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Article

Global assessment of nature's contribution to people

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ABSTRACT

Synergistically maintain or enhance the numerous beneficial contributions of nature to the quality of human life is an important but challenging question for achieving Sustainable Development Goals. However, the spatiotemporal distributions of global nature's contributions to people (NCPs) and their interactions remain unclear. We built a rapid assessment indicator framework and produced the first spatially explicit assessment of all 18 NCPs at a global scale. The 18 global NCPs in 1990 and 2018 were globally assessed in 15,204 subbasins based on two spatial indicator dimensions, including nature's potential contribution and the actual contribution to people. The results show that most of the high NCP values are highly localized. From 1992 to 2018, 6 regulating NCPs, 3 material NCPs, and 2 nonmaterial NCPs declined; 29 regulating-material NCP combinations (54 in total) dominated 76% of the terrestrial area, and the area with few NCPs accounted for 22%; and synergistic relationships were more common than tradeoff relationships, while the relationships among regulating and material NCPs generally tradedoff with each other. Transitional climate areas contained few NCPs and have strong tradeoff relationships. However, the high synergistic relationship among NCPs in low latitudes could be threatened by future climate change. These findings provide a general spatiotemporal understanding of global NCP distributions and can be used to interpret the biogeographic information in a functional way to support regional coordination and achieve landscape multifunctionality for the enhancement of human well-being.

1. Introduction

Because of climate change, biodiversity loss and environmental pollution, how to synergistically maintain or enhance the numerous beneficial contributions of nature to the quality of human life is an important but challenging question for achieving Sustainable Development Goals [1,2]. Nature's contributions to people (NCP) are all the contributions, both positive and negative, of living nature (diversity of organisms, ecosystems, and their associated ecological and evolutionary processes) to people's quality of life, and highlights both context-specific and generalizing perspectives [1,3,4]. Under the generalizing perspective, the NCP classification system categorizes nature's contributions into 18 NCPs with 3 major fuzzy categories, namely, regulating (NCP1–NCP10), material (NCP11–NCP14) and nonmaterial (NCP15–NCP18) [4]. However, the spatiotemporal distributions of these NCPs and their interactions remain unclear, which directly limits practices to maximize the multiple beneficial contributions of nature [5,6].

Previous assessments of NCPs have assessed nonspatial trends and mapped selected indicators. A recent global assessment based on the scientific literature found declining trends in the potential for nature to contribute to most of the material, nonmaterial, and regulating NCPs [4]. This assessment provided nonspatial evidence for trends in NCPs at a global scale. Based on spatial datasets, a global assessment projected the continued loss of nature in the future by modeling three regulating NCPs [5], and a European-scale assessment at a 1 km × 1 km resolution found that present biodiversity conservation priorities rarely overlap with selected NCP priorities [6]. These exercises have provided spatially explicit and temporally consecutive evidence for the synergies and tradeoffs among NCPs. Nevertheless, there are still no complete spatially explicit global NCP assessment, which leads to difficulties in identifying potential tradeoffs among NCPs in key regions and coordinating the management of regional and local NCPs.

Several theoretical and technological issues stand in the way of quantitatively producing all 18 spatially explicit global NCP

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assessments. First, NCP may not necessarily have to be assessed qualitatively. The NCP concept engages a broad social science audience and indigenous perspective, which weaken the ability to attribute quantitative values [7], so NCPs are often applied by qualitative methods [8]. The second issue is the nonuniqueness of values. NCPs enable diverse factors to represent nature-people interactions at different scales and for different audiences and decision-makers [9]. The perception and requirements of nature by diverse participants can result in a diverse NCP evaluation [10]. The third issue is broad indicators. The relevant indicators are also diverse for each NCP, especially nonmaterial NCPs, as they reflect subjective and psychological aspects of human well-being [11]. Thus, completely quantifying all indicators for each NCP for every stakeholder could be an endless task. Fourth, scaling effects are existed. NCP values cannot be easily compared across scales. The many diverse value systems of stakeholders and institutions should therefore be integrated across scales, otherwise local perceptions of NCPs cannot be directly applied to regional decision-making for landscape management [12]. Finally, numerous spatial datasets are required. Remote sensing information has encouraged a simplified view of the spatiotemporal values of NCPs; however, the uncertainty in quantification and mismatches with local subjective perceptions has hindered the generalization of remotely sensed datasets in NCP evaluations [13].

A series of spatially explicit global NCP assessments could provide evidence for global spatiotemporal patterns of nature's contributions [14–16]. Moreover, to capture a diversified set of indicator attributes and limited spatial data, a simplified global spatiotemporal NCP indicator system is required as a benchmark for further theoretical and technological exploration of NCPs at fine scales [17]. Accordingly, we aim to assess the spatiotemporal distribution of the 18 global NCPs and identify the key regions requiring landscape multifunctionality management at global scale. The assessments are focusing on three objectives: first, the spatiotemporal distributions of global NCPs; second, the tradeoff and synergistic relationships among the change of global NCPs; last, the critical areas for landscape multifunctionality enhancement under global climate change.

2. Materials and methods

2.1. Spatial datasets

The global ecosystem classification provides the fundamental data for our NCP assessment, which was reclassified by the European Space Agency Climate Change Initiative-land cover (ESA CCI-LC) product [18]. The classification system comprises 10 categories oriented from 22 land cover classes (Table S1 online). We united similar land cover terms in the ecosystem classification based on the NCP assessment requirements (Supplementary materials online). The spatial resolution is 300 m and is reclassified to 1 km by the nearest neighbor method. The overall time points of the datasets were 1992, 2005, and 2018.

Twenty kinds of spatial datasets were used in the NCP assessment (Supplementary materials online). Most of the raster datasets we applied have spatial resolutions no coarser than 10 km so that enough pixels can be averaged in a subbasin unit. The biodiversity maps were downloaded from BiodiversityMapping.org. There were three richness maps: amphibians, birds, and mammals [19]. The spatial resolution was 10 km. The Global Inventory Modeling and Mapping Studies (GIMMS) vegetation leaf area index (LAI)3g was used, and the spatial resolution was 1/12 arc degrees [20]. The global human settlement layer (GHSL) was downloaded from the Joint Research Center (JRC) and included built-up grid, population grid, and settlement model grid data [21]. The gross primary production (GPP) dataset was estimated by a revised light use efficiency model, with a spatial resolution of 0.05 arc degrees [22]. The Global Mangrove Watch (GMW) datasets are vector, and we transformed them into 1 km spatial resolution data [23]. The actual evapotranspiration (ET) was a synthesized product with a 1 km spatial resolution [24]. The Terra Moderate Resolution Imaging Spectroradiometer (MODIS) Land Water Mask (MOD44W) Version 6 data product was provided by the Land Processes Distributed Active Archive Center (LP DAAC) and had a spatial resolution of 250 m [25]. The annual streamflow maps from the FLO1K dataset were at a resolution of 1 km [26]. The pesticide risk scored based on the most used active ingredient was at a spatial resolution of 1/12 arc degrees [27]. The soil erosion score was evaluated by previous work of our research group at a spatial resolution of 1/12 arc degrees [28]. The Harmonized World Soil Database was at a spatial resolution of 1 km [29]. The elevation and slope data were from the Shuttle Radar Topography Mission digital elevation model, which has a resolution of 3 arc seconds [30]. The aridity index (AI) was mapped at a 30 arc second resolution relative to evapotranspiration processes and rainfall deficits for potential vegetative growth [31]. The floodplain data were at a 250 m resolution [32]. The crop yield data, as well as the aggregated value of crop production data, were derived from the Spatial Production Allocation Model dataset in 2010 (SPAM2010), with a spatial resolution of 1/12 arc degrees [33]. The "best crop" map that indicated the maximum achievable bioenergy yields was derived from the dataset of lignocellulosic bioenergy crops and had a spatial resolution of 0.5 arc degrees [34]. The aboveground carbon biomass density was derived from a harmonized map in 2010 with a spatial resolution of 300 m [35]. The nighttime light was a harmonized dataset from two satellites with a spatial resolution of 30 arc seconds [36]. The location of natural and mixed world heritages was downloaded from WHC.UNESCO.org. The vector road dataset was downloaded from the Socioeconomic Data and Applications Center (SEDAC) and was named the Global Roads Open Access Data Set, Version 1 (gROADSv1) [37].

By taking advantage of the nested subbasins at multiple scales for regionalization, the HydroBasin data in HydroATLAS database was applied [38]. The Köppen-Geiger climate classification data, including present and future climate classifications, was given in 1 km resolution [39]. The Ecoregions2017 dataset was downloaded from Ecoregions.appspot.com [40].

2.2. Study area

A basin was the hydrological unit that was used; it has both physiogeographic integrality and an ecological management operability relevance. In consideration of the spatial resolution of the datasets, we used HydroBasin level 06 and HydroBasin level 04 as the assessment units and merged the units that were smaller than 500 km^2 into the adjacent largest units in order to include more than 4 pixels of 1/12 arc degree raster data in a subbasin, and there are totally 15,204 subbasin units for basic assessment. The setting of two-level units was used for different potential applications to regional or local landscape management.

We linked functional information on NCPs to biogeographic information on climate and ecosystem classifications that was scaled from subbasin to basin [41] (Figs. S1 and S2 and Table S1 online). The biogeographical region was defined by the Köppen-Geiger climate classification and the ecosystem classification in 2018. The information for present and future climate classifications was upscaled to the subbasin and basin scales for most of the climate classifications. Then, the two kinds of climate classifications were each combined with most of the ecosystem classification in 2018 as the biogeographical classification of each subbasin and basin. Except for ecosystem classification, we counted the changes in dominant climate classifications at the subbasin scale from present to future and mapped them with the "circlize" package in R software.

2.3. Spatial assessment

This study is an indicators-based approach, so as to fill in temporal gaps in modeled data. In general, we set the two indicator dimensions as nature's potential contribution and the actual contribution to people (Table 1). The former had the perspective of the potential of nature's provision, and the latter had the perspective of actual human local requirements. Because the actual human local requirements mostly increased as the population increased, we set the indicators in this dimension as static to observe the changes in NCPs driven by ecosystem changes. In other words, the increase in human requirements could lead to an increased NCP assessment; it would mask the potential threats of natural ecosystem loss and might misguide local landscape management [5].

We built an indicator framework for a globally rapid assessment of all NCPs that emphasizes demonstrating the spatiotemporal heterogeneity of the distribution rather than simulating a certain value for biophysical units. To ensure generalizability and expansibility for further regional and local assessment, no more than three global parameters were set for each NCP in our rapid assessment framework. The exception is NCP9 since the diverse hazard types can hardly be generalized by three indicators. In addition to the ecosystem classifications that provide the locations of potential provisions of nature, the parameters that were used were listed in Table 1 (see the Supplementary materials online for calculation details). The weighted parameters were multiplied to get the initial value of NCPs.

We used semiqualitative assessment at the subbasin scale, which generally assigned the biophysical or social parameters as spatial weights of corresponding ecosystem classifications. The initial values of the parameters at the subbasin scale have a lowest value of 0 and varied highest values. The 90th percentile values of each originally assessed NCP value in 1992 was regarded as the maximum value in min–max normalization for the two time points. The normalized value of every NCPs was in the range of 0–1.

The changes in NCPs were calculated at the subbasin scale using the 2018 value minus the 1990 value. A "large" decrease or increase means that the difference in values was more than 0.1

Table 1
Connotation of the indicators in calculating terrestrial nature's contributions to people[a)].

NCP	Nature's potential contribution	Actual contribution to people	Weighted parameter
NCP1: *habitat*	**Natural and mix ecosystems**: *potential natural habitats*	**Animal biodiversity**: *actual biodiversity indicated by amphibians, birds and mammals*	*Animal biodiversity*
NCP2: *crop pollination*	**Mix ecosystems**: *key place of seed dispersal to cropland*	**Production for cross-pollinated crops**: *yield of crops required pollination*	*Production for cross-pollinated crops*
NCP3: *air quality regulation*	**Vegetation Leaf Area Index in natural and mix ecosystems**: *potential pollution entraining vegetation*	**Built-up land requiring pollution entrainment**: *actual emission from human habitat required entrainment*	*Built-up land and vegetation LAI*
NCP4: *climate Regulation*	**Gross primary productivity in perennial vegetation**: *carbon sequestration*	**Default**: *not valued because of the global scale requirement*	*GPP*
NCP5: *Ocean acidification regulation*	**Amount of mangrove forest in coast**: *key place of long-term carbon sink from ocean*	**Default**: *not valued because of the global scale requirement*	*Distribution of mangroves*
NCP6: *water quantity & flow regulation*	**Evapotranspiration in natural and mix ecosystems**: *participation of ecosystem in water cycle*	**Streamflow**: *actual requirement for flow regulation by ecological processes including evapotranspiration*	*Evapotranspiration and streamflow*
NCP7: *water quality regulation*	**Natural ecosystems surrounded rivers**: *natural capacity on decontamination*	**Nonpoint source pollution indicated by pesticide risk**: *actual requirement for decontamination*	*Water location and pesticide risk*
NCP8: soil protection	**Soil retention of natural ecosystems**: *potential amount of soil retention*	**Soil fertility indicated by organic carbon**: *actual contribution of fertility retention*	*Soil retention amount and organic carbon*
NCP9: hazard regulation	**Natural ecosystems reducing landslide, desertification, flood and storm tide**: *potential places preventing case hazards*	**Value of crop productions**: *agricultural value benefit from hazard prevention*	*Dryland and floodplains distribution, slope, and crop production value*
NCP10: pest regulation	**Bird biodiversity in mix ecosystems**: *pest enemy diversity for agricultural production*	**Value of crop productions**: *actual value of crops prevented from pest*	*Bird biodiversity and crop production value*
NCP11: bioenergy	**Shrub, grass and mix ecosystems**: *potential land for bioenergy plants in high probability*	**Potential lignocellulosic bioenergy crops**: *score of bioenergy production could be harvested*	*Lignocellulosic bioenergy crops*
NCP12: food	**Cultivated and mix ecosystems**: *potential land for food production*	**Yield of production for food crops**: *actual yield of food crops*	*Yield of food crops*
NCP13: wood material	**Forest ecosystems**: *potential land for logging*	**Aboveground biomass carbon density**: *actual yield of logging*	*Aboveground biomass carbon density*
NCP14: medicine	**Diversity of natural and mix ecosystems**: *species diversity indicated by landscape diversity*	**Rural population**: *local people potentially using native herbal medicine*	*Natural landscape diversity and rural population*
NCP15: learning & inspiration	**The diversity of ecosystem**: *diversity of nature, include artificial landscape*	**Social development indicated by nighttime light**: *people's requirement in a developing society*	*Landscape diversity and nighttime light*
NCP16: experience	**Density of natural and mix World Heritage sites**: *proximity of unique natural landscape*	**Accessibility indicated by road density**: *people's accessibility to get the unique experience*	*Density of natural and mixed world heritages and road density*
NCP17: identity	**Change rate of landcover**: *landscape stability*	**Population on the changed landscape**: *actual amount of people within identity shaping*	*Rates of land cover and population changes*
NCP18: options	**Diversity of the other 17 NCPs**: *diversity of nature to provide future benefits*		*Shannon's diversity index*

a) The indicators are in bold, and the descriptions of indication are in italic.

between the two years, and "small" decrease or increase means the difference in values was no more than 0.1.

2.4. Statistical analysis

We applied the geographical detectors (GeoDetector) to describe the spatial stratified heterogeneity among NCPs [42]. By comparing stratigraphic variance and total variance of the dependent variable across the region, GeoDetector can detect whether explanatory variables lead to spatially stratified heterogeneity of the dependent variable. Here, we tested the ability of climate classification and ecosystem classification (Fig. S1 and Table S1 online) to explain the spatial heterogeneity of NCPs. In addition, we examined the interaction effects of the two explanatory variables using GeoDetector's interaction detector, which interprets the value of the interaction as whether the interaction between two variables is enhanced or weakened compared to the effect of a single variable.

We defined the "dominant NCP" as the highest valued NCP at the subbasin scale. In detail, due to a global assessment usually concealing indigenous cultural contributions to nature in nonmaterial NCPs, the dominant NCP considered categories of only regulating and material NCPs designated by a "+", with the NCP value of no less than 0.3 as a threshold. If both of the categories failed to meet the condition, the subbasin was designated "few NCPs", and if one of the categories failed to meet the condition, this category lacked the "+" in the name; for the other subbasins, the name was derived from the highest value of either regulating or material NCPs at the subbasin scale. Since the basin was not an elementary unit, considering only the highest NCP value among the subbasins could neglect the secondary high value. Accordingly, most of the NCPs with values of no less than 0.3 among the subbasins were selected as the dominant NCP at the basin scale.

The analyses of tradeoff and synergy were based on a Pearson correlation of the bundle of NCPs at a subbasin scale using the "corrplot" package in R software. A negative correlation indicated a tradeoff, a positive correlation indicated synergy, and the non-significant correlation with a $P > 0.05$ indicated independence. The correlations were calculated for the NCP values in 1992 and 2018, as well as the changed NCP values from 1992 to 2018. Then, we counted the number of pairs of the tradeoff and synergy relationships for the changed NCP values in each dominant NCP region and each dominant climate classification at the subbasin scale. Among the 18 NCPs, the total number of pairs should be 153.

The 18 NCPs were all considered when measuring multifunctionality. At the subbasin scale, the multifunctionality was counted as the types of NCPs with values no less than 0.3. At the basin scale, in order to better demonstrate elementary unit information, the multifunctionality was the total of the subbasins in each basin. Then, we averaged the multifunctionality score in each dominant NCP region and each dominant climate classification at the subbasin scale.

The regions were grouped based on the dominant NCP classification with the information of NCP relationships and multifunctionality. We used the pair number in the tradeoff relationship to define the pair number in the synergy relationship as a tradeoff-synergy score among the dominant NCP classifications with no less than 50 subbasins (29/54 regions). The classifications with a tradeoff-synergy score higher than 0.5 (13/29 regions) and a multifunctionality lower than 7 (13/29 regions) were defined as "low synergy and low multifunctionality". The classifications with a tradeoff-synergy score of no more than 0.5 and a multifunctionality lower than 7 were defined as "low multifunctionality". The classifications with a tradeoff-synergy score higher than 0.5 and a multifunctionality higher than 7 were defined as "low synergy". The classifications with a tradeoff-synergy score no more than 0.5 and a multifunctionality higher than 7 were defined as "relative synergy". The classifications with less than 50 subbasins was defined as "not enough samples", which accounts for only 2.295% of the total area. The subbasins with no dominant NCPs were defined as "few NCPs".

3. Results

3.1. Spatial distributions and temporal changes of NCPs

The spatial patterns of the 18 NCPs assessed in 15,204 subbasins were divergent (Fig. 1). Low latitudes often had high NCP values, including NCP1 (habitat creation and maintenance), NCP4 (regulation of climate), NCP5 (regulation of ocean acidification), NCP6 (regulation of freshwater quantity, location and timing), NCP10 (regulation of detrimental organisms and biological processes), NCP11 (energy), NCP13 (materials, companionship and labor), and NCP14 (medicinal, biochemical and genetic resources). The latitudinal distribution of forest ecosystems was consistent with this pattern. Correspondingly, resource exploitation and human activity, such as urbanization and cultivation, were not latitudinally distributed and influenced the spatial pattern of NCP2 (pollination and dispersal of seeds and other propagules), NCP3 (regulation of air quality), NCP12 (food and feed), NCP15 (learning and inspiration), NCP16 (physical and psychological experiences), and NCP17 (supporting identities).

The changes in NCPs from 1992 to 2018 reveal that most NCPs decreased in the three categories of regulating, material and nonmaterial (Fig. 2). The 7 regulating NCPs that decreased included NCP1 (habitat creation and maintenance), NCP2 (pollination and dispersal of seeds and other propagules), NCP3 (regulation of air quality), NCP7 (regulation of freshwater and coastal water quality), NCP8 (formation, protection and decontamination of soils and sediments), NCP9 (regulation of hazards and extreme events), and NCP10 (regulation of detrimental organisms and biological processes). The 2 material NCPs that decreased included NCP13 (materials, companionship and labor) and NCP14 (medicinal, biochemical and genetic resources). The 2 nonmaterial NCPs that decreased included NCP16 (physical and psychological experiences) and NCP17 (supporting identities). Notably, although NCP4 (regulation of climate), NCP6 (regulation of freshwater quantity, location and timing), NCP11 (energy), and NCP12 (food and feed) increased at a global scale, they experienced an abrupt decrease in a number of subbasins. Based on the parameters in the assessment (Supplementary materials online), most of these decreases can be attributed to the loss of natural ecosystems. In contrast, other increases in NCPs were not due to ecosystem restoration, e.g., the increase in NCP4 (regulation of climate) and NCP6 (regulation of freshwater quantity, location, and timing) in a number of subbasins could be attributed to accelerated carbon and water cycles in a warming climate, which enhance the participation of ecosystem in biogeochemical cycles [43,44].

The changes of spatial stratification heterogeneity among NCPs suggest that climate classification has a strong explanatory ability for most regulating NCPs and non-material NCPs (Table S2 online). In contrast, ecosystem classification has a strong explanatory ability for material NCP, with some exceptions including NCP4 (regulation of climate), NCP9 (regulation of hazards and extreme events), and NCP17 (supporting identities). Most of these NCPs, which are mainly determined by ecosystem stratification, can be contributed to their close association with ecosystem types, such as the GPP of different vegetation types, the uniqueness of different vegetation types in terms of resistance to drought, floods, and coastal risks, and ecosystems that situated with indigenous populations. Considering the interaction between climate classification

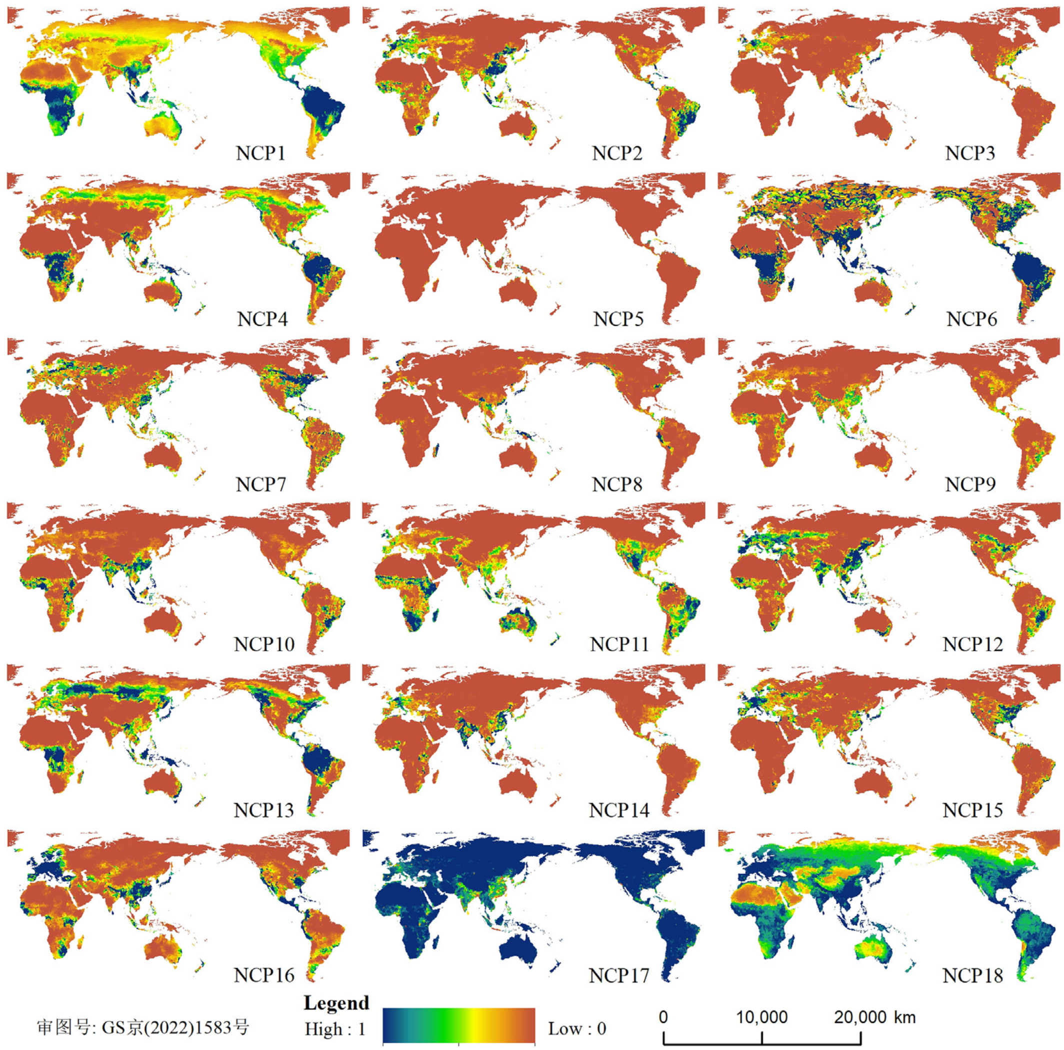

Fig. 1. Global distribution of NCP values in 2018. The assessment unit is HydroBasin level 06. NCP1 (habitat creation and maintenance); NCP2 (pollination and dispersal of seeds and other propagules); NCP3 (regulation of air quality); NCP4 (regulation of climate); NCP5 (regulation of ocean acidification); NCP6 (regulation of freshwater quantity, location and timing); NCP7 (regulation of freshwater and coastal water quality); NCP8 (formation, protection and decontamination of soils and sediments); NCP9 (regulation of hazards and extreme events); NCP10 (regulation of detrimental organisms and biological processes); NCP11 (energy); NCP12 (food and feed); NCP13 (materials, companionship and labor); NCP14 (medicinal, biochemical and genetic resources); NCP15 (learning and inspiration); NCP16 (physical and psychological experiences); NCP17 (supporting identities); NCP18 (maintenance of options).

and ecosystem classification can increase the explanatory ability of each NCP, which shows a nonlinear-enhancement in NCP3 (regulation of air quality) and NCP5 (regulation of ocean acidification).

3.2. Dominant NCPs

The dominant NCP for a subbasin was considered the combination of the highest regulating and material NCP with a value of no less than 0.3, and 78.1% subbasins had no less than a dominant NCP (Fig. 3). As the most widely distributed regulating NCP, 28.1% subbasins were dominated by NCP1 (habitat creation and maintenance), inferring that habitat should be the foundation of other regulating NCPs. NCP6 (regulation of freshwater quantity, location, and timing) was ranked second, with 20.9% subbasins dominated by NCP6, inferring the pervasive participation of ecosystems in the water cycle. In addition, NCP2 (pollination and dispersal of seeds and other propagules) was the dominant regulating NCP in mixed natural and cultivated landscapes. The most widely distributed material NCP was NCP13 (materials, companionship, and labor), which dominated 26.6% of subbasins, and the secondary NCP was NCP11 (energy) which accounted for 21.3%, while NCP12 (food and feed) accounted for only 15.2%. According to these ranks, the top three combined dominant NCPs were NCP1 + 11, NCP1 + 13, and NCP6 + 13, with subbasins of 12.5%, 9.4%, and 8.4%, respectively.

When scaling up the dominant NCPs to the basin scale, the dominant NCPs in different regions were agglomerated (Fig. S3 online). There were 6 dominant regulating NCPs, including NCP1, NCP2, NCP4, NCP6, NCP7, and NCP10. For the dominant material NCPs, NCP14-dominated basins were much fewer than NCP11-, NCP12-, and NCP13-dominated basins. This reduction in the number of dominant NCPs at the basin scale indicates that a coarser unit could omit the local dominant NCPs.

3.3. Relationships among NCPs

Spatial tradeoff and synergistic relationships were defined by negative and positive correlations, respectively. Most of the NCPs were spatially synergistically distributed at the subbasin scale, and the relationships varied slightly between 1992 and 2018 (Fig. S4 online). Among regulating NCPs, NCP1 was positively related to all the other regulating NCPs. Among material NCPs,

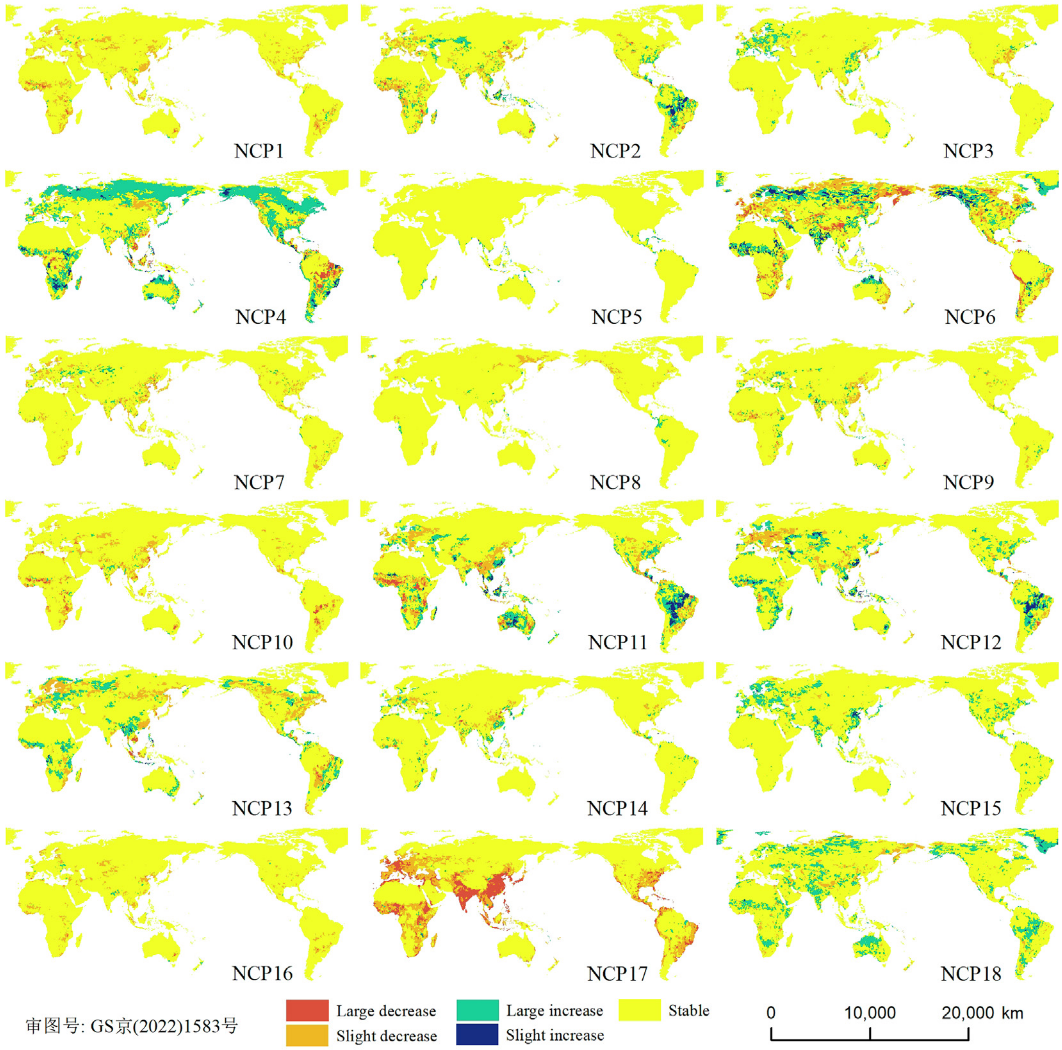

Fig. 2. Spatiotemporal changes in NCPs from 1992–2018. "Large" means the difference in values was more than 0.1 over the time period with a value range of 0–1. The unit is HydroBasin level 06.

NCP13 was highly synergistically distributed with NCP1, NCP4 and NCP6. This distribution indicates the potential opportunity cost of logging for habitat maintenance, carbon neutrality and water balance. Among nonmaterial NCPs, NCP17 had tradeoff relationships with other NCPs; as a result, places with high contributions of nature were often exploited, so these areas experienced landscape changes with altered local identities.

The altered NCP values from 1992 to 2018 at the subbasin scale showed most changes in regulating NCPs were synergistic or independent, while relationships among regulating NCPs and material NCPs changes were mostly tradeoffs or independent (Fig. 4). In particular, the change in NCP12 had a tradeoff relationship with seven regulating NCPs, and the only one with high synergy was NCP2 because of the pollination function of ecosystems that cannot independently exist without the distribution of cropland. In addition, the changes in nonmaterial NCPs were weakly related to regulating and material NCPs, inferring the necessity of independently managing these landscape functions.

3.4. Regions requiring the synergistic enhancement of NCPs

We counted the number of NCPs with values no less than 0.3 as a measure of multifunctionality at the subbasin scale. Humid regions had higher levels of multifunctionality than arid areas, and the highest level of multifunctionality often appeared in the subbasins with intensive human activity (Fig. S5a online); 96.011% of subbasins with no more than 10 NCPs had a value no less than 0.3 (Fig. 5b online). Based on the relationship among the changes in NCPs (Fig. 4), the enhancement or management on NCPs at a subbasin scale should not only consider the level of multifunctionality but also the regional relationships among the changes in NCPs. This consideration ensures that multifunctionality is maintained through time.

Based on the classification of dominant NCPs (Fig. 3), we calculated the correlations of the changes in NCP values in each classification and counted the number of tradeoff pairs of NCPs and synergistic pairs of NCPs, as well as the mean multifunctionality in this classification (Fig. 5a). We combined the tradeoff – synergistic pairs with the mean multifunctionality measure to identify-four classification types (Fig. 5b). The regions dominated by NCP9 + 12, NCP4 + 13, NCP4 + 11, NCP1, NCP4, and NCP11 were identified as regions with low synergies and low multifunctionality. Most of these subbasins were distributed in transitional climate areas, such as the margins of dryland and the cryosphere. The exceptions were New Guinea Island and the Congo basin, which had only a few NCPs because of low exploitation. These key regions were mostly highlighted because further exploitation of material NCPs would probably be at the expense of a decrease in regulating NCPs.

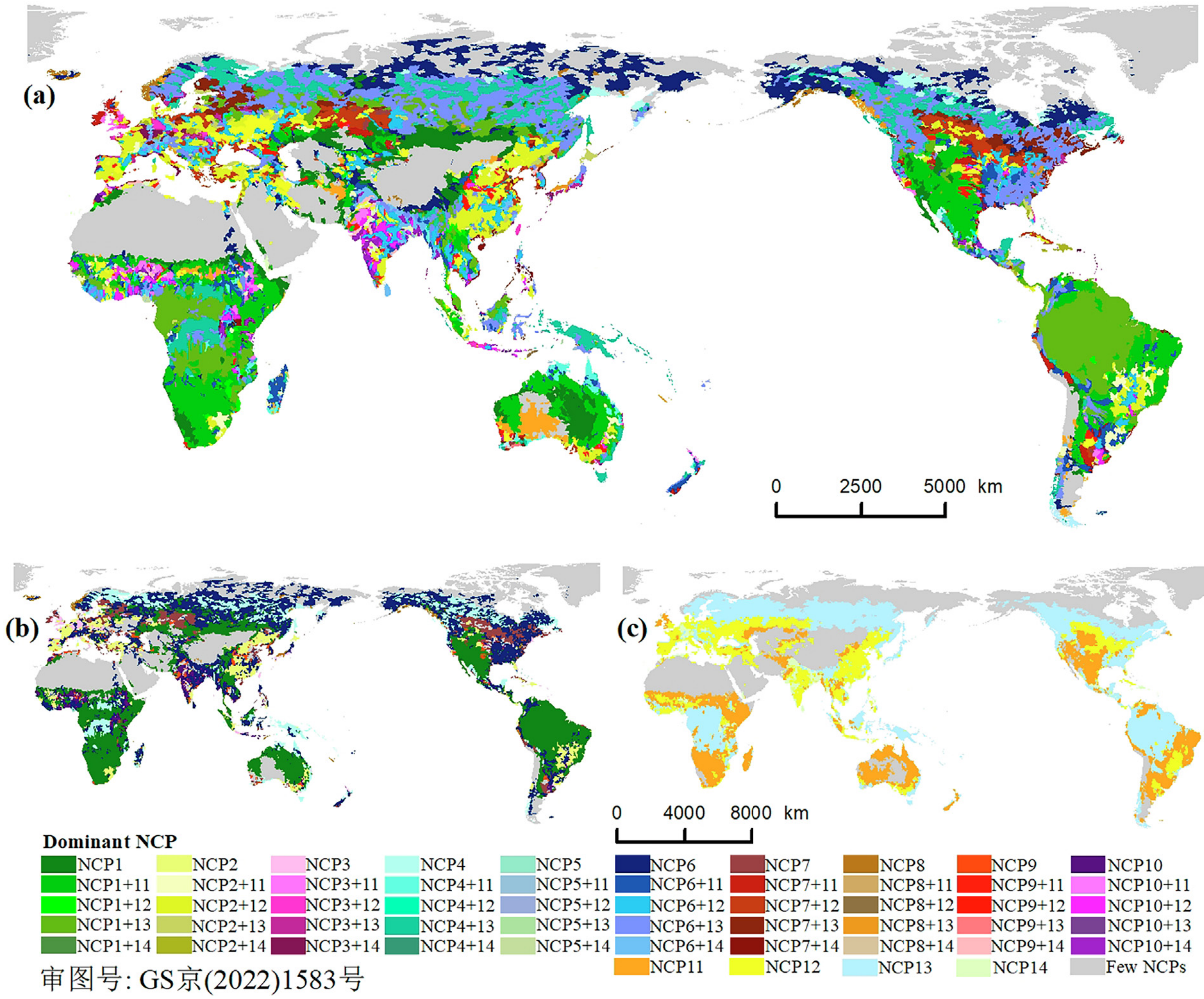

Fig. 3. Global distribution of dominant NCPs in 2018. Regulating and material NCPs are separated by a "+". (a) Combination; (b) regulating; (c) material. The unit is HydroBasin level 06.

The regions dominated by NCP1 + 12, NCP1 + 13, NCP2 + 13, NCP6 + 13, NCP7 + 13, NCP7 + 14, and NCP10 + 11 were identified as regions with low synergies and high multifunctionality. For example, boreal coniferous forests and the Amazon rainforest had abundant regulating NCPs, while they were nearly inevitably threatened by logging due to the coinciding distribution of NCP13 (Fig. 1). The regions dominated by NCP7 + 11, NCP7 + 12, NCP1 + 11, NCP7, NCP14, NCP6, and NCP12 were identified as regions with low multifunctionality and high synergies. Most of the subbasins in this group were dominated by NCP1 + 11 and contained grass and shrub ecosystems. The regions dominated by NCP6 + 14, NCP3 + 13, NCP2 + 12, NCP2 + 11, NCP6 + 12, NCP10 + 14, NCP8 + 13, NCP10 + 12, and NCP6 + 11 were identified as regions with relative synergies of NCP distribution, where many more synergistic relationships than tradeoff relationships existed, and the multifunctionality was high. Most of the subbasins in this group were highly populated, indicating a high and diverse local acquirement and utilization of nature.

By grouping the subbasins by their dominant climate classifications, tropical and temperate climates had high multifunctionality and NCP relationships with either tradeoffs or synergies (Fig. 6a). Temperate climates with no dry season and hot summers (Cfa) were the only climates where the mean multifunctionality was higher than 9, and polar frost climates (EF) were the only climates where the mean multifunctionality was lower than 2. Climates with cold and dry winters and hot summers (Dwa) had the lowest ratio of tradeoffs to synergistic pairs, with 8 tradeoffs and 53 synergistic pairs of NCP changes. Polar tundra climates (ET) had the highest ratio of tradeoffs to synergistic pairs, with 35 tradeoffs and 27 synergistic pairs of NCP changes. The cross-information of dominant NCPs (Fig. 5a) and climate classes (Fig. 6a) suggests the need to apply a two-layer regionalization system that combines biogeographical information, such as climate and ecosystem classes, and landscape multifunctionality information, such as NCPs, at specific scales [41].

Under future climate change [39], the number of subbasins cold climates with no dry seasons and cold summers will largely decrease (Dfc), and the subbasins with cold climates with no dry seasons and hot summers will correspondingly increase (Dfa) (Fig. 5b). However, considering only the present high multifunctionality and high number of synergistic pairs in Dfa compared to Dfc could result in neglecting the high threats to the subbasins dominated by temperate and tropical climates. The dominant climate changes, from temperate climates with dry winters and hot summers (Cwa) to tropical savannah climates (Aw), hot arid steppe climates (Bsh) to hot arid desert climates (Bwh), Aw to Bsh, and tropical rainforest climates (Af) to tropical monsoon climates (Am) could occur at the expense of decreasing multifunctionality and even increasing tradeoff relationships in the latter two transformations. Consequently, the high multifunctionality of NCPs

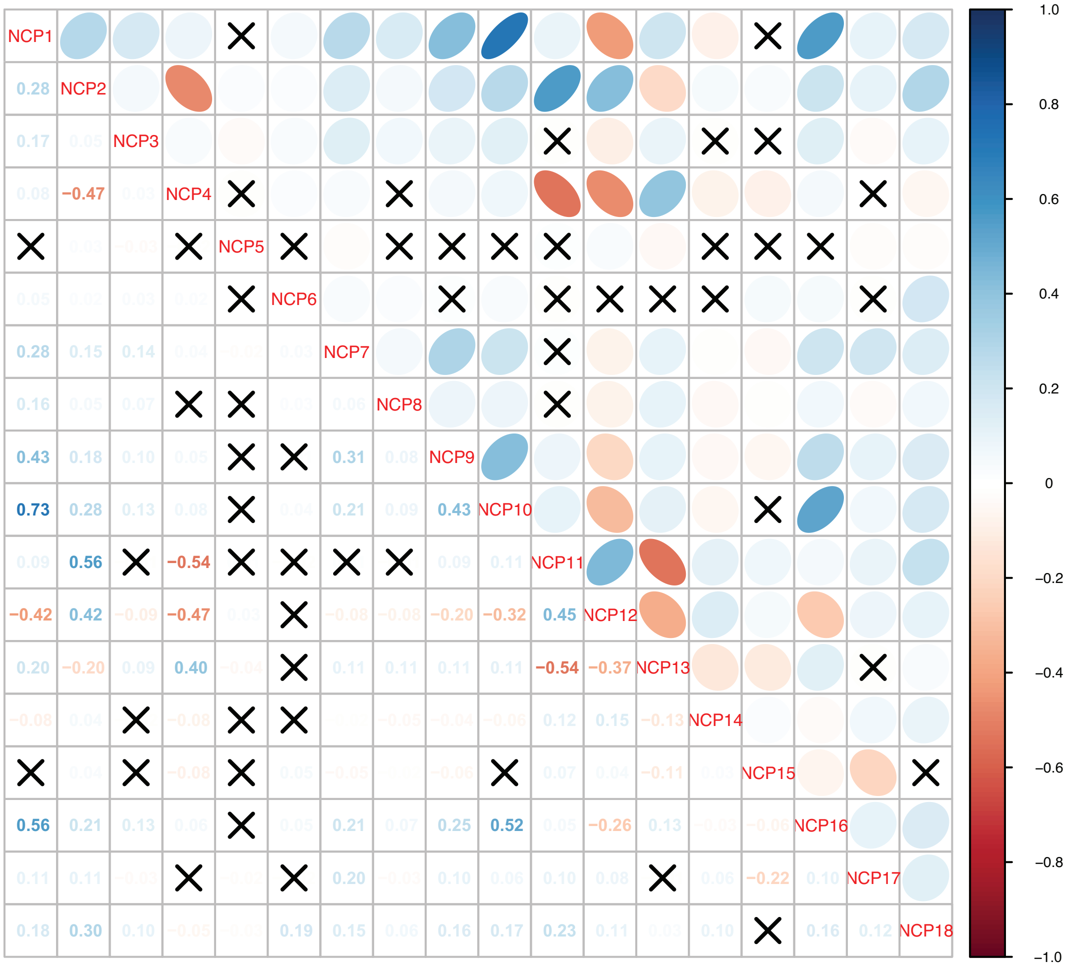

Fig. 4. Correlations of the changes in NCP values from 1992 to 2018 at the subbasin scale. Red indicates a tradeoff, blue indicates synergy, and crosses indicate nonsignificance with $P > 0.05$.

and highly synergistic relationships among NCP changes in low latitudes could be threatened by future climate change, which should act as a warning sign to future regional landscape multifunctionality management.

4. Discussions

All maps simplify the real world to provide interpretable patterns and orientations [45], and the spatial explicit information is usually indispensable for supporting landscape management activities [46,47]. Depending on land cover as a medium to connect the 18 NCPs in a comparable assessment system, we built the first spatially explicit assessment of all 18 NCPs and their changes through time. The result on spatial stratified heterogeneity of NCP distribution under the geographical gradient of elevation, temperature, precipitation and human footprint was mostly correlated with some of the former global and regional assessments [5,6]; and the result of decreasing trends on most global NCP have been evidenced by a global synthesized analysis based on scientific literature [4].

The different assessment models and temporal benchmarks could result in inconsistent trends in some ecosystem processes, e.g., carbon and water cycles. These inconsistencies can be attributed to the diverse interpretation of "nature's contribution" in indicator quantification [4,48,49]. With a sacrifice in terms of quantifying the physical amounts of NCPs, an advantage of using our rapid assessment indicator framework is the ability to spatiotemporally identify the relationships among all NCPs, which can prevent landscape managers from focusing on only easily evaluated landscape functions and lead to biased ecological governance decisions [50,51]. Moreover, using the nested multiple basin levels as assessment units, the production observation, benefit assignment, and management of NCPs are simplified across different spatial scales [52–54], and the NCP demands of local stakeholders are positioned in an enveloped geographical unit [55–57].

Taking advantage of the multifunctionality concept [58], the NCP distributions at the subbasin and basin scales could supplement ecoregion classifications as a functional classification approach [59,60]. The basins with high levels of multifunctionality were distributed in the upstream Amazon River, Yangtze River, Mississippi River, and Congo River (Fig. S6 online) and did not overlap with the Ecoregion-based habitat protection objectives for either the "Half Protected" regions or the "Nature Could Reach Half" of the regions [40]; thus, this distribution could serve as additional spatial guidance for regional ecological management. This distribution could be evidence for basin classification based on NCPs being independent of existing habitat conservation schemes

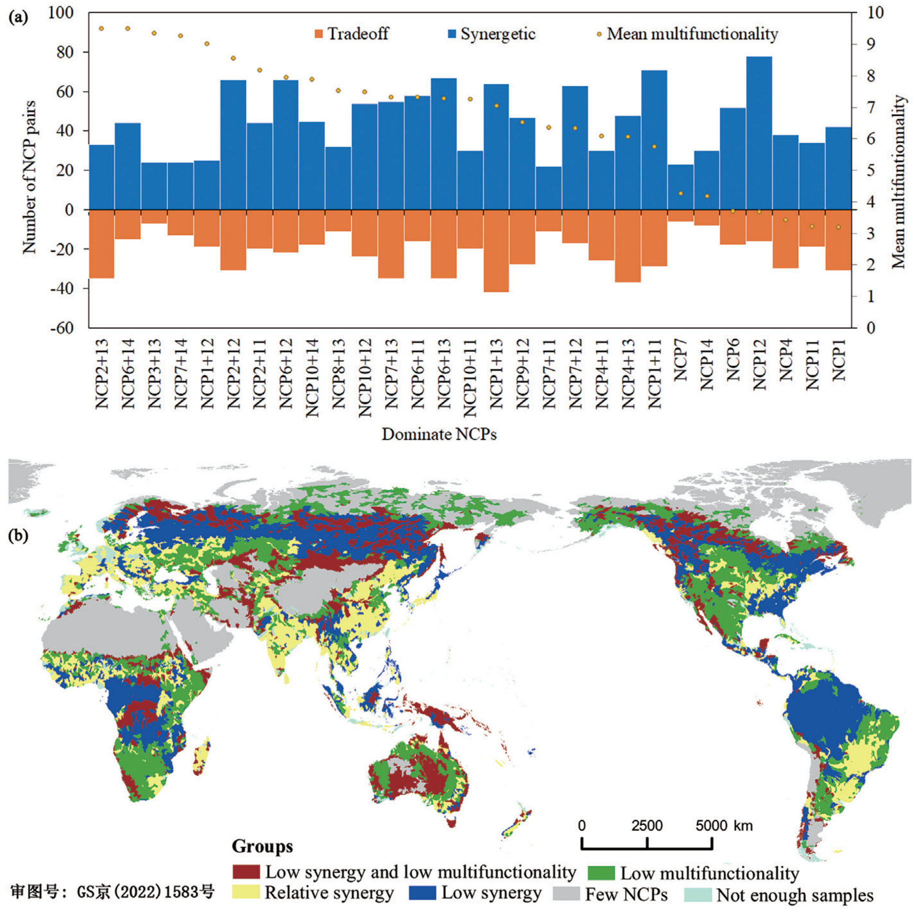

Fig. 5. Grouped regions based on the correlations and multifunctionality of NCPs. (a) Number of NCPs and their relationship of the changes in values from 1992 to 2018. (b) Global distribution of grouped regions. The statistic unit is HydroBasin level 06.

with similar numbers of regionalization units [61,62]. To conserve habitats without the loss of material and nonmaterial NCPs, a shared landscape that connects people and nature rather than separating them could be advocated for in high multifunctionality regions to coordinate nature conservation, resource utilization and local livelihoods [2,63,64].

Climate classification and climate change predictions are essential considerations in identifying priority areas for biodiversity conservation [65–67]. Following the theoretical framework for NCPs [3], our results provide a further perspective on the priority regions for conserving and regulating NCPs and to adapt to future climate change (Fig. S3 online). The relationships and multifunctionality of the NCPs were quantified within each climate classification; this quantification can provide the combined information of both biogeography and people's benefits from nature towards a better linkage between nature and people in key regions compared to considering only habitat protection from a biogeographical perspective [41,68]. This spatially explicit information is also critical for achieving the Sustainable Development Goals [69], as our quantification of synergies, tradeoffs and multifunctionality help to identify regions were these goals may conflict and where they may be synergistic. Importantly, this could lead to the development of new targeted policies in some regions to reduce conflicts between different Sustainable Development Goals [2].

Several theoretical, methodological and practical research perspectives are relevant to assessing global NCPs. Theoretically, whether the nonmaterial NCPs can be quantitatively or semi-qualitatively assessed should be explored [70]. Moreover, to utilize spatial NCP information across scales, the spatially explicit description of NCPs should be strengthened [53]. Methodologically, in addition to the exploration of modelling [5], how to standardize the high and low levels in NCP measurement should be explored, the local tradeoffs between the dominance and multifunctionality of NCPs should be assessed. When landscape optimization and functional maximization are regionally required [71], NCP assessments and regionalization should be used to inform landscape decision-making [72]. Local measurements should be either coordinated by central governments and/or coordinated through collaboration with neighboring districts [73,74] to achieve spatially explicit NCP assessments at regional scales, and the spatial flow of NCPs across regions should be identified to better support people's well-being [75].

Global spatial priority of NCPs is not a cure-all solution, as it may inaccurately reflect local social and ecological processes [76]. However, a lack of broad-scale spatial assessments of nature is inadvisable, as the absence of global spatial information can hamper integrated approaches to meeting economic, social and environmental objectives [77]. As such, our bundle of spatially explicit NCP can provide a global vision for this concept and help to foster integrated approaches on regional landscape management. The next step is to develop nested approaches at local scales that capture specific local, social and economic contexts. Further, the tradeoffs in the change in NCPs remind us of the difficulty in coordination to achieve the Sustainable Development Goals [78,79]. This difficulty on sustainable development is especially true in transitional climate areas, where regional and local explo-

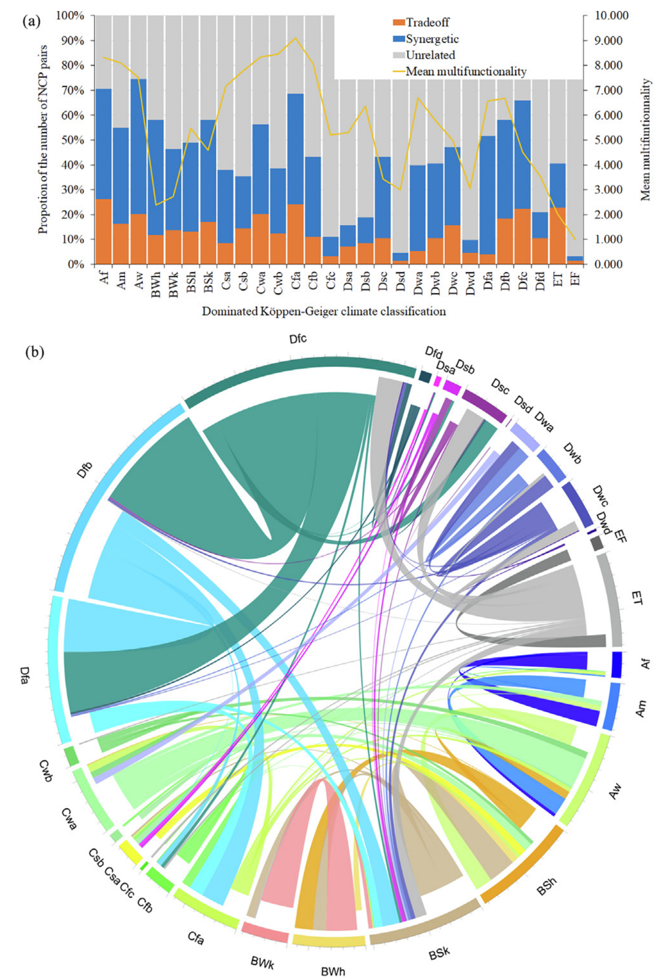

Fig. 6. Relationship and multifunctionality information of NCPs among dominant climate classifications. (a) Relationships of the changed NCP values from 1992 to 2018 and the multifunctionality of NCPs among the dominant climate classifications at the subbasin scale. (b) Numbers of subbasin changes from present dominant climate classifications to future climate classifications. The blank bottoms of the cords indicate a transfer out from the present, the colored bottoms of the cords indicate a transfer into the future, and the thicknesses of the cords indicate the number of subbasins. The statistic unit is HydroBasin level 06. Full names of the abbreviations are listed in Table S1 (online).

rations of achieving adaptive landscape multifunctionality should be further strengthened [80,81].

5. Conclusions

We built a rapid assessment indicator framework and produced the first spatially explicit assessment of all 18 NCPs at a global scale. There are four findings that provide a general spatiotemporal understanding of global NCP distributions, including: 12 NCPs decreased from 1990 to 2018, mainly due to decreases in natural ecosystem areas; 29 regulating-material NCP combinations (54 in total) dominated 76% of the terrestrial area, and the area with few NCPs accounted for 22%; synergistic relationships were more common than tradeoff relationships, while the relationships among regulating and material NCPs generally traded-off with each other; and the regions with few NCPs and many tradeoff relationships were often located in transitional climate areas, and areas with high numbers of NCPs and synergistic relationships occurred in low-latitude regions but could be threatened by climate transitions. The indicators we selected for NCPs assessment are not complete because of the related connotations among NCPs, e.g., mangrove is not the most suitable indicator for the regulation of ocean acidification (NCP5), but introducing the indicator of the terrestrial vegetation masses that drive NCP4 would cause autocorrelation. We only focus on the global spatial information of some particular indictors that are not highly related to calculate landscape multifunctionality. The findings can be used to interpret the biogeographic information in a functional way to support the global enhancement of human well-being.

Conflict of interest

The authors declare that they have no conflict of interest.

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Author contributions

Yanxu Liu and Bojie Fu designed the research. Yanxu Liu drafted the manuscript. Shuai Wang, Jonathan R. Rhodes, Yan Li, Wenwu Zhao, Changjia Li, Sha Zhou, and Chenxu Wang informed the study design and edited the manuscript. All authors contributed to the writing of the manuscript.

Appendix A. Supplementary materials

Supplementary materials to this article can be found online at https://doi.org/10.1016/j.scib.2023.01.027. The NCP values and the dominant NCP can be downloaded from https://pan.bnu.edu.cn/l/lu8APO.

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