Ecosystem restoration on Hainan Island: can we optimize for enhancing regulating services and poverty alleviation?

Ruida Li1,2*, Hua Zheng1,2, Stephen Polasky1, Peter L Hawthorne1, Patrick O’Connor1, Lijuan Wang1,2, Ruonan Li1, Yi Xiao1, Tong Wu1 and Zhiyun Ouyang1,2

1 State Key Laboratory of Urban and Regional Ecology, Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences, Beijing 100085, People's Republic of China
2 University of Chinese Academy of Sciences, Beijing 100049, People's Republic of China
3 Department of Applied Economics, University of Minnesota, St. Paul, MN 55108, United States of America
4 Institute on the Environment, University of Minnesota, St. Paul, MN 55108, United States of America
5 Centre for Global Food and Resources, University of Adelaide, Adelaide 5005, Australia

E-mail: zhenghua@rcees.ac.cn

Keywords: efficiency frontier, spatial weighting, ecosystem services, poverty alleviation, land-use planning

Abstract

The restoration of ecosystems provides an important opportunity to improve the provision of ecosystem services. Achieving the maximum possible benefits from restoration with a limited budget requires knowing which places if restored would produce the best combination of improved ecosystem services. Using an ecosystem services assessment and optimization algorithm, we find choices that generate maximum benefits from ecosystem restoration. We applied a set of weights to integrate multiple services into a unified approach and find the optimal land restoration option given those weights. We then systematically vary the weights to find a Pareto frontier that shows potentially optimal choices and illustrates trade-offs among services. We applied this process to evaluate optimal restoration on Hainan Island, China, a tropical island characterized by multiple ecosystem service hotspots and conditions of poverty. We analyzed restoration opportunities with the goal of increasing a provisioning service, plantation revenue, and several water-related ecosystem services that contribute to improved water quality and flood mitigation. We found obvious spatial inconsistencies in the optimal location for maximizing separate services and tradeoffs in the provision of these services. Optimized land-use patterns greatly out-performed the non-target restoration scheme. When explicit consideration of the importance of poverty alleviation was taken into account, the location of the prioritized areas shifted and trade-offs among services varied. Our study emphasizes the importance of integrating social concerns into land-use planning to mitigate conflicts and improve equity, especially in the areas where poverty and hotspots of biodiversity and ecosystem services are highly geographically coincident.

1. Introduction

Landscapes worldwide are under pressure to provide multiple services to meet growing human needs. The rise in demand for food, fiber, energy, and minerals from increasing population and economic growth has triggered conversion of natural landscapes to human-dominated uses (Foley et al 2005) and reduced the provision of many ecosystem services (Díaz et al 2019). These changes can ultimately inhibit achieving sustainable development goals and reduce human wellbeing through long-term degradation of ecosystem services (ES) (Díaz et al 2019).

Natural habitat restoration has been widely implemented in many countries and offers a way to increase the provision of ecosystem services (Turner and Daily 2008, Ouyang et al 2016). Through the Bonn Challenge, for example, over 30 countries have committed more than 100 million hectares to forest landscape restoration (Bonn Challenge 2016). For example, China implemented the Sloping Land Conversion Program to increase forest cover through long-term plan and enormous investment (Li et al 2011). Many programs ideally aim to improve the quality and utility of restoration for many stakeholders. In reality, however, limited by funding
and comprehensive assessment approaches, these decision processes are finally determined by subjective judgment or one prominent objective (e.g. species diversity) (Polasky et al 2008, Convertino et al 2013). Even when several ES are established as goals, decision makers usually have limited information to navigate and balance the relative benefits of competing services (Verhagen et al 2018), such as the regulating services (soil retention, water purification, flood mitigation, etc) and provisioning services (rubber, Areca cathecu, etc) (Wen et al 2019, Zheng et al 2019a). There is a need to develop and apply methods to multi-objective decisions in the allocation of limited land resources to identify priority areas for restoration (Orsi and Geneletti 2010, Zheng et al 2019b).

Despite use of the best available biophysical information and the investment of considerable time and effort, many restoration initiatives have been ineffective in motivating and guiding communities to implement the desired actions. Consequently, these efforts fail to achieve their objectives (Wilson et al 2007, Knight et al 2008, Ban et al 2013). Contributing important factors that lead to failure to implement restoration planning include poor understanding of the socioeconomic constrains that shape implementation (Cowling and Wilhelm-Rechmann 2007, Knight and Cowling 2007, Diaz et al 2019) and outside agendas that conflict with local needs (Chan et al 2007, Smith et al 2009). As part of a social process, ecosystem restoration planning is often negatively affected by differences in power between those who make decisions about ecosystem restoration and those who are affected by its outcomes (Knight et al 2008, Ban et al 2013). For example, some farmers were plunged into poverty during natural ecosystem restoration which decreased their household incomes from plantations or croplands (Wang and Maclaren 2012, Santika et al 2019). Consequently, the social concerns impaired the desired restoration actions and effectiveness (Wang and Maclaren 2012, Wang et al 2016). The consideration of poverty issues in land allocation optimization may therefore assist in better designing multi-functional landscapes with desirable outcomes in the social, ecological and economic dimensions (Cowling et al 2008, Martin et al 2014). However, during ecosystem restoration increasing knowledge on the supply side of ES provision is usually not matched by knowledge of social preferences or social concerns from the ES demand side in current ES assessments (Seppelt et al 2013, Keefer et al 2019).

Given the trade-offs among ES and the conflicts between corresponding social and ecological outcomes with changing land use, it is important to ask both what changes will occur and where they will occur (Polasky et al 2008, Setälä et al 2014, Kennedy et al 2016). In this study, we took Hainan Island, a tropical island characterized by multiple ecosystem service hotspots and conditions of poverty, as a case to present how multiple ecosystem services response to land allocation optimization in implementing natural forest restoration planning (a 359-km² goal for natural forest restoration by 2050) (NFGA 2016). First, we generate maximum benefits from ecosystem restoration by using an ecosystem services assessment and optimization algorithm. Second, we apply a set of weights for different ecosystem services to integrate multiple services into a unified approach and find the optimal land restoration option given those weights. Third, we embed social consideration (i.e. poverty alleviation) into the weights to find an efficiency frontier that shows potentially optimal choices (Seppelt et al 2013). The efficiency frontier (also called a production possibility frontier) illustrates what can be achieved in terms of biological and economic objectives through the careful spatial allocation of activities across the landscape. The efficiency frontier also demonstrates the necessary tradeoffs between the biological and economic objectives on the landscape and the degree of inefficiency of other land-use patterns not on the frontier (Polasky et al 2008). Our specific objectives are to determine: (i) how to optimize ecosystem restoration patterns to maximize multiple regulating ES and plantation revenue, and (ii) what are the impacts of social consideration on optimization of ecosystem restoration patterns?

2. Methods

2.1. Study area

Hainan Island (33 900 km²) located in the South China Sea near the southern coast of the mainland of China. The island is characterized by a tropical monsoon climate, with a distinct rainy season (from May to October) and a dry season (November to April). The interior uplands of the island are defined as a national ‘Ecological Function Conservation Area’ (EFCA; figure 1). EFCA focuses on conservation and restoration in places with high biodiversity and ES, especially regulating services (e.g. soil retention, water purification, and flood mitigation) (Zhai et al 2012, Wang et al 2019, Wen et al 2019). The central mountainous EFCA of Hainan Island provides multiple ES for the whole island. Of particular importance are the ES of provision of clean water for domestic consumption across the island, and flood mitigation.

From 1950s to 2010, the natural forest experienced a considerable decrease from 41.4% to 24.2% (Lin et al 2017). Since the 1980s, Hainan Island has experienced rapid expansion of rubber plantations, which has come at the cost of significant natural forest clearance (Zhai et al 2012). Although plantations have contributed to the local economy and rural livelihoods, they have resulted in reduced provision of ES (Ren et al 2014, Zheng et al 2019a). For example, in 2010, Hainan suffered from a severe flood partly as a result of extensive deforestation (Huang et al 2014).
Many of the inhabitants of the interior uplands of Hainan have very low incomes and poverty is widespread. Ninety percent of this low-income people on Hainan live in the mountains (Zheng et al. 2019a). Most people in the interior uplands are from ethnic minority groups, such as the Li or Miao (Davies and Wismer 2007). Ecosystem services conservation and poverty reduction are therefore closely intertwined policy objectives for the interior upland areas.

2.2. Planning and potential location of natural forest restoration

In order to improve water-related ecosystem services, the National Forestry and Grassland Administration issued a 359 km² goal for natural forest restoration on Hainan by 2050 (NFGA 2016). Based on previous forest restoration practice (Wang et al. 2011, Dong et al. 2018), we proposed potential opportunities for natural forest restoration based on three criteria, demonstrating these areas where natural forests are most likely to be restored: (i) where forest cover was lost for plantations (i.e. garden land and rubber land) between 1998 and 2017 (Gourevitch et al. 2016); (ii) where the plantation lands were of low-quality (Aide et al. 2000), that is, the relative biomass density (a quality index for forests) was lower than 25% (Dong et al. 2018) within the same zone after forest site zoning; and (iii) where plantations are planted on steep slopes (> 25°) (Wang et al. 2011).

2.3. Mapping potential ES values from natural forest restoration

Because of the extreme importance of plantation revenue and water-related regulating ES (water purification, soil retention and flood mitigation) on Hainan Island, we analyzed plantation revenue, nitrogen export, sediment export and quick flow (runoff during and immediately flowing storm events) to cover economic benefit, water quality and flood control. The potential ES values from natural forest restoration are differences of ES value between restoration scheme and actual land-use in 2017. Land use-land cover types were classified using a supervised classification method at a pixel size of 30 m × 30 m (Zheng et al. 2019a). We use the following ecosystem service models that calculate ecosystem service outputs based on land use-land cover types.

(a) Plantation revenue modeling

Plantations were the main source of income for 74% of households and provided 46% of their total income in EFCA of Hainan Island (Li et al. 2020). To identify the relationships between rural household livelihood and tree plantation dependence, we conducted household livelihood survey by using multi-stage sampling in hierarchical administrative divisions (counties, townships and villages) in the central mountainous region of Hainan Island in 2014 and 2016. A total of 877 valid questionnaires were acquired. The questionnaire mainly focused on demographic characteristics, forms of capital, main income-generating activities and corresponding net income, and main expenses on agriculture (Li et al. 2020). In terms of household livelihood survey data and land-use data, average forestry profit from garden land and rubber plantations was calculated as $5053/ha and $3200/ha (US$1 = 6.6 CNY in 2016), respectively. In reality, plantation revenue varied with its types and location (e.g. slope, soil, etc). In our study we only consider the revenue differences of garden land and rubber plantations due to the lack of more detailed spatial data. Finally, we unified the revenue of garden land and rubber plantation as plantation revenue.
(b) Water-related ecosystem services (WES) modeling

We analyzed nitrogen export, sediment export and quick flow (runoff during and immediately following storm events) to address both water quality and flood control concerns (Bagstad et al. 2018, Zheng et al. 2019a). The nitrogen export reduction, sediment export reduction and quick flow reduction were quantified by the models of Nutrient Delivery Ratio, Sediment Delivery Ratio and Seasonal Water Yield within the InVEST 3.5.0 tool (Sharp et al 2018) and ArcGIS 10.1 (http://www.arcgis.com/index.html). The Nutrient Delivery Ratio model is based on the export coefficient approach and can generate main output for nitrogen (N); the nutrient export to streams and the nutrient retained by each parcel on the landscape. The Sediment Delivery Ratio model generates grid files for sediment export to streams and the sediment retained by each pixel on the landscape. The 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 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 generally for the region. We acquired data related to export coefficients, crop and land management and soils from locally conducted studies. Input values for each of these models are provided as follows (tables 1 and 2) (Zheng et al. 2019a).

Using the same logic as Kennedy et al. (2016), we normalized the difference of each WES at pixel scale. Then, we can estimate the potential benefits of WES by summing the normalized scores of each WES.

2.4. Weighting multiple ES and spatial location

The preference among multiple ecological and social objectives would influence the decision-making of land use planning (Keeler et al. 2019, Mengist et al. 2020). To identify the impacts of ecological and social preferences on ES optimization, we used three methods of setting weights: (i) Weight I targets the preference between WES and plantation revenue; (ii) Weight II targets the priorities among the components of WES; (iii) Weight III targets considerations of social equity, namely poverty alleviation (figure 2).

(a) Weight I

Weight I explores preferences between the WES and plantation revenue (PR). We use a weight α, which we vary between 0 and 1 with 0.1 intervals (Hawthorne et al. 2017). We then maximized the sum: \( \alpha \text{WES} + (1 - \alpha) \text{PR} \), for the different values of α.

(b) Weight II

Weight II changes the weights among the three components of WES (table 3). We used four different weights. WES0 gives equal weight to all three components (nitrogen export reduction, sediment export reduction, and quick flow reduction). We use three other weights that give additional weight to each of the three components (table 3).

(c) Weight III

Weight III is a spatially dependent weight to reflect concerns of social equity using a relative poverty index. The areas with higher index mean lower possibility to be used for natural ecosystem restoration. The relative poverty index was identified as follows:

(1) Select poverty factor as social concern. Plantations were the main household income, especially for the poor households in the central mountainous regions (Li et al. 2020). While natural ecosystem restoration might accelerate the poverty of the households whose income mainly comes from plantations. In that event, the poverty would impair the implementation of natural ecosystem restoration planning (Wang and Maclaren 2012, Wang et al. 2016). In this study, we tried to integrate poverty factor into natural ecosystem restoration planning, so as to achieve the desired restoration action and outcomes of high water-related services. That is, the areas with low levels of poverty were considered priorities for restoration to increase ES, and the areas with high levels of poverty maintained plantations to increase their revenue.

(2) Identify proxy indicator for poverty factor. Though net income per capita is the direct indicator for economic poverty, we lacked explicit and spatially distributed net income data to present poverty. However, in Hainan Island per capita net income is positively correlated with per capita GDP (\( R^2 = 0.76, P < 0.001, n = 18 \)) (Statistics Bureau of Hainan Province 2017). We then took per capita GDP as a proxy indicator of relative poverty (Adam et al. 2013). Namely, low per capita GDP means low per capita net income or relative poverty. The GDP data with 1-km\(^2\) resolution was collected from the Resource and Environment Data Cloud Platform, supported by the Chinese Academy of Sciences.

(3) Calculate relative poverty index as weight III. We normalized the per capita GDP between 0.1 to 1, namely relative poverty index (\(sw_{pi}\)), for each 1-km\(^2\) spatial grid as follows:

\[ sw_{pi} = 0.1 + 0.9 \times \frac{x_{\text{max}} - x_i}{x_{\text{max}} - x_{\text{min}}}, \]

where \(sw_{pi}\) is the spatial weight (weight III) of plantation revenue for grid \(i\); \(x_i\) is the raw average GDP per capita of each grid \(i\), and \(x_{\text{min}}\) and \(x_{\text{max}}\) are the minimum and maximum values of the average GDP per capita across the whole island, respectively. The areas with low value of \(sw_{pi}\) mean low relative poverty and high possibility to be used for natural forest restoration (figure 3).
Table 1. Biophysical coefficients for InVEST.

| LUCODE | LULC_DESC       | USLE_C | USLE_P | LULC_veg | load_n | eff_n | crit_len_n |
|-------|-----------------|--------|--------|----------|--------|-------|------------|
| 1     | Natural forest  | 0.003  | 1      | 1        | 3      | 0.8   | 300        |
| 2     | Garden land     | 0.06   | 1      | 1        | 10.21  | 0.45  | 30         |
| 3     | Rubber plantation | 0.06  | 1      | 1        | 79.05  | 0.35  | 30         |
| 4     | Grassland       | 0.015  | 1      | 1        | 7      | 0.4   | 150        |
| 5     | Farmland        | 0.04   | 0.15   | 1        | 53.5   | 0.25  | 30         |
| 6     | Urban           | 0.001  | 1      | 0        | 13.8   | 0.05  | 15         |
| 7     | Wetland         | 0.001  | 1      | 0        | 15     | 0.05  | 15         |
| 8     | Bare land       | 0.2    | 1      | 0        | 0.88   | 0.05  | 10         |

2.5. Optimizing restoration for multiple ecosystem services

We optimize the provision of ES using the Restoration Opportunities Optimization Tool (ROOT) (Hawthorne et al. 2017). The Natural Capital Project and IUCN developed ROOT to find optimal solutions for ES provisions and to communicate the importance of ES to decision makers (Beatty et al. 2018). We defined our objective function as:

$$\max \sum_i w_i V_i (1 - s w_i)$$

where $w_i$ is weight I assigned to plantation revenue and WES; $V_i$ represents the ES value of each unit; $s w_i$ is weight III assigning for this unit.

Based on the workflow of ROOT, we first prepared marginal ES maps in terms of section 2.2, which reflect the changes in ES values between restoration and baseline. Second, we set the natural forest restoration area (359 km$^2$ goal) from the National Forestry and Grassland Administration (NFGA 2016) as optimization constraint. Finally, we established three independent sets of objective functions based on the different weighting schemes described in section 2.4. We also show the optimal location for
| LUCODE | LULC_DESC         | CN_A | CN_B | CN_C | CN_D | Kc_1 | Kc_2 | Kc_3 | Kc_4 | Kc_5 | Kc_6 | Kc_7 | Kc_8 | Kc_9 | Kc_10 | Kc_11 | Kc_12 |
|--------|-------------------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|
| 1      | Natural forest    | 0    | 55   | 0    | 79   | 1    | 1    | 1    | 1    | 1    | 1    | 1    | 1    | 1    | 1    | 1    | 1    |
| 2      | Garden land       | 0    | 60   | 0    | 94   | 0.9  | 0.9  | 0.9  | 0.9  | 0.9  | 0.9  | 0.9  | 0.9  | 0.9  | 0.9  | 0.9  | 0.9  |
| 3      | Rubber plantation | 0    | 75   | 0    | 94   | 0.95 | 0.95 | 0.95 | 0.95 | 0.95 | 0.95 | 0.95 | 0.95 | 0.95 | 0.95 | 0.95 | 0.95 |
| 4      | Grassland         | 0    | 70   | 0    | 89   | 0.5  | 0.5  | 0.5  | 0.5  | 0.5  | 0.5  | 0.5  | 0.5  | 0.5  | 0.5  | 0.5  | 0.5  |
| 5      | Farmland          | 0    | 61   | 0    | 94   | 0.68 | 0.77 | 1.13 | 0.98 | 1.08 | 1.20 | 1.14 | 1.13 | 1.40 | 1.05 | 0.98 | 0.68 |
| 6      | Urban             | 0    | 95   | 0    | 98   | 0.1  | 0.1  | 0.1  | 0.1  | 0.1  | 0.1  | 0.1  | 0.1  | 0.1  | 0.1  | 0.1  | 0.1  |
| 7      | Wetland           | 0    | 1    | 0    | 1    | 1.05 | 1.05 | 1.05 | 1.05 | 1.05 | 1.05 | 1.05 | 1.05 | 1.05 | 1.05 | 1.05 | 1.05 |
| 8      | Bare land         | 0    | 80   | 0    | 86   | 0.3  | 0.3  | 0.3  | 0.3  | 0.3  | 0.3  | 0.3  | 0.3  | 0.3  | 0.3  | 0.3  | 0.3  | 0.3  |
Figure 3. Spatial pattern of relative poverty index based on per capita GDP in Hainan Island.

Table 3. Weight II settings for deciding the priority of three water-related services.

| Name | Weight II | WES objective |
|------|-----------|---------------|
| WES0 | nitrogen export reduction + sediment export reduction + quick flow reduction | No priority among three WES |
| WES1 | 2* nitrogen export reduction + sediment export reduction + quick flow reduction | Priority for nitrogen export reduction |
| WES2 | nitrogen export reduction + 2* sediment export reduction + quick flow reduction | Priority for sediment export reduction |
| WES3 | nitrogen export reduction + sediment export reduction + 2* quick flow reduction | Priority for quick flow reduction |

maximizing either nitrogen export reduction, sediment export reduction or quick flow reduction individually.

2.6. Comparing optimal and non-target options
To identify whether the optimization of land allocation can improve the outcomes in ecological and social concerns, we compared the outputs of multi-objective optimization solutions with a non-target scheme for restoration. The non-target scheme represents an approach where an equal distance expanding along the outside of current natural forests (Stræde and Treue 2006), as is similar to plantation expansion in Hainan Island. We estimated the plantation revenue and WES scores both with and without spatial weight for the non-target scheme.

3. Results

3.1. Optimal solutions for separate ES
The optimal allocation of land for separate services shows distinct spatial inconsistency in prioritization (figure 4). The west plain areas, where rubber plantations are widely distributed, are clustered for restoration if the goal is maximizing plantation revenue. Most of the prioritized area for maximizing nitrogen export reduction is located within the EFAC, with additional areas spreading north of the EFAC. Similarly, most of the priority area for sediment export reduction maximization is in the EFAC with an additional aggregation of sites in the mountainous area to the northeast of the EFAC. The optimal locations for maximum quick flow reductions are mainly situated in the north and the eastern areas of the island, which are characterized by high runoff potential due to high precipitation and low vegetation cover.

3.2. Optimal solutions with equal weight among WES
Compared with the optimal scenario, the non-target scenario shows inefficiencies in both WES and plantation revenue objectives. It generates a plantation revenue of 106 Million CNY and a WES score below
Figure 4. Optimal solutions for separate ES: plantation revenue; nitrogen export reduction; sediment export reduction; flood mitigation or quick flow reduction.

300,000, which is far below all the points on the frontier curve (figure 5). These results indicate that there is significant potential for improvement in both WES and plantation revenue if the land allocation of natural forest restoration targets suitable plots rather than expands along the current edge.

There exist trade-offs between WES and plantation revenue. On the frontier curve, moving from point A to point B reduces total possible WES gain by 50% but increases total possible plantation revenue by 87%. During this process, large economic benefits come at the expense of small losses of WES. Moreover, the restoration allocations partly shift from the north and east plains toward central mountainous areas. Moving further down the frontier from point B to point C results in a small gain of plantation revenue along with a big loss of WES. During this process, the prioritized areas for restoration increasingly cluster within the central part and western plains of the island (figure 5).

3.3. Optimal solutions with different weights among WES
To further identify how potential trade-offs might change if a particular service is preferred, we compare the efficiency frontiers and spatial allocation for four situations with different preferences for the water-related services, indicated by varying the negative slope of each efficiency curve (figures 6(a)–(d)). All of the optimal land-use patterns (i.e. Optimal scenario) outweigh the non-target scenario in terms of higher plantation revenue and higher WES given identical conditions.

Point A shows the maximum scores for WES, with clear spatial disparities for restoration due to the inconsistency of priorities for separate WES. Moving from Point A to Point B (figures 6(a), (b) and (c)), excepting the option of priority for quick flow reduction (figure 6(d)), results in a small loss of WES but a large gain in plantation revenue, which shows the advantage of elaborated spatial configuration in contributing to higher land use efficiency. The land allocations are identical under all settings for maximizing plantation revenue, which cluster around the edge of the EFAC.

Priority for nitrogen export reduction options shows more spatial disparity than the other plans when weights were placed on WES, with more of the interior mountain areas included for restoration (figure 6(b)). However, the nitrogen export reduction-dominated efficiency frontier has the shortest and flattest curve when compared with other situations, indicating the weak trade-off potential between WES and plantation revenue if nitrogen reduction is a priority. Therefore, this may indicate that if policy prefers nutrient reduction, the interior mountain areas could be more prioritized for restoration, along with smaller trade-offs.

Sediment export reduction-dominated options have a high correspondence with the equally-weighted options in terms of spatial configuration and the efficiency frontier, emphasizing the small
contribution of sediment export reduction to the overall water-related regulating services (figure 6(c)). In contrast to the other curves, the nitrogen export reduction-dominated curve is shorter along the x-axis, indicating that preferences for nitrogen export reduction would induce a smaller trade-off between WES and plantation revenue loss. In contrast, the quick flow reduction-dominated option generates...
the steepest curve, indicating a small spatial overlap between the optimal locations for plantation revenue and quick flow reduction (figure 6(d)).

3.4. Optimal solutions with spatial weight for poverty alleviation
When poverty alleviation is included as spatial weight, presented by relative poverty index, in optimizing land configuration, the allocation disparities are shown in the land use maps (figure 7). First, to maximize WES (figure 7, point A), some restoration plots would be allocated in the interior of island, which overlaps the majority of privation areas. Second, to maximize plantation revenue (figure 7, Point C), the restoration plots are intensively clustered around the west of the island, where rubber plantations are widely cultivated.

Compared to optimization without spatial weights (figure 6), the current frontier shows a greater range for plantation revenue, which means less geographic consistency in maximizing nutrient reduction and plantation revenue while also considering poverty alleviation. The efficiency frontier is also clearly reshaped with the additional weighting of poverty. In contrast to the nutrient export reduction-dominated option (figure 7(b)), the position of Point B moves closer to Point A in the other options. This indicates small differences between WES and plantation revenue, as decision-makers prefer WES to plantation revenue. But the curves drop (from point B to point C) when plantation revenue weights are greater than those for WES, indicating that further plantation revenues come at a higher expense to WES. It also indicates the large overlaps in the geographic locations of valuable ecosystem services and human poverty.

4. Discussion
Our study illustrates the potential of forest restoration to increase ecosystem services and mitigate the tradeoffs among multiple ES. We show how preferences on the importance of regulating services related to water quality and flood mitigation relative to the importance of a provisioning service (plantation revenue) change the optimal restoration plan. These trade-offs are examined using a multi-weighting structure within an optimization algorithm. Our work expands on previous efficiency frontier studies with a primary concern for the optimization of biodiversity conservation and returns from economic activity (Polasky et al 2008, Smith et al 2012, Kennedy et al 2016) by quantitatively integrating social equity into the redesign of land-use configurations. The approach provides a framework and a case study for furthering our understanding of the trade-offs and thresholds in provision of ES and economic returns within the context of a developing region. The framework has important implications for mitigating conflicts and improving equity, especially in those areas where poverty and hotspots of biodiversity and ecosystem services are highly geographically coincident (Barrett et al 2011). However, though landscape-level planning can greatly improve the performance of restoration (Kennedy et al 2016) in comparison with traditional farm-level planning, market influences and personal or household decisions are stronger driving forces of land-use changes in some areas (Adam et al 2013, Abtew et al 2014). The tailored governance system that is adopted should be selected within the specific policy context.

Unifying multiple services as the objective for optimization makes sense in our study area, because the location of restoration for maximizing the reduction of nitrogen export, sediment export and quick flows are not spatially coincident (figure 4). This type of spatial disparity is not uncommon and other studies have found spatial disparities across different types of ES (Kennedy et al 2016, O’Connell et al 2018), such as carbon storage, biodiversity and water quality (Gourevitch et al 2016). Our study examines the issue in more detail for multiple water-related services, that is, the optimal restoration locations for maximizing sediment reduction do not completely overlap with the locations for nutrient reduction. We found that options for maximizing the reduction of nitrogen and sediment exports, required restoration actions to be concentrated within the EFCA, mainly due to the steep gradient of slopes. To maximize quick flow reduction, however, restoration locations needed to be concentrated in sites with high precipitation and low vegetation cover scattered across the island’s north plain, and along the eastern coast. These spatial disparities can be ascribed to complex geographical interactions, including the specific mechanism of each service, such as precipitation and evaporation within different topographies. We showed that restoration in a particular location would not provide the same relative benefits for each ES objective (Naidoo et al 2008, Gourevitch et al 2016), and that the optimal location for one service may not be ideal for other services (Bennett et al 2009, Kennedy et al 2016). Placing all the weights on one service in a modeled situation may result in impractical solutions, especially where there is demand for a landscape to be multifunctional (Kennedy et al 2016), such as in regions with high competition for land resources. This problem is common not only in terrestrial landscapes, but also competing demands over space are the norm in the oceans as well (White et al 2012). The application of multi-objective planning is required to balance these conflicts (Verhagen et al 2018) for workable solutions that take account of the drivers of resource competition.

This study provides a perspective for understanding the impacts of a given preference on ES and
Figure 7. Land-use patterns and efficiency frontiers with spatial weight for poverty alleviation. (a), (b), (c) and (d) are the efficiency frontiers with equal weights for WES (WES0), priority for nitrogen export reduction (WES1), priority for sediment export reduction (WES2) and priority for quick flow reduction (WES3), respectively. The black points on the frontier associated with capital letters have corresponding land-use patterns. Point A means maximizing WES; point B means giving equal importance to WES and spatial-weighted plantation revenue; point C means maximizing spatial-weighted plantation revenue.

their trade-offs. By varying weights within the WES, we produced efficiency frontiers with specific curve shapes. The nitrogen export reduction-dominated frontier curve is relatively short and flat, indicating that the prioritized areas for high nitrogen export reduction and plantation revenue are geographically coincident, so ES would not change dramatically if land configuration changed. In contrast, the quick flow reduction curve is steep, indicating that the relationship between quick flow reduction and plantation revenue is more sensitive to land configuration. For sediment export reduction, weighting has a small effect on the trade-off curve and land configuration for restoration. Our findings would be more tenable if the optimal locations for increasing multiple services had high spatial coincidence.

An important innovation from our study is the integration of social concern as spatial weights in the optimization process; an approach which is seldom quantified in conventional land-use planning. The shape of the curves and spatial allocations show clear changes after the addition of spatial weights (figures 6 and 7). Restoration locations indeed shift towards economically well-developed areas. Noticeably, for nitrogen export reduction-dominated options, the addition of spatial weights reinforces the trade-off between WES and plantation revenue, indicating that areas of poverty and the optimal locations for nitrogen export reduction are spatially coincident. This is not only the case in China, but is a common situation in many countries and regions where poverty is highly intertwined with biodiversity or ecosystem service hotspots (Liu et al 2015, Zheng et al 2019a). Hence, a difficult policy question that follows from our study is whether to compensate local people to encourage them to abandon plantation cultivation or find a less ecologically efficient area for restoration. If the local households have the capacity to find alternative livelihood activities or can obtain payments for ecosystem services which are not lower than the benefits from plantation cultivation, implementing natural forest restoration might be a better choice for the poor areas to improve ecological efficiency for restoration. However, if plantation cultivation or other agricultural activities are their irreplaceable livelihood choices, land-use planning should incorporate this social concern, and may have to sacrifice part of the anticipated utility in ES improvement. Additionally, one compelling strategy is to develop agroforestry, an adaptive management approach with diversified plant layers, to simultaneously enhance forestry income and regulating services (Zheng et al 2019a). Conclusively, we have shown that the integration of spatial weights better ensures that ecological
efficiency complements social equity improvement, which may provide information for designing compensation programs for biodiversity and ES restoration (Sparovek et al 2012, Tallis et al 2015).

Our study has some key limitations and uncertainties. First, we only considered the revenue differences of two main plantation types and used the corresponding gap in per-capita GDP as a proxy for poverty due to the lack of spatially-defined data. In fact, besides the volatility of forestry production prices, the spatial heterogeneity of production also influences plantation revenue (Fu et al 2010, Abtew et al 2014). Further research characterizing forest benefits, as well as the monitoring and mapping of social data, would improve the quantity and quality of the scientific information available for decision-making (Kline and Mazzotta 2012). Second, we do not calibrate or validate ecosystem service models, due to data limitation like data-scarce parts of the world (Redhead et al 2018). To reduce the uncertainty of these models, we derived parameter values based on empirical data within our study area or comparable systems, as described by Kennedy et al (2016). In addition, to further reduce the uncertainty for all models, we adopted relative values rather than absolute values, which are more tenable in representing the changes of ES (Redhead et al 2018), in order to show the impacts of land use changes. Third, our study focused on the impacts of land allocation on key ecosystem services and their trade-offs. However, other external driving forces (e.g. climate change) also have impacts on forest restoration. Additionally, the stochastic pathway of natural forest restoration with long-term succession influences the outcomes of afforestation (Chazdon 2008). Our study excluded the effects of climate change and narrowly focused on the effects of land configuration on the relationships between services, since predictions of climate change and forest succession are associated with great uncertainties (Reilly et al 2001, Whitmarsh 2011).

5. Conclusion

The findings confirm the importance of applying optimization tools to balance multiple objectives in land-use planning, because the optimal locations to maximize each single service are not spatially coincident. In addition, by astute spatial configuration, the efficiency of land use could be greatly improved over simple and rigid land use planning; this has positive implications for areas with intense land-use conflicts. Accounting for social concerns in decision making could mitigate conflicts and improve equity. In this context, our study provides a framework for future land-use planning at regional scale. Varying the weights for different services helps deepen our understanding of the relationships and thresholds among multiple services, under different preferences for flexible policy design.

Acknowledgments

This work was supported by the National Natural Science Foundation of China (Grant Nos. 41925005, 41871217), and the Strategic Priority Research Program of the Chinese Academy of Sciences (Grant XDA19050504).

Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

ORCID iD

Ruida Li https://orcid.org/0000-0003-4206-3184

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