Realizing the values of natural capital for inclusive, sustainable development: Informing China's new ecological development strategy

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A major challenge in transforming development to inclusive, sustainable pathways is the pervasive and persistent trade-off between provisioning services (e.g., agricultural production) on the one hand and regulating services (e.g., water purification, flood control) and biodiversity conservation on the other. We report on an application of China's new Ecological Development Strategy, now being formally tested and refined for subsequent scaling nationwide, which aims to mitigate and even eliminate these trade-offs. Our focus is the Ecosystem Function Conservation Area of Hainan Island, a rural, tropical region where expansion of rubber plantations has driven extensive loss of natural forest and its vital benefits to people. We explored both the biophysical and the socioeconomic options for achieving simultaneous improvements in product provision, regulating services, biodiversity, and livelihoods. We quantified historic trade-offs between rubber production and vital regulating services, finding that, over the past 20 y (1998–2017), there was a 72.2% increase in rubber plantation area, leading to decreases in soil retention (17.8%), water purification [reduced retention of nitrogen (56.3%) and phosphorus (27.4%)], flood mitigation (21.9%), carbon sequestration (1.7%), and habitat for biodiversity (6.9%). Using scenario analyses, we identified a two-pronged strategy that would significantly reduce these trade-offs, enhancing regulating services and biodiversity, while simultaneously diversifying and increasing product provision and improving livelihoods. This general approach to analyzing product provision, regulating services, biodiversity, and livelihoods has applicability in rural landscapes across China, South and Southeast Asia, and beyond.

ecosystem services | green growth | natural capital | trade-offs | poverty alleviation

Ecosystems as natural capital assets play fundamental roles in supporting human well-being. However, the patterns of human development that have dominated over the last few centuries have resulted in dangerous depletion of natural capital and uneven delivery of essential ecosystem services. In general, services for which there are well-functioning markets (e.g., provision of agricultural products) have increased greatly, at the expense of those public benefits without such markets (e.g., water purification, flood control, and climate stabilization) (1, 2). Such an imbalance has severe consequences today, as reflected in the increasing frequency and severity of catastrophic events (3). In China, for instance, severe flooding along the Yangtze River killed thousands of people, rendered 13.2 million homeless, and caused about US $36 billion in property damage in 1998 (4), due to massive deforestation for timber production.

In response to these global trends, a new vision for human development is emerging, focused on dual goals of securing people and nature (5–7). Actionable, new insights in science, policy, and finance are being applied, perhaps most profoundly in China, to quantify and manage trade-offs between immediate, local human needs and future, regional requirements (8–11). Stemming from underlying biophysical processes, some trade-offs are innate, such as between carbon sequestration and water provision in some grassland and shrubland regions (12, 13). However, it has been repeatedly suggested that some trade-offs (e.g., crop product provision and nutrient retention) can be lessened or even neutralized through management decisions (e.g., switching to alternative crop systems such as legumes), creating "win–win" situations (14, 15).

Few cases where management has achieved such success exist, however (16). The few cases that do show the feasibility of delivering a large "bundle" of services usually do not include provisioning services within the bundle (17, 18). In other words, management can diversify the regulating, supporting, and cultural services provided by a single landscape, but the trade-off between provisioning and all other services appears pervasive and persistent (17–19).

China aims to overcome this trade-off through a new Ecological Development Strategy, designed to increase forest, grassland, and wetlands while, at the same time, enhancing well-balanced suites of ecosystem services produced per unit area (20). China has the largest forest plantation area in the world (0.62×10^8 ha) (21), providing a suite of important benefits: timber and nontimber

Significance

Achieving inclusive, green development is crucial to China and the world. Over the past century, great increases in agricultural production have been achieved at the expense of other ecosystem benefits, such as flood control, water purification, climate stabilization, and biodiversity conservation. We report on an application of China's new "Ecological Development Strategy," which aims to break these trade-offs and be scaled nationwide. Focusing on Hainan Island, where rubber production has driven loss of natural forest, we identified a two-pronged strategy that would eliminate these trade-offs, simultaneously diversifying and enhancing product provision, rural incomes, and many other ecosystem benefits. This win–win approach has broad applicability in the plantation regions in China, across South and Southeast Asia, and beyond.

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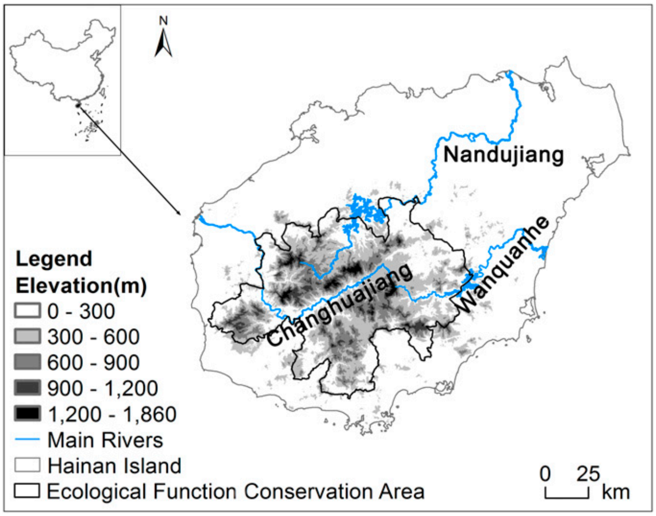

Fig. 1. The study area is Hainan Island's EFCA (outlined in black) in the central mountainous region of the island.

products (e.g., rubber, medicinal plants), regulating services (e.g., flood mitigation, hydropower production efficiency, erosion control, carbon sequestration), and cultural services (e.g., recreation, tourism). However, natural forest has been extensively cleared in some regions. For example, natural forest loss of 41% over 1950–2010 in Hainan (22) exacerbated the severe flooding in 2010 (23).

Today, China's forest assets and poverty appear intimately related. The average gross domestic product (GDP) per capita in the counties with >30% forest cover was just 81% of the national average GDP per capita in China (24). In many other countries, extreme poverty and biodiversity hot spots are similarly geographically coincident and concentrated in rural areas where livelihoods depend disproportionately on natural capital embodied in forests (25). There is an urgent need to align livelihoods of forest product provision with enhanced regulating, supporting, or cultural services in forest regions.

In addition, to realize the dual goals of ecosystem service protection and poverty alleviation, China established a network of "Ecological Function Conservation Areas" (EFCAs). These areas aim to conserve and restore places with high ecosystem services, especially regulating services. They span 49.4% of China's land area, where forest plantations are widely distributed, and contain more than 70% of China's counties in poverty. EFCAs receive ecological transfer payments from the central government in exchange for protecting and restoring natural ecosystems to enhance provision of vital regulating services (26) (*SI Appendix*, section S1). Still, EFCAs face major challenges in coordinating the trade-offs of ecosystem product provisioning services and regulating, supporting, or cultural services.

High-impact human activities often still occur within EFCAs. For example, rapid expansion of rubber plantations continues to destroy natural forest, and extensive application of fertilizer and pesticide in plantations leads to other devastating environmental consequences (27, 28). Extensive studies have been conducted on these environmental effects, especially in south China (e.g., refs. 27 and 28). However, an approach for a more comprehensive assessment is urgently needed in cases like these to provide citizens, conservationists, and decision makers with the best scientific information on land use dynamics and their implications for conservation to manage the trade-offs between provisioning of ecosystem goods and regulating services (29–31).

Here, we quantify the environmental effects of rapid land use and land cover (LULC) changes and explore a pathway for realizing win–win goals of increasing both production of marketed goods and regulating and cultural services. We focus on the EFCA of Hainan Island, China (Fig. 1), as a case relevant to extensive regions of China and the world. We first identify the land use changes within the EFCA. Second, we use Integrated Valuation of Ecosystem Services and Trade-offs (InVEST) models (32) to quantify the impacts of land use changes and alternative land use scenarios for win–win outcomes of important provisioning and regulating services (Fig. 2). Finally, we use household survey data to analyze the livelihood implications of alternative land use scenarios, and to define realistic approaches for minimizing or reversing ecosystem service trade-offs.

Results

LULC Changes. From 1998 to 2017, the area under rubber plantation increased 652.5 km^2, and natural forest declined by 414.6 km^2 (Fig. 3) in the EFCA on Hainan Island. By 2017, 36.7% of the rubber plantation area had been established at the expense of natural forest present in the EFCA in 1998 (*SI Appendix*, Table S1). Similar trends were found outside the EFCA (*SI Appendix*, Fig. S1). Natural forest was more stable within the EFCA, where the land converted from and to natural forest between 1998 and 2017 was 21.9% and 16.1%, respectively. Outside the EFCA, this was 47.3% and 47.1%, respectively (*SI Appendix*, Table S1). The results suggest that establishing the EFCA helped support natural forest conservation in the face of great pressure to intensify land use.

Impacts of Observed LULC Changes on Ecosystem Services. The increase of rubber provision (72.2%) came at the expense, however, of significant decreases in natural tropical forest habitat (−6.9%), soil retention (−17.8%), flood mitigation (−21.9%), nitrogen retention (−56.3%), phosphorus retention (−27.4%), and carbon sequestration (−1.7%) (Fig. 4*A*). The results show significant trade-offs between the provisioning service and the conservation of natural habitat and regulating services.

We developed a scenario of "No Rubber Plantation Expansion," in which 1998 baseline rubber plantation conditions remain into 2017. We use this counterfactual scenario to estimate the changes in LC and associated ecosystem services in the absence of rubber plantation expansion. We find that the natural tropical forest habitat increased 8.3% relative to observed 2017 conditions, and all

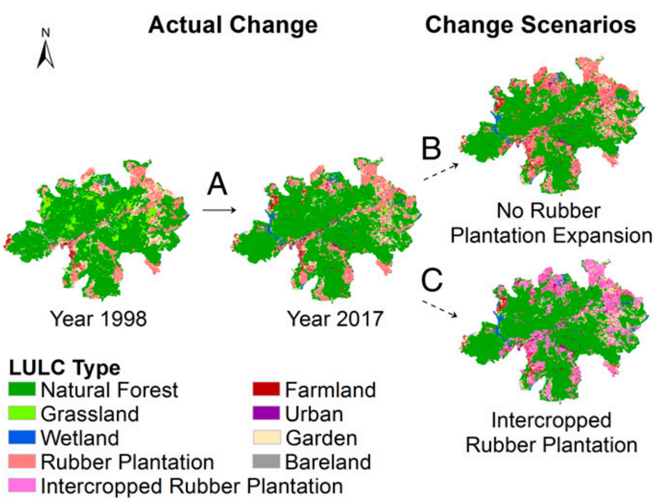

Fig. 2. Actual LULC changes between 1998 and 2017 and LULC scenarios in the Hainan Island EFCA, depicting the decision alternatives considered in the analysis. The observed LULC changes from 1998 to 2017 show great expansion of rubber plantation (map *A*). Under No Rubber Plantation Expansion, 1998 baseline rubber plantation conditions remain into 2017; we used this scenario to estimate the changes in LULC and associated ecosystem services had there been no rubber plantation expansion (map *B*). The Intercropped Rubber Plantation scenario keeps natural forest and rubber plantation areas in line with the observed 2017 data, but rubber trees are intercropped with an understory of medicinal plants (*Methods*) (map *C*). This allows us to explore whether improved management can yield a win–win outcome for provisioning of products, regulating services, and cultural services, and for livelihoods.

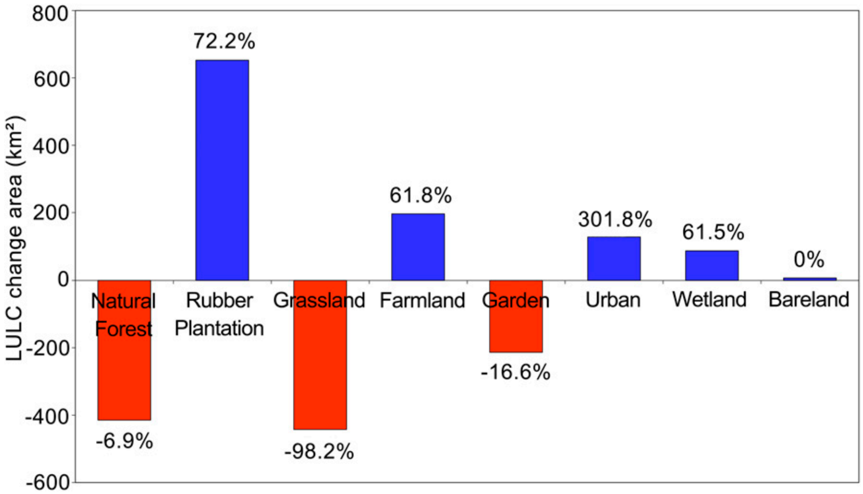

Fig. 3. LULC changes between 1998 and 2017 in the EFCA on Hainan Island.

of the regulating services also increased (soil retention, 18.9%; flood mitigation, 11.6%; nitrogen retention, 30.4%; phosphorus retention, 18.2%; carbon sequestration, 1.9%) (Fig. 4*B*). These modeling results show that rubber plantation expansion significantly increased ecosystem provisioning services but also severely reduced ecosystem regulating services and natural tropical forest habitat.

Reducing or Eliminating Ecosystem Service Trade-Offs. Complex ecosystem management (illustrated in the Intercropped Rubber Plantation scenario) could effectively reduce or even eliminate the trade-offs between provisioning, regulating, and cultural ecosystem services. The Intercropped Rubber Plantation scenario keeps natural forest and rubber plantation areas in line with the observed 2017 data (notwithstanding potential but negligible changes in soil carbon from intercropping). This keeps carbon sequestration unchanged from observed 2017 conditions and not only increases provisioning services (by 102%) but also significantly contributes to increased soil retention (37.4%), flood mitigation (20.6%), nitrogen retention (54.3%), and phosphorus retention (41.3%) (Fig. 4*C*). The retention of natural forest maintains potential for recreation and tourism.

Costs and Benefits of Monoculture Rubber Plantation Versus Intercropped Rubber Plantation. In addition to modeling the scenarios outlined in Fig. 2, we also estimate the net costs and benefits of conventional monoculture rubber plantation (the 2017 baseline) and intercropping rubber plantation using household survey data collected in the Hainan Island EFCA. The estimated net benefit (economic income) from intercropping rubber plantations is twice that of monoculture rubber plantations (Table 1). The difference comes primarily from having additional marketable products from the same area of land. There is no significant difference in the relative investment in pesticide, fertilizer, or other inputs, including costs of conversion from monoculture rubber (Table 1).

Discussion

Our focal region, Hainan Island, is experiencing rapid expansion of rubber plantations (Fig. 2), helping support rapid economic development (rural per capita net income increased by 400% from 1998 to 2017) and population growth (23.5% increase from 1998 to 2017) (33). However, intensive cropping practices and high agrochemical inputs frequently result in negative environmental impacts, including runoff of sediments and agrochemicals to surface waters, and reductions in cultural services (27, 28). Farmers and local governments often share the desire to eliminate or mitigate the negative environmental impacts of rubber plantations and to enhance ecosystem services (such as regulation of soil erosion and water quality). Actionable knowledge for ecological intensification of agriculture tells us that increased soil cover and diversification of production system are potential approaches to achieve these goals (34). We analyzed a scenario of intercropping rubber plantations, focusing on both vegetation coverage increase and diverse products.

We found that intercropping rubber plantations offers an opportunity to reduce the negative externalities often associated with increased production, allowing income generation while maintaining ecosystem services. Different mechanisms contribute to this result. (*i*) Intercropping vegetation can decrease splash erosion through low canopy height with high subcanopy coverage. Intercropping vegetation species [e.g., tea (*Camellia sinensis*), cacao (*Theobroma cacao*), coffee (*Coffea arabica*) and shrubs (e.g., *Ficus macrophylla*)] with rubber plantations can help increase subcanopy coverage (35). Selecting low, near-surface intercrops for constructing rubber-based agroforestry systems can lead to significant reduction in splash erosion beneath multiple canopies compared with monoculture (35). (*ii*) Intercropping rubber plantations can improve water, soil, and nutrient retention mainly through increasing fine root biomass and litter quantity (36). Compared with monoculture rubber plantations, intercropping rubber plantations have significantly higher fine root biomass and litter quantity, which contribute to the increase of soil and water conservation (37). (*iii*) Intercropping species can help retain soil water and enhance the water use efficiency of rubber trees. Interspecies competition for water can enhance water use efficiency of drought-avoidance rubber trees and lead to complementarity between the root distributions of plants in rubber agroforestry systems (i.e., rubber with tea, coffee, or cocoa) (38). (*iv*) The economic income of rubber plantations can be increased by intercropping high-return crops. Intercropped rubber plantations may not only reduce the negative externalities but also increase other provisioning services from additional crop production beyond rubber (e.g., tea, coffee, cacao) (34). In addition, crop diversification reduced risks to farm income by reducing reliance on a single crop that is subject to crop failure or falling market prices (39). In all of these ways, we can see how various management objectives are connected with ecological outcomes, and can assist stakeholders in their decision-making to be better positioned to reach rubber plantations' biophysical and social–economic targets.

Our approach provides a general methodology for managing trade-offs between provisioning and regulating services. We examined three axes of land use trade-offs, namely, biodiversity, selected ecosystem services, and net income, and compared the changes of ecosystem service trade-offs between monoculture and intercropped rubber plantations at the regional scale. We found that intercropped rubber plantations not only generated income from rubber and other products (e.g., Chinese medicine *Alpinia oxyphylla*) but improved a wide variety of other ecosystem

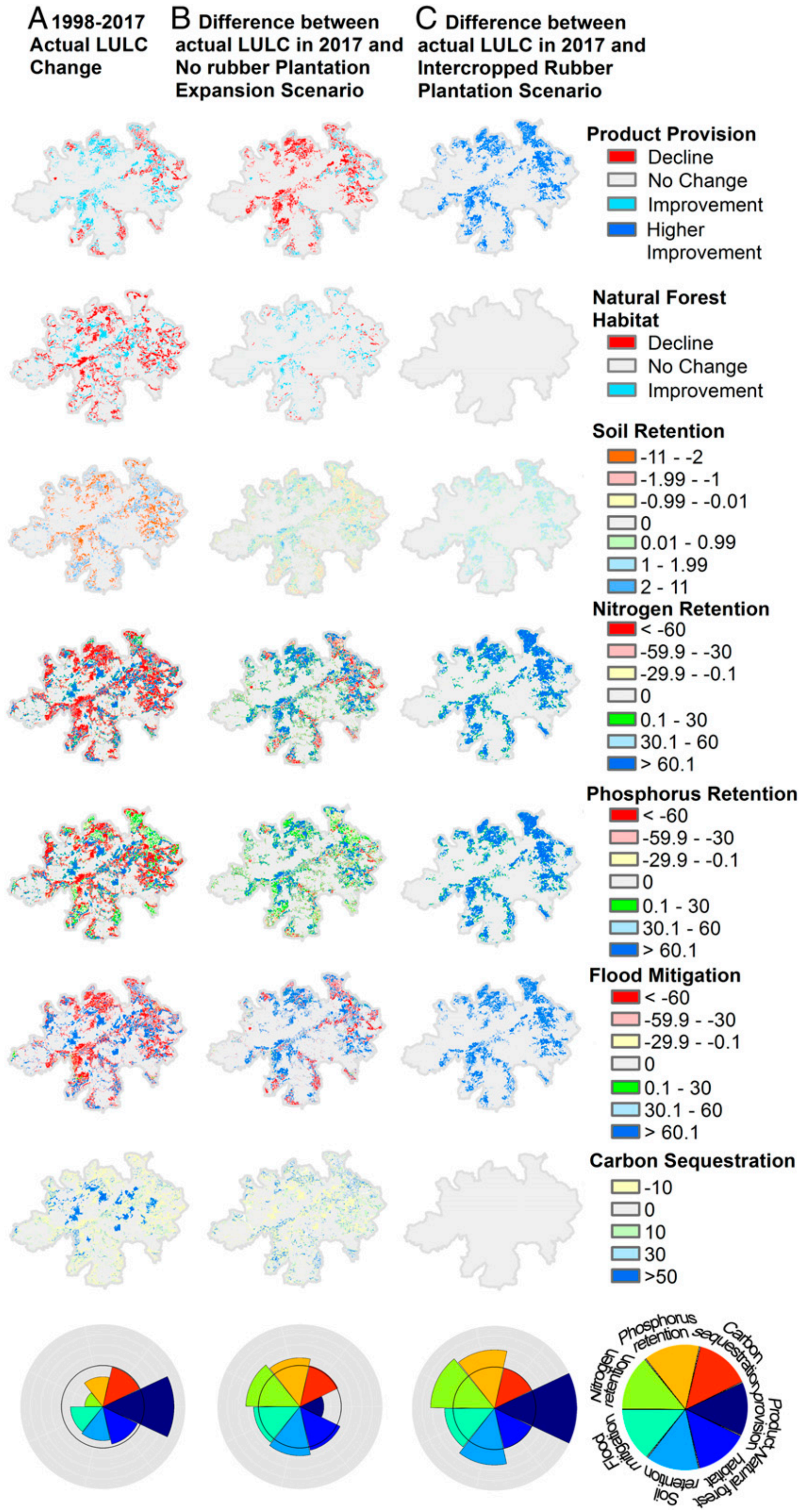

Fig. 4. Impacts of LULC changes and the implications of alternative land management scenarios on ecosystem services across the landscape. (*Upper*) (*A*) Changes in ecosystem services are relative to the actual change over 1998–2017, involving expansion of conventional rubber production, with declines in ecosystem services shown in red, increases shown in blue, and gray representing no change. (*B*) The implications for 2017 had there been no rubber expansion from 1998, compared with 2017. (*C*) The implications for 2017 had there been a shift of all monoculture rubber plantation in 2017 to Intercropped Rubber Plantation. (*Lower*) The circles show ecosystem service provision under each scenario, relative to the baseline (the black circle in each diagram). A longer petal indicates higher production of a particular service.

services, including soil retention, nutrient retention, and flood mitigation.

Clarifying the trade-offs between multiple ecosystem services and using stakeholder input to identify the desired ecosystem services and their spatial distribution can help encourage the adoption of actions that achieve desirable outcomes in multiple dimensions (34). The application of complex ecosystem management in intercropped rubber plantations will help to reduce threats to regulating services and promote regionally sustainable land use on Hainan Island.

Our findings have important development implications beyond Hainan Island. Potential trade-offs between biodiversity and provisioning and regulating ecosystem services exist in many regions in China and beyond. China has the largest area of plantation forest in the world, and two-thirds of the plantations are monocultures of conifer species (40). Monoculture plantations in China may promote

Table 1. Comparison of annual economic benefits and costs between monoculture rubber plantation and intercropped rubber plantation

Items	Monoculture rubber plantation, $n = 134$, Mean (SD)	Intercropped rubber plantation, $n = 60$, Mean (SD)	Differences
Costs			
Pesticide, US$/ha	60.1 (83.3)	66.2 (85.4)	6.1$^{\text{n.s}}$
Fertilizer, US$/ha	89.2 (136.8)	114.6 (199.7)	25.4$^{\text{n.s}}$
Other investments, US$/ha	0.2 (2.0)	0.5 (4.1)	0.3$^{\text{n.s}}$
Subtotal, US$/ha	149.4 (182.7)	181.3 (247.7)	31.9$^{\text{n.s}}$
Benefit			
Products, US$/ha	1,845.8 (4,800.5)	2,166.2 (5,799.0)	320.4$^{\text{n.s}}$
A. oxyphylla, US$/ha	—	1,425.9 (2,885.7)	1,425.9
A. villosum Lour., US$/ha	—	546.9 (2,032.9)	546.9
Subtotal, US$/ha	1,845.8 (4,800.5)	4,139.0 (8,269.2)	2,293.2*
Net benefit, US$/ha	1,696.4 (4,763.8)	3,957.7 (8,261.9)	2,261.3*

An "n.s." superscript means no statistically significant difference.
*Significant difference at the level of $P < 0.05$.

forest degradation, biodiversity loss, high soil erosion, and catastrophic flooding compared with natural forest cover (41). However, conservation investments in China have improved the flow of important ecosystem services (26).

Targeted investments can improve income and livelihoods along with ecosystem services (42). The loss of forest cover through agrarian conversion to oil palm in insular Southeast Asia provides a parallel (43). Actionable knowledge on how to achieve win–win outcomes is context-specific, however, and may change with changes in market or environmental conditions (34). We focused here on plantations in the mountainous central area of Hainan Island. However, our results suggest that more-nuanced, complex ecosystem management based on ecological principles may generate many benefits in EFCAs of China, and potentially across similar regions of South and Southeast Asia, diversifying and enhancing multiple ecosystem services and improving policy design and implementation for inclusive green growth (e.g., ecological monitoring of environmental restoration projects), while diversifying and securing human livelihoods.

Methods

Study Area: EFCA of Hainan Island. Located in tropical southern China, Hainan Island (18°10′N to 21°10′N, 108°37′E to 110°03′E) is 3.39×10^4 km^2, and the population comprised 9.26 million people in 2017. The central mountainous region of Hainan Island, where the EFCA is situated, plays a key role in the conservation of biodiversity and important ecosystem services (e.g., soil retention, water purification, flood mitigation) (Fig. 1) (*SI Appendix*, section S2). Also concentrated in the central mountainous area are the most poverty-stricken villages and towns and 90% of the low-income population of Hainan Province (44).

Rapid expansion of rubber plantations greatly reduced the natural forest and created environmental risk for downstream regions. There exist significant conflicts between ecosystem service conservation and economic development in the central mountainous region. Recognizing this, and to protect biodiversity and important ecosystem services, the central government of China named the central mountainous region of Hainan Island a pilot EFCA in 2011 (Fig. 1) (*SI Appendix*, section S1 and Fig. S2).

LULC. We analyzed the LULC change between 1998 and 2017 to identify the contribution of the EFCA to regional ecosystem service conservation. To classify LULC types, we used atmospherically corrected Landsat-5 (1998) and Landsat-8 (2017) images provided by the China Remote Sensing Satellite Ground Station, which has a pixel size of 30 m × 30 m. Eight LULC types were classified using a supervised classification method: natural forest, rubber plantation, grassland, farmland, garden, urban, wetland, and bare land. In this study, arboreal forest and open woodland were all considered to be elements of natural forest, based on the standards of the National Forest Inventory of China (45). The classification accuracy rates in 1998 and 2017 are 92% and 93%, respectively (*SI Appendix*, section S3).

Actual LULC Change and Scenarios. Rubber plantations are expanding rapidly throughout montane Southeast Asia (28, 29). Current data are too sparse to quantify the extent of the impacts (28) and provide farmers, other residents, conservationists, and decision makers with the scientific information needed to inform policy, finance, and management for sustaining both livelihoods and vital ecosystem services. In this study, we examine the actual LULC change between 1998 and 2017 and its impact on ecosystem provisioning and regulating services (soil retention, flood mitigation, nitrogen retention, phosphorus retention, and carbon sequestration) and natural tropical forest habitat conservation across the landscape.

There are trade-offs between the priority regulating services and the rubber production that underpins rural livelihoods (44). To illustrate the different trade-offs associated with different land use policies, we analyzed the actual LULC changes and developed alternative scenarios of potential land use change (relative to 2017 conditions) based on three principles: (*i*) maintaining or improving rubber production, (*ii*) using approaches shown to be most effective through scientific assessment, and (*iii*) minimizing trade-offs by improving regulating services in the rubber production areas.

We first developed one scenario to determine whether rubber plantation expansion has significant impact on ecosystem services and, if so, how significantly, by comparing ecosystem services provision in 1998 with that in the scenario of No Rubber Plantation Expansion during 1998–2017. To reduce the trade-offs, we selected one principle management approach likely to be feasible in biophysical, socioeconomic, and political terms: conversion of monoculture rubber plantation to an Intercropped Rubber Plantation system (e.g., together with the Chinese medicines *A. oxyphylla* and *Amomum villosum Lour.*) (46) (*SI Appendix*, Fig. S3), a system that accounted for only 0.7% of the plantation area in 2017 (33).

Thus, we present three sets of calculations:

i) The first set is actual change: LULC changes between 1998 and 2017.
ii) The second is scenario 1: No Rubber Plantation Expansion. Rubber plantation area and distribution do not change between 1998 and 2017, while other LULC categories change as observed. This scenario allows us to understand the impacts of rubber plantation expansion on ecosystem services by comparing ecosystem services in 2017 and scenario 1.
iii) The third set of calculations is scenario 2: Intercropped Rubber Plantation (2017). The conventional monocultural rubber plantations in 2017 are replaced with intercropped rubber plantation. This scenario allows us to compare the impact of monocultural versus intercropped plantation.

Ecosystem Service Selection and Quantification. We focused on the important roles of the Hainan Island EFCA in preventing biodiversity loss, soil erosion, flooding, water quality degradation, and climate change. First, we translated the rubber plantation area into economic value based on the net benefit of monoculture rubber plantations and intercropped rubber plantations, using household surveys to assess the income from each plantation type. Second, we reported the area of natural tropical forest habitat as a proxy for biodiversity conservation. Third, we quantified the ecosystem services of soil retention, flood mitigation, total nitrogen retention, and total phosphorus retention by using the InVEST 3.5.0 models (https://naturalcapitalproject.stanford.edu/) (32) and ArcGIS10.1 (https://www.arcgis.com/index.html). We used average climate parameters (annual precipitation, monthly mean precipitation, annual mean temperature, monthly mean temperature, mean hours of daylight) between 1998 and 2017 to create results general for the region. We acquired data related to export coefficients, crop and land management, soils, and carbon sequestration rates from locally conducted studies. Input values for each of these models are provided in *SI Appendix*, Tables S2 and S3.

- *i*) For soil retention, the InVEST sediment delivery ratio model generates grid files for sediment export to streams and the sediment retained by each pixel on the landscape. We used the reduction in rate of soil erosion to represent the soil retention service.
- *ii*) For flood mitigation, the InVEST seasonal water yield model can estimate the relative contribution of each pixel to generate quick flow (the amount of precipitation that is converted to direct runoff, entering streams soon after a rain event), local charge, and base flow based on monthly climate values and curve number methods. We used the reduction in the rate of quick flow to represent the flood mitigation service.
- *iii*) For nitrogen and phosphorus retention, the InVEST nutrient delivery ratio model is based on the export coefficient approach and can generate two main outputs for both nitrogen (N) and phosphorus (P): the nutrient export to streams and the nutrient retained by each parcel on the landscape. We used the reduction in rate of N and P export as indices for nitrogen and phosphorus retention services.
- *iv*) For carbon sequestration, generally, we assumed that each LULC type sequestered carbon at a steady rate. We estimated the annual sequestration as tons of carbon sequestered, and then compared the final carbon sequestration status of different LULC types under the different scenarios (47).

Cost−Benefit Analysis for Rubber Plantation Management. To examine the costs and benefits of monoculture rubber plantations and intercropped rubber plantations, we conducted household surveys in each of the four villages (Hongmao, Luoshuai, Wengcun, and Nankai) in the EFCA of Hainan Island in June 2017. After obtaining informed consent, we surveyed 60 households that manage intercropped rubber plantations (such as with *A. oxyphylla*) and 134 neighboring households that manage monoculture rubber plantations. We could not locate more households managing intercropped rubber plantations, because there was low adoption of that system at the time of surveying (only 0.7% of the total plantation area).

Our questionnaire focused mainly on the agricultural investments and outputs involved in the two rubber production systems. The costs of both systems included the following elements: fertilizers, pesticides, and other investments (such as expenditures on seedlings, manure, renting machinery, and irrigation). We do not take the labor costs of farmers into consideration when calculating planting costs, because, in the EFCA, subsistence livelihoods dominate, and production and consumption activities are inseparable (48, 49). The benefits of plantations mainly come from the sale of products. We used unpaired t test to compare annual economic cost−benefit between monoculture rubber plantations and intercropped rubber plantations. Statistical significance was assumed when $P < 0.05$.

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