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Optimizing Protected Area Expansion Across Protection Gradients: A Dose–Effect Framework Using Cohen's d to Maximize Conservation Gains

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Abstract

Global biodiversity loss poses critical challenges to achieving the UN Sustainable Development Goals, particularly SDG 15 (Life on Land) and the 30 × 30 target. However, translating broad sustainability targets into regionally optimized conservation strategies remains challenging, as current planning approaches typically treat coverage targets as fixed constraints rather than optimizing ecological outcomes. Here, we propose a dose–effect framework that integrates spatial prioritization with standardized effect-size analysis to identify protection coverage that maximizes gains in ecosystem multifunctionality, supporting sustainable ecosystem management. Using the Loess Plateau of China as a case study, we constructed a composite ecological function index from five ecosystem services, identified conservation priorities using Zonation with existing protected areas locked in as the highest-priority foundation, and quantified the dose–effect relationship between incremental coverage and standardized multifunctionality gains. Results revealed a nonlinear, threshold-dependent curve, with an optimal threshold at 30.79% coverage where the standardized effect reached its maximum. Beyond this threshold, marginal gains declined as the study incorporated lower-quality habitats. This study demonstrates that explicit dose–effect assessment provides a replicable, sustainability-oriented protocol for optimizing protected area expansion, enabling decision-makers to balance conservation effectiveness with sustainable land-use planning across diverse contexts.

Keywords: protected area expansion; ecosystem multifunctionality; sustainable development; dose–effect framework; Zonation; Loess Plateau; conservation prioritization; ecosystem services management

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1. Introduction

Global biodiversity loss and ecosystem degradation pose fundamental challenges to achieving the United Nations Sustainable Development Goals, particularly SDG 15 (Life on Land) and its Target 15.4, which calls for the conservation of mountain ecosystems, as well as to the Kunming–Montreal Global Biodiversity Framework's ambition of protecting at least 30% of terrestrial and inland water areas by 2030 (the 30 × 30 target) [1–3]. While this target has spurred widespread efforts to expand protected area (PA) networks and identify regional and national conservation priorities, translating a global percentage into regionally appropriate action remains a persistent sustainability challenge [3,4]. In particular, the

ecological effectiveness of incremental expansion—and whether a given coverage level delivers proportionate ecosystem benefits—is rarely evaluated explicitly, leaving decision-makers to rely on arbitrary thresholds rather than evidence-based optimization.

Systematic conservation planning (SCP) has become the dominant paradigm for operationalizing these sustainability goals [5,6], employing decision-support tools such as Marxan [7] and Zonation [8] to identify spatial priorities that efficiently represent biodiversity features. Historically, many existing protected area networks were designed primarily around species distributions, habitat rarity, or taxonomic representativeness [9,10]. While this species-centered approach remains important for preserving evolutionary heritage, it may not fully capture the capacity of landscapes to sustain multiple ecological processes simultaneously—a prerequisite for long-term ecosystem resilience and the delivery of ecosystem services upon which human well-being depends [11,12]. Optimizing conservation priorities based on ecosystem multifunctionality therefore offers a complementary perspective that aligns PA expansion with the integrated provision of key ecosystem functions and services, advancing the sustainability agenda beyond single-feature targets [13,14].

Despite these advances, current SCP applications often treat the protection target (e.g., 30%) as a fixed constraint rather than a variable to be optimized—a practice that runs counter to the principles of sustainable resource management [6]. Studies often report whether an optimized scenario is "statistically significantly better" than a baseline or present absolute improvements, such as increases in carbon storage, water yield, or habitat representation [15,16]. Although these approaches confirm that a difference exists, they provide limited insight into how much better an optimized scheme is in practical terms [17,18]. This limitation reflects the lack of a standardized framework for explicitly linking the intensity of conservation actions to their ecological outcomes [19–21].

In pharmacology and clinical research, dose–effect relationships quantify the magnitude of a therapeutic response relative to treatment intensity, distinguishing statistically detectable effects from clinically meaningful ones [22]. Conservation planning can be viewed analogously as a large-scale ecological intervention, in which the "dose" corresponds to the intensity of conservation action—such as the proportion of land protected, the budget invested, or the level of management enforcement—and the "effect" corresponds to the resulting improvement in conservation outcomes, such as enhanced biodiversity, increased ecosystem service flows, or improved ecosystem multifunctionality. Without a standardized framework linking conservation dose to ecological effect, it is difficult to determine whether a given coverage target is ecologically sufficient, unnecessarily excessive, or potentially inefficient relative to these competing sustainability objectives [23]. In this study, conservation effectiveness refers to the degree to which prioritized expansion areas improve ecosystem multifunctionality relative to the regional background, rather than the mere achievement of a predefined coverage target or the implementation of management procedures.

To address this methodological gap, we propose a dose–effect assessment framework [22] that moves beyond the mechanical application of the 30 × 30 target [2] by identifying the optimal conservation proportion for specific regions, thereby supporting more nuanced and context-sensitive sustainability planning. In this framework, protected area coverage is the "dose", and the standardized improvement in ecosystem multifunctionality is the "effect". Our framework evaluates incremental PA expansion outward from the existing protected area network, quantifying how each additional coverage level improves ecosystem multifunctionality relative to the regional background. Specifically, this study aims to: (1) construct a composite ecological function index (CEFI) based on five key ecosystem services and identify spatial conservation priorities using the Zonation algorithm with existing protected areas locked in as the highest-priority starting point for expansion; and (2) quantify the dose–effect relationship between incremental PA expansion and stan-

dardized gains in ecosystem multifunctionality against the regional background, thereby identifying the optimal protection coverage that maximizes conservation effectiveness.

We applied this framework to the Loess Plateau of China, a socio-ecologically sensitive region where decades of ecological restoration programs have sought to balance ecosystem recovery with the livelihood needs of millions of residents—a quintessential sustainability challenge [24,25]. By linking spatial prioritization with a standardized effect-size assessment, this study offers a replicable approach to determining how much protection is ecologically justified, rather than assuming more protection is always better. The framework supports the sustainable development imperative of "doing more with less" by identifying the coverage level at which marginal conservation gains diminish [26], thereby informing efficient allocation of limited conservation resources within broader sustainable land-use planning frameworks.

2. Materials and Methods

2.1. Study Area

The Loess Plateau (33°43′ N–41°16′ N, 100°54′ E–114°33′ E) lies in the middle reaches of the Yellow River in north-central China (Figure 1) and covers approximately 640,000 km^2. The region's topography slopes from northwest to southeast, with elevations predominantly between 1000 and 2000 m. It has a temperate continental monsoon climate, with precipitation decreasing from semi-humid conditions in the southeast to arid conditions in the northwest. The annual mean temperature is 7.6 °C, annual precipitation is about 441 mm [27], and more than 60% falls during the summer months (July–September). This climatic pattern, combined with highly erodible loess soils and a long history of intensive land use, has caused severe soil and water loss, making the region's ecosystems inherently fragile and spatially heterogeneous. These environmental constraints, coupled with a population exceeding 100 million people whose livelihoods depend on agriculture and natural resource extraction, make the Loess Plateau one of the world's most challenging regions for balancing ecological restoration and human well-being.

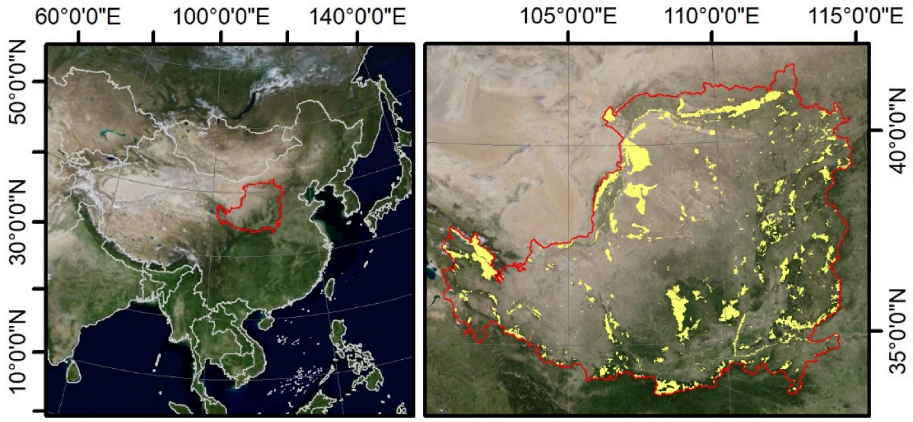


Figure 1. Location of the Loess Plateau in China (red polygon) and spatial distribution of existing protected areas (yellow color). The white border color presents the country lines.

Over the past several decades, the Loess Plateau has undergone substantial ecological restoration through the Grain for Green Program, the Three-North Shelterbelt Program, small watershed management, check-dam construction, and the expansion and reorganization of natural protected areas [28]. These measures have markedly increased vegetation cover, reduced soil erosion, and improved habitat conditions across the region [29]—representing one of the world's largest attempts to reverse ecosystem degradation at a continental scale. By the end of 2017, the plateau hosted 148 nature reserves covering about

5.81 million hectares (58,110 km^2), or about 9% of its total land area. This coverage remains well below the 17% target set by the Aichi Biodiversity Targets [30], the more recent 30% target under the Kunming–Montreal Global Biodiversity Framework [2], and the national average of 14.86% for nature reserves [31]. From a sustainability perspective, this gap underscores the urgency of identifying where and how additional protected areas can most efficiently contribute to both biodiversity conservation and the sustained provision of ecosystem services.

The protected area (PA) network on the Loess Plateau has evolved through distinct phases of expansion [32]. As illustrated in the cumulative trajectories (Figure 2a,b), the total number of PAs has plateaued at 148, and the cumulative area reached approximately 5.81 million hectares, accounting for 9% of the total land area. The annual increase plots (Figure 2c,d) reveal that the region experienced a concentrated period of rapid expansion between the late 1990s and 2005, coinciding with major national ecological engineering projects. Following 2005, both the establishment of new reserves and the expansion of existing ones slowed markedly, indicating that the current PA network has largely stabilized.

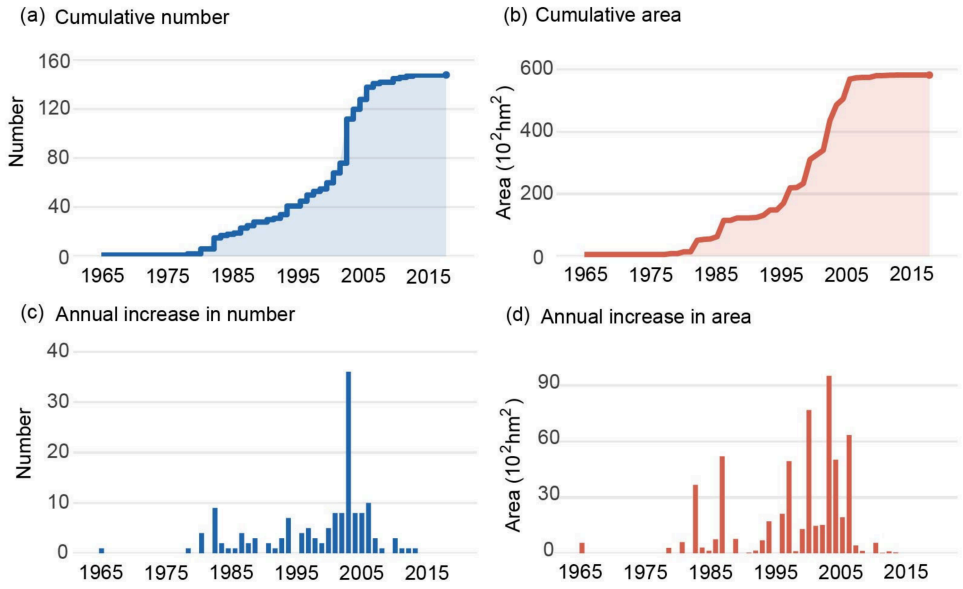


Figure 2. Evolution of number and size of protected areas on the loess plateau (modified from An et al. [32]). Different colors represent statistics of different indicators (blue: number; red: area).

Historically, these reserves were established primarily to protect specific wildlife species or forest ecosystems [32]. However, the current network covers only a fraction of the plateau's diverse habitats, and its spatial configuration may not fully align with areas of high ecosystem multifunctionality. Rather than continuing the historical pattern of area-based expansion, it is therefore necessary to adopt a dose–effect approach that identifies priority areas where incremental protection can yield the greatest marginal gains in ecosystem multifunctionality—an approach that aligns with the sustainability principle of maximizing ecological returns on limited conservation investments [33]. In this study, we treat the current protected area network as a fixed baseline and evaluate how incremental expansion from this baseline would affect ecosystem multifunctionality relative to the regional background. We do not reconstruct the full historical trajectory of protected area establishment; instead, we use the existing network as the starting point for systematic conservation prioritization and dose–effect assessment. The existing PA network for the Loess Plateau (2017) is sourced from the China Nature Reserve Specimen Resource Sharing Platform (http://cnpapc.zrbhq.cn, accessed on 8 May 2026).

2.2. Ecosystem Multifunctionality Assessment

We undertook a comprehensive assessment of ecosystem multifunctionality by amalgamating five pivotal regulating and supporting services—carbon storage, soil conservation, water yield, habitat quality, and biodiversity—that are central to regional sustainability. This selection aligns with widely accepted frameworks, such as the Millennium Ecosystem Assessment [34], and captures the fundamental ecological functions that are paramount to regional sustainability and human well-being.

Carbon Storage

We used a 1 km resolution dataset of soil organic carbon density for China [35], developed by integrating Landsat satellite imagery with topographic and meteorological data using a Random Forest machine learning algorithm. This dataset provides a robust estimate of below-ground carbon stocks, a major component of the terrestrial carbon cycle.

Soil Conservation

This service is quantified as vegetation-mediated soil retention, computed via the Revised Universal Soil Loss Equation (RUSLE) model (U.S. Department of Agriculture, Washington, DC, USA) [36]. The model integrates five standard biophysical factors: rainfall erosivity, soil erodibility, slope length and gradient, crop management, and conservation practices. The soil conservation data (30 m resolution) were derived from the ecosystem service dataset of Liu et al. [37].

Water Yield

We estimated annual water yield (1 km resolution) using the corresponding module in the InVEST (Integrated Valuation of Ecosystem Services and Trade-offs) model (Stanford, CA, USA) [38]. The model calculates water yield for each raster cell (x) as the difference between precipitation and actual evapotranspiration (AET), based on the Budyko curve:

$$Y_{xj} = \left(1 - \frac{AET_{xj}}{P_x}\right) \times P_x \quad (1)$$

where Y_{xj} is the annual water yield (mm) for land-use type j, AET_{xj} is the annual actual evapotranspiration (mm), and P_x is the annual precipitation (mm).

Habitat Quality

We also assessed habitat quality (1 km resolution) using an InVEST model [38]. The model degrades habitat based on proximity to and the intensity of various threat sources, including cropland, built-up land, unused land, highways, and railways in our study. The habitat quality index Q_{xj} for each cell is modeled as:

$$Q_{xj} = H_j\left[1 - \left(\frac{D_{xj}^z}{D_{xj}^z + k^z}\right)\right] \quad (2)$$

where Q_{xj} represents the habitat quality index of raster cell x within habitat type (j); k denotes the half-saturation constant; D_{xj}^z is the habitat degradation level experienced by raster cell x within habitat type j; z represents a normalization constant; and H_j denotes the habitat suitability score assigned to habitat type j.

Biodiversity

We employed distribution data for 361 dominant tree species, compiled by Zhang et al. [39], as a proxy for biodiversity. These species span 58 families and 141 genera, effectively representing the region's flora. We constructed a biodiversity index by spatially overlaying species distribution ranges, with areas of high overlap indicating biodiversity hotspots (10-min resolution). This approach is justified because, among the 401 recorded invasive species, invasive plants on the Loess Plateau are predominantly herbaceous [40]. Within Zhang et al.'s dataset of 361 dominant tree species, only three are invasive: *Robinia pseudoacacia*,

Salix fragilis, and *Amorpha fruticosa*. Consequently, tree species distributions reliably represent regional biodiversity patterns.

To enable direct intercomparison of the five ecosystem services, all individual service maps were normalized to a uniform 0–1 scale using the min-max method [41]. This preprocessing removed dimensional differences and ensured comparability across indicators. The soil conservation and biodiversity layers were first resampled to a consistent 1 km resolution using Kriging interpolation, and all rasters were projected to the WGS_1984_Albers coordinate system. The spatial distribution patterns of the five normalized indicators are shown in Figure 3.

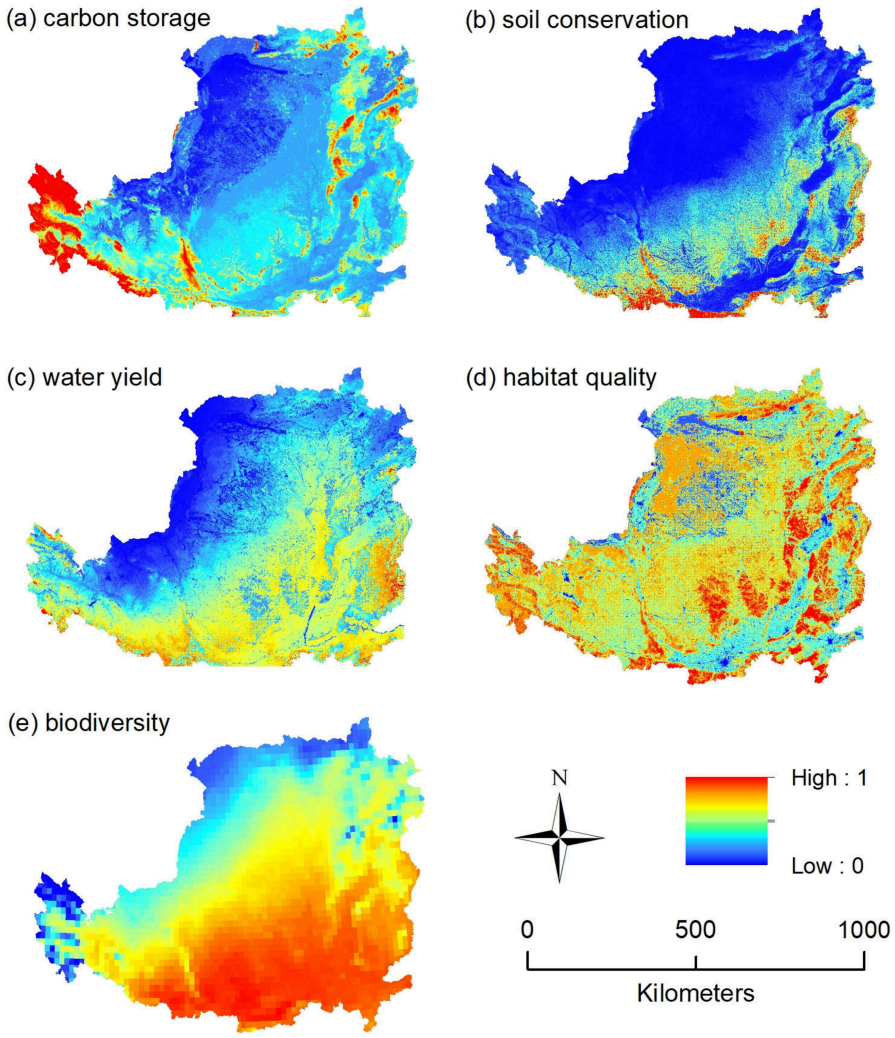


Figure 3. The distribution patterns of normalized indicators for five ecological functions on the Loess Plateau.

2.3. Construction of the Composite Ecological Function Index (CEFI)

To create a single, integrative metric of ecosystem multifunctionality, we developed a CEFI. We computed the CEFI using an equal-weighted summation method:

$$CEFI = \frac{1}{n}\sum_{i=1}^{n} f(x, ef_i) \quad (3)$$

where $f(x, ef_i)$ is the normalized value of the i-th ecosystem function for raster cell x, and n is the number of ecosystem functions (n = 5). This approach assumes that all five functions are equally important, providing a balanced representation of overall ecosystem

performance. The resulting CEFI layer is a continuous surface, with higher values indicating areas with greater capacity to provide multiple ecosystem services simultaneously.

2.4. Identification of Conservation Priorities

We used Zonation 5 (University of Helsinki, Helsinki, Finland) to identify spatial conservation priorities across the Loess Plateau [8], employing a decision-support approach that directly informs sustainable land-use planning. Specifically, we employed the Core Area Zonation 2 (CAZ2) algorithm, which identifies networks of sites that preserve the distributional cores of all input features. The algorithm iteratively removes the grid cell that causes the smallest marginal loss in the aggregate distribution value of all features, producing a hierarchical priority rank for every cell in the landscape. A key feature of our model setup was the treatment of the existing protected area network. All current PAs were assigned a "lock-in" status in Zonation, ensuring that they were retained in every conservation scenario and treated as the foundational baseline for subsequent expansion. This design anchors all expansion scenarios to the existing conservation network, so that each additional coverage level represents incremental improvement in ecosystem multifunctionality beyond the current PA system, rather than a de novo prioritization of the entire landscape. The CEFI map served as the primary feature layer guiding prioritization. From the resulting priority ranking, we extracted cumulative conservation scenarios corresponding to protection coverage levels from 10% to 50% of the total study area, in 5% increments. This gradient of scenarios forms the "dose" axis of our dose–effect analysis, providing a structured approach to evaluating how conservation investments at different scales contribute to sustainable ecosystem management.

2.5. Standardized Dose–Effect Assessment

To evaluate the ecological effectiveness of protected area expansion in a comparable and interpretable manner—a prerequisite for evidence-based sustainability planning—we developed a three-stage dose–effect assessment framework. In this study, conservation effectiveness refers to the degree to which prioritized expansion areas improve ecosystem multifunctionality relative to the regional background, rather than the mere achievement of a predefined coverage target.

Protected area expansion scenarios. We constructed a series of PA expansion scenarios ranging from 10% to 50% of the Loess Plateau's total area, spanning the range from the current protection level (~9%) to well beyond the GBF 30% target. Critically, the current protected area network was assigned the highest priority rank in the Zonation output, serving as the fixed baseline for all expansion scenarios. Under this design, each coverage scenario represents the current PA network plus incrementally added areas selected in descending order of conservation priority. This ensures that all expansion scenarios build upon the existing conservation foundation, and the resulting dose–effect curve reflects the marginal gain of expanding outward from the current PA network rather than starting from an empty landscape. This approach enables decision-makers to assess whether additional conservation investments deliver proportionate ecological returns—a central question in sustainable resource management.

Stage 1: Statistical significance testing. For each of nine PA coverage scenarios (10%, 15%, . . ., 50%), we randomly sampled 500 points from the cumulative prioritized area, which includes the current protected areas plus the incrementally added cells ranked highest by Zonation. We compared the mean CEFI of these points with the overall mean CEFI for the entire Loess Plateau using a one-sample t-test. This step assessed whether the areas selected under each scenario had significantly higher ecological function than the regional background.

Stage 2: Standardized effect size calculation. To quantify the magnitude of improvement under each PA coverage scenario relative to the regional background (i.e., the entire Loess Plateau), we calculated Cohen's *d* for independent two-sample comparisons [17,42,43]:

$$d = \frac{\overline{X_1} - \overline{X_2}}{SD_{pooled}} \quad (4)$$

where $\overline{X_1}$ and $\overline{X_2}$ are the mean CEFI values for the sampled prioritized area ($n_1 = 500$) and the Loess Plateau background ($n_2 = 1000$), respectively; SD_1 and SD_2 are their corresponding sample standard deviations; and SD_{pooled} is the pooled standard deviation:

$$SD_{pooled} = \sqrt{\frac{(n_1 - 1)SD_1^2 + (n_2 - 1)SD_2^2}{n_1 + n_2 - 2}} \quad (5)$$

The pooled standard deviation provides a robust estimate of population variance by weighting the sample variances according to their degrees of freedom. Cohen's d therefore expresses the standardized difference in ecosystem multifunctionality between the prioritized expansion areas and the regional background, with larger positive values indicating stronger conservation effectiveness.

Stage 3: Optimal threshold calculation. To characterize the nonlinear relationship between protected area coverage and enhanced ecosystem multifunctionality, we fitted a three-parameter gamma-type dose–effect kernel to the observed Cohen's d values across the nine coverage scenarios [44]. We selected the gamma-type form because it flexibly captures initial increases, diminishing returns, and potential saturation in ecosystem responses. The function was specified as:

$$d(x) = ax^b e^{-cx} \quad (6)$$

where $d(x)$ is the Cohen's d value at protected area coverage x; a is a scaling parameter controlling the overall height of the curve; b is a shape parameter determining the steepness of the initial increase; and c is a decay parameter controlling the rate of decline after the peak. This functional form is suitable for describing a unimodal response in which the standardized conservation gain increases slowly at low coverage, rises rapidly at intermediate coverage, and then declines as coverage continues to increase.

Model parameters were estimated by nonlinear least squares using the nls() function in R 4.5.1 (Vienna, Austria). Initial values were set to facilitate convergence (start = list(a = 0.001, b = 3, c = 0.05)), and parameter estimates were obtained by minimizing the residual sum of squares. Goodness of fit was assessed using the coefficient of determination (R^2). The optimal protected area coverage corresponding to the maximum Cohen's d was derived from the first derivative of the fitted function, yielding a peak at $x^* = b/c$.

3. Results

3.1. Spatial Patterns of Ecosystem Multifunctionality

The spatial distribution of the CEFI across the Loess Plateau showed a pronounced southeast-to-northwest gradient, closely aligned with regional hydrothermal conditions (Figure 4). High CEFI values were concentrated in the southeastern forest-steppe ecotone and the southern warm temperate forest zone, where favorable precipitation and vegetation cover support the synergistic provision of multiple ecosystem services. In contrast, low CEFI values dominated the northwestern arid and semi-arid regions, particularly in the Mu Us Sandy Land and adjacent desert transition zones, reflecting systemic constraints linked to water scarcity and fragile soils—conditions that limit both ecological function and agricultural productivity. A broad transitional belt of medium CEFI

values extended diagonally across the central agricultural-pastoral ecotone, displaying a mosaic pattern that indicates strong human–nature interactions and heightened sensitivity to land-use change. Notably, scattered medium-to-high CEFI patches embedded within the northern low-value matrix suggest localized ecological improvement, which may be associated with previous restoration initiatives such as the Grain for Green Program. This spatial heterogeneity implies that although the southeastern region is the core functional zone, targeted interventions in the central transition belt and northern restoration hotspots could be critical to enhancing regional ecosystem resilience and supporting sustainable livelihoods.

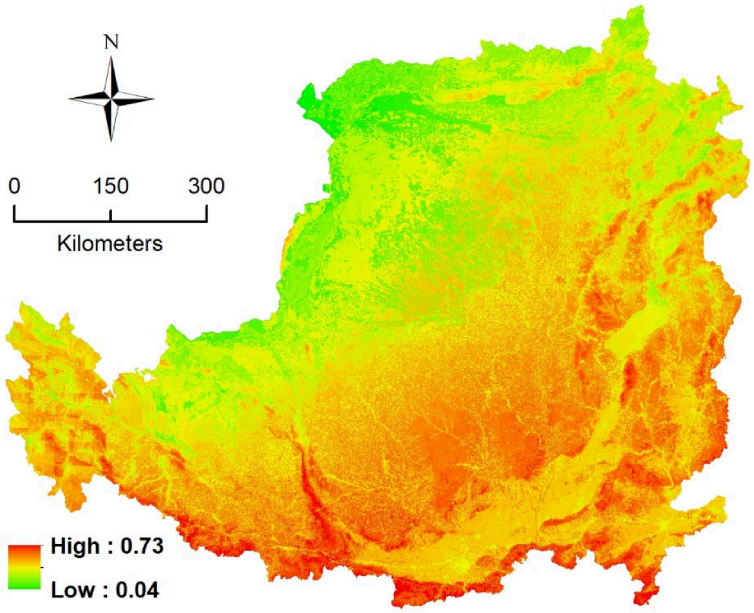


Figure 4. Spatial distribution of the composite ecological function index (CEFI) across the Loess Plateau.

3.2. Spatial Priorities for Conservation Expansion

The spatial prioritization analysis revealed a conservation landscape characterized by a "high-value mosaic embedded in a low-value matrix" (Figure 5). Because existing protected areas were locked in as the highest-priority foundation, they formed the structural backbone of the priority network. Additional high-complementarity areas (top 10–20%) were spatially discrete and concentrated primarily along three zones: the western margin (102° E–104° E), the northern arid zone (>40° N), and the southeastern forest-steppe ecotone. These zones largely adjoined or extended outward from existing protected areas, indicating that the current PA network has already captured some of the most ecologically sensitive regions, while also revealing substantial conservation gaps. The most notable gaps were the large high-priority cluster in the west and the continuous moderate-priority band in the southeast. By contrast, the extensive green matrix covering much of the central and northern plateau contributed relatively little to aggregate conservation targets under the current weighting scheme, although fine-scale heterogeneity within these areas may still warrant site-specific attention. Importantly, identifying high-complementarity zones outside existing PA boundaries—especially the western cluster and the southeastern corridor—provides a spatial blueprint for "smart expansion" that concentrates limited conservation resources on areas likely to yield the highest ecological returns, consistent with sustainable investment principles in natural capital management.

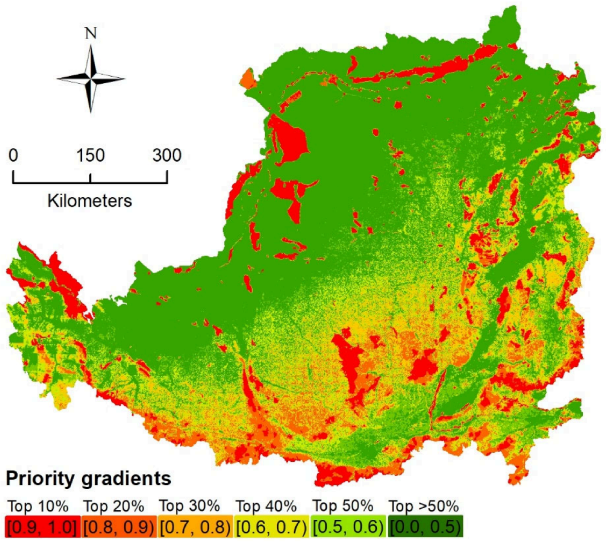


Figure 5. Spatial priority potential gradients for conservation expansion of protected areas on the Loess Plateau.

3.3. Statistical Validation of Priority Gradients

To quantify the effectiveness of the conservation prioritization, we compared CEFI values across priority gradients with the baseline mean (0.335 ± 0.101) using one-sample t-tests. All tested priority thresholds showed statistically significant improvements relative to the baseline (Table 1). At the top 10% threshold (mostly existing protected areas), the mean CEFI reached 0.363 ± 0.110, significantly exceeding the background landscape ($t = 5.745$, $p < 0.001$). The magnitude of improvement increased sharply at higher thresholds: the top 20% and 30% gradients had mean CEFI values of 0.420 ± 0.101 and 0.424 ± 0.085, respectively, with t-values of 18.665 and 23.590 ($p < 0.001$). Statistical significance remained robust across the entire 10–50% range (all $p < 0.001$), confirming that the identified high-priority zones possess substantially higher ecological value than the background landscape. However, mean CEFI values stabilized around 0.40–0.42 between the 15% and 50% thresholds, peaking at 0.424 at the 30% threshold and declining slightly to 0.403 at 50%, suggesting a saturation-like pattern in which further expansion of the priority area yields diminishing marginal gains in average multifunctionality. This pattern indicates that the initial 20–30% of prioritized area captures most of the high-CEFI core zones, providing an efficiency-oriented basis for subsequent dose–effect evaluation and informing decisions about the optimal scale of conservation investment.

Table 1. Statistical validation of priority gradients: CEFI means, standard deviations, t-values, *p*-values and Cohen's d for each protection level.

Priority Gradient	Mean CEFI	Standard Deviation	T-Value	*p*-Value	Cohen's *d*
10%	0.363	0.110	5.745	<0.001	0.308
15%	0.409	0.113	14.619	<0.001	0.744
20%	0.420	0.101	18.665	<0.001	0.882
25%	0.421	0.089	21.602	<0.001	0.931
30%	0.424	0.085	23.590	<0.001	0.981
35%	0.417	0.084	21.821	<0.001	0.904
40%	0.414	0.072	24.281	<0.001	0.901
45%	0.409	0.071	23.035	<0.001	0.847
50%	0.403	0.070	21.755	<0.001	0.792

3.4. The Non-Linear Dose–Effect Curve

To evaluate the standardized effectiveness of protected area expansion, we quantified the dose–effect relationship between PA coverage (dose) and CEFI improvement (effect) using Cohen's d (Figure 6). The fitted gamma-type function, $d(x) = ax^b e^{-cx}$, captured the nonlinear dynamics with high precision (R^2 = 0.92), revealing a distinct unimodal response pattern. At the top 10% expansion level (mostly existing protected areas), the effect size was moderate (d = 0.308), indicating that initial prioritization captured some high-value areas but with limited overall impact. As coverage increased, the effect size rose rapidly, entering the "large" range at 15% (d = 0.744) and reaching d = 0.882 at 20% coverage (Table 1).

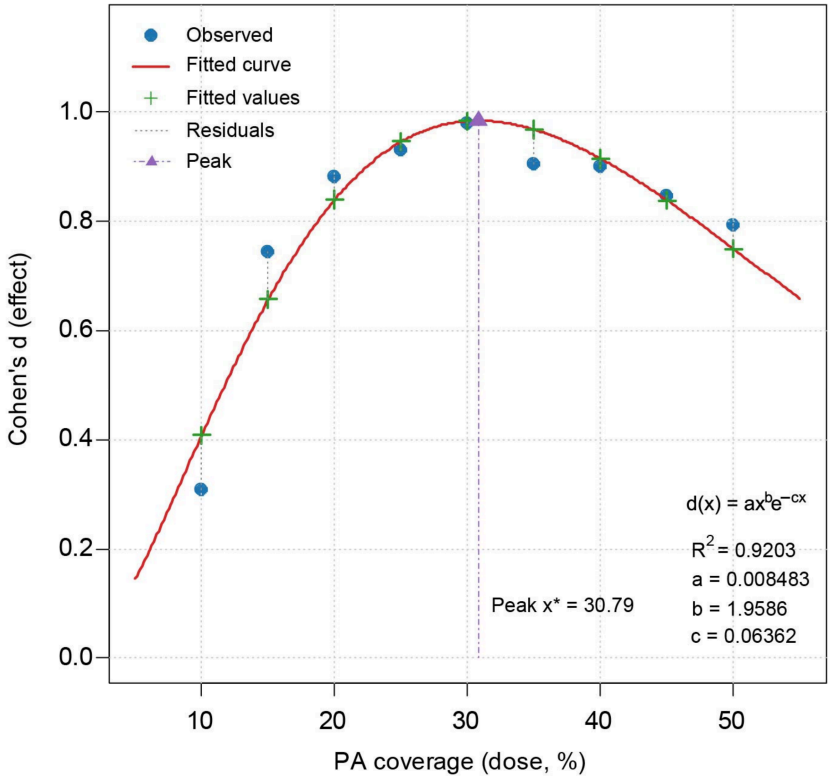


Figure 6. Dose–effect curve of protected area expansion: standardized effect size (Cohen's d) versus PA coverage on the Loess Plateau. * represents the x value at which the maximum gain in Cohen's d occurs.

The model identified an optimal conservation threshold at 30.79% coverage, where the standardized effect reached its global maximum. Beyond this optimum, the curve declined gradually, with the effect size dropping to roughly 0.79 at 50% coverage (Figure 6). This nonlinear pattern suggests that conservation effectiveness is threshold-dependent rather than linearly cumulative—a finding with important implications for sustainable conservation planning, as it indicates that expanding protection beyond the optimal threshold may not deliver proportionate ecological benefits and could divert resources from other sustainability priorities such as poverty alleviation, food security, and rural development.

4. Discussion

4.1. A Threshold-Dependent Relationship Rather than a Linear Gradient

It is essential to clarify the mechanism underlying the non-monotonic pattern of Cohen's d, given that Zonation generates a priority ranking in descending order of conservation value. In our model setup, the existing protected area (PA) network was assigned a "lock-in" status, effectively serving as the highest-priority foundation. Consequently, the prioritization process did not rank the entire landscape de novo; instead, it identified

optimal expansion zones outward from this established baseline. Furthermore, our dose–effect assessment quantifies the standardized improvement in ecosystem multifunctionality relative to the current baseline, rather than the absolute priority score of individual cells. While Zonation ensures that cells are added in decreasing order of marginal contribution, the aggregate effect size (Cohen's d) reflects the collective functional gain of the expanded set. From a sustainability perspective, this distinction is crucial: it means that the dose–effect curve does not simply mirror the Zonation priority ranking but instead captures how incremental conservation investments translate into measurable improvements in ecosystem services—the very metric that underpins the sustainability rationale for protected area expansion.

The resulting nonlinear dose–effect curve reveals a threshold-dependent relationship between PA coverage and multifunctionality enhancement on the Loess Plateau, deviating from a simple linear gradient (Figure 6). The fitted gamma-type function, $d(x) = ax^b e^{-cx}$, captured this dynamic with high precision (R^2 = 0.92). Notably, the current PA network on the Loess Plateau was not originally designed through systematic planning with ecosystem multifunctionality as an explicit objective. As a result, baseline multifunctionality is relatively modest, which partly explains why the standardized effect of the initial 10% expansion was only moderate (Cohen's d = 0.308). This value corresponds to the capture of discrete, high-CEFI patches embedded within a low-value matrix. As the prioritized area expanded, the selected zones increasingly encompassed core functional areas and ecologically coherent corridors. This structural integration produced a rapid rise in standardized effectiveness, with the effect size entering the "large" range at 15% (d = 0.744) and nearly peaking at d = 0.981 at 30% coverage. From a sustainability standpoint, this pattern suggests that strategically targeted expansion—rather than blanket coverage increase—is the most efficient pathway to enhancing ecosystem multifunctionality, a finding that resonates with the growing emphasis on precision conservation in sustainable land-management practice [45,46].

The model identified an optimal conservation threshold at 30.79% coverage. Beyond this optimum, the curve declined gradually (d = 0.904 at 35%, decreasing to 0.792 at 50%). This trajectory indicates that while the ~31% threshold captured most multifunctional portions of the landscape, expanding into lower-priority areas diluted the average gain in CEFI. This does not render areas beyond the threshold ecologically irrelevant; rather, it suggests their marginal contribution to aggregate multifunctionality is smaller under the current weighting scheme [47]. These findings empirically support the rationale behind the GBF's 30% target [2], indicating that this coverage level captures the core high-CEFI areas while highlighting the need to consider spatial configuration alongside aggregate targets [48]. From a sustainability perspective, identifying an optimal threshold near 30% provides compelling evidence that globally negotiated targets can be grounded in region-specific ecological evidence, strengthening the scientific legitimacy of international sustainability agreements and informing national reporting under SDG 15.1.

4.2. Moving Beyond p-Values: Why Standardized Effect Sizes Matter for Conservation Prioritization

Our findings underscore the limitations of relying exclusively on binary significance testing to evaluate conservation plans. All priority gradients from 10% to 50% were statistically significant relative to the baseline (all $p < 0.001$), yet their practical implications differed markedly. A decision framework based solely on p-values would offer little basis for distinguishing a modest improvement under a 10% expansion from the substantially larger ecological gains achieved at 25–35%. By incorporating Cohen's d, our dose–effect framework shifts the focus from whether a difference exists to how large that difference is, expressed in standardized, interpretable units [17,18]. The transition from a moderate

effect at 10% (d = 0.308) to large effects across the 15–50% range (d = 0.744–0.981) provides a quantitative basis for evaluating the substantive effectiveness of alternative PA expansion scenarios. Notably, the effect size more than tripled from the 10% to the 30% threshold (from 0.308 to 0.981), highlighting how the standardized metric captures gradients of conservation effectiveness that *p*-values alone cannot distinguish. This standardized metric also facilitates cross-regional and cross-study comparisons because it is independent of sample size and original measurement units [17,42,43]—a feature that is particularly valuable for monitoring progress toward SDG 15 targets across diverse ecological and administrative contexts.

More broadly, these results highlight a persistent gap in current systematic conservation planning (SCP) applications. Despite recent advances, SCP often treats the protection target (e.g., 30%) as a fixed constraint rather than a variable to be optimized [49]—a practice that can undermine the efficiency and legitimacy of conservation investments in contexts where land-use competition is intense and fiscal resources are limited [50]. Under such a formulation, the central question becomes whether a predefined coverage level can be achieved, rather than how ecological benefits change across alternative expansion levels. Our dose–effect framework addresses this limitation by explicitly linking PA coverage to standardized gains in ecosystem multifunctionality, thereby supporting more flexible and evidence-based target setting. In this approach, protection goals can be calibrated to diminishing returns, management feasibility, and competing land-use demands—considerations at the heart of sustainable development practice. As such, the proposed framework complements traditional significance testing and aligns SCP evaluation with emerging expectations in ecology and environmental science to report effect sizes alongside *p*-values [51], while simultaneously advancing the sustainability agenda by providing decision-makers with a transparent tool for optimizing conservation investments [52].

4.3. Strengths, Limitations, and Future Directions

A key strength of the proposed framework is its simplicity and transferability. Because Cohen's d is a standardized, dimensionless metric, it can be applied across conservation objectives, ecological indicators, and geographic contexts [17,42,43], enabling more comparable assessments of PA effectiveness across studies—an attribute that is particularly valuable for monitoring progress toward globally agreed sustainability targets such as SDG 15. Moreover, the dose–effect perspective allows conservation expansion to be evaluated not as a binary choice but as a continuous decision problem, in which ecological returns can be assessed relative to incremental increases in protected area coverage. This continuous framing aligns with sustainable development practice, where resource allocation decisions are rarely all-or-nothing and instead involve trade-offs between competing priorities.

Several limitations should be acknowledged. First, the CEFI assigns equal weights to the five ecosystem services. Although this provides a transparent baseline, stakeholders may prioritize services differently based on local sustainability priorities—for example, communities in water-scarce regions may value water yield more, while agricultural communities may prioritize soil conservation. Future applications could use stakeholder-informed or scenario-based weighting to test how sensitive the dose–effect curve is to different sustainability perspectives. Second, the current analysis does not include socioeconomic costs. Integrating land acquisition costs, opportunity costs, or management expenditures would extend the framework into a cost-effectiveness dose–effect assessment [53], more directly applicable to real-world planning contexts where fiscal constraints shape conservation outcomes [54]. Third, the analysis is spatially static. Future work could employ time-series remote sensing, ecosystem service modeling, or PA performance data to develop dynamic dose–effect models that account for climate change, land-use transitions,

restoration trajectories, and changes in PA management effectiveness—all of which are critical dimensions of long-term sustainability [55]. Finally, although Cohen's d provides a robust measure of standardized mean difference, it is intentionally non-spatial: its role is to quantify the magnitude of multifunctionality gains in a form that is comparable across studies with different spatial structures. We acknowledge that explicit spatial metrics—such as connectivity indices [56], compactness measures, and representation analyses [57]—could offer valuable complementary information. In our framework, however, spatial configuration is addressed through complementary mechanisms. The Zonation algorithm (CAZ2) generates spatially explicit priority rankings that tend to favor contiguous, ecologically coherent networks over fragmented patches, thereby embedding spatial considerations within the prioritization step. The lock-in mechanism further helps preserve the spatial configuration of existing protected areas across all expansion scenarios.

4.4. Management Implications for the Loess Plateau

For conservation planning on the Loess Plateau—a region where ecological sustainability and human livelihoods are inextricably linked—the results suggest that the current PA coverage of approximately 9% falls well below the threshold at which large, standardized gains in ecosystem multifunctionality are realized. The expansion window from 10% to approximately 31% represents a critical phase for improving ecological effectiveness, particularly by protecting high-complementarity zones outside the existing PA network (Figure 5). Prioritize areas that enhance connectivity among high-CEFI patches, such as riparian corridors, forest-steppe ecotones, and buffers around existing reserves. These areas could be incorporated by expanding existing nature reserves, refining Ecological Conservation Redlines, or establishing community co-managed conservation areas [58]—approaches that align with the sustainable development principle of inclusive governance. Importantly, such expansion should minimize conflicts with local livelihoods, for example by prioritizing degraded or low-productivity lands where conservation and human activities can coexist [59,60].

Once coverage approaches the ~31% threshold, conservation strategy should shift from quantitative expansion to qualitative improvement—a transition consistent with the sustainability imperative to maximize outcomes per unit of investment [48]. Management efforts could focus on improving PA governance, restoring degraded habitats within the prioritized network, strengthening ecological connectivity, and reducing edge effects and human disturbance [61]. Because the Loess Plateau remains a socio-ecologically sensitive region where over 100 million people depend on ecosystem services for their livelihoods, future expansion should also account for local livelihoods, agricultural production, and water constraints. The dose–effect framework presented here does not prescribe a single optimal coverage level for all contexts; rather, it provides a replicable protocol for identifying where additional protection yields the greatest standardized ecological benefit and where further expansion may require more careful trade-off assessment. By making the ecological returns to conservation investment explicit and quantifiable, this framework can inform more transparent and accountable decision-making—a cornerstone of sustainable governance and a prerequisite for achieving the integrated environmental, social, and economic objectives enshrined in the 2030 Agenda for Sustainable Development.

5. Conclusions

This study presents a dose–effect assessment framework that integrates spatial prioritization with standardized effect-size analysis to optimize protected area expansion for ecosystem multifunctionality—a contribution that speaks directly to the sustainable development imperative of achieving measurable ecological outcomes from conservation

investments. Applying this framework to China's Loess Plateau, we identified an optimal conservation threshold of 30.79% coverage, where standardized improvement in ecosystem multifunctionality reached its global maximum. Beyond this threshold, marginal gains declined as lower-quality habitats were incorporated, revealing a threshold-dependent rather than linearly cumulative relationship between protection coverage and ecological effectiveness. This finding shows that conservation effectiveness depends not only on area protected but also on where and how expansion is strategically targeted—an insight with profound implications for sustainable natural resource management.

Our findings make three key contributions to the sustainability literature. First, they demonstrate that the existing PA network on the Loess Plateau—originally established without explicit multifunctionality objectives—operates at a relatively modest baseline level, underscoring the need for systematic, function-oriented expansion strategies that maximize ecological returns on conservation investments. Second, the dose–effect framework provides a transparent, quantitative basis for moving beyond binary significance testing and fixed-target approaches, enabling conservation planners to identify coverage levels that maximize ecological returns while accounting for diminishing returns and competing land-use demands—thereby operationalizing the sustainability principle of efficient resource allocation. Third, the empirically identified optimum at ~31% coverage provides concrete support for the GBF's 30% target while illustrating how region-specific optimization can refine global guidelines into actionable conservation strategy, strengthening the scientific foundation of international sustainability agreements such as SDG 15 and the Kunming–Montreal Framework.

Looking forward, the framework can be extended in several directions to enhance its applicability to real-world sustainability challenges. Incorporating stakeholder-informed weighting schemes, socio-economic cost data, and dynamic time-series analyses would enhance its relevance for integrated assessment and adaptive management in socio-ecological systems. Ultimately, the dose–effect framework offers a replicable protocol for translating global biodiversity targets into regionally optimized, ecologically justified conservation action, thereby contributing to the broader sustainability mission of balancing ecological integrity with human development needs across diverse geographical and socio-economic contexts.

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