

Designing a biodiversity credit accounting framework for environmental investment and financing

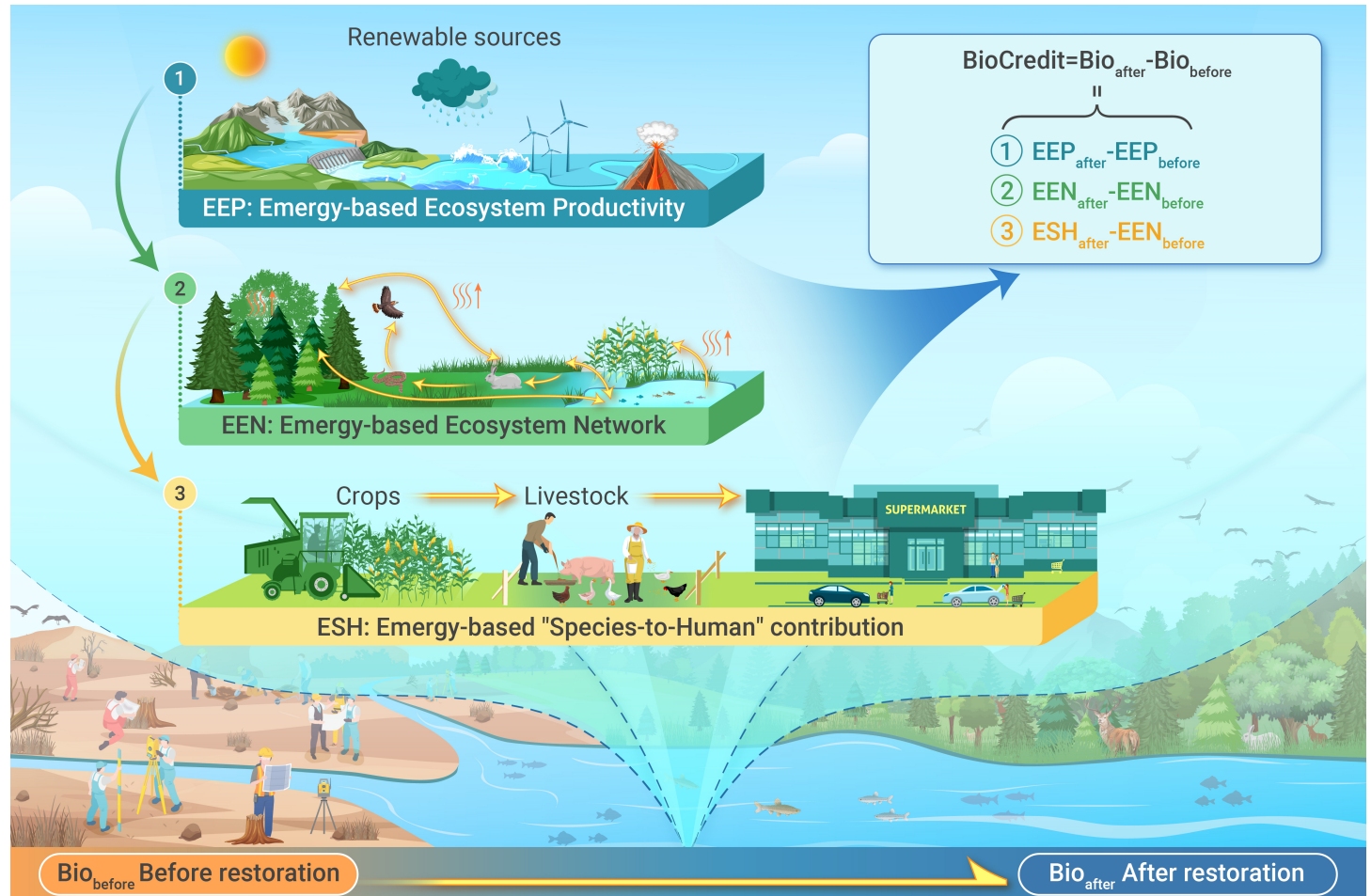
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GRAPHICAL ABSTRACT



PUBLIC SUMMARY

- Ecosystem productivity, networks, and human well-being were considered in a biodiversity credit accounting method.
- Among the 157 ecological restoration projects, approximately 66% achieved an improvement in biodiversity credit.
- It may take at least 10 years for the profits from a biodiversity credit transaction to cover the construction costs.
- Biodiversity credit accounting and trading will support the the Kunming-Montreal Global Biodiversity Framework.

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Achieving biodiversity goals and targets poses a significant financial challenge due to biodiversity externalities. Efforts to address this challenge have focused on market-based solutions for biodiversity offsets to bridge the financial gap. However, accurately calculating biodiversity credits remains a barrier to promoting and implementing these solutions. Here, we propose an innovative accounting framework for biodiversity credits based on the emergy accounting approach. Emergy (spelled with an m) represents the biosphere work performed over time and space (ecosystem services) that supports species, human societies and economies, and is measured in units of solar equivalent energy (emergy, sej). This unified accounting method considers the perspectives of ecosystem productivity, ecosystem networks, and human well-being. We evaluated the biodiversity credits in 157 restoration projects and found several advantages in terms of differentiating project types and setting thresholds for biodiversity credit increases in restoration projects. Only 66% of the projects achieved biodiversity credit increases, and only 29% of the generated credit can be traded on the market. This study provides a scientific foundation for decision-making in ecosystem restoration management and contributes to broader biodiversity conservation solutions as well as to bridging the financial gap in achieving biodiversity goals.

INTRODUCTION

Biodiversity is crucial for supporting life on Earth, including human activities and processes.^{1,2} Recently, the United Nations Convention on Biological Diversity (CBD) 15th Conference of Parties (COP15) approved the Kunming–Montreal Global Biodiversity Framework (GBF), which sets the tone for conservation actions over the next few decades.³ A key commitment of the GBF (Target 2) is safeguarding 30% of the Earth's land and oceans by 2030, with an emphasis on restoring, maintaining and enhancing ecosystems.⁴ Previously, the United Nations declared 2021–2030 as the Decade on Restoration, acknowledging the importance of restoring environmental policy.⁵ To achieve biodiversity goals, accurately determining and securing financing is crucial.⁶ COP15 also highlights the importance of finance (Target 19), and it is estimated that an additional more than 700 billion United States dollars (USD) annually will be required to meet the new goals of the GBF.^{7,8} Despite commendable efforts and investments by governments, nongovernmental organizations and international and national conservation agencies,^{9,10} a significant biodiversity-financing gap still exists worldwide.^{11,12} It is crucial to make additional efforts to reduce or eliminate the financing gap of 4.1 trillion USD in nature by 2050.¹²

A significant financial challenge for biodiversity conservation is the inadequate consideration of biodiversity and ecosystem services within the economic system.¹³ This lack of consideration leads to the neglect of externalities, which can be seen as a “values crisis” underlying the interconnected crises of biodiversity loss and climate change.^{14,15} To address this issue, it is suggested that an investment value should be assigned to biodiversity, based on its environmental value and market demand, to facilitate conservation efforts.^{16,17} By properly valuing these resources in the market, i.e., overcoming economic blind spots, both species and their habitats would acquire tangible investment value, providing people with an incentive to protect them.¹⁸ The

integration of the intrinsic value of biodiversity and other related values into the biodiversity offset mechanism, a new financial approach, has become a part of global practice.^{19,20}

The importance of shifting focus from conserving the remaining biodiversity to restoring ecosystems is becoming increasingly evident in addressing biodiversity loss.^{21–23} Ecological restoration is now recognized as a significant strategy for not only increasing the provision of ecosystem services but also reversing biodiversity losses.²⁴ Notably, 108 countries have already implemented biodiversity-offset policies; however, only 14 of these countries have documented guidelines on how to assess biodiversity during offsetting.²⁵ Emerging market-based mechanisms may have the potential to address some key issues facing biodiversity offset, primarily by reducing economic transaction costs and improving the security of delivering the required benefits.^{26,27} Notably, New South Wales (NSW), Australia, launched a biobanking scheme, which is a market-based biodiversity offset program designed to mitigate biodiversity loss caused by habitat degradation and development. Under this program, landowners and developers can generate biodiversity credits by committing to enhancing and protecting biodiversity values on their land through a biobanking agreement. Such a market-based mechanism for protecting and restoring natural ecosystems is one of the best ways to mitigate the biodiversity loss crisis and close the financing gap by investing. This strategy requires that the problem of accurate assessment of biodiversity and its credits is well addressed.

Quantifying biodiversity and its related functions is undeniably critical to the rational and effective management of ecosystems and the formulation of conservation actions.^{28–30} The connotation of biodiversity credit depends on people's understanding of the value of biodiversity as well as how credit is calculated. Establishing market-oriented biodiversity offsets (e.g., biobanking) to promote biodiversity conservation requires solving the problem of how to achieve unified accounting and market trading of biodiversity.³¹ This process involves addressing the challenge of determining the degree of biodiversity credit change at a site through a series of conservation, management and other measures. First, the complexity and diversity of ecosystems make it difficult to properly and comprehensively account for biodiversity,^{32–34} especially because of natural complexity and budgetary constraints. Current studies use mainly single indicators, such as habitat (or ecosystem) area and species richness, to characterize biodiversity.³⁵ This approach conceals important information about biodiversity (such as the structure of ecosystems), resulting in overestimation or underestimation due to the lack of monitoring of basic spatial and ecological data, such as individual species, populations or habitats, in most ecosystems.³⁶ Second, standardizing the design and measurement of “credits” in biodiversity offsetting schemes is a critical and complex aspect of market transactions.²⁰ As with any market, a biodiversity bank needs to develop a common currency to facilitate biodiversity promotion and market trading.³⁷ To measure biodiversity in a consistent manner, it is necessary to account for biodiversity with a unified unit. However, the complexity of biodiversity accounting indicators will impact the accessibility of the results.^{38,39} This issue creates a trade-off between using complex indicators (which provide more detailed information) and simple indicators (which are easier to understand and apply).

Increasing efforts have been made to develop a unified accounting method

for biodiversity, which can generally be categorized into two levels based on species and ecosystem.⁴⁰ However, controversies in biodiversity accounting still exist, making it challenging to establish a standardized method for biodiversity credit. Unlike greenhouse gases, which are measured in the common currency of a ton of carbon, biodiversity does not have a universally accepted 'common currency' for measurement. The NSW biobanking scheme features a systematic method for biodiversity credit assessment, primarily using a scoring-based approach. However, it does not consider multiple values of biodiversity, such as its impact on human well-being. Additionally, it does not provide clear thresholds for determining changes in biodiversity credits resulting from various ecosystem management practices. Furthermore, quantitative calculation methods for multiple and diverse types, particularly from different dimensions, are lacking. Rolling out biobanking in other countries and regions requires addressing these issues to effectively facilitate biodiversity conservation and financing. This process necessitates a more precise assessment of the various aspects of biodiversity by considering the threshold range and the specific vegetation conditions within the ecosystem, as well as their impact on human well-being.

Emergy provides a unified accounting of resource flows to and stocks within a system and is measured as a solar equivalent joule (sej, solar enjoules). It provides a new perspective on the "common biodiversity currency". According to the ecological approach, plants absorb solar energy to produce chemical energy stored in chlorophyll and organic matter. This energy is then transmitted through the food chain in the ecosystem, including both plant-based and animal-based production. In the late 1980s, emergy theory was introduced as a system-based open thermodynamics and general system approach by H.T. Odum,⁴¹ expanding the hierarchical structure of ecosystems to include all human-dominated systems, including the economy and societies. It represents the biosphere work that supports a system or process in the form of energy and material resources, traced back to a common denominator,⁴² generally "solar energy". The emergy-based approach utilizes the concept of 'solar energy value' as a standardized measure for converting various input flows within a system to a common unit that can be added to a final total value. Because of its advantages, the emergy approach has been applied to assess the overall environmental support and sustainability of systems in terms of physical and economic aspects at both local and global scales.⁴³ There has been significant research on quantifying the value of different types of ecosystem services via emergy, which enables the aggregation of diverse ecosystems and their respective services, including water, forests, rivers, and lakes.³¹

This study aims to quantify the effects of ecological restoration projects on biodiversity and proposes market-based solutions to enhance the evaluation methodology of biodiversity. It recommends implementing a market-driven strategy to increase biodiversity conservation, address decision-making barriers and bridge the finance gap. To achieve this goal, this study proposes a new biodiversity credit accounting framework based on emergy theory, as shown in Figure 1. This study was carried out in the following stages (Figure S1): First, we reviewed the existing understanding and algorithms for biodiversity, as well as the credit calculation of the currently successfully operating NSW biobanking scheme. Second, the proposed framework is applied to biodiversity analysis across different ecosystem types, such as woodlands, grasslands, and wetlands. Furthermore, to verify the newly proposed method, we used both the emergy method and the credit assessment method of NSW biobanking to evaluate and comparatively analyze a total of 157 projects, including 57 river projects, 25 lake projects and 75 greenway projects in the Xixian New Area (XNA), Shaanxi Province, China. Finally, we conducted a cost analysis to examine the possibility and potential economic benefits of biodiversity credits for market transactions.

MATERIALS AND METHODS

The proposal and compromise of current biodiversity credit accounting methods

In 1992, the Convention on Biological Diversity defined biodiversity as diversity found within species, between species and within ecosystems. Human actions have been dismantling the Earth's ecosystems, resulting in the alarming elimination of genes, species, and biological traits.⁴⁴⁻⁴⁷ When measuring biodiversity, the focus is most often on the species and ecosys-

tem levels.⁴⁸⁻⁵⁰ In particular, at restoration project sites, habitat indicators such as plant species diversity, biomass, and vegetation coverage are commonly used.

There are two broad classes of credit in NSW biobanking: ecosystem credits and species credit. NSW biobanking introduces a systematic credit accounting framework for biodiversity protection. One of the advantages of the biodiversity credit accounting method, i.e., the biodiversity assessment method (BAM), is its ability to convert biodiversity value into credit by assigning scores and making ecological conditions comparable. In addition, assessors must use BAM to determine credits based on the Biodiversity Information database, which contains at least 1,600 cultivated areas and the locations and ranges of listed threatened species.⁵¹ The credits gained at the stewardship (project) site are determined primarily by the area of the vegetation zone and the vegetation integrity, which includes its composition, structure and function condition scores.⁵² The accounting of NSW biobanking credit (NSW credit) depends on the richness of vegetation types, the extent of vegetation coverage, and some attributes that represent the function of vegetation. This method reduces uncertainty regarding the success of offsetting project impacts and provides more cost-effective opportunities for compensatory mitigation. If this biobanking framework can be extended to other countries and regions, it could have significant implications for global biodiversity conservation.

Importantly, however, the scheme is currently limited to NSW, as it is an NSW government initiative and is available only within the New South Wales state (Australia). In addition, it is heavily dependent on project databases and bioinformation databases, and the benchmark and some parameters in the calculation of NSW credit are very local and may not be applicable to other regions, which makes it difficult to apply and promote in other regions, where well-established data are not available.

In addition, NSW biodiversity credit does not comprehensively cover the various levels of biodiversity, despite considering species and ecosystems. Although there are two types of credit, ecosystem credit and species credit, they are interrelated in nature and are obtained by multiplying the VI (vegetation integrity) and area of the ecosystem or species habitat. When the site is a wetland, the calculation of the VI does not work because the characteristics of the wetland do not conform to the attributes of composition, structure and function condition scores. Specifically, the vegetation communities at the project site consist primarily of coniferous forests, broadleaf forests, mixed forests, shrub forests, grasslands, meadows and shrub grasses. A scoring system is used to evaluate different ecosystem types on a scale of 0 to 100, and the assessment focuses on quantity rather than quality. Notably, however, this grading system may not capture all important biological information. Additionally, wetlands, including rivers, lakes, and oceans, play a significant role in providing and influencing biodiversity and other ecosystem services.⁵³

Furthermore, the assessment relies heavily on the assessors' familiarity with the ecological unit types and their professional judgment, highlighting the need for proper training to minimize subjective judgment errors among different assessors. In practice, this credit assessment method is time-consuming and labor-intensive and presents challenges when implementing it on a larger spatial scale with a unified standard.

A new biodiversity credit accounting method based on emergy

This study proposes a new biodiversity credit accounting framework based on emergy theory (EmBio-credit) to overcome the limitations of existing biodiversity credit (see Figure 1 & S1). EmBio-credit is defined as the biodiversity resulting from the implementation of restoration projects (including preservation, enhancement, restoration, creation and other measures). The framework introduces three improvements in calculating biodiversity credit. First, it adopts a fully quantitative method based on biophysical indicators derived from the emergy accounting approach developed by systems ecologist H.T. Odum.⁴¹ It converts all resources into standardized measures, replacing traditional scoring and counting methods. Second, it classifies ecological projects and identifies microecological units for each project based on the classification, considering various influencing factors of the project site. The calculation of EmBio-credit for each project is obtained by the weighted sum of credits of units at the project site. Finally, it combines

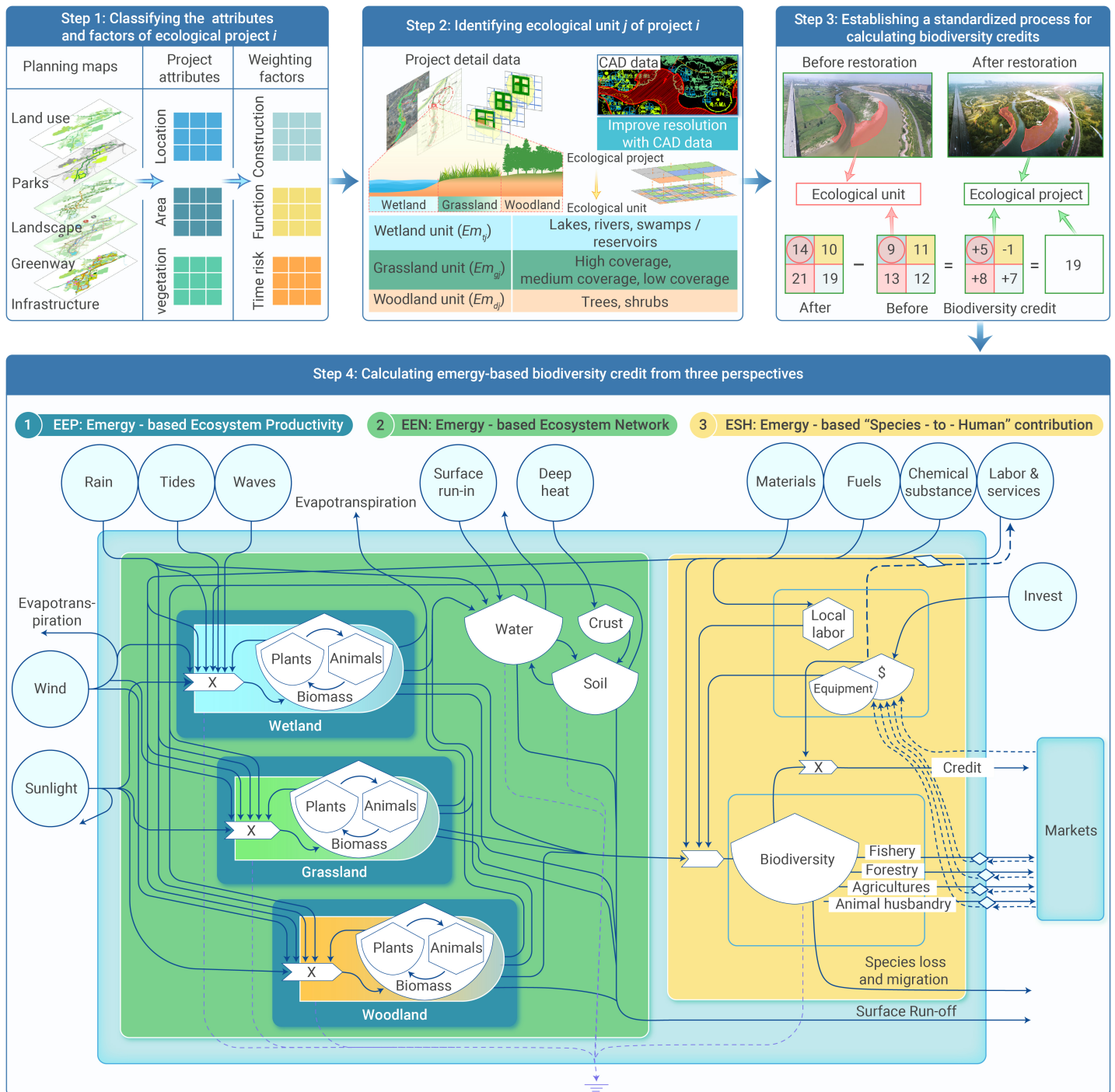


Figure 1. The accounting framework of EmBio-credit from different perspectives.

ecosystems and species, considering natural resource endowment, ecosystem network structure and the contribution of domesticated species to human well-being. Furthermore, the study introduces three perspectives on EmBio-credit. A comprehensive analysis can be conducted by comparing the characteristics of each restoration project in these three dimensions.

Conceptually, the ecosystem and species levels of biodiversity are combined while simultaneously considering ecosystem productivity, natural resource endowment, ecosystem network structure and the contribution of domesticated species to human well-being. For the sake of clarity, the calculation is performed under three perspectives. The first approach adopts the perspective of ecosystem productivity (energy-based ecosystem productivity, i.e., EEP-credit) and focuses on the potential ability of the local ecosystem's natural endowment to sustain biodiversity. The renewable resources of the ecosystem are the drivers of ecosystem services, and the emergy cost is

associated with maintaining biodiversity potential. The second approach, EmBio-credit from the perspective of the ecosystem network (energy-based ecosystem network, i.e., EEN-credit), involves measuring species at each trophic level of the ecosystem network and food webs, thus taking into account complex species interactions and emergy transfer in ecosystems. Finally, the third perspective considers the EmBio-credit from the perspective of species' contribution to human well-being (energy-based species-to-human contribution, i.e., ESH-credit). It establishes a relationship between biodiversity and human well-being by evaluating the impact of biodiversity on local economies through assessing the nonrenewable resources required to domesticate species into agricultural products.

Technically, EmBio-credit adopts a fully quantitative and standardized method based on biophysical indicators derived from the emergy accounting approach, classifies ecological projects and identifies microecological units

for each project on the basis of the classification, carefully considering various influencing factors of the project site. The credit calculation performed in this research incorporates both macro remote sensing data and micro planning data (CAD) to extract 9 types of ecological features from each project site. This approach enables a more comprehensive and accurate calculation of credits, enhancing the level of detail and precision.

EmBio-credit: A new biodiversity credit accounting method based on emergy

Although emergy methods have been applied in biodiversity research,^{45,54,55} there are still gaps in our understanding with respect to analyzing emergy-based biodiversity from multiple perspectives and exploring its connection to biodiversity offset and biodiversity credit transactions. Biodiversity offset is typically conducted off-site through restoration projects, while biodiversity credits are calculated on a case-by-case basis for each project. These restoration projects are intricate and encompass a variety of interconnected ecological elements, such as water, grass, wood and soil. Each component participates in its own unique material exchange, both internally and externally, and serves distinct functions and provides different services. To calculate and analyze the biodiversity credit of restoration projects, it is important to identify the ecological elements and categorize them into different types of ecological units, such as grasslands, woodlands, wetlands, and other microunit types.

This study applies the concept of emergy theory, which is based on ecological thermodynamics, specifically, the value of solar available energy, to perform credit accounting. The biodiversity credit, referred to as EmBio-credit, is defined as the utility of the biodiversity value generated by a specific amount of solar emergy, measured in solar equivalent joules (sej). This approach allows for a more precise quantitative calculation of restoration projects by utilizing ecological units, thereby eliminating the subjective nature of traditional scoring methods that involve classifying different ecological elements, units, and projects.

To calculate EmBio-credit accurately for the investigated projects, we developed a microecological unit identification technology. This technology combines macroscopic remote sensing data and microscopic engineering CAD data to extract ecological units from the project. The extraction is based on spatial distribution characteristics, vegetation characteristics, remote sensing data, the normalized vegetation index (NDVI), and the digital elevation model (DEM) of the restoration project. There are 8 types of microecological units, including woodland units (with trees and shrubs), grassland units (consisting of high/medium/low coverage grasses), and wetland units (including lakes, rivers, coastal areas). This procedure involves analyzing and adjusting the grid data to accurately identify the units and key features of restoration projects and then calculating the weighted superposition based on these features.

The EmBio-credit of various microecological units is calculated individually in ecological units and projects, taking into account their characteristic attributes and influencing factors. EmBio-credit and its calculation process in each ecological unit are standardized, allowing for comparison and summation via a unique unit (1E10 sej). The specific calculation formula is as follows:

$$EBC_i = EmBiocredit = \Delta EmBio = EmBio_{after} - EmBio_{before} \quad (1)$$

$$EmBio_i = \begin{cases} EEP_{after} - EEP_{before} \\ EEN_{after} - EEN_{before} \\ ESH_{after} - ESH_{before} \end{cases} \quad (2)$$

$$EmBio_i = \sum (Em_{w_i}, Em_{g_i}, Em_{d_i}) \times w_i \quad (3)$$

where EBC_i refers to the EmBio-credit of restoration project i ; $EmBio_i$ refers to the emergy-based biodiversity of restoration project i ; Em_{w_i} , Em_{g_i} , and Em_{d_i} represent the biodiversity of wetland, grassland, and woodland units of project i , respectively; and w_i refers to the weighing factor of the project, including the construction level weight, the function level weight, and the time/risk loss factor. The details of the weighting factors are provided in Supporting Information Table S3. Considering that the construction of

projects often takes a long time to achieve optimal ecological benefits and frequently falls short of expected outcomes, it is crucial to consider the factors associated with each project's construction progress. The duration of restoration project construction directly affects the enhancement of biodiversity, and failure risks are also present. Thus, it becomes essential to consider these factors when determining the increases in biodiversity.

EEP: Emergy-based biodiversity from the perspective of ecosystem productivity

The cycle of the entire biosphere, including ecosystem productivity, is based on the input of renewable emergy, such as solar energy, wind, rain, etc., and follows the laws of energy conversion.⁵⁶ Many studies have demonstrated a positive correlation between biodiversity and ecosystem productivity from both observational and experimental perspectives.^{57,58} Similarly, there is a positive relationship between biodiversity and emergy (i.e., the sum of all types of emergy inflows to generate species in an ecosystem) across time and space, and these factors increase in proportion to the increase in the amount of renewable emergy available.^{41,54} Therefore, more emergy inflows support the presence of more species in the system and facilitate more species interactions. In other words, when the ecosystem contains more species (that is, greater genetic information related to species richness in the cycle), more solar emergy is needed to drive the ecosystem, and the entire ecosystem maintains the cycle of generating species genetic material. This perspective provides a new way of approaching the evaluation of biodiversity credits; that is, the emergy value corresponding to local renewable resources can be used to calculate the ecosystems' potential to maintain the cycle of generating species genetic material. Therefore, we propose a method to calculate emergy-based biodiversity from the perspective of ecosystem productivity, referred to as EEP. The calculation is as follows:

$$EEP_j = MAX(\sum(E_{so}, E_{td}, E_{ge}), E_{wn}, E_{wa}, E_{ra}, E_{rf}, E_{ch}) \quad (4)$$

where EEP_j refers to the biodiversity maintenance potential of the site in ecological unit j , which is the total renewable resources within the considered time range and provides a baseline for natural contributions to biodiversity maintenance at the project site; E_{so} represents solar emergy; E_{td} represents tidal emergy; and E_{ge} represents geothermal emergy. The sum of the three forms of emergy is used to determine the static maintenance potential of local renewable resource emergy to support biodiversity. E_{wn} refers to wind emergy, E_{wa} to wave emergy, E_{ra} to rainwater chemical potential, E_{rf} to runoff geopotential and E_{ch} to runoff chemical potential. The detailed calculation procedure of each renewable resource is from Brown and Ulgiati.⁵⁹

EEP aims to enhance the biodiversity accounting method stemming from the size of the habitat area. This approach considers that a greater number of renewable resources available at the restoration project site can support a higher level of biodiversity. Given its geographical location and natural characteristics, the restoration project site is endowed with more renewable resources, such as solar energy, rain, and wind, which contribute to the potential increase in and support of local biodiversity. Several studies have demonstrated positive correlations between biodiversity and ecosystem functions, such as primary productivity and nutrient cycling.⁴⁴ According to previous research, there is a direct link between biodiversity and the emergy value of renewable resources. When renewable resources are available to a system, biodiversity tends to increase.⁴¹ The environmental services available within the system boundary stimulate plant growth and reproduction, highlighting the potential of the project site to sustain local biodiversity.

EEN: Emergy-based biodiversity from the perspective of ecosystem networks

Previous authors have proposed an approach for calculating biodiversity based on systems theory that can be applied across trophic levels. This approach provides a condition benchmark that accounts for food web interactions, specifically the emergy conversion rates of species in ecosystem biological networks. It has been successfully applied to calculate the biodiversity of the Florida Everglades and the Hubbard Brook forest ecosystems in the United States.^{45,54} One of the advantages of this approach is its ability to explain the expected grade distribution of the population's physical quantity at different trophic levels, as well as the observed distribution of flow levels in

the ecosystem's food network. Consequently, we propose a method, EEN, to measure emery-based biodiversity from the perspective of the ecological network.

Unlike EEP, which considers solely the biodiversity maintenance potential of renewable resources in an ecosystem (static and baseline), EEN takes into account the emery transfer in the ecosystem's food network (species hierarchy) to assess its biodiversity maintenance potential. The calculation involves determining the turnover time of a specific species and the emery input from the supporting species area, which allows for the calculation of the emery required to sustain a species.

The calculation of EEN, which is the sum of emery flows required by the species at each trophic level of the ecosystem food network in a region, is as follows:

$$EEN_j = \frac{(NP_k \times T_{jk})}{TET} \quad (5)$$

$$TET = \sum (NP_k \times T_k) \quad (6)$$

where EEN_j refers to the maintenance of species k in ecological unit j and NP_k refers to the net primary productivity (J/yr) of species k in ecological unit j . T_{jk} refers to the emery value conversion rate of species k in ecological unit j . TET is the total emery throughput in the entire ecosystem (sej/m²/yr), which is needed to calculate the emery needed to maintain local biodiversity. NP_k represents the net primary productivity (NPP) of species k in the food web (J/yr); T_k refers to the emery value conversion rate of species k , which is generally measured by the emery flow matrix of components in the ecosystem and optimization techniques, as detailed by Bardi et al.⁶⁰ To determine the emery value required to maintain biodiversity in the food network of forest and wetland ecosystems, specific data such as the emery conversion rates of different species are needed.

Obtaining species emery flow data in food networks poses real challenges. Moreover, the New South Wales Biodiversity Accounting Guidelines suggest that habitat characteristics can be used as a reference instead of species characteristics.⁵² Therefore, we can estimate the emery value per unit area required for biodiversity in each ecosystem food network based on the literature. This value can then be multiplied by the net primary productivity at the unit site and the area of the unit to determine the total emery value required to sustain biodiversity for each project unit.

ESH: Emery-based biodiversity from the perspective of domesticated species' contribution to human well-being

As species' genetic information evolves over time, some species development requires interventions, such as domestication. Certain species can be domesticated to achieve large-scale and specialized production, thus creating additional investment value. In this study, inputs from renewable resources are considered natural inputs (EEP), whereas inputs from human intervention (e.g., fertilization or species selection) in the form of "species domestication" are considered human inputs. Therefore, by calculating the nonrenewable resources associated with the domestication of animals and plants into agricultural and pastoral products, along with the required emery value, we can characterize the impact of species on human well-being (ESH).

ESH assesses the contribution of biodiversity to humans based on the number of domesticated species. The formula for calculating ESH is as follows:

$$ESH_j = Em_{dn} \times PDN_j \quad (7)$$

$$Em_{dn} = \frac{Em_{ag}}{DN} \quad (8)$$

$$Em_{ag} = Em_{global} \times P_{ag} \quad (9)$$

$$PDN_j = RN_j \times P_{dn} \quad (10)$$

$$P_{dn} = \frac{DN}{TN} \quad (11)$$

where ESH_j refers to the contribution of biodiversity to human well-being in ecological unit j ; Em_{dn} refers to the emery value required for each domesticated species per year (sej/species/yr); PDN_j refers to the number of potentially domesticated species in ecological unit j ; Em_{ag} refers to the emery requirements for global agricultural production (sej/yr); DN refers to the number of domesticated crop species, estimated approximately as 2500 by Meyer et al.⁶¹ and Stetter et al.,⁶² Em_{global} refers to the emery corresponding to the nonrenewable resources used by the global human economy (sej/yr), with data available online,⁶³ P_{ag} refers to the parameter, which is the percentage of global agricultural added value in global GDP (%), obtained from the Food and Agriculture Organization of the United Nations (FAO) website,⁶⁴ RN_j refers to the species richness within unit j ; P_{dn} refers to the percentage of the number of domesticated crop species to the total number of plant species (%); and TN refers to the total number of plant species in the world, currently estimated to be 391,000.⁶⁵

RESULTS

Two methods, the newly developed EmBio-credit and the exiting NSW credit, were utilized in this study to calculate biodiversity. The properties and construction details of the 157 ecological restoration projects were highly varied. To offer an all-encompassing analysis in the Results section, we carried out a three-part examination. First, we selected three typical restoration projects to provide an overview of all the projects (Figure S2). Second, we analyzed the biodiversity credits from three perspectives of EmBio-credit for all the projects and examined the characteristics of the biodiversity credits. Finally, a cost-benefit analysis was conducted for all projects to demonstrate the cost of biodiversity credit and the potential economic benefits of ecological restoration projects.

EmBio-credit innovative case studies for selected restoration projects

The 3 typical projects include a greenway project (G34), river project (R11) and lake project (L17). They are located at the intersection of the Jinghe River and the Weihe River, the two major tributaries of the Yellow River, the mother river of China, and at the junction of the cities of Xi'an and Xianyang, which has significant geographical characteristics. In addition, the construction of the project includes various elements, such as grassland, woodland and wetland units. The EmBio-credit of each restoration project is calculated as the sum of the different ecological performances characterizing each project. These credits are calculated based on the involved areas, vegetation characteristics, and site attributes. For instance, in project R11, the EEP-credit amount is 2.66E+06, which is the combined value of woodland, grassland, and water areas (refer to Figure S3 and Table 1). The value of the EEN-credit amount is 6.13E+06, which is very close to that of the EEP-credit but quite different from that of the ESH-credit, which is 5.81E+09. ESH, which represents the contribution of domesticated species to human well-being, is considerably higher than EEN and EEP-credit across various types of restoration projects. This trend is observed in the four restoration projects, as shown in Figure 2. The red border represents the values corresponding to R11. Although the species number and area of R11 are smaller than those of G34 and L17 and the investment is also smaller than that of L17, the credit per unit area and unit investment of R11 are not the smallest values. This observation is closely related to the functional level, construction level and construction period of the project.

Overall EmBio-credit of all 157 projects investigated EEP-credit: A baseline for judging the success or failure of a project after implementation.

A total of 4.96E+18 sej of EEP-credit is accounted for by all 157 restoration projects. Compared with EEN-credit and ESH-credit, EEP-credit is usually lower and generally increases with the project area. Figure 3 shows that greenway projects have more total EEP-credit than lake and river projects do, mainly because of the larger coverage areas of greenway projects. However, several greenway projects have lower EEP-credit than EEN-credit. In both lake projects and river projects, the value of EEP-credit is smaller than that of EEN-credit. This finding suggests that these projects are more effective in terms of improving biodiversity, while the effectiveness of greenway projects may be influenced by their engineering characteristics, so not all greenway projects have positive effects on promoting biodiversity conservation.

Table 1. EmBio-credit calculation for River project R11

Item		Woodland units	Grassland units	Wetland units	Total
Weighting factor	Construction level	1	1	1	-
	Function level	0.9	0.9	0.9	-
	Time risk/loss	1	1	1	-
Main content	Species	2	5	1	8
	Area (m ²)	2.52E+05	5.64E+05	3.60E+05	1.18E+06
Renewable resources (sej)	Solar energy	8.23E+14	1.84E+15	1.18E+15	3.84E+15
	Geothermal energy	2.35E+14	5.25E+14	3.35E+14	1.09E+15
	Tidal energy	-	-	-	-
	Wind energy	2.20E+15	8.07E+15	5.15E+15	1.54E+16
	Wave energy	-	-	-	-
	Rain (chemical potential)	4.39E+15	9.84E+15	6.28E+15	2.05E+16
	Runoff (potential potential)	5.71E+15	1.28E+16	8.15E+15	2.66E+16
	Runoff (chemical potential)	4.43E+15	9.92E+15	6.33E+15	2.07E+16
EmBio-credit (sej)	EEP-credit	5.71E+15	1.28E+16	8.15E+15	2.66E+16
	EEN-credit	4.70E+16	1.90E+15	1.24E+16	6.13E+16
	ESH-credit	1.44E+19	3.60E+19	7.20E+18	5.76E+19

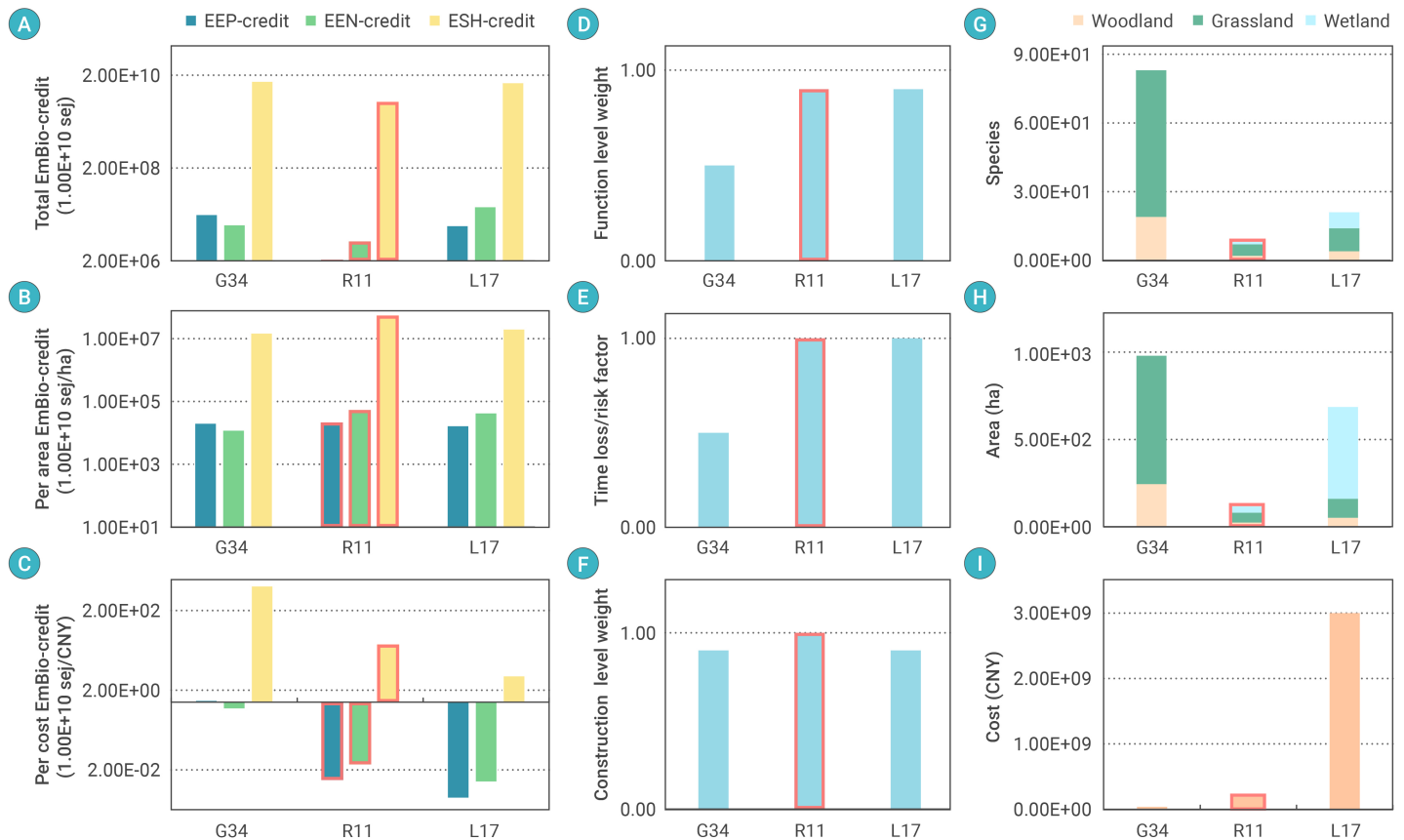


Figure 2. EmBio-credit features of typical restoration projects Project G34 is greenway project No. 34, R11 is river project No. 11, and L17 is lake project No. 17. In short, Figure 2 shows the following: (A) The total EmBio-credit from the three perspectives (i.e., EEP, EEN and ESH). (B) Per area EmBio-credit from the three perspectives. (C) Per investment EmBio-credit from the three perspectives. (D-F) The weighting factors of the projects. G The species of the ecological unit of the projects. (H) The ecological unit of the projects. And (I) The cost of the ecosystem restoration projects. Note that in A-C, the red border indicates the value corresponding to R11, which is illustrated in detail in Table S1.

EEP-credit represents the potential of natural resources at a restoration project site to sustain biodiversity. It is determined primarily by the energy

support resulting from sun, geothermal heat, rain, wind, and other natural resource inflows to a given area, which cannot be increased and is



Figure 3. EmBio-credit for all projects Detailed explanation of diagrams: (A-C) The three perspectives of EmBio-credit (i.e., EEP-credit, EEN-credit and ESH-credit) in the investigated 75 greenway projects, 25 lake projects, and 57 river projects, respectively. (D) The rate of successful projects and the rate of EEN-credit to market. (E) Comparison of NSW credits and EEN credits to market. NSW credit is the biodiversity credit calculated by the BAM. In D and E, EEN-credit is greater than EEP-credit for the case of EEN-credit to market.

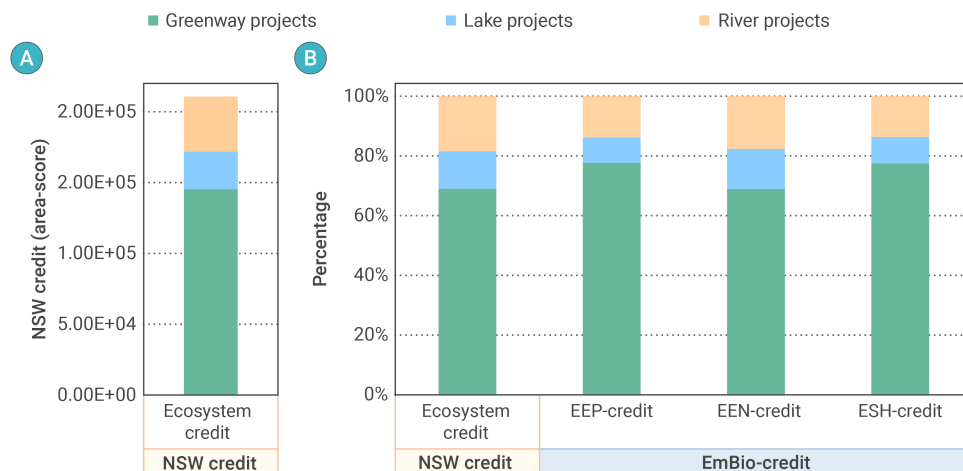


Figure 4. The NSW credit and EmBio-credit of all ecological projects (A) The total NSW credit (ecosystem credits). (B) The percentages of different ecological project types.

ESH-credit. In some cases, certain sites have higher biodiversity without human interference, indicating that certain ecological management measures may not improve biodiversity. From this point of view, by 2030, after the completion of all projects, the success rate will only be approximately 66%; the success rate of lake projects will be 100%, that of river projects will be 95%, and that of greenway projects will be only 33% (Figure 3D).

considered the empower density of a given area. This energy inflow, which can be used to facilitate the project's success, generates a minimum credit enhancement after the implementation of the restoration project. A project is considered valid when its value is lower than the values of EEN-credit and

EEN-credit: A direct indicator used to measure changes in biodiversity credit due to the actual generation of species networks and hierarchies.

After completion of the projects, an overall EEN-credit of 6.63E+08 sej will be generated, of which greenway projects will account for 4.57E+08, lake

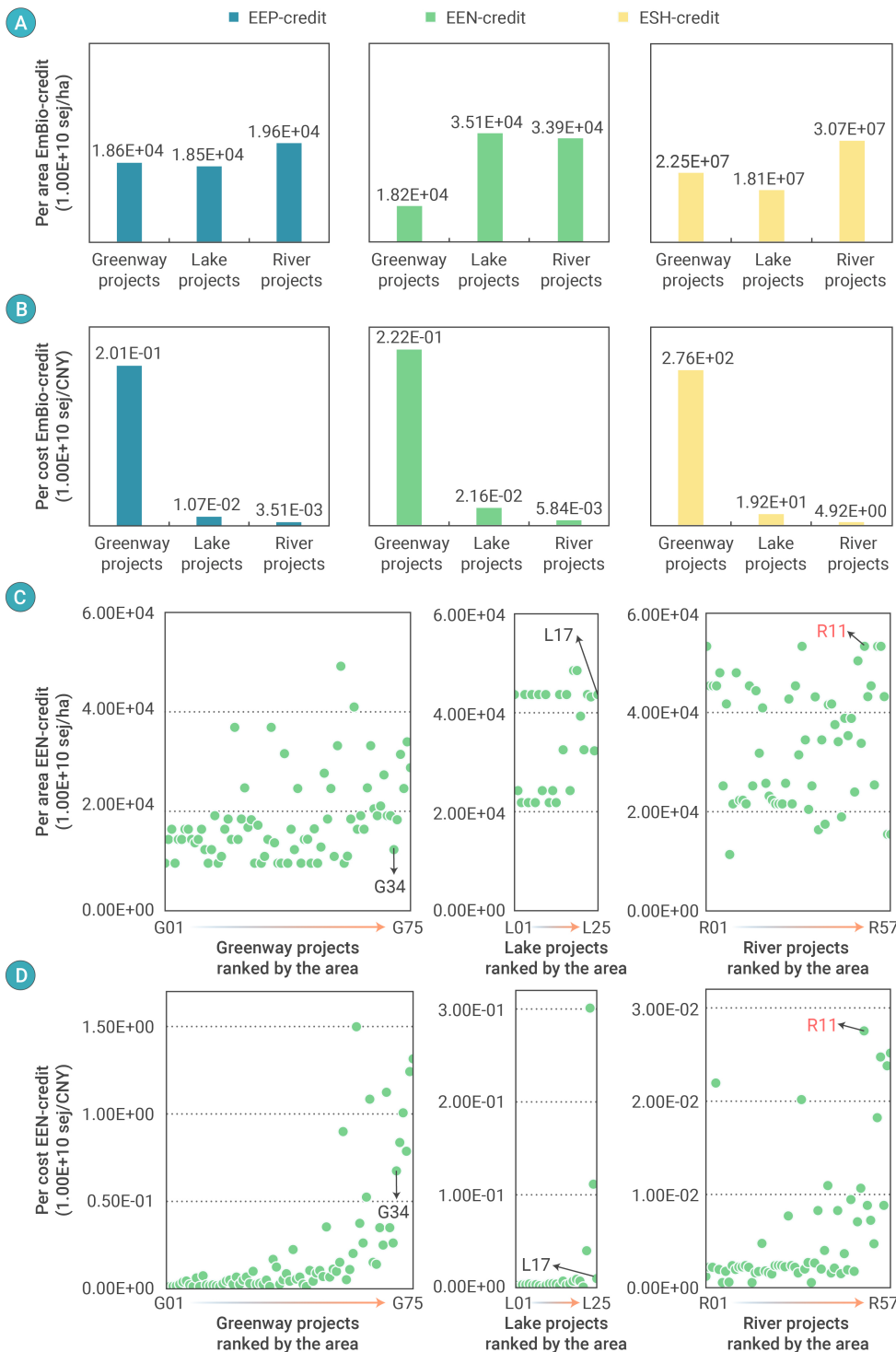


Figure 5. EmBio-credit per unit input (A) The average per unit area of EmBio-credit. (B) The average per unit CNY of EmBio-credit. (C) Per unit area of EEN-credit in all projects. (D) Per unit CNY of EEN-credit in all projects.

proportion of different project types to credit, among NSW credits and EEN-credits, greenway projects account for 69%, lake projects account for 13%, and river projects account for 18%. The NSW credit conversion ratio with EEN-credit to market is approximately $3.15\text{E}+03$ (area score/1E10 sej).

ESH-credit: Impact of human-generated biodiversity (domesticated species) on societal wellbeing

Overall, ESH-credit accounts for $7.30\text{E}+11$ across all projects, with greenway projects accounting for $5.66\text{E}+11$, lake projects accounting for $6.45\text{E}+10$, and river projects accounting for $1.00\text{E}+11$. Figure 3 shows that while EEP-credit increases with area for different project types, ESH-credit does not increase at the same rate, especially for lake projects and greenway projects. This difference can be attributed to the influence of vegetation type on the project site. In the study area, there is a relatively large number of greenway project and lake project sites, and their geographical distributions span two watersheds with significantly different climatic conditions in terms of precipitation and temperature. Therefore, there are substantial variations in the selection of vegetation types. ESH-credit can serve as an indicator of the long-term impact of biodiversity on human society.

ESH-credit provides a new perspective of species' contribution to human well-being by incorporating the contribution of biodiversity to human well-being into the credit accounting system. Note that such a contribution is quantified via a standardized unit of measurement, allowing effective comparison with other dimensions of biodiversity across different scales. ESH-credit offers the maximum benefits and establishes a threshold for the benefits of restoration projects in combination with EEP-credit. From a numerical standpoint, there is still much room to enhance the benefits of restoration projects in the future because EEP-credit considers only natural endowments,

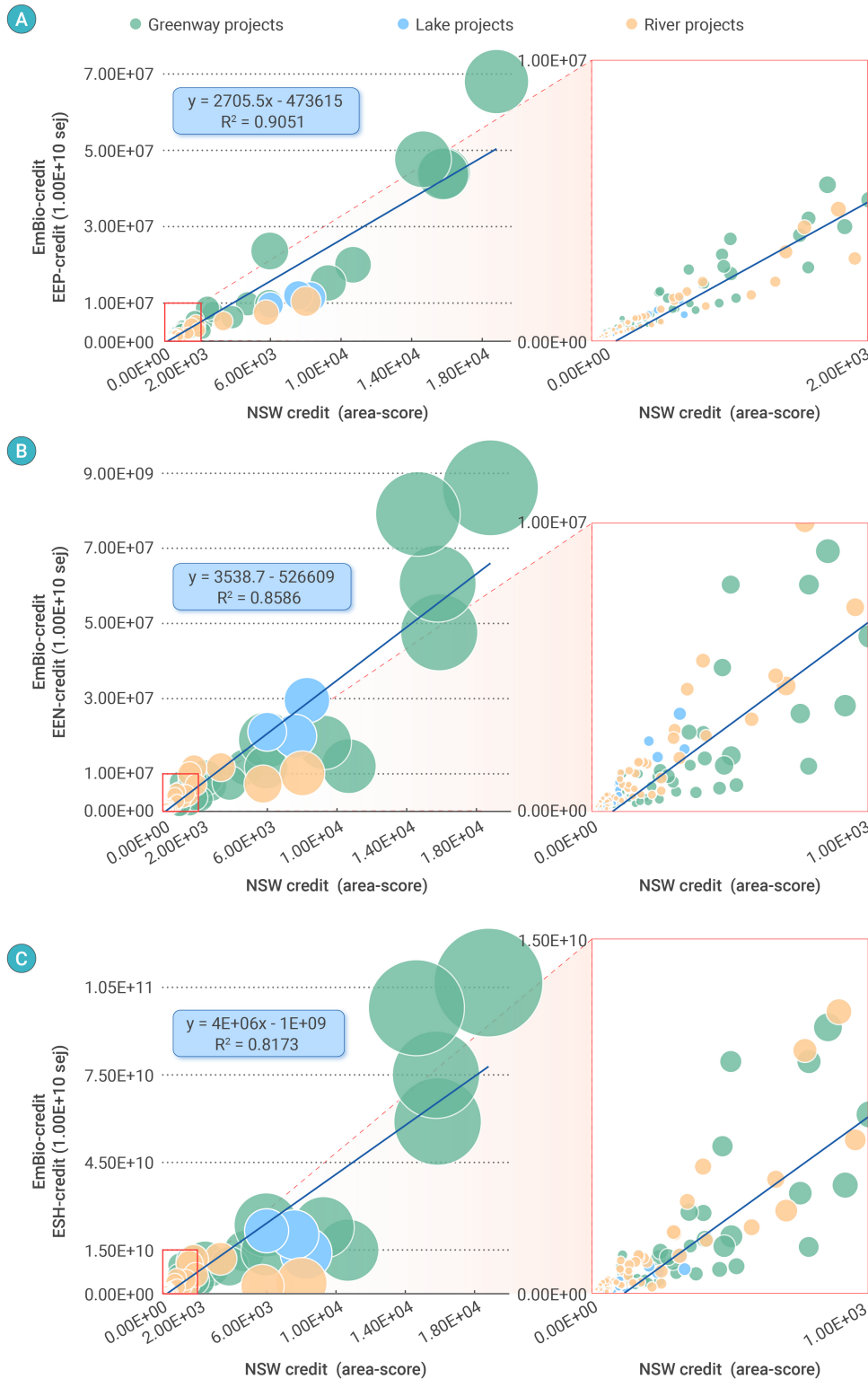
while ESH-credit takes into account human inputs. However, there is a limit to the extent to which restoration project sites can be transformed through human intervention.

Cost analysis of biodiversity credits

Here, we utilize the land area and construction cost of ecological restoration projects to assess the biodiversity credit per unit cost. In addition, we analyze the land contribution to biodiversity credits and the economic input into biodiversity credit.

Ecological management will be carried out on approximately 24,589 hectares of land, which encompasses 157 restoration projects, accounting for 28% of the total land area. In terms of credit enhancement per unit area, by 2030, the projects will generate EEP-credit, EEN-credit, and ESH-credit totaling $1.89\text{E}+04$, $2.66\text{E}+04$, and $2.48\text{E}+07$, respectively, per hectare annually

projects will account for $8.94\text{E}+07$, and river projects will account for $1.17\text{E}+08$. The distribution of EEN-credit among the 157 projects does not follow a linear increase with the project area. Instead, it varies and is sometimes higher and sometimes lower than the EEP-credit (Figures 3A-C). This variation occurs mainly because EEN-credit is determined by the energy flow of an ecosystem's network (for details, see the Methods section). Therefore, when EEN-credit is greater than EEP-credit, the project can be considered successful, and credit transactions can be carried out. From this point of view, by 2030, all projects will generate $6.63\text{E}+08$, and only 29% of the EEN-credit will be able to be traded on the market, specifically, $1.92\text{E}+18$ sej per year. The rates of trade for lake projects, river projects and greenway projects are 53%, 42% and 21%, respectively (Figure 3D). Importantly, the overall NSW credit for the 157 projects is $2.11\text{E}+05$ area score (Figure 4). In terms of the



(Figure 5A). River projects and lake projects will generate nearly twice as many EEN-credits per hectare as greenway projects will (Figure 5C). The improvement effect of EEN-credit per unit area reflects the variation in project types. Notably, there are significant differences in the degree of credit enhancement among different types of projects. When considering the EEN-credit of all projects, the differences among greenway projects, lake projects, and river projects are highly significant, and lake projects still show a certain increase per area.

The total cost (investment) of implementing these projects by 2030 is estimated to be nearly 33.96 billion CNY, representing approximately 54% of China's GDP in 2022. Based on the analysis of the credit per unit cost, from

Figure 6. The relationship between EmBio-credit and NSW credit (A-C) The relationship between total EEP-credit, EEN-credit, ESH-credit and NSW credit. (D) The relationship between per area EEP-credit and per area NSW credit. (E) The relationship between per area EEN-credit and per area NSW credit.

the perspectives of EEP-credit, EEN-credit and ESH-credit, greenway projects generate approximately ten times more credits than River projects do at the same cost, which is significantly higher than that of both river projects and lake projects (Figure 5B & D). This discrepancy can be attributed to the fact that greenway projects are implemented on land, whereas river projects and lake projects involve both water bodies and land. When implementing ecological engineering measures, greenway projects feature lower technical difficulty and economic costs than river projects and lake projects do. EEN-credit provides further insights, indicating that for each unit of economic input, greenway projects generate $2.22E-01$ credits ($1E10$ sej/CNY), while lake projects generate $2.16E-02$ credits ($1E10$ sej/CNY), and river projects generate $5.84E-03$ credits ($1E10$ sej/CNY).

DISCUSSION

The relationship between NSW credit and EmBio-credit

Through empirical research and comparative analysis, EmBio-credit is found to be rigorously grounded in scientific eco-thermodynamic principles and to demonstrate clear advantages in quantitative calculations. In addition, it offers distinct measurement ranges, facilitating the differential calculation of characteristic attributes between projects. As illustrated in Figure 6, there is a strong relationship between EmBio-credit and NSW credit. All the perspectives of EmBio-credit, including EEP-credit, EEN-credit, and ESH-credit, exhibit highly positive correlations with NSW credit, with correlation coefficients R^2 of 0.9051, 0.8586, and 0.8676, respectively. These results indicate that the new biodiversity credit (EmBio-credit) accounting method proposed in this study matches well with the overall principles and distribution of restoration project credits calculated via the traditional method (NSW credit). Furthermore, EEP-credit has the strongest correlation with NSW credit. This finding is based mainly on the ecosystem area and composition scoring (Figure 6A) since EEP-

credit is determined mainly by the natural endowments in a given ecosystem area, resulting from available energy, such as sunlight, rain, and wind.

Notably, there are three trends in the relationship between NSW credit and EmBio-credit for the greenway projects, lake projects and river projects, which are associated primarily with different types of restoration projects (previously shown in Figures 3A-C). Greenway projects include woodlands and grasslands, which are characterized by trees, woods, and grasses. Lake projects and river projects are part of the wetland ecosystem, which exhibits a lower diversity of vegetation types, less vegetation quantity, and lower coverage. The attributes used by NSW have rough vegetation characteristics, making them more suitable for forest land- and grassland calculations.

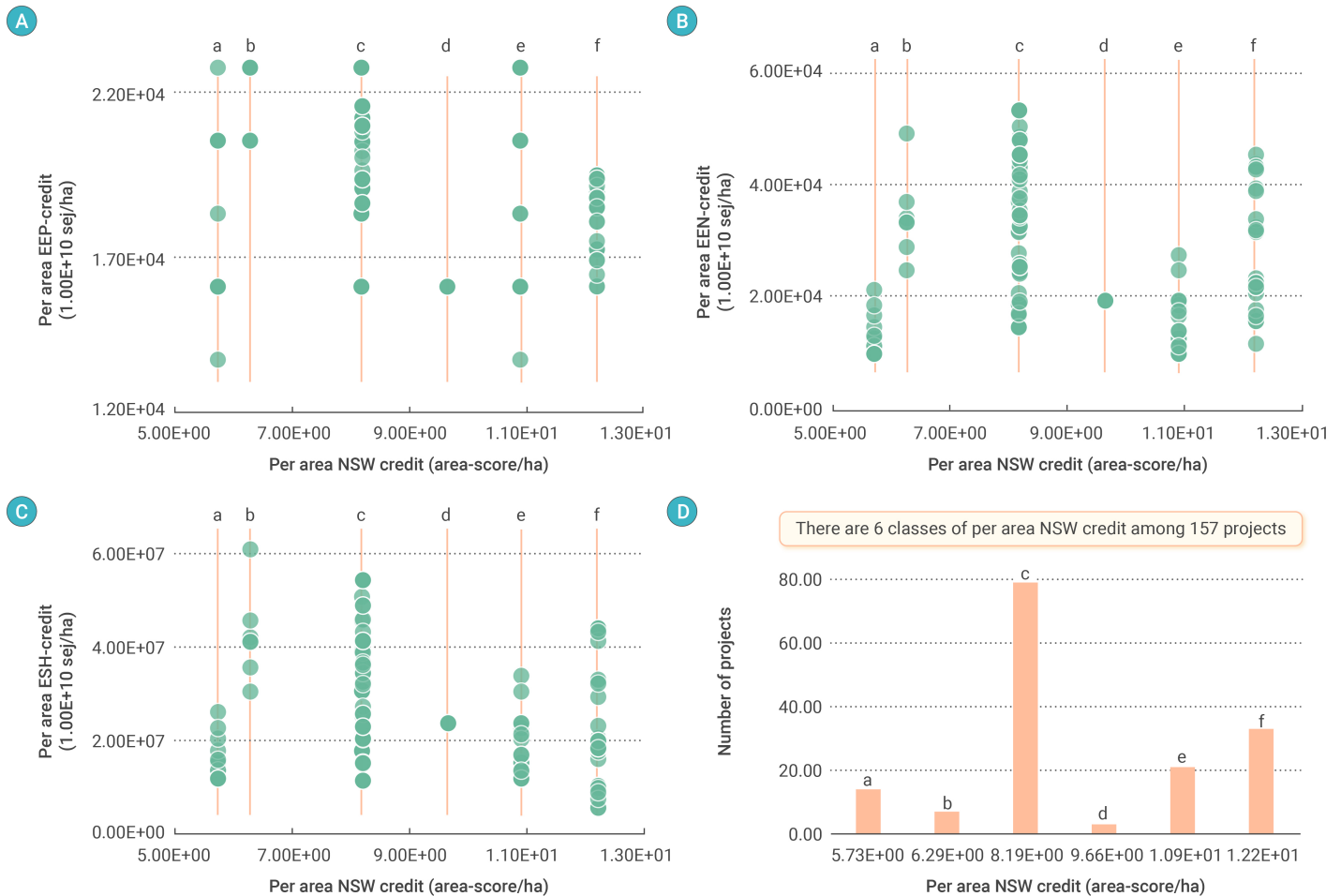


Figure 7. The relationship between per area EmBio-credit and per area NSW credit (A) The relationship between per area EEP-credit and per area NSW credit. (B) The relationship between per area EEN-credit and per area NSW credit. (C) The relationship between per area ESH-credit and per area NSW credit. (D) Per area NSW credit among 157 projects.

However, since lake projects and river projects focus primarily on water body management and have less vegetation, the calculation of NSW credit for wetland ecosystems can potentially overshadow other service functions. In contrast, EmBio-credit is calculated by identifying the vegetation and the species adjacent to the water body, which helps to obtain more detailed information about water body vegetation, thus allowing for the differentiation of credits among different projects. In particular, compared with the per area credit of NSW credit, EmBio-credit shows more advantages in terms of project type differentiation and the accuracy of the results. Figure 7 shows that the per unit area of NSW credit is clearly stratified into 6 levels, while EmBio-credit provides more information about the difference and diversity of values. The numerical range per area EmBio-credit, in which the unit is $1\text{E}10$ sej per ha, is very large and continuous. For example, EEP-credit ranges from $1.36\text{E}+04$ to $2.27\text{E}+04$, per area EEN-credit ranges from $9.56\text{E}+03$ to $5.33\text{E}+04$, and per area ESH-credit ranges from $5.58\text{E}+06$ to $6.09\text{E}+07$. These results further highlight the improvements in the biodiversity accounting method by EmBio-credit.

The impact of different kinds of ecological restoration patterns on EmBio-credit

EmBio-credit reveals the differences in biodiversity credits of different perspectives corresponding to different ecological engineering characteristics and inspires us to adopt different strategies according to the target characteristics and input-output benefit trade-offs when implementing ecological restoration and management. Figure 7 shows that the biodiversity credit is quite different from the three perspectives of EEP-credit, EEN-credit and ESH-credit across the different project types. After standardization, the total amount of credit in the three dimensions of greenway projects is relatively

balanced, although the difference in credit per unit area is relatively large (Figures 8A-B). The reason for the above results is threefold. First, greenway projects involve larger areas and higher vegetation density in green spaces. Second, they focus on afforestation and have higher connectivity. Finally, functional types of greenway projects are quite different, especially in terms of traffic and display, which are more artificially disturbed.

In terms of functional type, traffic-type projects have advantages in terms of total biodiversity credits because of their large area. However, when credit standardization per unit area is considered, traffic-type projects generate the lowest credit for the same reason, while ecological-type projects generate the highest credit. Among the functional types of traffic, tourism, living and esthetics, the EEP-credit, ESH-credit and EEN-credit projects are relatively balanced. The differences among the ecological types of river projects are small, while the differences between lake projects and greenway projects are relatively large. Compared with other function types, ecological projects generally have higher credit, with EEN-credit being the most prominent, followed by EEP-credit and ESH-credit. Additionally, compared with ecological and tourism projects, esthetic, living and traffic projects generate fewer credits relative to their natural endowments. This finding indicates a significant disparity between EEN-credit and EEP-credit as well as between ESH-credit and EEP-credit, as these projects are more susceptible to human interference.

In general, greenway projects generate more credits than Lake projects and River projects do with the same economic input, while they generate fewer credits per unit of land input (see Figures 5, 6A-B & 8). Additionally, the rates of successful projects and credit-to-market ratios for greenway projects are lower than those for lake projects and river projects (see Figure 3). The main reason for this difference is functional types of greenway

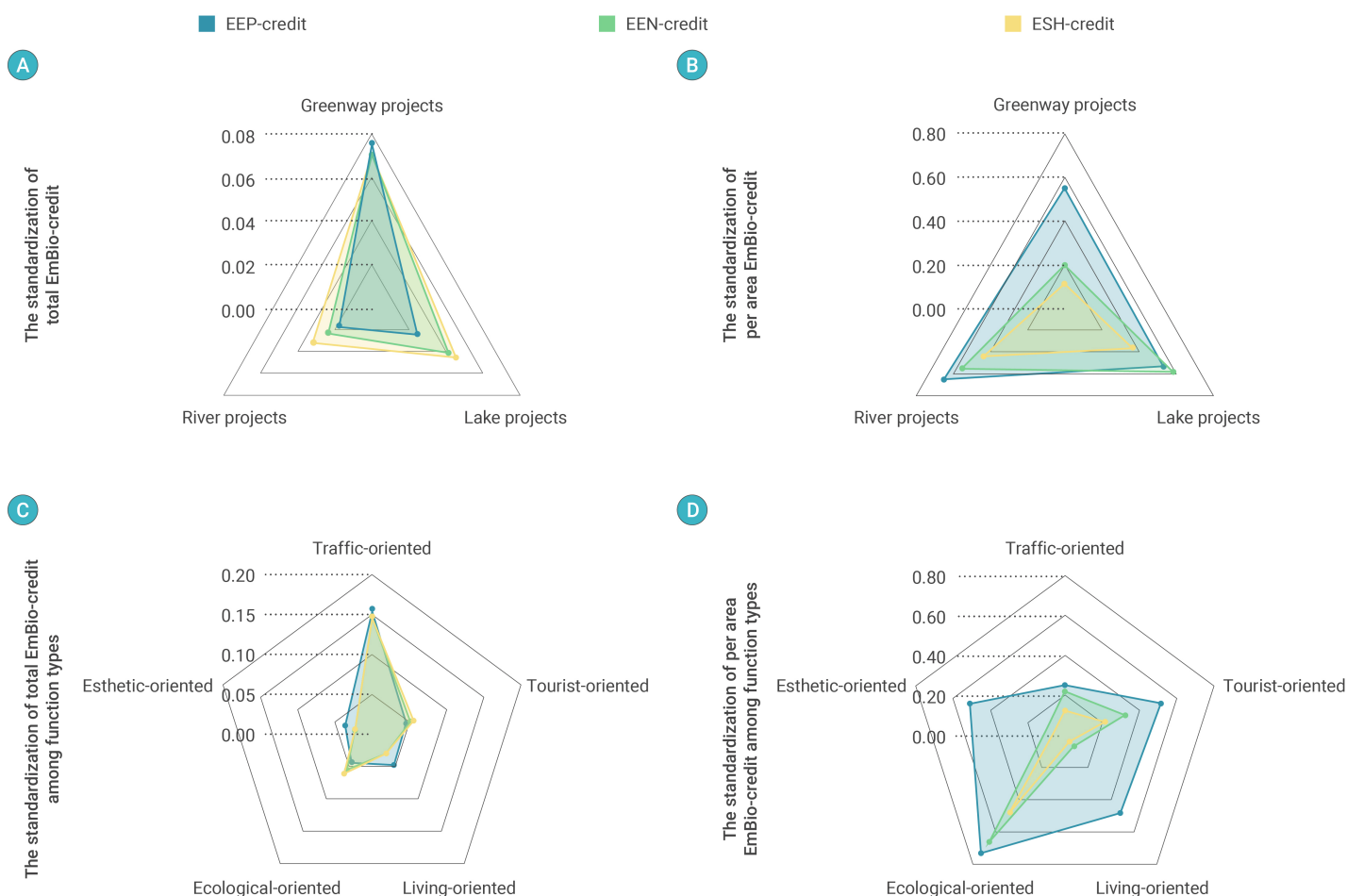


Figure 8. The impact of different function types of projects on EmBio-credit The standardization of (A) the total EmBio-credit, (B) the per area EmBio-credit, (C) the total EmBio-credit among different function types and (D) the per area EmBio-credit among different function types.

projects, such as esthetic and traffic projects, are more susceptible to human interference. Therefore, the role of river projects and lake projects in maintaining biodiversity should not be underestimated. Moreover, land-and-water projects, such as lake projects and river projects, which incorporate water and vegetation, have more potential for biodiversity credit transactions. Despite their higher costs, river projects and greenway projects can quickly achieve economic benefits. For purely land-based greenway projects that focus solely on vegetation, a higher risk of failure in biodiversity protection exists, although their initial economic cost is relatively low. Additionally, the EEN-credits of greenway projects are less tradable in the potential biodiversity credit market (see Figure 3D). Therefore, when conducting ecological management and biodiversity conservation in the future, it is crucial to consider the trade-off between cost and investment and implement appropriate strategies based on the protection goals and input–output benefits.

The potential of EmBio-credit's application in the biodiversity market

In this study, EmBio-credit provides the baseline of renewable resources supporting local biodiversity in a specific area through EEP-credit, which represents the static baseline. EEP-credit acts as the minimum threshold to determine whether a project's biodiversity credits are eligible for trading. Additionally, through ESH-credit, which assesses the contribution of biodiversity to human well-being based on the historical presence of domesticated species at the project site (this contribution arises from the process of selection and cultivation, as humans choose and nurture species that provide the greatest utility by providing support through fertilizers and other external energy inputs), EmBio-credit sets limits and constraints for biodiversity change. Both EEP-credit (baseline) and ESH-credit (constraint) serve as threshold tests to evaluate the impact of biodiversity in restoration projects, which focus on the supporting species that are recognized as most useful to

humans, even if they may not be useful for other local species. There are sometimes minimal differences in EEP-credit and ESH-credit among various projects, while EEN-credit offers more detailed differentiation. Specifically, EEN-credit measures the dynamic potential and uplift potential of exiting species in the ecosystem food web, providing insights into the dynamic changes in biodiversity credit and the potential for project credit transactions. In addition, EEN-credit can serve to directly quantify the degree of biodiversity change before and after the implementation of restoration projects. Different from ESH-credit, in which species are selected by humans, EEN-credit focuses on all the species present at the project site. Finally, EEP-credit focuses more on potential resource availability than on species.

The biodiversity credit accounting method proposed in this study offers a scientific foundation and a "common currency" for future development policies concerning market-based mechanisms for biodiversity offset in China and other countries and regions. By comparing the total amount of credit, credit per unit area, credit per unit cost, and the correlation between EmBio-credit and NSW credit, this study verifies the scientific robustness and reliability of the newly proposed biodiversity credit accounting method (EmBio-credit) and improves the biodiversity credit that has been successfully used internationally in terms of accuracy and generalizability. The conversion ratio between EmBio-credit and NSW credit provides a localized transformation plan promoted by biobanking in other countries and regions. According to public data on NSW biobanking, the price of ecosystem credit was 2,390 Australian dollars (latest date of sale: 25/07/2023),⁶⁶ which is approximately 11,594 CNY. Based on these figures, for the 2.11×10^5 NSW credits generated by all projects in this study, can we obtain a reference price of 2.44 billion CNY? As with any market, including more developed markets such as housing or stock markets, future biodiversity prices are not guaranteed. In many cases, the price of biodiversity credits on the open market depends on the

amount of credit that buyers and sellers are willing to pay or accept, which often differs from the cost of credit. Pricing options, including pricing via market information and pricing via cost accounting methods, are critical to both developers and landowners. Therefore, we believe that this price provides an overall sense of the benefits of ecological restoration.

Notably, the success of NSW biobanking depends largely on its strong regulatory foundation and comprehensive, long-term biodiversity management, which is worthy of reference. When implementing EmBio-credit in mechanisms such as biobanking, it is essential to take EEP-credit as the entry threshold, which represents the minimum requirement for participation. If the EEP-credit is greater than the EEN-credit, the project's biodiversity credit cannot be considered in the trading indicators. The reason is that it fails to meet the minimum requirement since it falls below the biodiversity level that ideally should be maintained through the natural contribution of the project site. Conversely, if the EEN-credit is greater than the EEP-credit, the project's biodiversity can be traded. The unified accounting method for biodiversity's multiple values offers a standardized unit in accounting for biodiversity credit for different restoration projects and their function types. In the future, biodiversity compensation may be integrated into land use planning and approval processes, and the method developed in this study can be effectively utilized. The measurement of biodiversity credits that developers need to purchase is based on changes in biodiversity before and after construction/development projects. This approach can be used to calculate biodiversity credit at both the restoration site and the development site, corresponding to the gains and losses of biodiversity credit.

This study introduces a newly proposed biodiversity credit called EmBio-credit, which is based on biophysical indicators derived from the emergy accounting approach developed by systems ecologist Howard Odum⁴¹. The proposed new method (named EmBio) helps assign nature-based financial value (credits) to biodiversity, with specific applications for assigning value to the benefits of restoration. This method can help to broaden biodiversity conservation solutions and bridge the financial gap in achieving biodiversity goals. EmBio-credit provides comparable and commensurable results to account for biodiversity in various ecosystem restoration projects via a unified accounting unit. It also overcomes the limitations of traditional methods (such as scoring, assigning, and counting methods) and offers a more objective approach. Specifically, it facilitates the measurement and analysis of biodiversity by considering the construction content of restoration projects and ecological units with different vegetation combinations. This emergy-based biodiversity credit accounting method, as a quantitative approach, is easier to promote and offers higher levels of objectivity, comprehensiveness, and predictability, as it is based on largely agreed-upon physical principles and metrics. It is also shown to be advantageous and scientifically based, providing higher levels of objectivity, comprehensiveness, and predictability.

The future application of this research relies on the availability and quality of observational data. More detailed spatial and ecological databases are needed to effectively facilitate biodiversity conservation and financing. The reason is that the determination of biodiversity credit and EmBio-credit, both before and after restoration projects, relies heavily on the availability of data. Currently, precise data for global species are still lacking, and cycle data change significantly in the literature; the values for different species may not differ greatly within the known species range. Observational studies have been limited by the oversimplified assumption that biodiversity is determined solely by species numbers,⁶⁷ especially with respect to native species and endangered species. Furthermore, to calculate biodiversity credits accurately, the threshold range needs to be considered, as do the specific vegetation conditions within the ecosystem, including their impact on human well-being. In addition, we need to consider the project construction time since there are significant time lags between the impacts of drivers and the realization of their full impacts on biodiversity.⁶⁸ Notably, successfully establishing a biodiversity credit market should be based on a thorough understanding of the connections among biodiversity, ecosystem functioning, and the production of ecosystem services.⁶⁹

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AUTHOR CONTRIBUTIONS

N.Y.Y., G.Y.L. and Z.F.Y. designed the study. N.Y.Y. and G.Y.L. developed the methods and carried out the computations. N.Y.Y., G.Y.L., S.U. and Z.F.Y. contributed to the analysis. N.Y.Y. and G.Y.L. wrote the article, with contributions from S.U. and Z.F.Y.. All authors contributed to and approved the manuscript

DECLARATION OF INTERESTS

The authors declare no competing interests.

DATA AND CODE AVAILABILITY

The datasets utilized to corroborate the presented results are accessible in the electronic supplementary material. Information pertaining to specific ecological projects was acquired through field studies, while the parameters employed for credit assessment are publicly available, as referenced in the article.

SUPPLEMENTAL INFORMATION

It can be found online at <https://doi.org/10.59717/j.xinn-geo.2024.100089>