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Optimized Plant Diversity and Carbon Storage for Priority Protection Areas in China

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Abstract: Biodiversity and carbon storage are two key ecosystem functions that are crucial to protect and maintain ecosystem balance. However, there is often little overlap between hotspots for these two different conservation purposes. Additionally, it is not well understood how these different spatial metrics affect these functions in protected ecosystems in China. Here, we explored the relationships between plant diversity metrics and carbon storage by using a large vascular plant distribution dataset, as well as soil fragile organic carbon and biomass carbon datasets in specific spatial areas across China. We also defined priority protection areas (PPAs) using a conservation prioritization method, where 30% of the study areas displayed the highest combined conservation value in carbon storage and plant species richness (SR), phylogenetic diversity (PD), phylogenetic endemism (PE) and evolutionary distinctness (ED). Our results indicated that the correlations between biodiversity metrics and carbon storage were very weak in spatial relationship. However, by including both of these functions in conservation targets, the PPAs could account for more than 95% of the species and evolutionary diversity (PD, ED), and stored large amounts of carbon. Additionally, we broadly divided the PPAs into win–win, high plant diversity, and high carbon areas based on the overlap of biodiversity and carbon storage hotspots. Altogether, our results highlight the importance of understanding and optimizing conservation efforts for different ecosystem functions in different PPAs. Ultimately, this work establishes an urgent need to expand protection in these areas to support mutual biodiversity and carbon storage beneficial solutions.

Keywords: biodiversity; ecosystem functions; hotspots; correlation; conservation

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1. Introduction

Climate change and biodiversity loss are two of the most urgent environmental challenges [1], human activities that cause climate change may further contribute to biodiversity loss [2]. For example, greenhouse gas emissions, including carbon dioxide, are a major component of climate change and exacerbate biodiversity loss [3]. In order to mitigate and reduce biodiversity loss due to climate change, we must increase holistic adaptation strategies based on different ecosystem approaches for varying priority protection areas (PPAs) [4].

Establishing protected areas (PAs) is an important measure to protect biodiversity, PAs can be established as biodiversity sites to reduce spatial effects on biodiversity [5,6]. However, climate change mitigation actions focus on the conservation and restoration of high-carbon stocks [7]. Under the context of changing climate, protecting these two functions is crucial and essential to keep ecosystems in balance. Still, it is not clear whether biodiversity and carbon can be protected simultaneously [8,9], since PPAs for biodiversity-based conservation do not adequately protect ecosystem services, such as carbon storage [10]. Similarly, PPAs that focus on carbon storage conservation do not effectively protect biodiversity [11–13]. In theory, defining PPA under two major ecosystem functions, i.e., carbon storage of the ecosystem and biodiversity, could protect these ecosystem services in limited areas [10,14,15]. However, there are several inconsistencies in the spatial relationship between biodiversity and carbon storage that are not well understood [16,17].

When identifying PPAs, there are synergies and trade-offs between biodiversity and carbon storage that need to be considered [17,18]. In some areas, there are opportunities to achieve carbon conservation through direct biodiversity co-benefits [9,19]. However, in the regions where the co-benefits cannot be pursued, integrative conservation planning has to be based on the prioritization of carbon storage and their specific biodiversity issues, which will require separate conservation plans for each function [20] to avoid adverse consequences. Nonetheless, there is still a lack of research on the common benefits of PPA and other area-specific regional planning.

Previously, PPAs identification research on biodiversity and ecosystem services was often dominated by the terrestrial vertebrate richness and often relied on biodiversity metrics limited to species numbers, i.e., taxonomic diversity (TD), e.g., [21,22]. However, vertebrate richness-based priority areas differ from plant-based biodiversity hotspots [23]. Additionally, when only species richness (SR) is considered for prioritizing conservation areas, it could result in the loss of unique evolutionary information [24]. Thus, it is essential to combine multi-biodiversity metrics to protect evolutionary characteristics in a region.

Recently, some phylogenetic indexes were raised for different biodiversity evolutionary history dimensions, such as phylogenetic diversity (PD) [25], phylogenetic endemism (PE) [26] and evolutionary distinctness (ED) [27]. By considering the evolutionary information represented within each taxon, PD reveals the underlying evolutionary, ecological and biogeographic processes of biodiversity [28]. In these indices, regions with high PE also capture PD not found elsewhere, and ED can be used to infer regions inhabited by evolutionarily distinct taxa [29]. Furthermore, unique evolutionary histories can affect a species' susceptibility to extinction, since extinction risk is non-random [30,31]. Thus, to maximize biodiversity conservation values, multiple biodiversity dimensions should be considered in conservation planning [32].

Meanwhile, China played an important role in maintaining the global carbon balance [33]. However, due to human activities, land use types and land cover were constantly changing [34], and a large amount of terrestrial ecosystem carbon storage was released into the atmosphere [35]. There was, in recent times, uncertainty about the scale and spatial distribution of terrestrial ecosystem carbon sequestration in China [36,37]. The analysis of spatial patterns of carbon storage was important for developing effective sequestration strategies [38]. However, because of the uncertainty in the spatial relationship between biodiversity and carbon storage, it was still unclear whether setting conservation targets could capture the co-benefits of both.

In this work, we used China as an example to explore (i) the synergy of plant diversity and carbon storage in different spatial regions and (ii) the spatial layout optimization of PAs under PPAs, since China covers many biome types and large latitude spans [39]. Based on several carbon storage and plant diversity datasets, we identified specific areas of great conservation importance based on the relationship between biodiversity and carbon storage. We further zoned PPAs according to the overlap of high carbon and high biodiversity and also explored the coverage and protection vacancies of existing PAs. Together, our results provide recommendations for the spatial layout optimization of PAs in China but can be used to understand diversity and carbon storage relationships in unique spatial areas around the world that are currently affected by climate change.

2. Materials and Methods

2.1. Plant Spatial Distribution Data

We collected distribution data for all available terrestrial vascular plants from national and provincial flora, local flora, inventory and herbarium records in China based on the Chinese Vascular Plant Distribution Database and the Global Biodiversity Information Facility (GBIF; available at https://www.gbif.org/, accessed on 15 December 2021). We divided the map of China into 50 km × 50 km grid cells and removed the grids with less than 50% of the boundary grid area, which resulted in 3805 grid cells. To reduce any effects of the area on diversity estimation, we transformed the county-level distribution data into gridded distribution data with a spatial resolution of 50 km× 50 km. Additionally, the coordinate data were converted into each covered grid, the county-level distribution data were matched to the grid cells, and duplicate data within each grid cell were removed to ensure that a species had only one record in each grid. We then standardized species names based on The Plant List system using the R program 'plantlist' package (https://github.com/helixcn/plantlist, accessed on 13 June 2022) and merged subspecies taxa into the corresponding species. In total, 2,945,870 distribution records with 33,519 terrestrial vascular plant species were kept for analysis.

2.2. Phylogenetic Tree

Based on a list of 33,519 terrestrial vascular plants, we used the V.PhyloMaker package [40] in R 4.1.2 (https://cran.r-project.org/src/base/R-4/, accessed on 15 June 2022), which is an interpreted language widely used in statistics for data exploration, statistical analysis and graphing, to generate phylogenetic trees. The backbone of the phylogenetic tree was implemented with a mega-tree derived primarily from Smith and Brown's [41] phylogeny for seed plants and Zanne et al.'s [42] phylogeny for pteridophytes. We utilized the Scenario 3 tree in V.PhyloMaker [40] to randomly insert each genus and species close to their relatives that were absent from the mega-phylogeny [40]. Of our total 33,519 taxa, 12,303 were matched at a species level, 18,973 at the level of genus and 2243 at the level of family.

2.3. Carbon Storage Data

In our analysis, carbon storage was the sum of the biomass carbon that included both above- and below-ground biomass carbon storage and vulnerable soil carbon storage. The biomass carbon dataset was from the publicly available global harmonized map of above- and below-ground biomass carbon density [43].

The vulnerable soil carbon was defined as the amount of carbon stock that may be lost due to land use in the next 30 years according to the Intergovernmental Panel on Climate Change (IPCC; https://www.ipcc.ch/, accessed on 2 December 2021) and Jung et al. [21]. Carbon in mineral and organic soil was considered vulnerable soil carbon and was found at a 30 cm and 200 cm depth, respectively [21]. Organic soils were defined as those soils with $\geq$5% probability of being histosols, according to the US Department of Agriculture soil order taxonomy. All other soils were considered to be mineral soils [21].

Based on this method, we estimated the probability of a soil sample to be mineral or organic for the soil organic carbon storage data (http://doi.org/10.5281/zenodo.2658183, accessed on 3 December 2021; https://doi.org/10.5281/zenodo.2536040, accessed on 2 December 2021). We then summed the vulnerable organic carbon and biomass carbon to obtain the total carbon and re-aggregated the 50 km^2 × 50 km^2 spatial resolution to match the biodiversity data.

2.4. Plant Diversity Metric Calculations

To measure the overall state of plant diversity for each grid, the TD, (i.e., SR), PD, PE and ED were used to present their current diversity and evolutionary history, respectively [29]. With these characteristics, PD was the sum of the lengths of branches that connect a set of species to the root of a phylogenetic tree [25], and the 'pd' function in the 'picante' package in the R program was used to determine this characteristic [44]. The 'pd' function is commonly used to calculate Faith's phylogenetic diversity. Additionally, PE is the sum of the branch length and/or evolutionary branch range for each branch on the spanning path of a set of taxa linked to the root of a tree [26], and we calculated PE in the function 'phylogenetic.endemism' in the 'phyloregion' package in the R program [45]. Additionally, ED represents the division of phylogenetic branch lengths by the total number of species against them, and each species was weighted according to the number of unique evolutionary histories they represent [27,46], and was calculated using the 'evol.distinct' function also in the 'picante' package in the R program [44].

2.5. Statistical Analyses

To better understand the spatial relationship between biodiversity and carbon storage, we calculated Pearson's correlation coefficients and significance levels (p-values) for SR, PD, PE, ED and carbon storage for 3805 grids in China. Statistical analyses were performed in R 4.1.2 (https://cran.r-project.org/src/base/R-4/, accessed on 15 June 2022).

2.6. Synergy Priorities for Biodiversity and Carbon Storage

PPAs and hotspots were set at the highest value (30% of the area) to respond at the national level to the draft Global Biodiversity Framework to conserve at least 30% of the global land area [22]. We then generated a combined plant diversity (TD, PD, PE and ED) and carbon storage value prioritization map and extracted the top 30% of the area as the priority areas for conservation using the Zonation conservation prioritization software [47]. Here, the synergistic effect depends on the relative importance of conservation for biodiversity and carbon storage. In this analysis, we equally set these three metrics to balance the importance of TD, evolutionary history-related indexes (e.g., PD, PE and ED), and carbon storage. Meanwhile, the equal weight was also set for the three evolutionary history-related PD, PE and ED metrics for the synergistic effects. We then calculated the proportion of biodiversity and carbon storage for each PPA using these methods.

2.7. Overlap Analysis of Synergy Priorities and Hotspots

To explore the co-benefits of biodiversity and carbon in PPAs, we overlapped PPAs with biodiversity and carbon storage hotspots using ArcGIS 10.2, since not all high biodiversity and high carbon areas were fully overlapped. We divided biodiversity hotspots into two categories: taxonomic diversity hotspots (TDHs) and evolutionary diversity hotspots (EDHs), where the EDHs were related to evolutionary history indexes. Biodiversity hotspots and carbon storage hotspots (CSHs) were also generated using the Zonation conservation prioritization software [47].

2.8. Gap Analysis

To identify protection gaps in the PPAs for biodiversity and carbon storage, we used a gap analysis to assess the coverage of each PPA in the PAs in China. The protected areas boundary data in China was from the China Nature Reserve Specimen Resource Sharing Platform (available at http://bhq.papc.cn/, accessed on 15 August 2022) and the World Database on Protected Areas (https://www.protectedplanet.net/en, accessed on 10 June 2022). We overlapped the PPAs with the nature reserve coverage map and identified that the grids were not covered by the PAs for the protection gaps. This spatial analysis was also performed in ArcGIS 10.2.

3. Results

3.1. Relationships between Biodiversity Metrics and Carbon Storage

The PD, SR, PE and ED biodiversity-related indexes were highly and significantly correlated based on their Pearson's correlations (Statistical test, $p < 0.001$, $n = 3805$), and the coefficients ranged from 0.70 to 0.99 (Table 1). However, the correlations between carbon storage and PD, SR, PE and ED were very weak, and the coefficients were only 0.18, 0.19, 0.08 and 0.17, respectively.

Table 1. Pearson's correlation coefficient matrix between species richness (SR), phylogenetic diversity (PD), phylogenetic endemism (PE), evolutionary distinctness (ED) and carbon storage ($n = 3805$). p-values are represented as *** $p < 0.001$.

	SR	**PD**	**PE**	**ED**	**Carbon Storage**
PD	0.970 ***				
PE	0.711 ***	0.704 ***			
ED	0.988 ***	0.981 ***	0.767 ***		
Carbon storage	0.190 ***	0.186 ***	0.082 ***	0.170 ***	

3.2. Priority Protection Areas

To locate the major PPAs in China, we used conservation priority values from the integrated plant diversity and carbon storage datasets and mapped these characteristics, which are illustrated in Figure 1a,b. We found that biodiversity and carbon synthesis priority hotspots were mainly distributed in southwest, south and northeast China (Figure 1a). In Figure 1b, the synergy priorities covered 96.7% of the species, 97.4% of the PD, 97.0% of the ED and 53% of the carbon storage. Because the PE calculations were related to the geographic extent of each branch, these results were based on equivalent spatial units that can be compared directly between regions but cannot be used to calculate the proportion of PE that was protected.

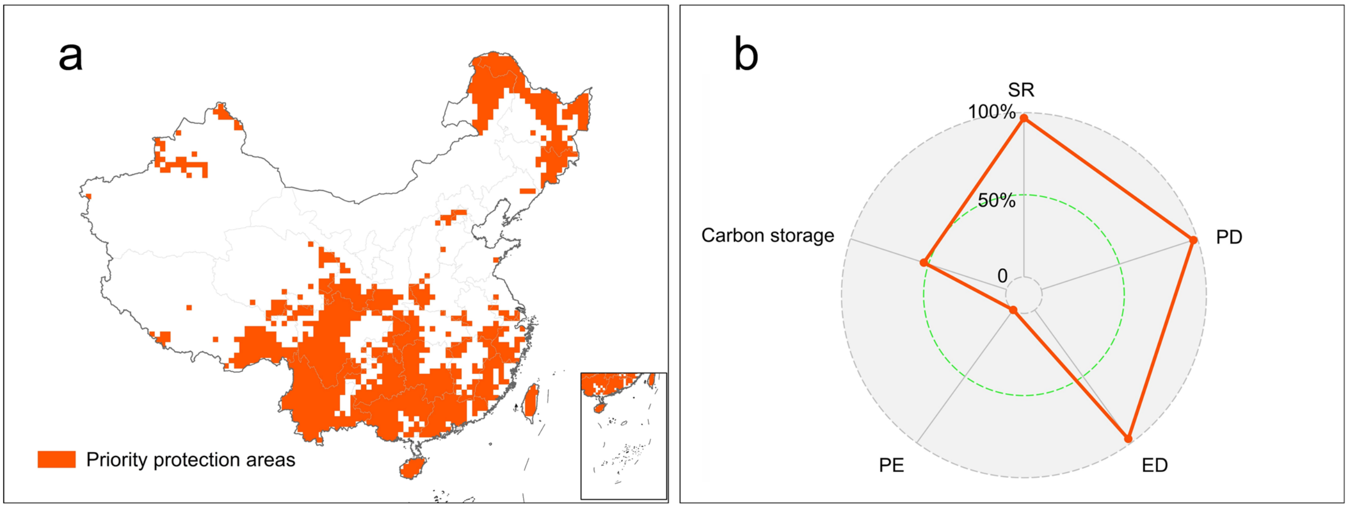

Figure 1. (**a**) Map of priority protection areas (PPAs) for plant diversity and carbon storage. PPAs were set as the 30% of land area with the highest combined value of taxonomic diversity (TD; i.e., species richness; SR), evolutionary history-related indices (e.g., phylogenetic diversity; PD, phylogenetic endemism; PE and evolutionary distinctiveness; ED), and carbon storage. The weights of taxonomic diversity, evolutionary history-related indices and carbon storage were equal. PD, PE and ED were also set the same weight, (**b**) Proportion of SR, PD, ED and carbon storage covered in the PPAs. The dotted circles show the proportion range of 0–100%. The orange line shows the extent to which the PPAs contribute to the protection of SR, PD, ED and carbon storage. Because the calculation of PE was related to the geographical extent of each branch, the percentage of PE coverage cannot be calculated.

3.3. Overlap of Priority Protection Areas with Independent Hotspots for Biodiversity and Carbon Storage

To understand the overlap between biodiversity and carbon storage hotspots in China, we mapped taxonomic diversity, evolutionary history and carbon hotspots in Figure 2a–e to understand how these characteristics extend across the mainland. We found the plant diversity hotspots were mainly concentrated in the southern regions (Figure 2a,b). However, the highest areas for carbon storage were concentrated in the northeast and southwest (Figure 2c). By overlapping synergy priorities with biodiversity and carbon storage hotspots (Figure 2d), we found that PPAs overlapped with 79.7% of TDHs, 78.1% of EDHs and 59.0% of CSHs. Additionally, 36.4% of the synergy priorities overlapped with TDHs, EDHs and CSHs, and 40.0% of the PPAs overlapped with TDHs and EDHs, while 18.0% of priorities overlapped only with CSHs. We also found a very small number of PPAs overlapped only with EDHs, TDHs and CSHs, or EDHs and CSHs, or with no hotspots at all (Figure 2e).

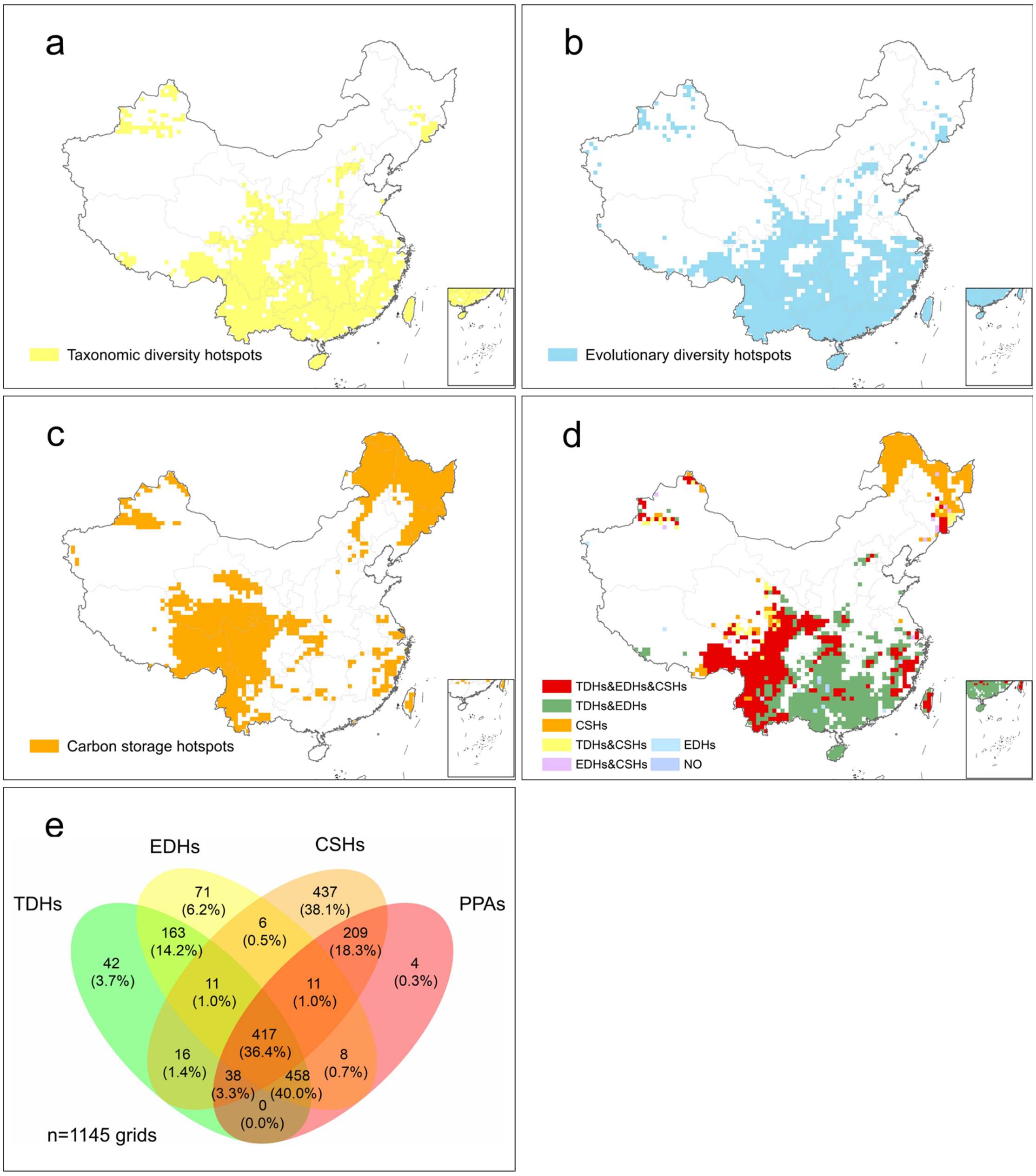

Figure 2. Hotspots map of taxonomic diversity (**a**), evolutionary diversity (i.e., evolutionary history-related indices) (**b**) and carbon storage (**c**). Hotspots were set as the highest value 30% of the area, (**d**) Overlapping map of taxonomic diversity hotspots (TDHs), evolutionary diversity hotspots (EDHs) and carbon storage hotspots (CSHs) in PPAs. For instance, TDHs & EDHs & CSHs means PPAs overlapped with TDHs, EDHs and CSHs, NO means PPAs did not overlap with any hotspot, (**e**) the number and percentage of grids where PPAs overlapped with TDHs, EDHs and CSHs ($n = 1145$ grids).

Based on the results of the overlap analysis, the synergy priorities can be broadly classified into three types: (1) win–win areas for biodiversity and carbon storage, (2) high biodiversity areas and (3) high carbon areas. Win–win areas for biodiversity and carbon storage were mainly in the southwestern and southeastern coast of China, and accounted for 36.4% of the priority protection areas and 11.0% of the national area. High carbon areas were mainly in northeastern China, and accounted for 18.3% of the priority protection areas and 5.5% of the national area. Additionally, high biodiversity areas were mainly in southern China, and accounted for 40.0% of the priority protection areas and 12.0% of the national area. (Figure 2d). The win–win areas for biodiversity and carbon storage showed that they can achieve a win–win situation to pursue mutual benefits, while the remaining high biodiversity/low carbon and high carbon/low biodiversity areas will still require careful planning to avoid adverse consequences based on biodiversity and carbon storage priorities.

3.4. Protection Gaps in Priority Protection Areas

After exploring the overlap of different hotspot types, we also investigated protection gaps for different biodiversity and carbon storage hotspots in PPAs. Figure 3a illustrates the number of different overlapping types of grids for biodiversity and carbon storage hotspots and their relative abundance in PAs. The overlap of PPAs and PAs in the coverage map showed that 54.9% (629 out of 1145) of the grid was covered by PAs. Among the three main types of synergy priorities, biodiversity and carbon storage win–win areas had a maximum coverage of 60.7% of the PAs, while high biodiversity areas accounted for 54.8% of the PAs and high carbon areas accounted for the lowest coverage of PAs at 48.8% (Figure 3a). We present the map of protection gaps in PPAs in Figure 3b, and it can provide a theoretical basis for the spatial layout optimization of PAs in China.

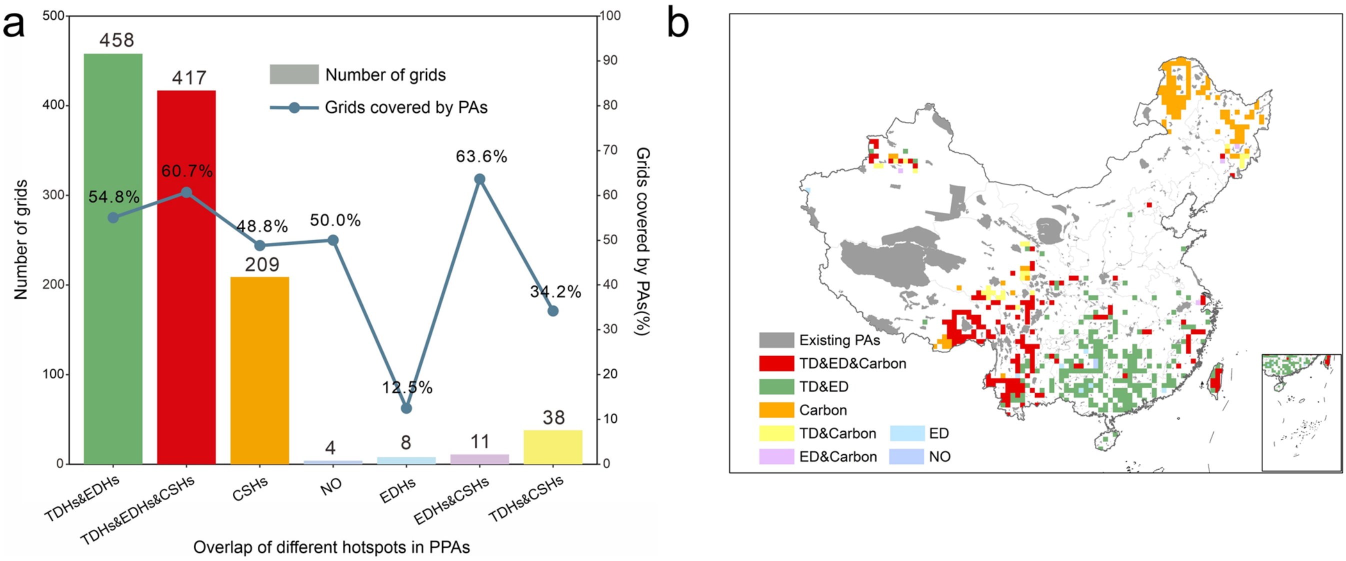

Figure 3. (**a**) The number of different overlapping types of grids for taxonomic diversity hotspots (TDHs), evolutionary diversity hotspots (EDHs) and carbon storage hotspots (CSHs) in priority protection areas (PPAs) and the proportion covered by the protected areas (PAs). The horizontal coordinate indicated the type of overlap between PPAs and TDHs, EDHs, CSHs, the bar chart indicated the number of grids in PPAs and the line chart indicated the proportion of the grids covered by PAs, (**b**) protection gap map of different biodiversity and carbon storage hotspots in PPAs in China. Areas in gray were existing protected areas.

4. Discussion

By using an integrated prioritization approach, we incorporated taxonomic and evolutionary dimensions of biodiversity with carbon storage into conservation objectives. This allowed us to explore the correlations between biodiversity and carbon storage at the national level and further divided the priorities into three potential conservation scenarios based on the relationship between high biodiversity and high carbon storage in PPAs.

From our data, we identified areas that contribute significantly to biodiversity conservation and climate stabilization and analyzed the win–win and trade-offs for both scenarios in PPAs. Together, our findings will contribute to the spatial optimization of PAs and provide recommendations to achieve biodiversity and climate goals.

4.1. Priority Protection Areas of Biodiversity and Carbon Storage

In previous research, there were many debates over how to maximize the co-benefits of carbon storage and biodiversity because of their different correlations at varied scales [9]. Several previous studies found a positive correlation between biodiversity and carbon storage in terrestrial ecosystems [18,48,49]. However, others also found limited or even negative correlations between biodiversity and carbon [50–52]. Our results indicated that even though plant diversity-related metrics were highly correlated (statistical test, $p < 0.001$, $n = 3805$), the relationships between carbon storage and these metrics were still very weak (Table 1) and showed little overlap in spatial hotspots in China. Therefore, setting conservation targets based on biodiversity or carbon storage alone will not provide effective protection for both.

To maximize the conservation of biodiversity and carbon, we need to use an integrated ranking approach to prioritize all biodiversity components and carbon storage [10]. PPAs were defined as the top 30% of the most conserved plants for diversity and carbon storage. These areas contain more than 95% of plant species numbers, 97.4% of the PD, 97.0% of the ED, which indicates their high efficiency and importance for diversity conservation. However, using limited priorities to protect carbon sequestration is not entirely effective. Still, they can protect more than 50% of carbon storage, which is higher than the mean function for all areas. A possible reason why carbon storage is in a smaller proportion compared to biodiversity may be because local species concentrate in small areas that sequester land surface use, which allows for carbon to be more evenly distributed [11]. These results imply that PPAs identification for these two ecosystem functions is generally worth using relatively small areas to protect maximum biodiversity and carbon storage to reduce the effects of climate change and human activities.

4.2. Synergies and Trade-Offs between Biodiversity and Carbon Storage

Although we identified important areas for biodiversity and carbon storage using an integrated ranking approach, synergies and trade-offs between them still exist in these PPAs. Many previous studies showed that high carbon and high biodiversity areas are limited because they do not geographically overlap, e.g., [17,51]. Specifically, areas where high carbon and high plant diversity do not overlap are more widespread than potential win–win areas [53]. Our results suggested that 36.4% of PPAs overlapped with plant diversity and carbon storage hotspots, which were labeled as win–win areas. These regions were not uniformly distributed and were mainly in the southwestern and southeastern coast of China. However, in other PPAs, high biodiversity and high carbon storage did not overlap.

Because of the limited spatial overlap of high biodiversity and high carbon storage areas, their spatial distribution needs to be considered when developing conservation strategies. For example, reducing emissions was an effective measure to mitigate climate change from deforestation and forest degradation (REDD+) [54–56]. This reduction in emissions from deforestation and forest degradation was seen as a win–win solution for carbon storage and biodiversity conservation [57,58]. However, since high biodiversity and high carbon storage areas do not always overlap, some areas with high biodiversity will not benefit from carbon-focused conservation [18]. Particularly, some studies found that focusing on large-scale carbon sequestration plantations may have a negative impact on biodiversity [59]. If the spatial distribution of biodiversity and carbon storage were not simultaneously considered when setting conservation targets, they could cause a shift in deforestation activities from areas with high carbon to areas with low carbon storage, and would also critically affect biodiversity conservation [60,61]. Our results showed that co-benefits can be achieved between biodiversity and carbon storage in win–win regions within certain PPAs. These results imply that specific policies that maintain carbon storage usually provide additional benefits to biodiversity conservation and those that conserve biodiversity would contribute to maintaining carbon storage. In other areas, however, the prioritization of biodiversity and carbon storage needs to be taken into account to develop separate conservation mechanisms [53].

In addition to the win–win areas, our results divided the PPAs into two other categories: (1) high biodiversity areas and (2) high carbon areas. High carbon areas are mainly located in the forested areas of northeastern China and possess high forest cover that acts as important carbon sinks. In the absence of accelerated natural disturbances, climate variability and land use change, forests are likely to continue to sequester carbon in the future [62]. In particular, high-carbon areas maintain carbon stocks to ensure that natural forests are not damaged further, while also maintaining long-term ecological integrity and taking advantage of opportunities to ensure a net positive impact on biodiversity [60].

In contrast, high biodiversity areas were mainly located in southern China. From our results, high biodiversity areas may represent opportunities for carbon storage policies to focus on ecosystem restoration and improve connectivity. Together, this approach would help to maintain high levels of biodiversity and improve carbon sequestration and storage potential in this area [53]. Ultimately, we suggest that the spatial relationship between biodiversity and carbon storage should be revisited when new conservation strategies are developed, and that different conservation measures need to be created based on examining high biodiversity and high carbon storage overlap patterns.

4.3. Conservation Implication

In this study, we identified areas that were important for biodiversity conservation and carbon storage maintenance. These PPAs may provide more protection for biodiversity and carbon storage with less land use. Our results showed that the existing PAs did not provide comprehensive protection for both biodiversity and carbon storage. Only 54.80% of the PPAs were covered by PAs, and among them, high carbon areas received even less attention. From our data, we recommended optimizing the spatial layout of current PAs based on our protection gaps map and the establishment of new PAs from the theoretical basis we created.

Although more research is needed in the future, the terrestrial, vascular plant data we used helps to start taxonomic diversity research in PAs in China. Ideally, future analyses should consider as many taxa as possible (e.g., vertebrates, invertebrates, etc.) to ensure data completeness, and we need to enhance the collection of data for other taxa in the future. Additionally, data on other ecosystem services (e.g., food, water, etc.) should also be integrated to provide other possible benefits in a limited area. However, with the continuous improvement of data monitoring methods, we expect to improve conservation planning by combining land use types at a higher resolution. Ultimately, with regard to evolving conservation planning due to climate change, new approaches to protect biodiversity and ecosystem services must be improved to ensure the well-being of future generations.

5. Conclusions

Using China as an example, we found that the correlations between biodiversity metrics and carbon storage were very weak in terms of large spatial relationships, but that PPAs could maintain significant carbon storage while conserving most plant diversity (e.g., SR, PD, ED). By examining the spatial distribution of high plant diversity and high carbon storage areas in the PPAs and their current coverage by PAs, it is concluded that the inclusion of plant diversity and carbon storage in conservation objectives can be effective in protecting the benefits of both. Even though there was limited overlap between high plant diversity and high carbon storage areas in the PPAs, conservation strategies need to be developed based on their spatial relationships.

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