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Ecosystem service synergies/trade-offs informing the supply-demand match of ecosystem services: Framework and application

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ABSTRACT

Ecosystem services (ES) underpin human well-being, but their complex synergies or trade-offs are a challenge for matching ES supply and demand. This study presents a framework for integrating ES synergies/trade-offs and approaches ("win-win", "small loss-big gain" and "ES replacement") to improve the match between ES supply and demand. We applied the framework in a watershed on China's Hainan Island, where local ES supply and demand are severely out of balance. Based on the analyses of ES synergies/trade-offs and their drivers, selecting the "win-win" approach (planting rubber with intercropped medicinal plants) and "ES replacement" approach (transitioning some secondary forest into rubber intercropped with medicinal plants) together could effectively improve the match between the supply and demand of agricultural product provision (its supply-demand ratio increased from 0.65 to 1.3) without disrupting the established supply-demand matches of water resource provision, soil retention, flood mitigation and water purification services. Our framework contributes to a new perspective for improving the match between ES supply and demand.

1. Introduction

Ecosystem services (ES) are the benefits that people obtain from ecosystems directly or indirectly (MA, 2005), and they provide a bridging communication platform between human society and nature. Humans depend on ES to survive (Mehring et al., 2018). However, fulfilling the food, fiber, water, and shelter needs of the more than 7 billion people on Earth often comes at the expense of degrading natural ecosystems (MA, 2005), and will influence the future supply of ES and in turn the long-term fulfillment of human needs. Therefore, minimizing the differences between ES supply and demand (ESSD) and simultaneously managing the trade-offs between multiple ES are critical for achieving the goal of sustainable ES management (Geijzendorffer et al., 2015).

ES supply cannot be studied without considering ES demand (Mehring et al., 2018). ES management targets should aim to ensure that the supply of ES is greater than demand (Maron et al., 2017), which here we refer to as the supply "matching" the demand. In recent years, studies have evaluated the matching of ESSD (such as using the ratio of supply to demand) to reveal resource shortages (Kroll et al., 2012; Boithias et al., 2014); clarify the spatial matching and dynamic changes of ESSD on the basis of land use and land cover (LULC) (Burkhard et al., 2012; Bryan et al., 2018) and disaggregated population characteristics; assess the mismatch between ES supply and demand to inform urban management (Larondelle et al., 2016); explore the relationship between the ES-providing area and ES-benefiting area by analyzing ES flow (Palomo et al., 2013); and construct an ES evaluation framework for integrating ES demand and supply (Wei et al., 2017). These studies help us understand ESSD mismatches in different contexts. However, improving the matching of ESSD is still one of the great challenges for satisfying human needs and demands (Geijzendorffer et al., 2015; Mehring et al., 2018).

The critical difficulty encountered when matching ESSD is that ES trade-offs can occur when the maximization of certain services comes at the expense of others (Rodríguez et al., 2006; Oconnell et al., 2018). Better matching of ESSD for some services is usually accompanied by

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poorer matching of ESSD for other services (Kroll et al., 2012). Information about the mechanisms of ES trade-offs can provide valuable information that can help us improve the relationship between ES and human well-being. Furthermore, empirical evidence clearly indicates that human interventions (labor, technology and capital) have often contributed to the maintenance and enhancement of ecosystems and thus the delivery of ES via land use management (Geertsema et al., 2016). Therefore, trade-off characteristics should be clearly identified based on understanding the complex relationship of ES in the process of management to reduce (or possibly eliminate) trade-offs and achieve win-win situations (Howe et al., 2014).

In practice, coordinated approaches to ES trade-offs can inform ecosystem management by designing specific landscapes (Dosskey et al., 2012), identifying and protecting areas of trade-off "hotspots" and high ES provision (Johnson et al., 2014; Zheng et al., 2016), increasing biodiversity (Gamfeldt et al., 2013), and adopting organic agriculture with economic and environmental benefits (Badgley et al., 2007), among others. Therefore, these approaches can be used to guide the implementation of land-use planning (Goldstein et al., 2012), environmental protection planning and mitigation actions (Kennedy et al., 2016) for specific ecosystem service improvement. Although improved ecosystem management can be achieved by understanding ES trade-offs and ES coordinating approaches can realize "win-win" goals in individual cases (Zheng et al., 2016), society's demand for ES is diverse (e.g., basic materials, health, security) (MA, 2005) and it remains a challenge to integrate ES trade-offs and coordinated approaches into the matching of ESSD to meet people's diverse demands at regional scale. This paper established a four-step analytical framework to integrate ES trade-offs and their coordinated approaches into the matching of ESSD. We demonstrated this approach in the Hongmao watershed in the central mountainous area of China's Hainan Island to show the practicality of the framework. Our goal is to provide a new research perspective for matching ESSD.

In this study the "supply of ES" referred to the services that a particular ecosystem can actually provide for human use within a given time period and region (Burkhard et al., 2012). Likewise, the "demand for ES" referred to the amount of a service required or desired by society (Villamagna et al., 2013).

2. Conceptual framework

A four-step conceptual framework was developed for integrating ES synergies/trade-offs into the matching of ESSD (Fig. 1).

2.1. Step 1: identifying stakeholders and the goals of ESSD assessment

The first step in applying the framework involves identifying stakeholders and the goals of ESSD assessment. The main tasks are:

(i) *Defining the stakeholders*. At the start, the different stakeholders (e.g., local people, the government, land managers or investors) are defined using a field survey, local or national policies and social statistics analysis (Cavenderbares et al., 2015a).
(ii) *Identifying the goals of ESSD assessment*. Based on the general analysis of ES flow, as well as of stakeholders and their ES demands for basic materials for a good life, health, security, good social relations, and freedom of choice and action (MA, 2005), the ES status (surplus or deficiency) and goals for specific stakeholders are identified and confirmed.
(iii) *Identifying the spatiotemporal scale*. Based on the stakeholders at different spatial scales and ES flows, the geographical boundaries (local, regional, watershed, national or global) and temporal scales (growth season, year, decade or century) are defined. These definitions are essential because past or present management practices will affect future ES supply, and future needs will also affect current management practices (McNally et al., 2011). Furthermore, spatial scale features often determine the ES of interest (García-Nieto et al., 2013; Palomo et al., 2013).

2.2. Step 2: assessing ESSD

Step 2 involves assessing and mapping ESSD within a specific spatiotemporal scale. The main tasks are:

(i) *Establishing an indicator system for ES assessment*. Based on different stakeholders and their different ES demands, an indicator system is established for ES assessment with an aim to improve the stakeholders' well-being.
(ii) *Assessing ESSD*. ES supply can be assessed using biophysical models, participatory questionnaire surveys, expert knowledge, monetary valuation, ecological footprint methods or other techniques (Wolff et al., 2015; Wei et al., 2017). ES demand can be assessed using social criteria (e.g., poverty line; water quality standard, average food or water resource consumption), experiential knowledge (e.g., allowable soil erosion) or other metrics.
(iii) *Mapping ESSD*. Mapping can reveal the spatial relationship between service-providing areas and service-benefiting areas and help managers to conduct spatial planning (Burkhard et al., 2012; Syrbe and Walz, 2012). An ES model and spatial tools such as ArcGIS (https://www.arcgis.com/), Integrated Valuation of Ecosystem Services and Trade-offs (InVEST) (Boithias et al., 2014), Soil and Water Assessment Tool (SWAT) (Pennington et al., 2017) and Artificial Intelligence for Ecosystem Services (ARIES) (Bagstad et al., 2014) can be used to identify and map the spatial distribution of ESSD.

2.3. Step 3: Judging the matching between ES supply and demand

In this step, judgements are made about the matching of ESSD. The main tasks are:

(i) *Establishing criteria for the matching of ESSD*. Depending on the types of ES (direct use/consumption services, risk reduction/prevention services, and cultural services) (Wolff et al., 2015), some methods may be more appropriate than others for identifying the criteria for matching ESSD. These techniques include the supply-demand ratio (Li et al., 2016) and the proportional contribution of ES supply to demand (Baró et al., 2015), among others.
(ii) *Judging the matching of ESSD*. A mismatch of ESSD occurs if differences exist in quantity or quality between the supply of ES and the human demand for ES (Geijzendorffer et al., 2015). Mismatches can occur at different temporal and spatial scales and among different stakeholders. Therefore, this step needs to clearly identify the matching aspects of ESSD (for different temporal or spatial scales or different stakeholders) and to determine the main types or aspects of ES supply that cannot meet demand (or that exceed demand).
(iii) *Assessing the trends of ESSD*. Partly due to the lack of a formal approach for identifying which ES are under threat and to what extent, ES provision is either incompletely or obliquely considered in environmental impact assessment, state of the environment reporting, and conservation planning (Koh et al., 2016; Maron et al., 2017). At this stage, the degree to which the adequate and sustainable provision of a given ES is threatened should be assessed by combining information on the states and trends of both ES supply and demand with reference to two critical thresholds: demand exceeding supply and ecosystem service "extinction" (Koh et al., 2016; Maron et al., 2017).

2.4. Step 4: Attaining goals or identifying solutions to goals

If a targeted ES supply matches demand (i.e., if supply equals or

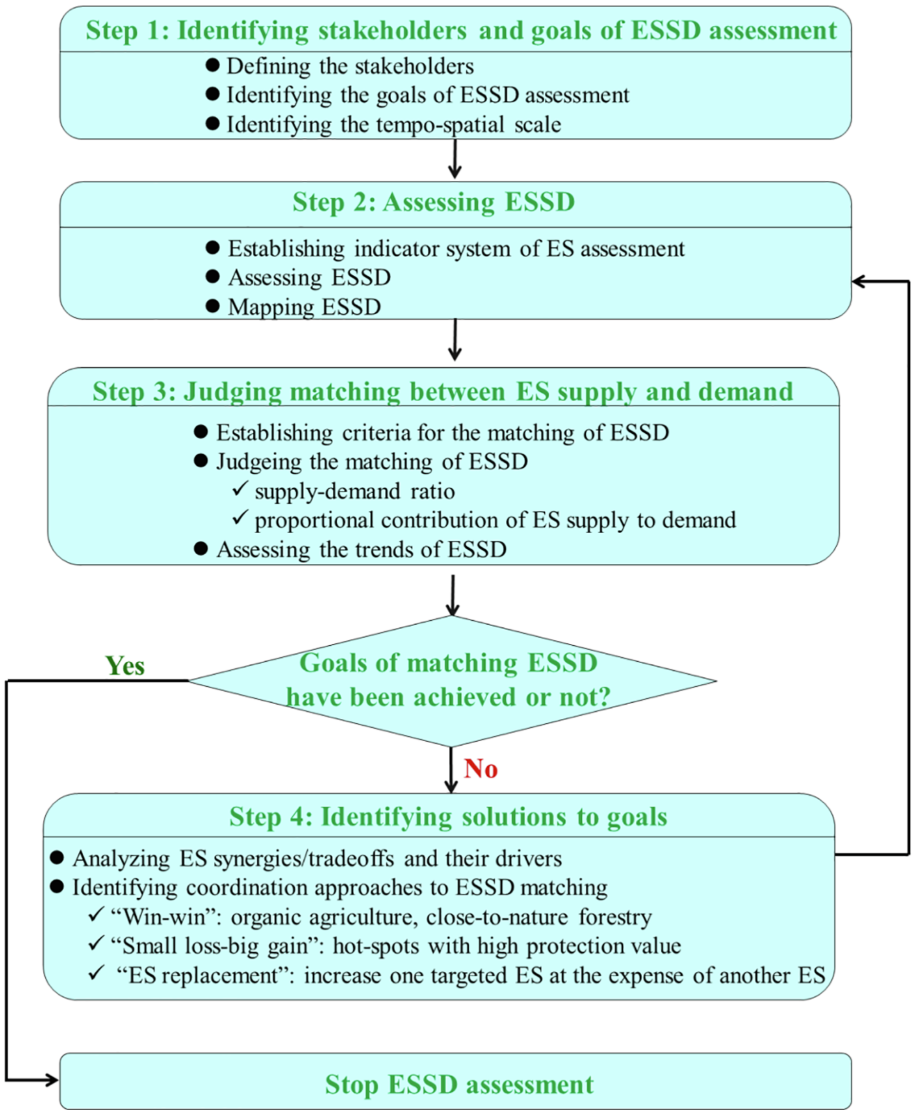

Fig. 1. Framework for matching the supply and demand of ecosystem services by using ecosystem service synergies/trade-offs.

exceeds demand), the goal is achieved and the analysis is complete.

If targeted ES supply does not match demand (i.e., if concerned supply is less than demand), coordination approaches can be found to improve the matching of ESSD through (i) analyzing ES synergies/trade-offs and their drivers and (ii) identifying coordinated approaches to match ESSD.

(i) *Analyzing ES synergies/trade-offs and their drivers*. A change in one ES can lead to changes of other ES due to their synergy or trade-off relationships (Lee and Lautenbach, 2016). First, the common relationships and synergy/trade-off characteristics between targeted ES under different LULC and land management practices should be understood through correlation analysis, trade-off curve analysis, a rose diagram (Mouchet et al., 2014; Landuyt et al., 2016) or other techniques. Then, the drivers of these complex relationships of ES should be identified, such as agricultural development, urban expansion, trade and ecological policies.

(ii) *Identifying coordinated approaches to match ESSD*. If synergistic relationships exist among the targeted ES, effective measures can be adopted to improve both the related ES. For example, ecological restoration improves soil retention, sandstorm prevention and carbon sequestration simultaneously (Ouyang et al., 2016). The main challenge is to coordinate the trade-off relationships of ES to improve the matching of ESSD for targeted ES. Currently, there are three main types of coordinated solutions.

A) *"Win-win" approaches.* Based on the shared driver(s) of multiple ES and agricultural production practice (Zheng et al., 2016), the ES trade-off relationship can inform coordinated approaches (e.g., changing land "extensification" and land management practices) while improving all targeted services. For example, choosing appropriate rubber inter-planting species can not only increase production provision services (Langenberger et al., 2016), but also improve regulation services (soil retention and flood regulation) (Liu et al., 2016b).

B) *"Small loss-big gain" approaches.* According to the ES trade-off drivers that are identified for different types of land, the supply of specific services can be reduced to improve services that are in lower supply (or higher demand) by transforming LULC. For example, Goldstein et al. (2012) found that by transforming low-income pasture into areas that produce higher-income biofuels, both the financial return from agricultural fields and water quality will increase considerably (a "big gain"), although carbon storage will decrease slightly (a "small loss") (Goldstein et al., 2012).

C) *"ES replacement" approaches.* The replacement approach involves increasing one targeted ES at the expense of another ES. When increasing agricultural production or expanding constructed areas to accomplish an ES goal, it is crucial to find the most appropriate areas for replacement. For example, Johnson et al. (2014) found that when converting grassland and forest into cropland by considering the trade-off between agricultural production and carbon storage, it was cost-effective to expand along the edges of currently cropped areas by selective extensification rather than by the "business-as-usual" intensification method (Johnson et al., 2014).

When the targeted ES supply does not match demand, Steps 2–4 of the framework involve an iterative process. After Step 4, the analysis returns to Step 2 for ESSD evaluation until the matching of ESSD is improved satisfactorily and a management approach is deemed to be feasible.

In addition, because human needs change with population growth, human preferences and other factors, ES supply and ES demand are unbalanced in most cases (Rodríguez-Rodríguez et al., 2015). ESSD matching is also a dynamic process. Thus, the ESSD matches should be checked at different development stages or in different policy and socio-economic contexts.

3. Case study

3.1. Research area

We applied the framework on Hainan Island, China. Hainan Island (18° 10′–20° 10′ N, 108° 37′–111° 03′ E) is located in the southern part of China and has a tropical monsoon climate. The central mountainous area of Hainan Island is the source of three main rivers (Changhua River, Wanquan River and Nandujiang River), it is one of the most important areas for ecosystem service conservation (Ouyang et al., 2016) and is one of the nine areas of intense biodiversity conservation in China (Chen, 1994). However, most of the economically disadvantaged towns in Hainan Island are concentrated in the central mountainous area, and natural disasters such as floods and soil erosion occur frequently (Zeng et al., 2009). Therefore, meeting the needs of residents for various ecosystem services (such as product provision, soil conservation and flood mitigation) is an important challenge for ecosystem management in this region.

A watershed is a suitable spatial extent for effective LULC management (Bisson et al., 1997). The Hongmao watershed in Baisha Li Autonomous County in the central mountainous area of Hainan Island was selected for verifying the framework described in Section 2. This watershed covers approximately 6.56 km^2, with elevations ranging from 420 m to 1490 m and annual precipitation of 1800–2700 mm. The main ecosystem types in the watershed include primary forest, secondary forest, and various types of plantations (Fig. 2). About 260 people live in the watershed. The ecosystems are the main source of income for the watershed residents (Wen et al., 2017). Furthermore, data availability in such a small watershed is good.

3.2. Materials and methods

3.2.1. The selection of ES

The major ecological problems (floods and soil erosion) in the study watershed, the relatively low economic level and need for key ES (basic materials for a good life, health and security, as identified in the Millennium Ecosystem Assessment) (MA, 2005) informed our selection of ES. We chose product provision services (representing basic material needs), water resource provisioning and water purification (representing health needs for clean water resource), and soil retention and flood mitigation services (representing safety requirements) as the ES under study. The assessment was conducted at the temporal scale of a year (2016). The specific indicators and data sources are listed in Table 1.

3.2.2. Assessment of ES supply and demand

3.2.2.1. Mapping and valuation of ES supply and demand. (1) Product provision

Supply. Product provision service refers to the diverse products provided by terrestrial and freshwater ecosystems (Ouyang et al., 2016) for maintaining human well-being. A range of agricultural products (e.g., rice, rubber, *Alpina oxyphylla*) were the main income source of the farmers supporting their demand for basic materials in the central mountainous region of Hainan Island (Eq. (1)). We standardized agricultural products with different units into monetary value (per capita net income of agricultural product provision per person) for the supply of product provision (S_{AP}) in Hongmao watershed to compare the supply and demand of basic materials for human well-being.

$$SAP = \left[\sum_{i=1}^{n} (Y_i \times C_i - E_i) \times A_i\right] \Big/ P \tag{1}$$

where S_{AP} is the per capita net income of agricultural product provision (yuan/person/yr). Y_i, C_i, E_i and A_i are a crop's annual yield ((including rubber, *Areca catechu*, rice and *Alpinia oxyphylla*) per km^2 (kg/km^2), the market price of the crop (yuan/kg), the crop's annual production cost per km^2 (yuan/km^2) and the crop's land area (km^2), respectively. P represents total population (person). The above parameters were obtained from the household questionnaire survey described in 3.2.2.2.

Demand. Demand for crop products referred to the minimum expenditure on goods and services to maintain basic subsistence demand under certain social development conditions. We used the per capita net income of rural residents (8000 yuan/person/year) as the income demand of residents which is the standard set by the Chinese government for comprehensively building a comfortable and successful society (CPC, 2012).

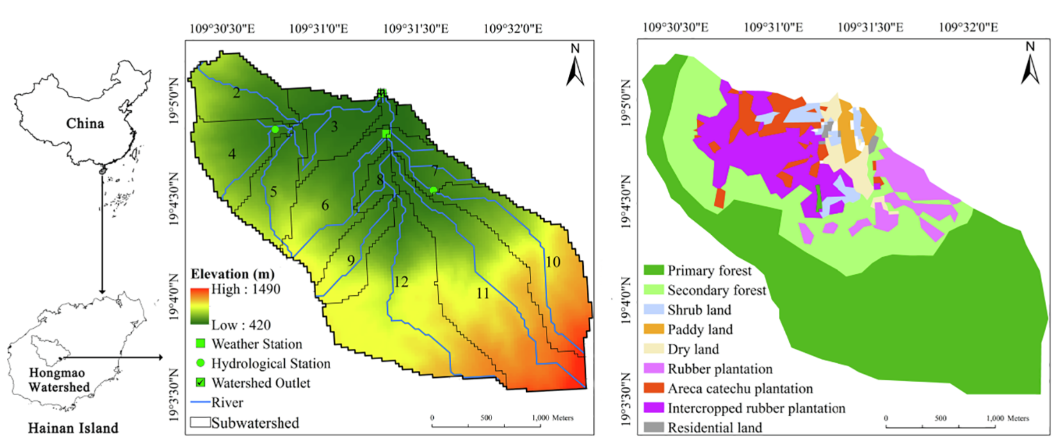

Fig. 2. Location of Hongmao watershed in the central mountainous area of Hainan Island, China.

Table 1
Ecosystem Service supply and demand indicator.

Demand aspects	Representative ecosystem services	ES supply variable	Data source	ES demand variable	Data source	Match variable
Basic materials for a good life	Product provision	Annual average net return of agricultural products (S_{AP}, yuan/person/yr)	Questionnaire survey	Well-off level of China (D_{AP}, 8000 yuan/person/yr)	Compilation of documents of the 18th National Congress of the Communist Party of China (CPC, 2012)	$M_{AP} = S_{AP}/D_{AP}$
Health	Water resource provision	Water yield (S_{WR}, m^3)	SWAT Model; observed data for calibration and validation	Human and environmental water requirements (D_{WR}, m^3)	Water resource quota of Hainan Province (Hainan provincial Water Affairs Department, 2017)	$M_{WR} = S_{WR}/D_{WR}$
	Water purification	Total nitrogen concentration (S_{WP}, mg/L)	SWAT Model; InVEST model for calibration and validation	National surface water quality requirement ($D_{standard}$, 1 mg/L)	Environmental quality standard for surface water in China (SEPA, 2002)	$M_{WR} = D_{standard}/S_{WP}$ *
Security	Soil retention	Soil erosion intensity (S_{SR}, t/km^2)	SWAT Model; observed data for calibration and validation	Allowable soil erosion intensity ($D_{standard}$, 500 t/km^2)	Soil erosion intensity classification standard of China (MWR, 2008)	$M_{SR} = D_{standard}/S_{SR}$ *
	Flood mitigation	Relative flood mitigation capacities of different land use types by surface runoff (S_{FM})	SWAT Model; land use data	Relative flood mitigation demand of different land use types by physical and economic data (D_{FM})	Land use data and questionnaire survey	$M_{FM} = (S_{FM} - D_{FM})/[(S_{max} + D_{max})/2] + 1$

* Because the inverse indicators for water purification (nitrogen concentration) and soil retention (soil erosion intensity) were used in this study, we select $D_{standard}/S$ to represent the match of ESSD, where the higher ratio, the higher the contribution to water purification and soil retention.

(2) Water resource provision, water purification, soil retention and flood mitigation

The SWAT model was used to model the provision of water resources, water purification, soil retention and flood mitigation services, which can predict the long-term effects of land management practices on water yield, soil yield and agricultural chemical load and flooding in complex watersheds with different soil types, LULC and management practices (Neitsch et al., 2011). Therefore, we used SWAT to model water resource provision, water purification and flood mitigation services.

(i) Water resource provision

Supply. Water resource provision refers to the available water yield for human use within a given region (Boithias et al., 2014). We used the outlet water yield for Hongmao watershed to quantify the supply of the water resource provision service (S_{WR}) in 2016 (Eq. (2)). The outputs of the SWAT model that were related to water quantity were used to quantify and map annual water yield (Neitsch et al., 2011):

$$S_{WR} = A_{watershed} \times (Q_{surf} + Q_{lateral} + Q_{gw}) \times 10^{-3} \tag{2}$$

where S_{WR} is the supply of water resource provision service (m^3). Q_{surf}, $Q_{lateral}$, Q_{gw} are the amount of surface runoff, lateral flow contribution and groundwater from streamflow for year (mm), respectively. $A_{watershed}$ is the area of Hongmao watershed (m^2).

Demand. Water resource demand (D_{WR}) is the sum of human water demand and river ecological flow requirements in a specific area. We used the human and environmental water requirements to represent the demand for water resource provision in the Hongmao watershed. Human water demand included water consumption by livestock, people and agricultural consumption (e.g., irrigation) based on population and the area of consumptive land in the Hongmao watershed. River ecological flow requirements referred to the average flow that a river should maintain in order to sustain good ecological function which account for 30% of the average annual discharge (MWR, 2014). Eq. (3) was used to determine water resource demand, as follows:

$$D_{WR} = P \times Q_P + \sum_{i=1}^{n} L_i \times Q_i + \sum_{j=1}^{n} I_j \times Q + F \times 30\% \tag{3}$$

where D_{WR} is the demand for water resource provision service (m^3); P is the total population, Q_p is the water quota of rural residents (m^3/person) and the unit is similar for the animals. L is the number of livestock of type i, Q_i is the water quota per unit of livestock type i, I is the sowing area of crop type j (ha), and Q is the irrigation water consumption of crop type j per unit area (m^3/ha). F is the annual discharge (m^3). The water quota and irrigation water consumption was referenced to the normal water use in Hainan Province (Hainan Provincial Water Affairs Department, 2017). Other parameters were obtained from the household questionnaire survey described in 3.2.2.2.

(ii) Water purification

Supply. Water purification supply (S_{WP}) refers to the ability of an ecosystem to purify polluted surface runoff (Bukvareva et al., 2017), which was represented by the reciprocal variable of monthly mean concentration of total nitrogen (TN) in our study. We used the outputs of the SWAT model that were related to N and the following equation to quantify and map the water purification service (Eq. (4)) (Carvalho-Santos et al., 2016):

$$S_{WP} = W_{TN\_OUT} = W_{ORGN\_OUT} + W_{NO3\_OUT} + W_{NH4\_OUT} + W_{NO2\_OUT} \Big/ Q \tag{4}$$

where W_{TN_OUT} refers to the TN concentration at Hongmao watershed outlet (mg/L). W_{ORGAN_OUT}, W_{NO3_OUT}, W_{NH4_OUT}, W_{NO2_OUT} and Q are organic N, nitrate N, ammonium N, nitrite N (mg) and total water yield (L), respectively.

Demand. Water purification demand (D_{WP}) refers to the water quality that meets the needs of local people for a healthy life. According to the environmental quality standard for surface water in China (SEPA, 2002), we used the water quality demand standard ($D_{standard}$) of local residents (1 mg/L) as the water purification demand.

(iii) Soil retention

Supply. Soil retention supply (S_{SR}) refers to the ability of ecosystems to retain soil within a given time which was presented by the inverse variable of soil erosion intensity (t/km^2/yr). SWAT uses the modified Universal Soil Loss Equation (USLE) to estimate soil yield (Eqs. (5) and (6)).

$$sed = 11.8(Q_{surf}\cdot q_{peak}\cdot area_{hru})^{0.56}\cdot K_{USLE}\cdot C_{USLE}\cdot P_{USLE}\cdot LS_{USLE}\cdot CFRC \tag{5}$$

$$S_{SR} = {[\textstyle\sum_{i=1}^{t} sed]\cdot 10^6}\Big/{A_{watershed}} \tag{6}$$

where sed is soil load in metric tons per day (t/day), Q_{surf} is surface runoff volume (mm/day), q_{peak} is peak surface runoff rate (m^3/s), $area_{hru}$ is the area of a hydrological response unit (ha), K_{USLE} is USLE soil erodibility factor, C_{USLE} is the USLE cropping management factor; P_{USLE} is the USLE conservation support practice factor, LS_{USLE} is the USLE slope length and gradient factor, and *CFRC* is a roughness factor (all factors are dimensionless), *i* is day and *t* is the total number of days of a year. $A_{watershed}$ is the area of Hongmao watershed (m^2).

Demand. The demand for the soil retention service (D_{SR}) refers to the demand for soil erosion reduction in inhabited areas that are prone to soil erosion which was represented by the inverse variable of allowable soil erosion intensity (the maximum intensity of soil loss that can be sustained by the land while still maintaining long-term soil fertility and land productivity) (Stefano et al., 2016). We used the allowable erosion intensity (500 t/km^2/yr) in our study area (MWR, 2008) as the demand line for the soil retention service. The less the soil erosion intensity is, the higher the soil retention services is.

(iv) Flood mitigation

Supply. The flood mitigation supply (S_{FM}) refers to an ecosystem's capacity to reduce the amount of storm runoff from heavy rainfall (Stürck et al., 2014); in other words, it refers to the contribution of an ecosystem to security and risk reduction (Wolff et al., 2015). A LULC matrix approach which linked different LULC to different capacities for flood mitigation within the Hongmao watershed were applied to quantify S_{FM}. The flood mitigation capacities of different land use types were based on the surface runoff reduction. Since Hongmao watershed's floods were mainly formed by surface runoff after torrential rain, we used the surface runoff from a typical torrential rain event (319 mm/24 h, 18 November 2016) to map the relative capacity of each LULC for flood mitigation in ArcGIS on a scale ranging from 0 to 5. Then, areas with similar flood mitigation capacities were united into a single polygon. The polygon was intersected with the LULC map and spatial statistics were derived from the LULC. Finally, we defined the flood mitigation capacity for every LULC on the base of their representation (in percent) within the polygons of corresponding capacity. The detailed method can be found in Nedkov and Burkhard (2012). A value of 0 represents no relevant capacity to supply flood mitigation service, a value of 5 represents the highest capacity (Nedkov and Burkhard, 2012).

Demand. The demand for flood mitigation service (D_{FM}) refers to the demand for flood reduction in inhabited areas that are prone to flood hazard. We assumed that the most vulnerable areas would have the highest demand for flood regulation, and that the demand can be determined by considering both vulnerability and risks (Nedkov and Burkhard, 2012). We used the LULC matrix method to quantify D_{FM}, which was represented by the relative flood mitigation demand of different LULC types according to historical flood inundation condition, topographic, demographic and economic data from local people and local authorities. The method has been widely used to quantify the relative magnitude of flood mitigation demand with a relative scale ranging from 0 to 5 (Nedkov and Burkhard, 2012; Nedkov et al., 2015). We determined that paddy land (value of 4) and residential land (value of 5) in the study area had the highest demand for flood regulation, primary and secondary forests, shrubland and waterbodies had no demand (value of 0), and *Areca catechu* plantation (value of 2), intercropped rubber plantation (value of 2), rubber plantation (value of 1) and dry land (value of 3) had intermediate demand by interviewing local resident.

3.2.2.2. *Data sources.*

(i) Household questionnaire data

Product provision data were collected by a face-to-face household questionnaire survey in May, 2017. A total of sixty households were surveyed. The survey included questions on the yield, area, income, cost of different crop types (e.g., *Areca catechu*, rice and *Alpinia oxyphylla*), the species and number of livestock (cattle, pigs, sheep and chickens), human population, historical flood inundation conditions and house prices. The method was similar to the previous survey organized by Peng et al. (2017).

(ii) SWAT model parameters

The LULC data were obtained from interpretation of digital images collected by the SPOT-6 satellite (1.5 m resolution) and corrected through a site survey using a global positioning system. A soil map (1:50,000) and related soil properties data were obtained from the Hainan Academy of Environmental Sciences, China and another site experiment (e.g., soil erosion intensity under different LULC) conducted by Wen et al. (2017). Daily climate data and observed surface water discharge data were obtained from a HOBO U30 weather station and two H-Water Weir auto-recording runoff instruments (sub-watershed 4 and 10) located in the Hongmao watershed. Digital elevation model data, with a spatial resolution of 30 m, were provided by the Institute of Remote Sensing and Digital Earth Chinese Academy, Beijing, China.

3.2.2.3. *SWAT model calibration and validation.*

The Hongmao watershed was divided into 12 sub-watersheds and 170 hydrological response units. Five out of twenty-two parameters were chosen as the most sensitive using a Latin hypercube sensitivity analysis in the SWAT CUP software package which can help SWAT model calibration of daily surface water discharge (Table A.1). Following the sensitivity analysis, we conducted calibration and validation of the SWAT model to reduce uncertainty and increase the accuracy of prediction results. Two sub-watersheds (Fig. 2) where we had hydrological stations were selected for calibration (sub-watershed 10) and validation (sub-watershed 4) of surface water discharge (daily data of 2016), respectively. We used Manual Calibration Helper to calibrate repeatedly. Model performance was considered good according to a Nash–Sutcliffe efficiency (NSE) of 0.90 and 0.79 and a coefficient of determination (R^2) of 0.91 and 0.91 in the calibration and validation period respectively (Mwangi et al., 2016) (Fig. A.1).

The soil erosion predictions from the SWAT model were calibrated using the soil export from 5 sub-watersheds (NSE = 0.69, R^2 = 0.79) which included the main LULC types in the Hongmao watershed and soil erosion data collected from experimental plots for each LULC type (Primary forest, Secondary forest, *Areca catechu*, Rubber and Rubber-*Alpinia oxyphylla* plantations) (Fig. A.2) (Wen et al., 2017). The nitrogen concentration was measured at the outlet of the same sub-watershed where soil erosion was calibrated (NSE = 0.69, R^2 = 0.79) by InVEST model (water yield and nutrient delivery ratio module) (Fig. A.3) (Sharp et al., 2018).

3.2.3. *Matching ES supply and demand*

ES can be classified into two main categories: those that satisfy human desires (regulation services and some cultural services) and those that satisfy consumption or direct use demands (provision services and some cultural services) (Wolff et al., 2015). Therefore, we used different methods to identify the matching between supply and demand of different ES.

(i) Consumption or direct use services

In this case study, direct use services were water purification and soil retention services. We used the supply-demand ratio to judge the matching of ESSD for product provision, water resource provision services (Table 1; (Eq. (7) and (8)).

$$M_{AP} = S_{AP}/D_{AP} \tag{7}$$

$$M_{WR} = S_{WR}/D_{WR} \tag{8}$$

where M_{AP}, S_{AP} and D_{AP} mean the ESSD match magnitude, supply and demand of product provision service. M_{WR}, S_{WR} and D_{WR} mean the ESSD match magnitude, supply and demand of water resource provision service.

(ii) Services that satisfy desires

Services that satisfy desires include water purification, soil retention and flood mitigation in this study. Because the inverse indicators for water purification (nitrogen concentration) and soil retention (soil erosion intensity) were used in this study, we selected $D_{standard}/S$ (supply) to represent the matching of ESSD, where higher ratios reflect a higher contribution to water purification and soil retention (Eq. (9) and (10)).

$$M_{WP} = D_{standard}/S_{WP} \tag{9}$$

$$M_{SR} = D_{standard}/S_{SR} \tag{10}$$

where M_{WP}, $D_{standard}$ and S_{WP} mean the ESSD matching magnitude, demand standard and supply of water purification service. M_{SR}, $D_{standard}$ and S_{SR} mean the ESSD matching magnitude, demand standard and supply of the soil retention service.

Since the magnitude of flood mitigation depends largely on natural conditions and it is difficult to quantify the demand, we evaluated their ESSD matching as follows (Eq. (11)) (Li et al., 2016):

$$M_{FM} = (S_{FM} - D_{FM})/[(S_{max} + D_{max})/2] + 1 \tag{11}$$

where M_{FM} means the ESSD match magnitude for flood mitigation; S_{max} and D_{max} means the maximum value of flood mitigation supply and demand.

For the above matching index for the five ecosystem services (product provision, water resource provision, water purification, soil retention, and flood mitigation), a ratio greater than or equal to 1 indicated that the supply at least matched demand. A ratio < 1 indicated supply was inadequate to meet demand.

3.2.4. Analysis and regulation of ES trade-offs

In the analysis and regulation of ES trade-offs, the degree of matching of ESSD immediately identified an ES that had an insufficient supply. Then, according to the main driver(s) of the ES, the relationships and trade-off characteristics among ES under the main drivers (such as LULC and land management measures) were analyzed. Based on the matching characteristics of ESSD and the spatial distribution of ES, potential ways to match ES were sought by making full use of ES trade-off characteristics. Finally, the matching of ESSD was achieved (or at least improved) by considering ES trade-off characteristics, ESSD relationships and land use scenarios.

In this case study, we analyzed ES trade-off characteristics under different LULC using the average ES benefit from different land uses. We develop the scenarios based on local land use planning and the local planting conditions of crops. (1) Local land use planning. We obtained information on transformable land from Baisha Li Autonomous County Multiple-Plan Integration map (General Planning of Baisha Li Autonomous County (Spatial Class 2015–2030)) where the goal was to protect natural forest and basic farmland to maintain local and regional food and ecological security (Lü et al., 2017). Land used for rice and corn production, abandoned rice land and natural forest were not considered eligible for conversion; (2) Planting condition of crops. For example, rubber and *Areca catechu* could be planted only in areas where the elevation was less than 700 m and the slope was less than 30° (Langenberger et al., 2016).

Then we used a rose diagram to show the trade-off magnitudes of different LULC. The ES benefit was calculated as Eq. (12) (Bradford et al., 2015):

$$ES_i = \frac{ES_{iobs} - ES_{\min}}{ES_{\max} - ES_{\min}} \tag{12}$$

where ES_i is the benefit of ES type i; ES_{ibos} is the observed value of ES type i; and ES_{max} and ES_{min} represent the maximum and minimum values, respectively, of ES_i.

3.3. Results

3.3.1. Step 1: identifying stakeholders and the goals of ESSD assessment

The ecosystems in Hongmao watershed provided diverse agricultural products and clean water for local farmers, basic cropland and natural disaster mitigation for local and national governments (as well as local farmers), and rich biodiversity for global beneficiaries. Therefore, the stakeholders in the study area were local farmers, governments and global beneficiaries. Due to the local poverty and rich biodiversity in the Hongmao watershed, the goals of the ESSD assessment were to increase the well-being of local farmers without sacrificing the benefits for government and global stakeholders, including the area of farmland and natural forest. To this end, we have interviewed 60 households in the Hongmao watershed.

3.3.2. Step 2 and Step 3: assessing ESSD and judging their matches

For agricultural product provision, the average net income per capita in the watershed was 5175 yuan/person/year on the basis of the income characteristics of different LULC. This amount was far less than the 8000 yuan/person/year needed to achieve China's national goal of building a comfortable and successful society. Therefore, the supply-demand ratio for agricultural product provision was only 0.65, meaning that local agricultural supply was inadequate to meet the goal. The annual water yield of the Hongmao watershed was $1.2 \times 10^7\ m^3$, which is far more than the annual total water demand of only $0.9 \times 10^6\ m^3$. The supply-demand ratio of the water resources provision was 13.76, indicating that supply is greater than demand (Figs. 3 and 4).

The mean monthly N concentration of the watershed outlet was 0.33 ± 0.19 mg/L, which was lower than the required standard of $<$ 1 mg/L. The supply-demand ratio for water purification was 3.1.

The soil erosion intensity of the whole watershed (66.97 $t/km^2/yr$) was lower than the allowable soil erosion standard (500 $t/km^2/yr$), indicating that the supply of soil retention was greater than its demand.

The areas with low flood mitigation service and high flood risk (value 0 and value 1) were mainly distributed in farmland and residential areas at low elevations, accounting for 6% of the whole watershed. The demand-supply ratio of flood mitigation service was 2.4 (Figs. 3 and 4).

Considering our goals in the watershed, we need to improve the supply and demand ratios of agricultural product provision without decreasing the ratios of other ecosystem services.

3.3.3. Step 4: identifying solutions to goals

The matching analysis of ESSD indicated that the main goals of ecosystem management were to improve the ecosystem services of agricultural product provision without decreasing the matches of other ecosystem services. The assessment and mapping of ecosystem services showed how LULC changes impacted the uneven delivery of multiple ecosystem services (Fig. 5) due to their synergies and trade-offs. The mapping also suggested that in contrast to secondary forest, increasing

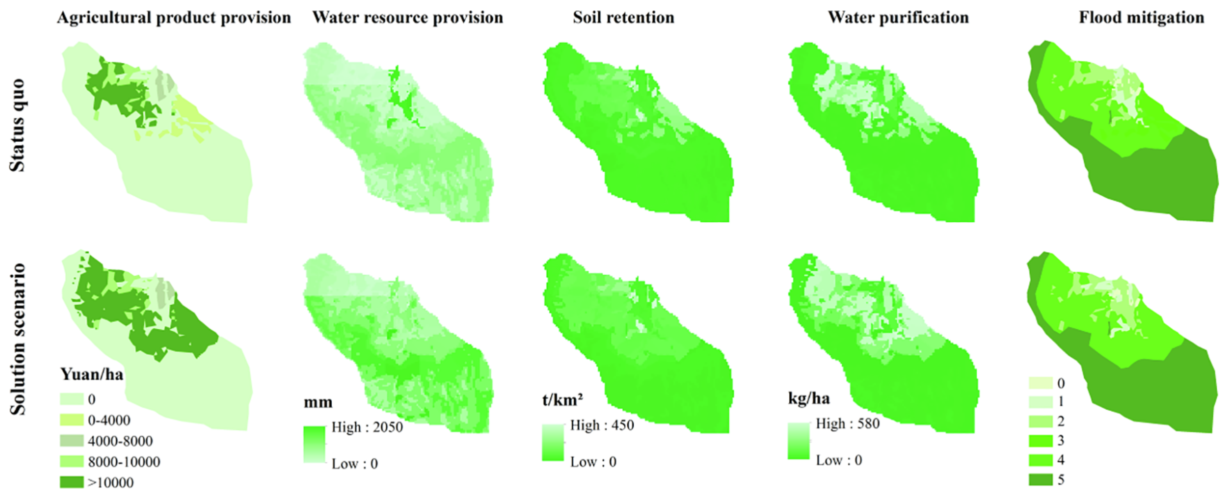

Fig. 3. Distribution of targeted ecosystem services in Hongmao watershed, Hainan Island, China. Note: for flood mitigation service, a 0 value shows that there is no relative capacity to supply flood mitigation service, value of 5 represents the highest capacity.

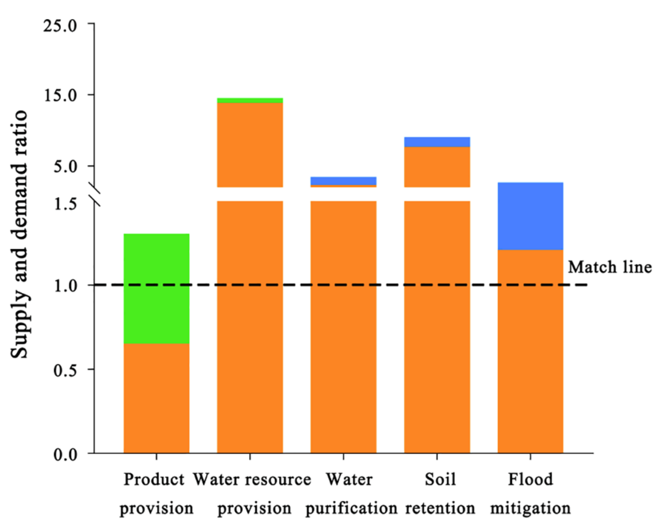

Fig. 4. Supply and demand ratios for targeted ecosystem services in 2016 under coordination scenario. Note: Orange bars and orange + blue bars represent the original condition of ES in 2016. The green and blue bars represent the increase and decrease of the supply-demand ratio, respectively, as a result of coordinated approaches. The match line (ratio = 1.0) indicates the ecosystem service supply equals its demand.

the areas of rubber plantations, *Areca catechu* plantations, and especially rubber intercropped with the medicinal plant *Alpinia oxyphylla* can increase the agricultural product provision service, but at the expense of water purification, flood mitigation and soil retention services (Fig. 5).

The matching characteristics of ESSD and ES relationship under different LULC types (Fig. 5) suggested that the following approaches may increase the matching of ESSD through increasing agricultural product provision and other regulating services simultaneously: (1) a "win-win" approach that transferred monocultural rubber plantations into rubber intercropped with *Alpinia oxyphylla* plantations (accounting for 5.5% of the whole watershed area); and (2) an "ES replacement" approach to that transferred some secondary forests into rubber intercropped with *Alpinia oxyphylla* plantations (Fig. 5). Then, we applied these two approaches together. We transferred the appropriate secondary forest (elevation < 700 m and slope < 30°) and rubber plantations into rubber intercropped with *Alpinia oxyphylla* plantations (accounting for 13.6% of the whole watershed area).

After implementing the two strategies together, the supply and demand ratio of agricultural product provision increased from 0.65 to 1.30. There was also slight increase in the supply and demand ratio of annual water yield (from 13.76 to 14.29). The supply and demand ratio decreased for water purification (from 3.09 to 2.10), soil retention (from 8.91 to 7.47) and flood mitigation (from 2.4 to 1.2) but still met its demand (Fig. 4).

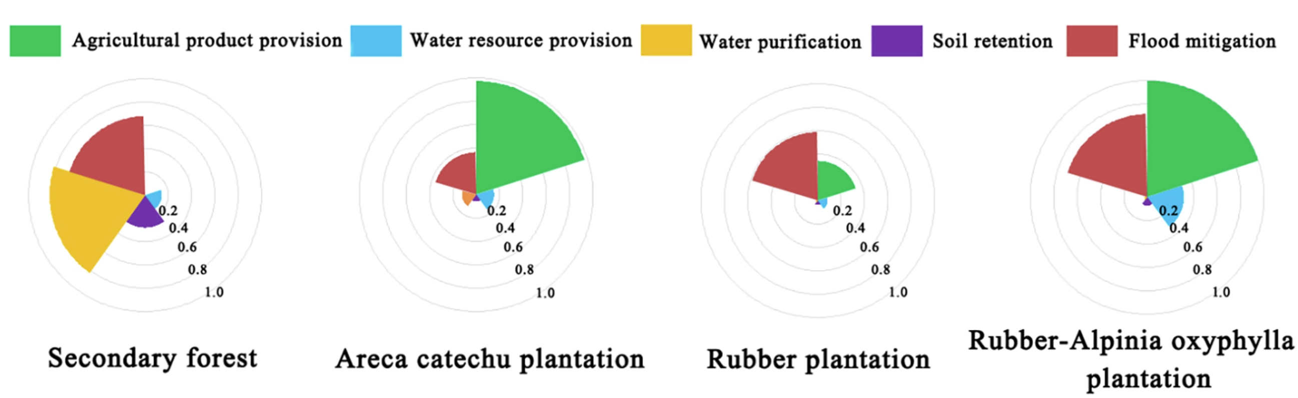

Fig. 5. The relationship among multiple ecosystem services under different land use and land cover types. Note: Larger radius indicates higher ecosystem service.

4. Discussion

The critical target for ecosystem management is to increase the matching of ESSD (Geijzendorffer et al., 2015) and improve well-being in multiple dimensions (e.g., basic material needs for good life, health, safety) (MA, 2005). However, one of the main challenges for improving the matching of ESSD is to reconcile ES trade-offs (Turkelboom et al., 2017; Cavenderbares et al., 2015a). Many case studies have shown that some trade-offs could be coordinated through different approaches (e.g., riparian vegetation conservation, organic agriculture development) (Power, 2010). In contrast to single exploration of ES synergy and trade-off characteristics (Mouchet et al., 2014; Lee and Lautenbach, 2016) and single analysis of the relationships between ESSD (Villamagna et al., 2013; Stürck et al., 2014), our study developed an effective research framework and a new perspective to integrate ES trade-offs and their coordinated approaches to matching ES supply and demand to meet the changeable ES needs of humans. ES trade-offs require us to first understand the mechanisms behind ES trade-offs. Two potential mechanisms may lead to ES trade-offs (Mouchet et al., 2014). (i) Intrinsic trade-offs reflect the fact that the delivery of multiple ES depend on the same ecosystem process. For example, afforestation in arid and semiarid areas will promote photosynthesis and, in turn, increase carbon sequestration at the expense of water quantity (Jia et al., 2014). (ii) Management-induced trade-offs, whereby focusing on one ES often leads to the decrease of other ESs through three main management measures. (a) A reduction in plant functional groups or traits will decrease the resistance of a community to diseases and the delivery of ES (Gamfeldt et al., 2013). For example, transformation of primary forest into agroforestry will result in the trade-off between carbon sequestration and crop production (Gamfeldt et al., 2013). (b) External human inputs (e.g., chemical fertilizers and pesticides) affect the biophysical chemical process and food web, which result in a trade-off between agricultural product provision and water purification (Johnson et al., 2014). (c) Altering landscape configuration and composition may impact the source-sink process, species and physical interdependency across space and in turn cause ES trade-offs, such as between surface-water quality and crop production (Qiu and Turner, 2015), and between crop pollination and crop production (Elmqvist et al., 2013). In our case study, the trade-offs between rubber production, soil retention, and water purification may be caused by the removal of plant functional groups (conversion from natural forest to monocultural rubber plantations), external human inputs (e.g., fertilizer application), as well as landscape changes (e.g., the area composition of landscape types).

The possible mechanisms leading to ES trade-offs also provide important information and knowledge for managers to coordinate the trade-offs and achieve win-win goals. Based on the different mechanisms behind ES trade-offs, different coordinated approaches could be taken. (i) For intrinsic ES trade-offs, coordination can come from choosing the appropriate species and location to replace one LULC ("ES replacement") or key ecosystem attribute (Felipelucia, et al., 2018). For example, choosing an area where precipitation is suitable for afforestation could reduce the trade-off between water quantity and net primary production in arid areas (Jia et al., 2014). (ii) Ecological intensification and biodiversity conservation approaches ("win-win") can increase functional diversity and, in turn, improve the delivery and resilience of ES (Geertsema et al., 2016), such as agroforestry and crop diversification. (iii) Identifying ecological leverage points ("small loss-big gain") could improve targeted ES, albeit at the expense of small losses of other ES (Qiu and Turner, 2015), such as protecting riparian zones (Zheng et al., 2016) and protecting important ES area (Ouyang et al., 2016). The latter two approaches can help reduce or even eliminate ES trade-offs from both LULC change and management choices. In our case study, to coordinate the trade-offs of ES, we implemented both a "win-win" approach (planting rubber and rubber intercropped with *Alpinia oxyphylla*) and an "ES replacement" approach (rubber intercropped with *Alpinia oxyphylla*) together, which were identified by an ES synergy/trade-off analysis under different LULC types (Fig. 5). As a result, the matching between the supply and demand of targeted ES (agricultural product provision and flood mitigation) improved. The supply of other ES still exceeded their demand (water resource provision, water purification and soil retention) (Fig. 4). The case study demonstrated that our framework provided a feasible approach to improving the match of ESSD by analyzing and coordinating the different trade-offs of ES.

Although many coordinated approaches already exist to mitigate ES trade-offs (Zheng et al., 2019), it's difficult to realize a complete matching of ESSD. On the one hand, ES demand is diverse and may change over time and spatial scale because of societal, governmental and cultural differences and market price fluctuation (Elwell et al., 2018; Wolff et al., 2015; Cavenderbares et al., 2015b;). For example, local people care more about direct sustenance of livelihood from ES while and governments consider biodiversity as the main goal (Turkelboom et al., 2017). On the other hand, the fulfillment of ES demand is constrained by biophysical conditions which need us exhibit multi-scale correlation and telecoupling (e.g. socioeconomic and environmental interactions between different places) (Liu et al., 2016a; Peng et al., 2017; Zheng et al., 2013). For example, the supply and demand of flood mitigation service is difficult to match because that people usually are located in places of low relevant supply capacities (Stürck et al., 2014). In our case study both static and sectional data were used to test the framework, which also support its applicability. In fact, ES trade-offs and ESSD characteristics will change with time and market price variations (Rodríguez et al., 2006; Pennington et al., 2017). Our framework was used to improve and inform the matches of ESSD in practice. Dynamic analyses are important to represent the changing relationships of ES trade-offs and ESSD in the real world.

5. Conclusion

Reconciling the mismatch between ES supply and demand is a great challenge for sustainable ecosystem management. In this study we developed an effective research framework and new perspective to integrate ES synergies and trade-offs under different drivers. We used coordinated approaches to inform the matching of ES supply and demand to meet the changeable ES needs of humans. By using the framework, we found that the mismatch between agricultural production within the watershed of China's Hainan Island could be improved by analyzing ES trade-offs under different LULC and identifying two coordination methods ("win- win" and "ES replacement") without sacrificing the matching of other ES. Our framework extends previous studies and provides a practical approach to quantitatively analyze the matching status and distribution characteristics of multiple ESSD (especially provisioning and regulating services), and to further improve the matching of ESSD.

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Appendix A

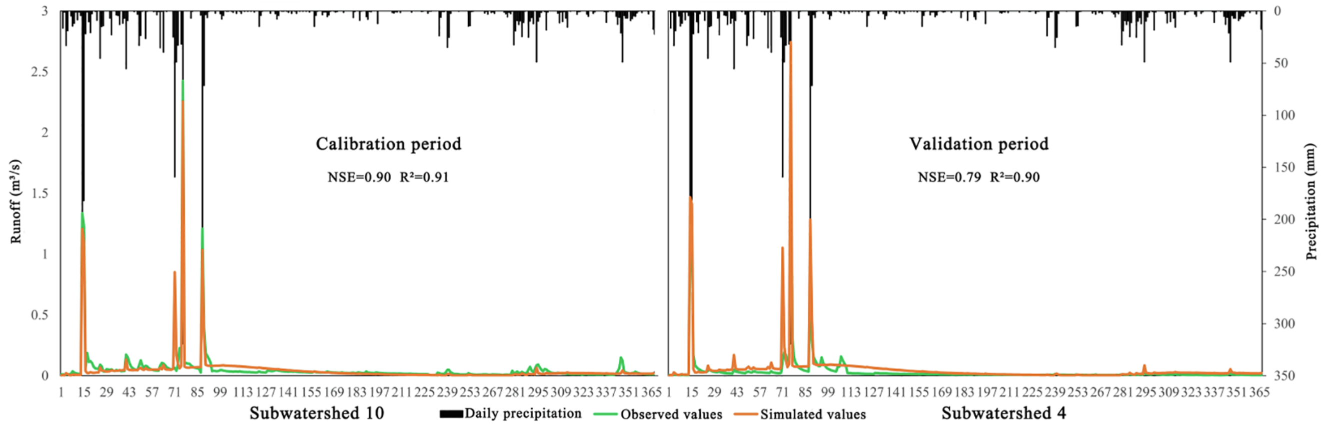

Fig. A1. Simulated and observed daily runoff in calibration and validation periods.

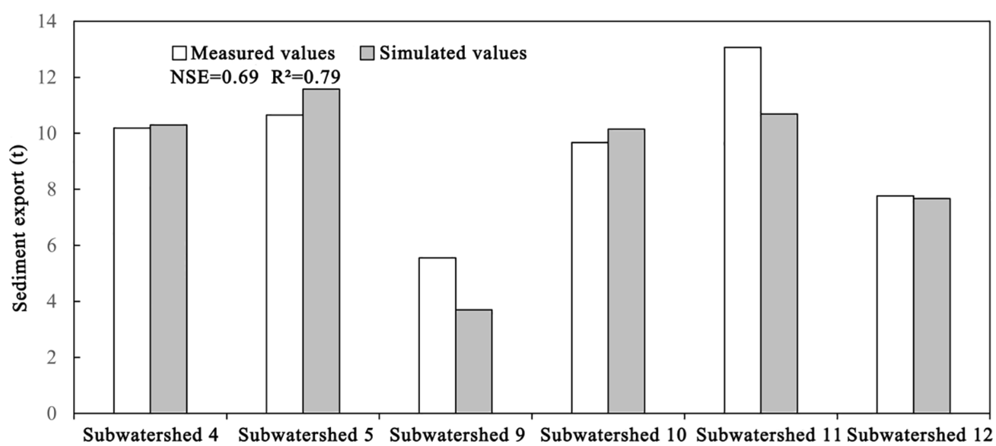

Fig. A2. Simulated and measured soil erosion intensity under different sub-watersheds.

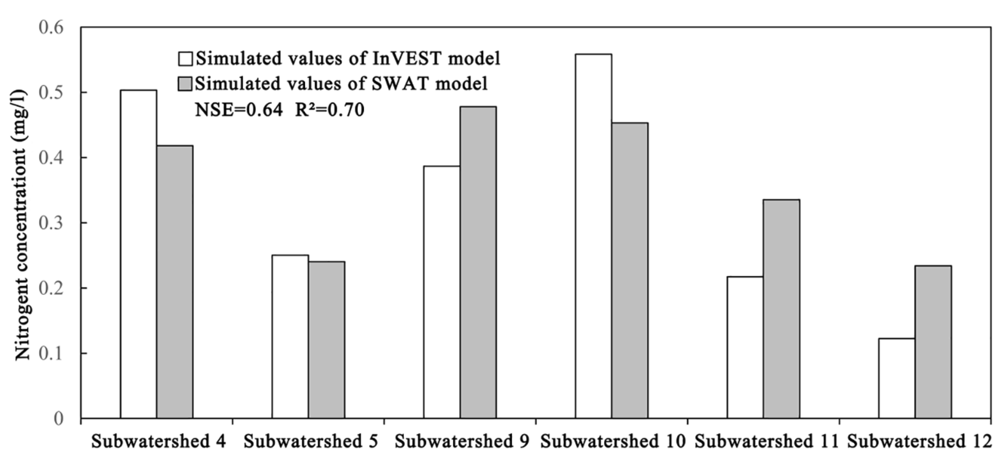

Fig. A3. Simulated nitrogen concentration values of InVEST and SWAT model under different sub-watersheds.

Table A1
The most sensitive parameters and final calibrated values of parameters.

Parameter	Description	Sensitivity index	Minimum	Maximum	Optimal values
CH_N1	Manning's "n" value for the tributary channels	0.0000	0.01	30	0.014
SOL_K	Soil hydraulic conductivity (mm/hr)	0.0004	0	2000	1.44
GWQMN	Threshold depth of water in the shallow aquifer required for return flow to occur (mm H_2O)	0.0477	0	5000	1000
USLE_P	USLE practice factor	0.0859	0	1	Primary forest: 0.015 Secondary forest: 0.01 Areca catechu: 0.6 Rubber:0.15 Rubber-Alpinia oxyphylla: 0.11
ESCO	Soil evaporation compensation factor	0.0925	0	1	0.04

Appendix B. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecoser.2019.100939.

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