Science of the Total Environment 726 (2020) 138565

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

# Quantifying variations in ecosystem services in altitude-associated vegetation types in a tropical region of China

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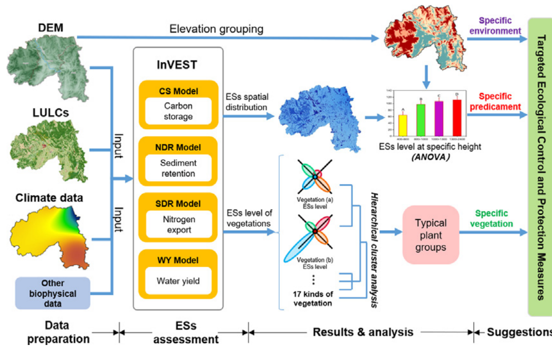
## HIGHLIGHTS

- Supply capacity of ecosystem services (ESs) varies among different vegetations.
- Vegetation types and ESs levels are different at each altitude in Xishuangbanna.
- ESs supply capacity of natural forests is better than commercial plants.
- Mixed ecological agriculture (in mid altitude) can be a sustainable measure.
- This framework based on ESs can act as reference for vegetation protection.

## GRAPHICAL ABSTRACT




## ARTICLE INFO

*Article history:*
Received 29 December 2019
Received in revised form 2 April 2020
Accepted 6 April 2020
Available online 13 April 2020

Editor: Paulo Pereira

*Keywords:*
Vegetation types
Ecosystem services
Altitude difference
Vegetation clustering
Protection schemes

## ABSTRACT

Natural vegetation is important for ecosystem services (ESs) provision, but is decreasing rapidly due to human-driven land use change, especially rapid expansion of commercial plantations. This is leading to a decrease in ESs provision, so measures are urgently needed to protect natural vegetation. Human activities, especially commercial plantations, can also lead to differences in vegetation types and associated ESs provision. This feature varies with altitude, an issue which has received insufficient attention. In this study, four ESs relevant to stakeholders (carbon storage, nitrogen export, sediment retention and water yield) were assessed. InVEST models and statistical methods (ANOVA; exploratory hierarchical clustering) were used to analyse: 1) similarities/differences in ESs provision between different vegetation types and 2) spatial differences in ESs in different altitude zones in the Xishuangbanna region of China. The results showed that vegetation types in Xishuangbanna and their ESs supply capacity differed markedly, with the overall ESs supply capacity of natural forests exceeding that of commercial plantations. Promotion of mixed organic agriculture can be a balanced measure to secure future economic development and ecological protection. This study can act as reference for vegetation protection in other areas within and beyond China.



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https://doi.org/10.1016/j.scitotenv.2020.138565

## 1. Introduction

Ecosystem services (ESs) are the direct or indirect contribution of ecosystems to human welfare (TEEB, 2010). Natural vegetation plays an important role in providing diverse ESs for human societies, but natural landscapes around the world are rapidly being replaced by human-made landscapes (Pan et al., 2011; Quijas et al., 2019). This has attracted global attention for several years and is on the political agenda of many countries (BGCI, 2002; BGCI, 2011; FAO, 1999). In China, the State Council (SC) has included protection of natural vegetation as an important part of its strategic policy of 'Ecological Civilization' (Hansen et al., 2018), which is aimed at coordinating economic development and natural protection to achieve sustainable development (SC, 2015). It is necessary to explore the relationship between vegetation types and their supply capacity of ESs, so as to formulate detailed natural vegetation protection plans.

Many studies world-wide have quantified the impacts of vegetation on provision of ESs (Andrade et al., 2020), such as carbon storage (Huang et al., 2007; Yi et al., 2014b), water yield (Caldwell et al., 2016), soil retention (Jiang et al., 2017; Wen et al., 2019) etc. Natural vegetation types are distributed diversely across different altitude gradients, which might lead to differences in the formation and diversity of ESs (Becker et al., 2007; Liu et al., 2019a). However, this important feature is often ignored in ESs studies (Liu et al., 2019a).The overall terrain of China is higher in the west of the country (up to 8844 m) and lower in the east (down to sea level). Diverse landforms make vegetation protection especially difficult in China. Due to lack of quantitative information on variations in ESs provision under vegetation types associated with different altitudes, implementation of effective vegetation protection measures is highly challenging and limited in scope (Figueira Branco et al., 2019; Liu et al., 2019c).

The capacity of different vegetation distribution types for ESs supply is influenced by both natural and human factors. Among natural factors, altitude gradient can impact ecological processes and form different landscape patterns (Becker et al., 2007), which may increase or decrease the supply of certain types of ESs (Briner et al., 2013). Among human factors, various activities intended to foster economic development can affect the vegetation coverage, especially planting commercial crops/trees in the living space of natural vegetation (Ahrends et al., 2015; Chen et al., 2016). This can lead to goal conflicts between ESs supply supported by natural vegetation and economic development supported by commercial plantations (Chen et al., 2016). Therefore optimised ecosystem management should involve the participation of multiple stakeholders and the creation of relevant mechanisms to achieve a balance between ESs supply and economic development in a sustainable development approach (Smajgl et al., 2015).

The aim of this study was to quantify variations in ESs in diverse vegetation types associated with altitude gradients, and to devise effective vegetation protection schemes to ensure ESs provision. The selected case study region, Xishuangbanna in southern China, is known as the 'tropical treasurehouse' of Chinese biodiversity, but human-related changes in vegetation types and ESs in Xishuangbanna are having profound impacts on its social, environmental, ecological, geological and human health (Jiang et al., 2017). In this study, InVEST models and statistical methods were used to: i) identify similarities or differences in ESs provision between different vegetation types, and ii) explore spatial differences in ESs at different altitudes in the Xishuangbanna region.

## 2. Materials and methods

### 2.1. Study region

Xishuangbanna (21°0′8–22°36′N; 99°56′-101°50′E) is located in the south of Yunnan Province, China (Xiao et al., 2019) and is characterised by mountainous landscape, with elevation ranging from 369 to 2404 m above sea level. Xishuangbanna consists of three county-level administrative units, namely Jinghong, Menghai and Mongla (Fig. 1). It has a tropical monsoon climate, with a dry season from November to April and a rainy season from May to October. Mean annual temperature is 20–22.5 °C and mean annual rainfall is 1200–1800 mm, with >90% of rainfall occurring in the rainy season (Hammond et al., 2015).

Over the past 30 years, Xishuangbanna has undergone dramatic land-use changes such as deforestation, agricultural expansion, and conversion of secondary vegetation to commercial rubber plantations (Ahrends et al., 2015; Stone, 2008). Rubber plantations have expanded from the most suitable terrain (600–1000 m) to the upper limit of the biological range of this plant species (around 1400 m) (Chen et al., 2016). These rubber plantations provide economic benefits for local residents, but have extremely limited capacity to provide ESs. This poses great challenges for Xishuangbanna in meeting central government requirements on sustainable development and ecological civilisation (Frayer et al., 2014; Putz and Redford, 2010).

### 2.2. Analytical framework for differentiation of vegetation types at different altitudes and its supply capacity of ecosystem services

The framework used for quantifying variations in ESs under diverse vegetation types associated with altitude gradients mainly comprised four stages (Fig. 2): (1) Data preparation, using Digital Elevation Model (DEM) data, Land Use & Land Cover (LULC) data, climate data and other biophysical data; (2) ESs assessment, involving model selection, assessment and validation; (3) compilation of results and data analysis, involving variance analysis and exploratory hierarchical clustering; (4) application of the results to formulate effective targeted vegetation protection schemes.

#### 2.2.1. Data preparation stage

The three most important forms of grid data (DEM, LULC and annual precipitation, all with resolution 30 m) were prepared for running the models (Table 1). We used 2016 (the latest year for which data were available from Yunnan Institute of Forest Inventory and Planning) as the benchmark year to characterise the current situation. For sources, formats and related descriptions of other biophysical data and parameters, see Tables S2-S4 in Supplementary Information (SI).

#### 2.2.2. ESs assessment stage: selection, calculation, and validation

We used stakeholder analysis to identify and select relevant ESs, considering ESs consumption, policy relevance (Daw et al., 2011) and data availability. Three main stakeholders were considered based on the local industrial structure: commercial plantation owners, residents and government (experts), whose different interests caused them to focus on different services (Table S5 in SI).

Four InVEST models were used to quantify the ESs. InVEST is an integrated model for assessment of ESs that has been widely used in various countries and regions (Bai et al., 2020; Fisher et al., 2011; Goldstein et al., 2012; Nelson et al., 2009). Compared with other models, InVEST can illustrate the ESs results spatially in a visualised map. InVEST also has many (sub-)models with different accuracy levels, providing users with a convenient and free environment to choose according to their needs and actual data accuracy (Sharp et al., 2016). In this study, the Carbon storage (CS) and Water yield (WY) models were used to assess the spatial distribution of carbon storage and water yield amount. The Sediment delivery ratio (SDR) model was used to calculate sediment retention amount, to quantify soil conservation services. The Nutrient delivery ratio (NDR) model was used to calculate the amount of nitrogen exported, as a reflection of water purification and nutrient supply services. When commercial plantation owners use chemical fertiliser to increase their own economic gain, this leads to clear trade-offs for residential water users by decreasing the pollution degradation capacity of rivers and reducing water quality (Kim et al., 2017). Details of all sub-models and the calculation process for each ES can be found in SI (Part 2).

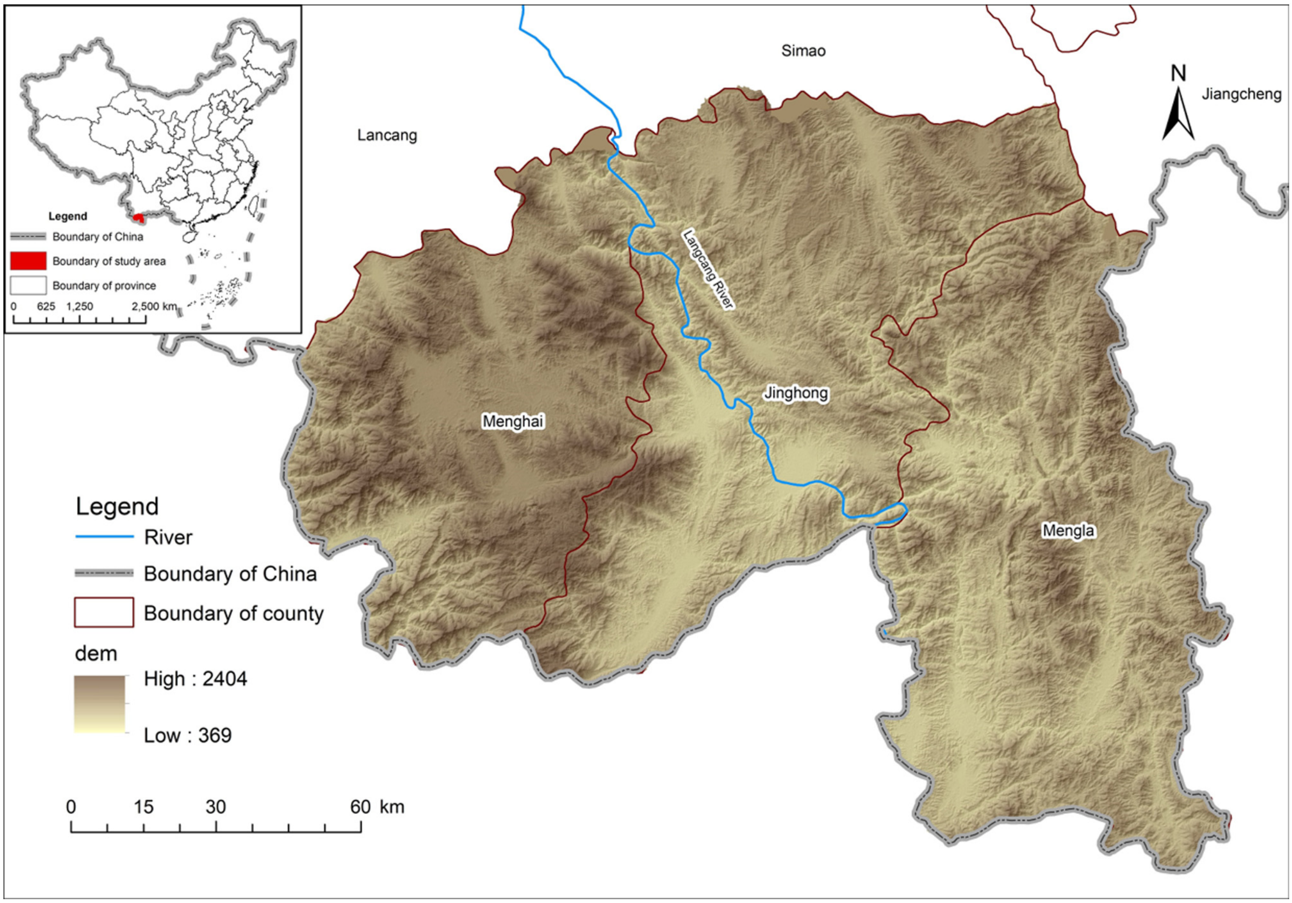


**Fig. 1.** Maps showing the location of the Xishuangbanna region in China.

In order to ensure the accuracy of the results, the results of all four models were validated with other reference data for Xishuangbanna. For the CS and WY models, other open source spatial data were sampled for validation and the correlation ($R^2$-value) between observed values and values simulated by the two models was found to be >0.93 in both cases. For the SDR and NDR models, mean values from other studies were used for validation and the simulation results also met the research requirements. In order to further reduce the error, ESs data with a more extensive spatial scope, including the Xishuangbanna region, were collected for auxiliary calibration. See SI (Part 2) for details of InVEST model parameterisation and validation.

### 2.2.3. Statistical analysis

Spatial statistical tools in ArcGIS were used as a complement to the InVEST model to quantify differences in ESs between altitude-relevant vegetation types. The whole study area was divided into four altitude gradients of similar area. Random samples of the four altitudes and vegetation types were then selected for variance and exploratory hierarchical cluster analysis.

Four zones of similar area (each about 25% of total area) were distinguished according to altitude (400–800 m, 800–1000 m, 1000–1300 m and 1300–2400 m), to examine distribution differences in vegetation types. Analysis of variance (ANOVA) was used to test for statistically significant differences in ESs supply between these four different altitude zones. Within each zone, 3000 points (in total 12,000 random samples) were randomly selected using the ArcGIS random point tool. This information was used as technical support for comparison of specific vegetation types and ESs supply in different altitude zones.

Exploratory hierarchical cluster analysis was used to cluster vegetation types supplying similar ESs into major types, based on the sampling of each vegetation type. This highlighted similarities or differences in ESs supply capacity between the 17 vegetation types. The vegetation in four main types showed high commonality, so these types were subjected to analysis to make the results more concise. Within each of the 17 vegetation types in each altitude zone, 250 points were randomly selected using the ArcGIS random point tool (1000 samples of each vegetation type), giving a total of 17,000 random samples. Clustering criteria were not set in advance, but were constantly revised in the process of exploratory clustering. Details of clustering criteria and the clustering process can be found in SI (Part 3). They can be used as guidance for specific vegetation restoration schemes at specific altitudes to improve ESs supply capacity throughout the region.

## 3. Results

### 3.1. Vegetation types in different altitude zones

There were differences in the distribution of vegetation at different altitudes (Fig. 3a–d). Two types of vegetation occupied the main proportion of the area. Monsoon evergreen broadleaved forest comprised the largest proportion of vegetation in the 800–2400 m zone (39.73–50.25%). Rubber plantation occupied the absolute majority of the 400–800 m zone (65.97%), and was also distributed at 800–1000 m (33.75%).

The altitude differentiation was also apparent for other vegetation (Fig. 3a–d). Mossy evergreen broadleaved forest occupied large area at 1300–2400 m (24.87%), but it hardly appeared at other altitudes. Meanwhile, cropland distributed evenly at all altitudes, and except for 6.84% at 8000–1000 m, it occupied >10% in other zones. Other vegetation accounted for no >10% of area in all altitude zones also showed a variety of distribution characteristics. For example, tea plantation was basically distributed in high altitude zones (1000–2400 m), but barely in low

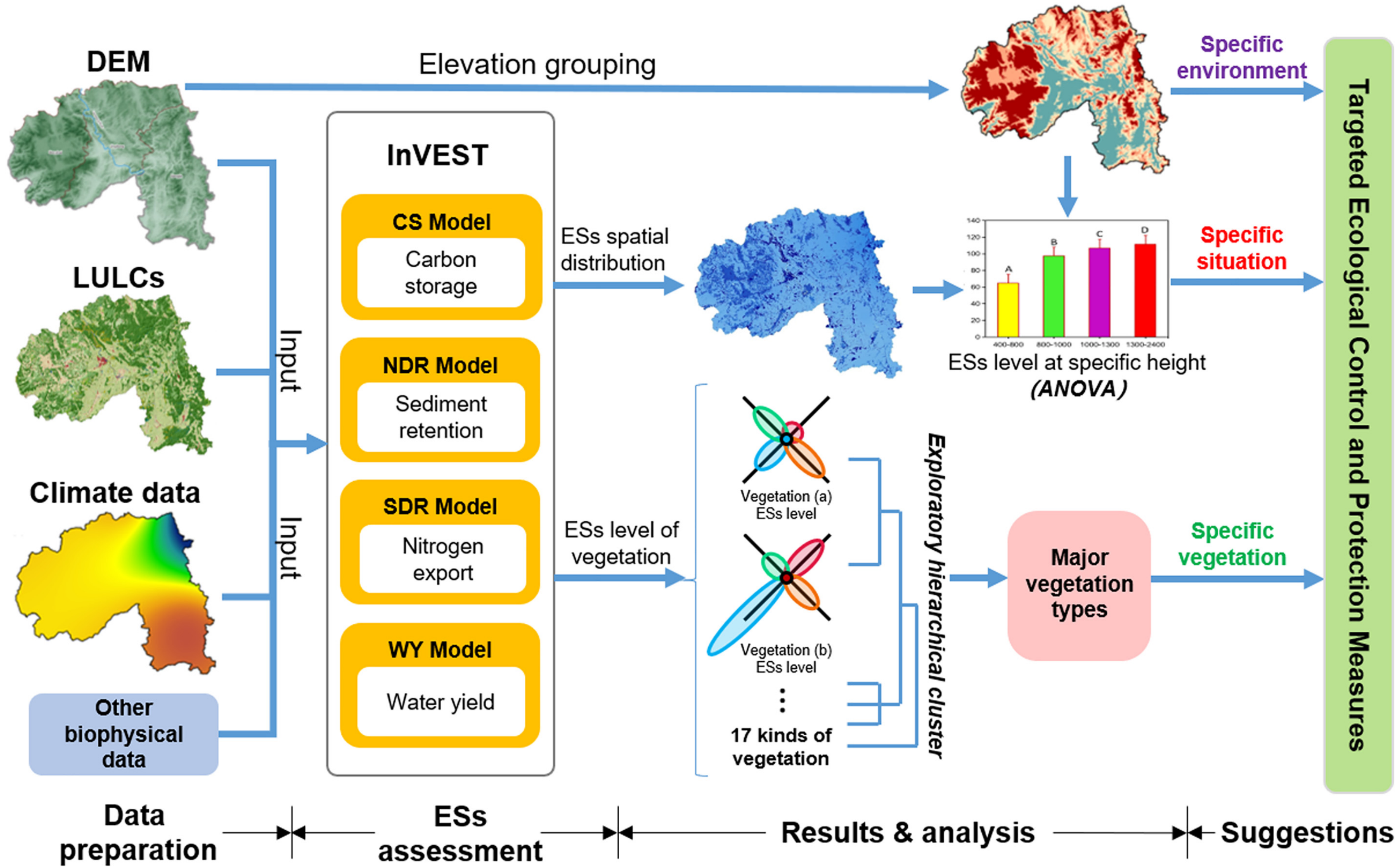


**Fig. 2.** Analytical framework used in relating altitude-associated vegetation types to ecosystem services (ESs) in devising schemes for vegetation protection. (CS = carbon storage, SDR = sediment delivery ratio, WY = water yield, NDR = nutrient delivery ratio).

**Table 1**
Key data used for running the models.

| Data | Type | Data source | Note |
|---|---|---|---|
| Digital Elevation Model (DEM) | Raster | Geospatial Data Cloud, http://www.gscloud.cn | Resolution 30 m × 30 m |
| Land use /land cover | Raster | Yunnan Institute of Forest Inventory and Planning | LULC of 2016 including 19 kinds of use types. Resolution 30 m × 30 m |
| Annual precipitation | Raster | China Meteorological Data Center, http://data.cma.cn/ | Resolution 30 m × 30 m |

altitude zones (400–1000 m). Seasonal rain forest and Limestone monsoon forest were almost distributed at low altitude zones rather than high altitude zones.

### 3.2. ESs levels in different altitude zones

The quantitative levels of the four selected ESs at each altitude are shown in Fig. S8 in SI, where the visualisation of differences is not clear. Therefore, ANOVA was used to assess differences in mean ESs levels (df = 11,998, $p < .05$). It revealed differences in ESs levels among the four altitude zones (Fig. 4a–d).

Carbon storage service in the two highest altitude zones was very similar (106.83 t/ha at 1000–1300 m, 111.57 t/ha at 1300–2400 m), and was significantly higher than in the 400–800 m zone (64.86 t/ha) and 800–1000 m zone (97.49 t/ha). Nitrogen export service was significantly lowest in the 800–1000 m altitude zone (1.84 kg/ha) and significantly highest in the 1000–1300 m zone (3.45 kg/ha), while it was rather similar in the 400–800 m zone (2.83 kg/ha) and 1300–2400 m zone (2.56 kg/ha). Sediment retention service was significantly lower in the 400–800 m altitude zone (2070.84 t/ha) and significantly higher in the 800–1000 m zone (2811.93 t/ha) than in the other zones. This service was similar in the other two zones (2453.38 t/ha and 2542.71 t/ha in the 1000–1300 m and 1300–2400 m zones, respectively). Water yield service was significantly lower in the 400–800 m zone (373.4 mm) and 800–1000 m zone (361.74 mm), and significantly higher in the 1000–1300 m zone (432.61 mm) and 1300–2400 m zone (426.09 mm).

In general, carbon storage and water yield were not as good in low altitude zones as in high altitude zones. The high nitrogen export in the 400–800 m and 1000–1300 m zones indicated high nutrient supply, which was good for economic plantations, but also put pressure on the excess nutrient water purification service. The overall level of ESs in the 800–1000 m zone was relatively balanced, especially in sediment retention.

### 3.3. Vegetation clustering and distribution in altitude zones

Assessment of similarities or differences in ESs supply capacity among the 17 vegetation types (1000 samples of each vegetation type, in total 17,000 points) through vegetation clustering revealed four new major types (a-d) (Fig. 5). It also allowed vegetation types occupying a small area to be considered, by clustering them into the major types.

'Natural forests' (type a) comprised all eight types of natural forests. Its carbon storage service (142.12 t/ha) and sediment retention service (3012.25 t/ha) were higher than the benchmark, while its water yield service (281.1 mm) and nitrogen export service (0.52 kg/ha) were lower than the benchmark. 'Natural forests' were distributed at all altitudes, but there were few at 400–800 m.

'Natural shrubs' (type b) comprised natural shrubs, grassland, and two types of bamboo forest. Its water yield service (736.19 mm) was higher than the benchmark, while its carbon storage service (49.86 t/ha) and nitrogen export service (0.73 kg/ha) were lower than the benchmark. Its sediment retention service (2344.77 t/ha) was similar to the benchmark. Hot bamboo forest and hot shrub forest were most distributed at low altitude (<1000 m), while warm bamboo forest and warm savannah shrub grassland were most distributed at higher altitude (>1300 m).

'Commercial plant 1' (type c) comprised orchards, arable crops, and tea plantations. Its carbon storage service (38.48 t/ha) and sediment retention service (1928.43 t/ha) were lower than the benchmark, while its water yield service (783.08 mm) and nitrogen export service (7.43 kg/ha) were higher than the benchmark. In fact, according to the ESs assessment results the nitrogen export service of cropland was 6.97 times higher than the benchmark (Fig. 5), which greatly improved the nitrogen export service of type c vegetation. 'Commercial plant 1' (c) was most distributed at high altitude (>1000 m).

'Commercial plant 2' (type d) comprised rubber plantations and other artificial forest, and all the ESs it provided were below the benchmark (carbon storage 142.12 t/ha, nitrogen export 0.52 kg/ha, sediment retention 2012.25 t/ha, water yield 281.1 mm). Rubber plantations were most distributed at 400–800 m, while other artificial forest was most distributed at 1000–1300 m.

The most distributed altitude zones for the four major vegetation types were further analysed in terms of the area they occupied after hierarchical clustering analysis (Fig. 6).

In general, the percentage area of 'Natural forests' and 'Commercial plant 1' increased with increasing altitude, while the percentage area of types 'Natural shrubs' and 'Commercial plant 2' declined (Fig. 6). The actual percentage area of 'Natural forests' increased from 15% in the 400–800 m altitude zone to 70% in the 1300–2400 m zone, while the actual percentage of 'Commercial plant 2' decreased from 66% in the 400–800 m zone to 4% in the 1300–2400 m altitude zone. Although the percentage of 'Natural shrubs' decreased from 6% in the 400–800 m altitude zone to 4% in the 1300–2400 m zone, it was almost evenly distributed in all zones. 'Commercial plant 1' was more frequent at high altitude (>1000 m) than at lower altitude (<1000 m). The relationship between these differences in vegetation distribution and differences in ESs supply capacity are discussed below.

## 4. Discussion

### 4.1. Different vegetation types provide different ESs

Among the four altitude zones studied, the capacity to supply carbon storage and sediment retention services was weakest in the 400–800 m zone (Fig. 4). The reason was that the proportion of natural vegetation in this zone was too small and instead it had a large amount of type (d) vegetation, particularly rubber plantations. Studies have shown that provision of the total biocarbon storage; and soil and water conservation services is lower in rubber plantations than in natural tropical forest (Jiang et al., 2017; Li et al., 2008; Ziegler et al., 2009), as confirmed in this study (Fig. 5). Thus the 400–800 m altitude zone is the most important region to target in efforts to protect the ecological system in Xishuangbanna, as its current ecological protection capacity needs comprehensive improvement.

The sediment retention capacity of the 800–1000 m altitude zone was higher than that of the other three zones (Fig. 4). This was due to the reasonable proportion of natural forests and commercial plants in the 800–1000 m zone (Fig. 6), where type (a) natural forests accounted for half the total vegetation. The area of type (d) commercial plants 2 also declined rapidly with increasing altitude and the area of type (c) commercial plants 1 with high nitrogen output and water production was relatively small. This resulted in low nitrogen export and water yield for the 800–1000 m zone (Fig. 4). The 'natural-commercial' mixed forest model has been recommended in other studies (Feintrenie

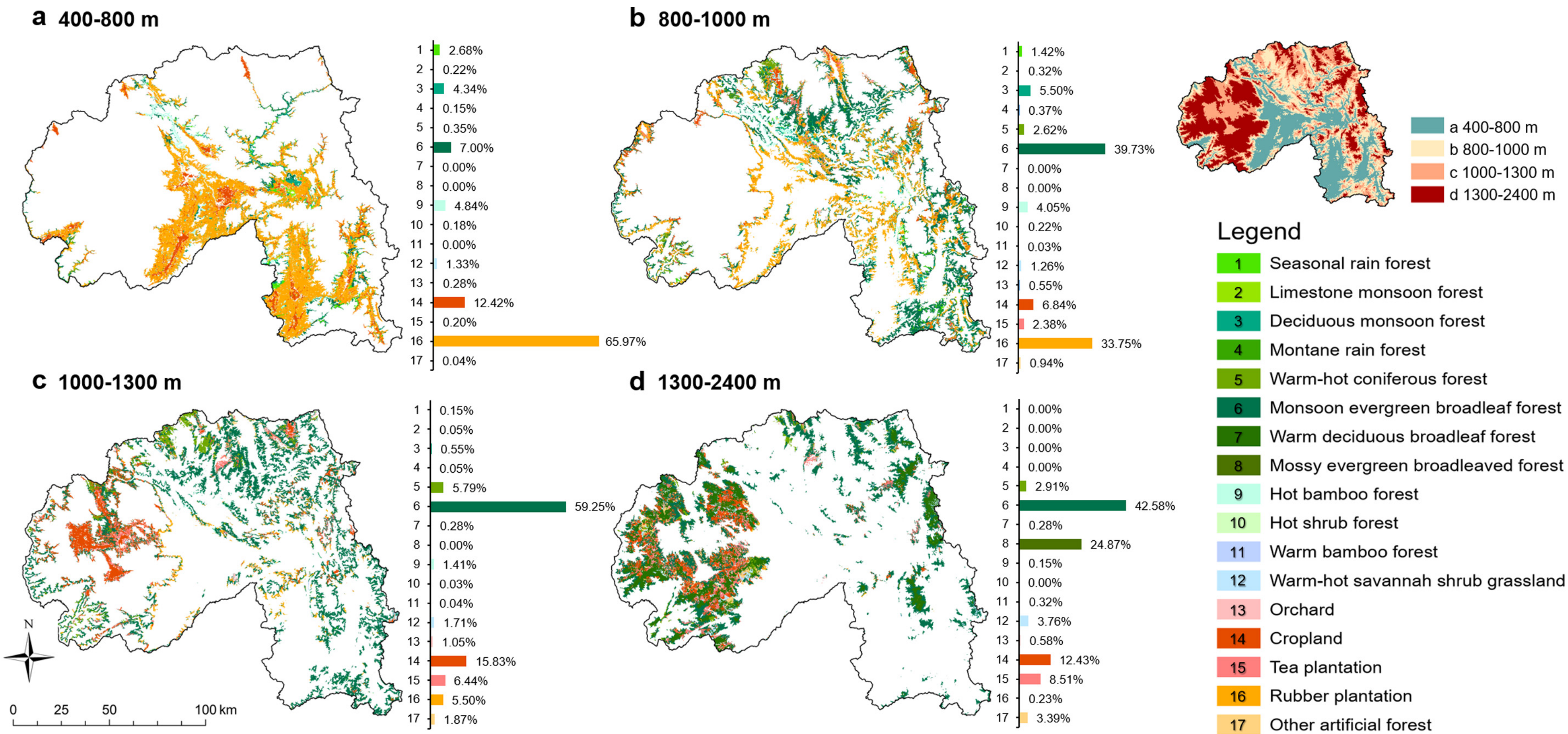


**Fig. 3.** a–d. Spatial distribution and percentage area of vegetation types in four altitude zones in the Xishuangbanna of southern China, 2016. (Note: Each zone is about 25% of total area.)

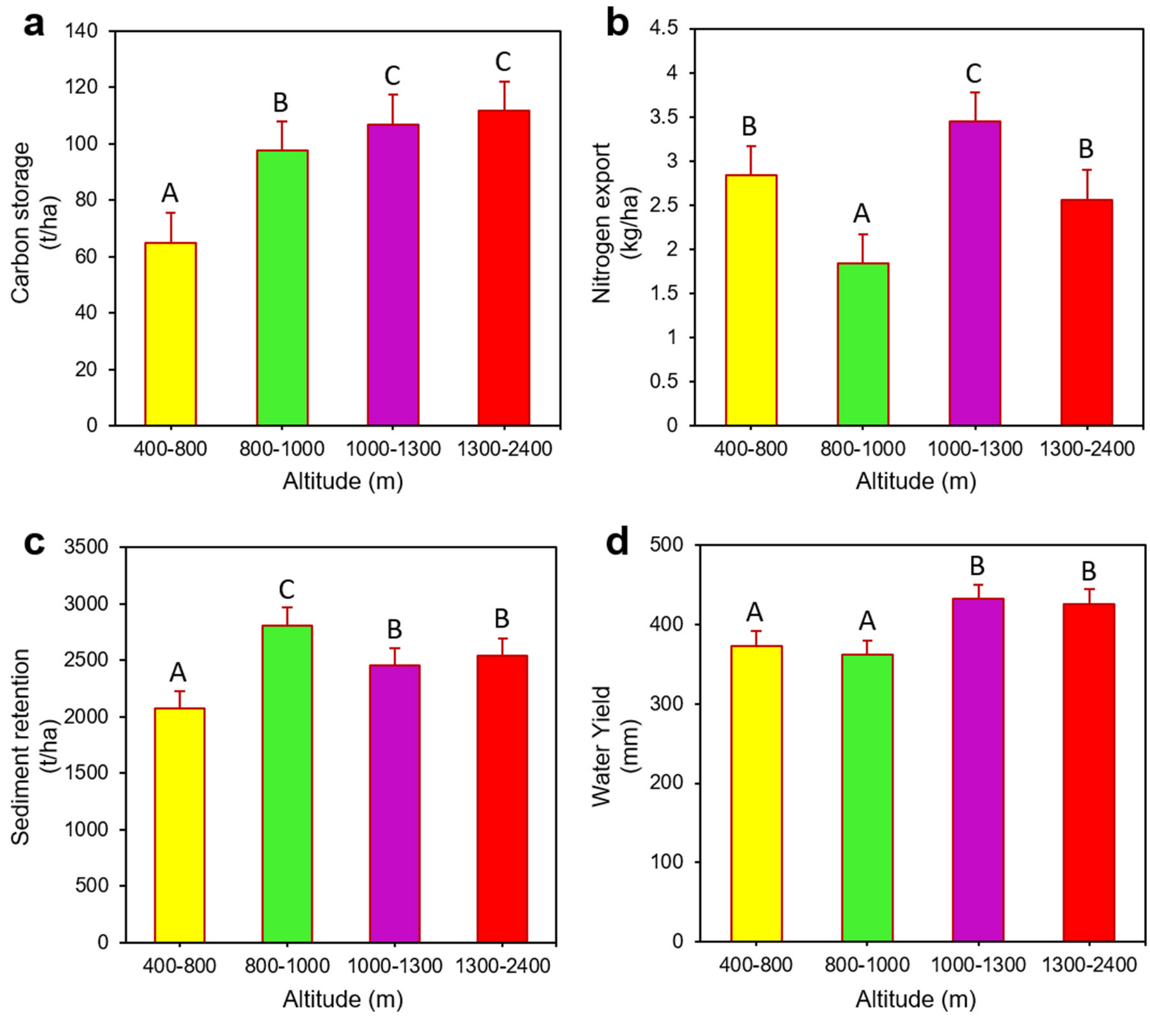


**Fig. 4.** a–d. Differences ($n = 12{,}000$, $p < .05$) in the provision of ecosystem services (ESs) between four different altitude zones in the study region.

and Levang, 2009; van Noordwijk et al., 2012), and provides a reference ecological protection measure for other regions.

The provision of ESs in the 1000–1300 m and 1300–2400 m zones was rather similar except for nitrogen export (Fig. 4). Both zones had high carbon storage capacity, resulting from their high proportion of type (a) natural forests (Fig. 5). However, they also had higher water yield capacity (Guardiola-Claramonte et al., 2008; Ziegler et al., 2009), with double the area of type (c) commercial plants 1 compared with lower altitude zones (Fig. 6), which lowers mean soil conservation (Zhang et al., 2007). The difference in nitrogen export between the two zones was due to the composition of their type (c) commercial plants 1, with more cropland in the 1000–1300 m zone and less cropland, but more tea plantations, in the 1300–2400 m zone. Because of the use of agricultural fertilisers (Wang et al., 2019), the nitrogen export of cropland was 6.7 times the benchmark level (Fig. 5), which led to nitrogen export from the 1000–1300 m zone being significantly higher than from other zones. Excessive nitrogen output in high altitude areas can lead to river pollution by hydrological processes (Wang et al., 2019), affecting the ecology and water quality in cities and towns in low altitude areas (Huang et al., 2018).

### 4.2. Vegetation protection measures in different regions

The Xishuangbanna government has already taken some measures to promote restoration and protection of natural vegetation, such as establishment of the Xishuangbanna National Nature Reserve. The Xishuangbanna Environment & Ecology Bureau (XEEB) has implemented an ecological protection plan (XEEB, 2016) and Sloping Land Conservation Program (SLCP) to encourage tree planting (Liu et al., 2019b). However, these policies and plans are based on macro-protection principles, with no detailed consideration of the suitability of various vegetation types for different environments (Miao et al., 2018). Detailed policies are difficult to implement, leading to rapid expansion of commercial planting and challenges to the success of protection policies (Liu et al., 2017). To solve this dilemma, we propose the following vegetation protection measures for different altitude zones of the Xishuangbanna region, based on different vegetation features:

i) Strengthen government ecological supervision of the rubber industry in the 400–800 m zone, especially when adding new rubber plantations. As the Xishuangbanna government itself needs to achieve local economic development through rubber plantations (Table S5), it is unrealistic for it to implement strict restrictions on the development of this industry (Smajgl et al., 2015), and it is more feasible for it to guide rational commercial development with low ecological impact (Stone, 2008). This is also in accordance with the demands of plantation owners, who are more willing to participate in ecological protection by providing money and labour, rather than reducing rubber production (Min et al., 2018). Commercial plants can be incorporated into mixed farming (Xu, 2011), in order to protect vegetation diversity, agricultural biodiversity and the livelihood flexibility of farmers in the region (Liu et al., 2006). Comprehensive protection measures are needed for natural forests, especially seasonal rainforest, in the study region (Fig. 5). For example, the boundaries of natural forest reserves should be monitored in an effective way, to prevent them from further damage. Lessons

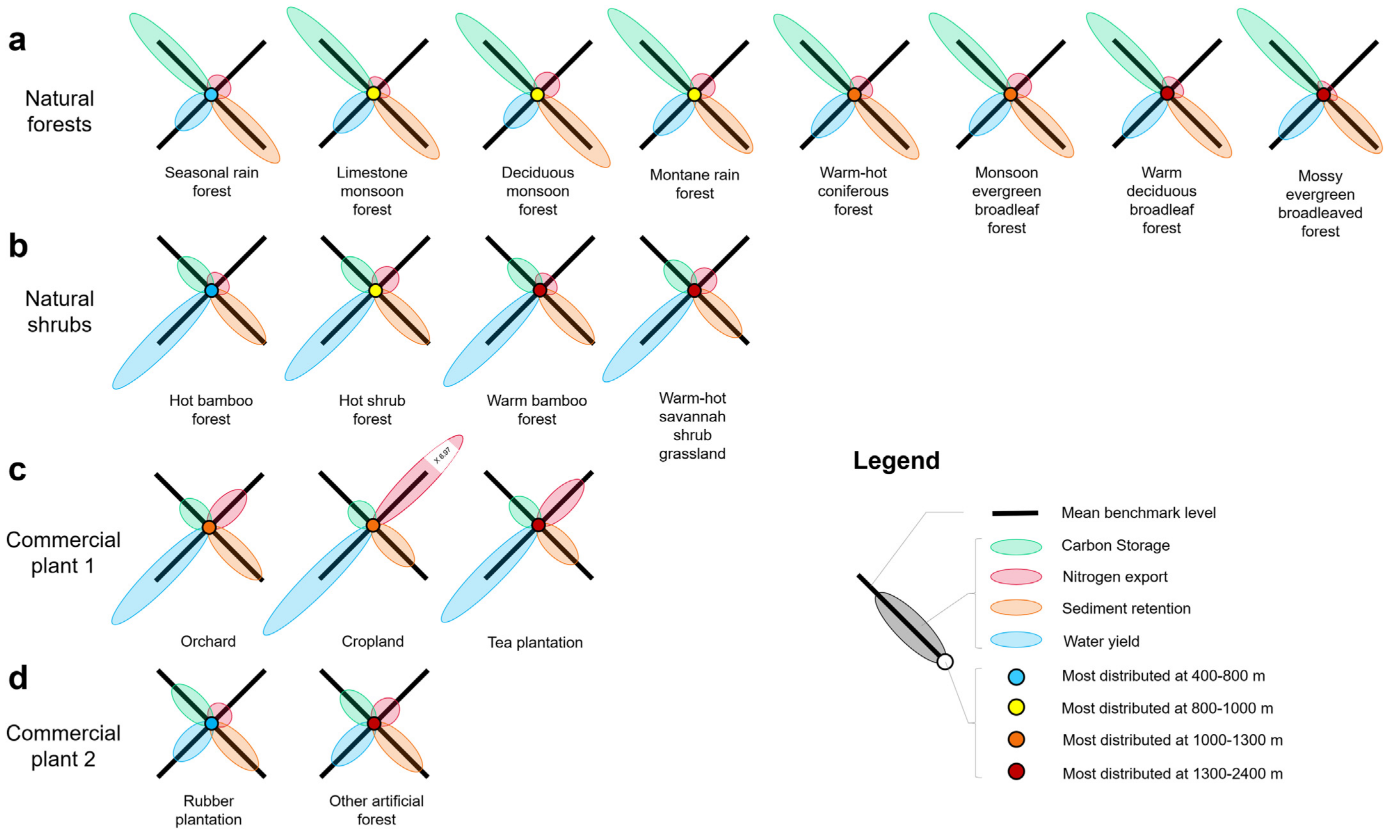


**Fig. 5.** a–d. Hierarchical clustering results showing ecosystem services (ESs) supplied by the 17 types of vegetation ($n = 17{,}000$) identified in the study region in 2016, divided into four major types (a–d) based on similarities.

can be drawn from the 'natural-commercial' mixed forest mode in the 800–1000 m altitude zone, by implementing mixed agroforestry systems which can upgrade ESs better than individual vegetation types (Ahmed et al., 2013; Li et al., 2013).

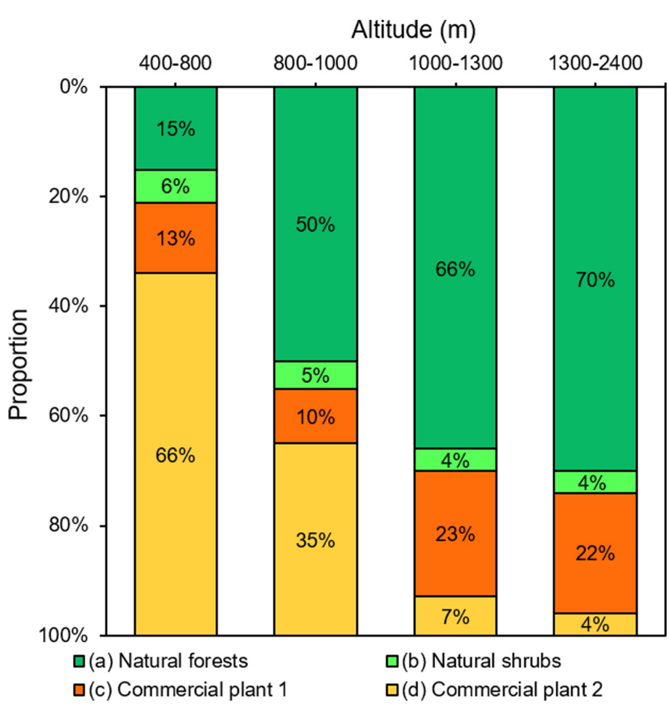


**Fig. 6.** Percentage area of the four major vegetation types (a-d) in different altitude zones in the study region.

ii) Maintain a good ESs level in the 800–1000 m zone, paying special attention to natural forests in the zone, e.g. limestone monsoon forest, deciduous monsoon forest, and montane rainforest (Fig. 5). Improving the agroforestry complex system by planting rubber interlaced with other commercial plants (such as fruits and medicinal materials) can improve the use of land resources in the study region (Jiang et al., 2017). This multi-layer structure of rubber agroforestry system can also maintain internal microclimate stability and control water runoff and erosion, promote the diversification of agriculture and forestry, and increase the return on agricultural investment (Liu et al., 2013). The government can set mixed agriculture as the development template, promote it in various regions and reward plantation owners who meet mixed agriculture standards (SC, 2019). Combined with ecological supervision, this can guide regional development towards a lower-impact system.

iii) The key task in high altitude zones (1000-1300 m and 1300-2400 m) is to raise the level of nutrient retention, and the most important measure is to control the use of agricultural fertilisers. This could be done by microdosing fertilisers, controlling the total amount of fertiliser applied and establishing 'organic' orchards, tea plantations and cropland with high output per unit area and less use of herbicides and pesticides, to reduce pollution of soil and aquatic environments (TEEBcase, 2013). Payments for ecosystem services (PES) has been proposed as an effective way to alleviate the pollution caused by cultivation of land and rubber planting (Liu et al., 2019b). However, due to differences in value standards, evaluation results are often very diverging and the final scheme needs to be further determined through multi-stakeholder consultation (Smajgl et al., 2015). The good news is that the majority of local people are interested in ecological protection (Min et al., 2018), which is very necessary for establishment of a consultation mechanism. Attention should also be paid to maintaining natural forests in the region, i.e. warm deciduous broadleaved forest, monsoon evergreen broadleaved forest, warm-hot coniferous forest and mossy evergreen broadleaved forest (Fig. 5).

iv) Build a consultation mechanism with multiple stakeholders, which has been proven to be effective in management of ESs (Adem Esmail et al., 2017). Strict implementation of vegetation protection may result in a certain loss of economic benefits (Liu et al., 2019b), causing a conflict of interest between stakeholders. Through consultation, targeted poverty alleviation projects can be discussed and implemented, such as the National Poverty Alleviation Project (Guo et al., 2019) and various compensation policies (e.g. Natural Forest Conservation Programme, Public Welfare Forest Policy, Sloping Land Conversion Programme) for forest protectors outside nature reserves (Friess et al., 2015; Jack et al., 2008). The framework presented in this study can provide technical support in that process, as spatially explicit modelling of ESs allows future scenarios of eco-management to be generated and explored (Adem Esmail and Geneletti, 2017; Burkhard et al., 2018). It should be combined with an internet-based business platform (e-commerce) and opening up of sale channels for local agricultural and forestry products in remote areas (Lin, 2019), so as to resolve the economic cost of ecological protection.

### *4.3. Main limitations and future research*

In this study, the intention was to use spatial distribution data from other studies for model calibration, due to lack of field sampling or survey data. However, we were only able to find data that could be used for spatial sampling comparisons in the Carbon Storage model and Water Yield model, while the other models were calibrated with the ESs mean level (SI, Part 2). This might have led to some uncertainty or deviations in the modelling results for the other ESs, but not major errors at the overall level. In addition, we directly used the latest available land use product in 2016 from Yunnan Institute of Forest Inventory and Planning as the benchmark, without further interpreting the remote sensing image data. Although age of the data did not have a very strong correlation to the objective of this study, using the latest data where possible would further reduce the uncertainty in the results. Moreover, biodiversity was not analysed in this study, due to lack of available data, but is one of the most important ecological services in the Xishuangbanna region (Guo et al., 2002; Yi et al., 2014a; Zomer et al., 2014), which is e.g. the only Asian elephant reserve in China. We recognise these limitations, and will re-calibrate the models and update the results when relevant data or reference data become available in the future.

Another limitation of this study was lack of participatory analysis involving multiple stakeholders. Participatory analysis is a direct and important pathway for selecting relevant final ESs by considering stakeholder demands (Das and Basu, 2020; Daw et al., 2011). In this study, we attempted to use the conceptual framework based on stakeholder consumption, policy relevance and data availability to fill this gap, considering vegetation protection policymaking and affected agents (residents, commercial plantation owners and government). This might have led to some ESs of importance to multiple stakeholders being overlooked. In future research, we recommend that participatory analysis be conducted using face-to-face interviews or surveys, to obtain public perceptions and preferences on ESs before selecting the final list of ESs to be evaluated.

The study region has a tropical climate, but the research framework can be applied to other regions of China in future to compare/verify the results. Future studies should also seek to provide decision support for future ecological protection through multi-year data comparison analysis or simulation of future land use pattern changes in different scenarios, thus enabling practical countermeasures and suggestions to be formulated. Since the InVEST model has been widely used worldwide, our framework based on InVEST combined with spatial statistical methods can be applicable to other countries.

## 5. Conclusions

This study quantified variations in ESs supply between altitude-associated vegetation types, an issue which has not received sufficient attention in previous research. The originality of this study is that we present a quantitative method for determining vegetation ESs supply, based on remote sensing technology and spatial statistical methods. Analysis of vegetation and ESs characteristics in different altitude zones revealed the main ecological patterns in different parts of the study region. Based on hierarchical clustering of vegetation types by ESs features, strategies for ecological management and specific natural plants that should be protected were identified for different altitude zones. For example, in the 400–800 m zone the focus should be on protection of natural forests and on supervising rubber plantations. The ecological condition of the 800–1000 m zone should be maintained and its development mode should be used as reference in the management of other zones. In the 1000–2400 m zone, the nitrogen export level is very high because of the greater proportion of cropland and tea plantations, so reducing chemical fertiliser use and developing mixed organic agriculture with low environmental impact should be considered. Specific natural vegetation types that should be protected in different altitude zones were identified. We suggest the introduction of stakeholder consultation mechanisms to implement ecological compensation and poverty alleviation by e-commerce, so as to reduce the economic pressure imposed on local communities by implementation of ecological protection measures. The framework described in this study can be used as an analytical method for this process, and also has a certain degree of technical applicability on a global scale.

## CRediT authorship contribution statement

**Zhou Fang:** Writing - original draft preparation, Writing - review & editing, Data curation. **Yang Bai:** Conceptualization, Writing - review & editing, Methodology, Software. **Bo Jiang:** Conceptualization, Writing - review & editing, Methodology. **Juha M. Alatalo:** Writing - review & editing. **Gang Liu:** Investigation. **Huimin Wang:** Supervision.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Acknowledgements

This research was funded by the Funds for International Cooperation and Exchange of the National Natural Science Foundation of China (Grant No. 51861125101), West Light Talent Program of the Chinese Academy of Sciences (Grant No. Y9XB011B01), Fundamental Research Funds for the Central Universities (Grant No. KYCX17_0510), Key Research Program of Frontier Sciences, CAS (Grant No. ZDBS-LY-7011), National Key Research and Development Program of China (Grant No. 2017YFC0404600). JMA was supported by Qatar Petroleum.

## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2020.138565.

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