has limitations regarding practical application, international comparison, and dynamic adjustment mechanisms. Future research should further deepen and refine these aspects, with particular emphasis on strengthening comparative analysis of major international carbon market systems—such as the EU ETS—to examine their successful experiences and shortcomings, thereby providing insights for improving China's carbon emission rights system. Furthermore, subsequent studies will specifically explore the differences in legal consequences between the usufructuary approach and EU ETS allowances regarding the qualification of objects, the effectiveness of security interests, and compensation mechanisms for public law interventions. This aims to provide empirical and comparative legal support for the convergence of global carbon market rules, thereby advancing the scientification and legalization of carbon emission rights systems.

Acknowledgments

The authors would like to express their gratitude to the peer experts who participated in the research discussions.

Author Contributions

X.W.: Conceptualization, Writing—Original Draft, Writing; Y.J.: Review & Editing.

Ethics Statement

This study did not involve human or animal subjects, therefore ethical approval was not required.

Informed Consent Statement

Not applicable as the study did not involve human participants.

Data Availability Statement

No external datasets were used in this study. All data were derived from publicly available literature or author analysis.

Funding

This research received no external funding.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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