摘要

热带雨林是一种独特的森林生态系统，是地球上生物多样性最高的植被类型之一。当前面临生物多样性迅速消失与生态功能严重退化等问题。在中国西双版纳热带雨林中，三达山是整体生态格局的重要节点，但农业生产与人工橡胶林的大量种植使当地的生态系统日渐破碎，植被生产力大幅下降。自2017年起，项目团队根据三达山现状生境条件，以30年为修复周期，采用从局部修复、斑块修复、廊道修复到生态完善的动态演替总体思路，借助建群种植物、先锋植物、立体复合型和协助自然再生4种修复方法重建三达山受损的热带雨林生态系统；并利用InVEST模型对修复前后的碳储量变化、生境质量和生态系统服务功能价值展开评估，以动态指导和修正修复计划，逐步实现热带雨林的回归。该项目是复杂而漫长的热带雨林修复实践的一次实验性探索，可为中国乃至全球热带雨林生态修复提供研究与实践基础。

关键词

热带雨林；生态修复规划；修复方式；效益评估；西双版纳

1 项目背景与问题

在中国现存的热带雨林中，西双版纳热带雨林是在纬度和海拔都较高的极限条件下形成的一种热带季节雨林。其平均生物量为462.84t/ha，是中国生物多样性最丰富的地区之一。20世纪50年代，西双版纳地区的雨林覆盖率高达55%，但到21世纪初却已不足30%，且目前受保护的热带雨林仅占当地热带雨林总面积的50%，它们零星分布在大面积的退化生境中，呈现出斑块状的“孤岛”。2017年初，作为国家重点生态功能区项目，云南省景洪市政府决定对西双版纳北部三达山区域约80km²的人工橡胶林进行修复，以贯通区域生态走廊，探索人与自然和谐共生之路。
曾经拥有连绵的原始热带雨林景观的三达山，如今正面临着两大严峻挑战：

1）生态系统破碎化：由卫星遥感影像所得西双版纳地区1990~2015年土地利用（图1）及景观生态格局的演变可见，区域生态格局正呈现破碎化趋势，具体表现为：耕地面积增加、林地面积减少，生态斑块数量显著增加、生态斑块平均面积减少。其中，农业生产活动和橡胶林种植对原有森林生态系统的侵蚀尤为明显。例如，西双版纳国家级自然保护区内约2 470 km²的森林被分割为5个片区，森林的破碎化严重减少了森林乡土物种及热带雨林组成成分，阻碍了物种基因的流动，大大削弱了热带雨林的生态价值。从西双版纳整体生态格局来看，三达山作为联系野象谷自然保护区和西双版纳原始森林公园的重要节点（图2），其范围内的人工造林直接导致区域生态廊道断裂，雨林植被群落结构受损，以致区域生态效益低下。

2）植被生产力下降：通过遥感数据反演景洪市2000~2015年植被净初级生产力（NPP）②可知，植被生产力从2005年起逐年增加，但仍远低于2000年的水平。其原因在于2003年前后景洪市大量砍伐森林以种植人工橡胶，具备高植物生产力的热带雨林系统遭到严重破坏，总体植被生产力急剧下降，同时脆弱物种日渐消失、生物多样性逐年降低。这种情况在三达山尤甚，该地以橡胶林和果林为主的经济林占比达70%以上（图4）。

2 热带雨林生态修复规划目标与技术框架

热带雨林修复是一个漫长而复杂的动态过程。雨林植被的恢复重建应顺应环境的动态变化，重在恢复生态系统的结构和功能，而非恢复为与过去完全一致的生态系统。在三达山雨林修复中，项目团队汲取国内外先进的修复经验，以现实生境条件为基础，采用多样的动态修复手段，构建“局部修复-斑块修复-廊道修复-生态完善”修复路线，以重建热带雨林植被群落结构与系统，提升物种多样性；为应对复杂多变的雨林生境系统，团队拟在修复过程中对生态修复效益进行动态评估和监测，以便为随时修正热带雨林的修复方法提供数据支撑（图5）。

3 生态修复策略

3.1 多元修复方式探索

在热带雨林的恢复过程中，针对不同立地条件与类型，植被恢复方式与重建模式也有所不同。立地条件的划分受到地形、地貌、气候、海拔、土壤、植被、湿度、人为活动等多重综合因子的共同作用。因此，项目首先运用权重分析法对场地进行生态多因子综合评价，并将研究区域划分为4个分区，分别因地制宜地利用建群种植植物法、先锋植物法、立体复合型修复法和自然再生法加以修复（图6）。
3.1.1 建群种植物修复法

建群种植物修复法即选用对热带雨林群落结构和群落环境形成有明显控制作用的优势植物作为群落建造者，在短时间内建立雨林体系。现状核心沟谷坡度、土壤及湿度等条件适宜各类沟谷雨林植被生长，因此主要采用此方法进行修复。具体而言，由望天树（Parashorea chinensis）、绒毛番龙眼（Pometia tomentosa）、千果榄仁（Terminalia myriocarpa）等热带雨林标志性树种构成森林上层，培育林下植物以形成多层次多物种的森林植被，补植其他地被物种。如此按照热带雨林的层次精细化种植，可在较短时间内形成植物种类丰富、层次复杂、郁闭度高的热带雨林体系，从而逐步实现山谷雨林的修复（图7）。

3.1.2 先锋植物修复法

在山脊、地势陡峭和种植条件恶劣的区域，利用热带先锋树种西南桦（Betula alnoides）、马占相思（Acacia mangium）、山桂花（Paramichelia baillonii）等造林，其可在较短时间内成为山脊优势物种，为后期其他热带雨林植物的生长提供有力的荫地条件。同时，先锋植物的快速生长亦可推动山脊地区结构单一的橡胶林逐步向混交林演替。此区域需控制割胶、砍伐等人为活动，并借助当地优越的气候、土壤条件，补植构成山地雨林的其他乔木、藤本及林下植物，使林分逐步增加，实现山脊雨林的修复（图8）。

3.1.3 立体复合型修复法

在芒果（Mangifera indica）林、茶树（Camellia sinensis）林等部分产量较高的果林和橡胶林区域采用立体复合型修复法，即保留橡胶林，逐步伐除部分果林，并补植其他珍贵的经济林木，结合生态农业、立体混种等方式构建复合型生态橡胶林。这一途径能显著增加区域生物多样性，提升生态功能，并在较短时间内产生经济效益（图9）。
4 修复效益评估

考虑到热带雨林生态系统在维持全球碳平衡和区域生物多样性方面的贡献，项目团队对生态修复前后的碳储量变化、生境质量及生态服务价值进行了定量模拟，以评估热带雨林修复的生态效益。

4.1 碳储量变化评估
4.1.1 计算方法与过程

团队借助由美国斯坦福大学、世界自然基金会和大自然保护协会联合开发的InVEST (生态系统服务评估与权衡) 模型中的碳储量评估模块，估算了热带雨林系统碳储量规划前后的变化情况及空间分布规律，可为实现热带雨林的保护和恢复提供数据参考。主要利用地上碳库、地下碳库、土壤和死亡有机物4个碳库来预测不同土地利用类型地块的碳储量。

InVEST模型碳储量模块的基本运算原理为，由已分类的土地利用面积与其对应的碳密度的乘积得出碳储量，再由不同土地利用类型的碳储量求和得出总碳储量。本次规划基于景洪市森林资源规划设计调查(简称二类资源调查)报告和访谈、调研与文献检索，最终划定近期规划(2020-2025)和远期规划(2020-2050)的7种土地利用类型，并参考燕腾等人估算的云南省森林生态系统植被的碳密度确定了4种碳库的碳密度，再将二者作为初始数据输入InVEST模型中，经过ArcGIS栅格数据处理，评估每个网格单元的碳储量高低，据此对不同土地利用类型进行赋值，最后求和得出总碳储量及其规划前后的变化。

4.1.2 结果分析

经模型测算，现状橡胶林储存的碳储量约为42 259.32MgC，占规划区总碳储量的83.5%。在近期完成斑块修复后，约有5km²的森林重造林产生，届时热带雨林的面积将增加一倍，经济林碳储存贡献率也将大幅下降，总碳储量将从50 609.60MgC降至47 605.64MgC（表1，图14）。在远期规划中，新种植的幼林将发展成为具有复杂生物结构层次的热带雨林，总碳储量将达到69 188.85MgC，比现状增加36.4%（表2，图14）。

4.2 生境质量评估
4.2.1 计算方法和过程

生境质量反映了一定的时间和空间范围内，生态系统对人类生存繁衍、经济发展的适宜程度。本规划借助InVEST生境质量模块，利用现状及远期规划土地利用类型数据，计算两个时期对应的生境质量指数，以揭示规划实施过程中土地利用变化对生境质量的影响。

生境质量模型结合土地利用和威胁因子的信息生成生境质量地图，通过考量威胁因子的影响范围及权重（表3）、生境对于威胁源的敏感系数等因素（表4），评价生境质量。输入生境质量模块的数据共分为6项，分别是现状及规划建成的土地利用覆盖数据、威胁因子（城
4.2.2 结果分析
通过对5个生态威胁因子及其影响范围进行模拟测算，识别现状高质量生境地区和低质量生境地区的位置。尽管规划道路将对生境质量指数产生较大影响——相较于现状，高质量生境的面积下降到12.02 km²，减少了7.84 km²，中低质量生境的面积由10.32 km²增加至11.55 km²——但规划区东北部及中部远离村镇建设地区的生境质量指数明显提高，且原生境（即现存的热带雨林生境）面积由现状5.82 km²增加至12.42 km²。因此，从不同质量指数下生境的面积来看，远期规划的生境质量将有所提升（图15）。

4.3 生态系统服务功能价值评估
4.3.1 计算方法和过程
生态系统服务功能价值是指人类直接或间接从生态系统中获得的利益，主要包括向经济社会系统输入有用物质和能量、接受和转化来自经济社会系统的废弃物，以及直接向人类提供的服务。本次修复规划参照余晓新等人提出的中国森林生态系统服务功能价值评估的方法，选取了供给服务、涵养水源、固碳释氧、积累营养物、保育土壤、净化空气和提升生物多样性7项指标，并依据景兆鹏等人提出的云南省西双版纳地区不同用地类型的生态服务价值的动态评估研究确定不同用地的生态服务价值，对修复前后各用地类型的生态服务功能价值进行评估。同时，研究中小尺度区域内生态资产变化与雨林修复进程的关系，可为规划区生态系统管理办法及生态补偿措施的制定提供科学依据。

4.3.2 结果分析
根据生态系统服务功能价值对不同用地类型进行赋值评估（表5），结合规划前后的用地占比，得出规划区域现状总生态系统服务功能价值为20 152万元；到修复后期，随着热带雨林成林增加，水源涵养、固碳释氧、积累营养物等指标明显提升，生态服务价值可提升至24 557万元（表6）。

5 讨论与结论
在制定修复规划的过程中，项目团队深刻认识到生态修复有别于以往以解决单一问题为导向的生态保护、环境治理、改善生态环境，是一个漫长、复杂且不断变化的生态演变过程，应强调持续培育、动态跟踪。当前团队仅初步完成了规划编制工作，尚未展开动态跟踪以对热带雨林修复手段与方法予以反馈，因此，项目中的动态跟踪举措目前只能停留于技术路线层面。由此大规模的雨林生态修复无论在

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5 © 中国城市规划设计研究院深圳分院
中国还是全球都是首例，本次规划实践是一次实验性探索，项目所积累的以下三大修复经验将为其他东南亚热带雨林地区的生态修复研究与实践提供宝贵经验。

（1）明确热带雨林生态修复阶段

基于恢复生态学理论，森林修复的过程基本可总结为“林隙阶段－建群阶段－成熟阶段”。而热带雨林生态系统物种组成极为丰富，群落结构也更加复杂，因此生态修复的难度和未知性更大。在本次西双版纳热带雨林生态修复实践中，团队总结出从人工橡胶林到热带雨林，修复周期基本可分为“封山育林－清除非雨林成分－建群－演替－生态完善”5个阶段（图16）。

首先采取人工措施封山育林，停止人类对热带雨林生态系统的干扰，为热带雨林的修复奠定环境基础；其次，结合地形条件，按照一定砍伐比例分批逐步清除部分人工橡胶林或非热带雨林成分，使其演替为热带雨林树种；第三，通过建群种植物修复法、先锋植物修复法、协助自然再生修复法、立体复合型修复法等提高生态系统的恢复能力。
留空间以为热带雨林成分的发展创造前期生境；在此基础上，根据计划所要恢复的热带雨林群落类型，补植必要的群落建群种或关键种，通过维持适当的种群数来营造热带雨林生境，保持合理的群落结构；经过多样植物群落的更替和发展，形成更为复杂、稳定的热带雨林群落和生境；在后期对雨林进行完善和管理，补植群落中其他层次的乔木种类，以提高热带雨林群落结构的丰富性和合理性。

（２）动态修复，创造新境

热带雨林的生态系统具有不可逆性，随着气候变化、关键物种丧失和新物种入侵，意图完全恢复某一历史状态几乎是不可实现的[18]。因此，应当根据动态修复规律，不断调整修复方法，通过恢复其部分结构与功能来创建新的生境，以达到一种新的动态平衡。

（３）建立修复评估和管理机制

热带雨林生态修复需要建立一个健全持续的跟踪评估和管理机制，以在不同修复阶段评价生态系统是否保持稳定且可持续，土壤条件是否得到改善等[19]。例如，哥伦比亚的热带雨林历经190年才恢复到接近原始森林的群落结构。从前期的调查、规划、实施、管理和后期维护与修复评估，均离不开对热带雨林的长期监测与研究[20]。
1 Project Background and Problems

The Xishuangbanna tropical rainforest, typical with its seasonal features among China’s existing tropical rainforests, grows under extreme conditions of comparatively higher latitude and altitude. It is ranked as one of the richest biodiversity areas in China with an average biomass of 462.84 t/ha. Early in the 21st century, the coverage rate of rainforest in Xishuangbanna has declined by 25% from 55% in the 1950s. Worse, only half of the tropical rainforests scattering as “forest islands” in the large-scale degraded habitats are under protection. At the beginning of 2017, the local government of Jinghong in Xishuangbanna Dai Autonomous Prefecture, Yunnan Province launched the restoration project of an 80-square-kilometer planted rubber forest in northern Sanda Mountain. This demonstrative project of national eco-functional zone explores the symbiosis between human and nature by reconnecting the ecological corridors.

Sanda Moutain, once with a continuous pristine rainforest landscape, is now confronting with two severe challenges:

1) Fragmented ecosystem: According to the satellite remote sensing data indicating the changes in land use (Fig. 1) and landscape ecological pattern of the Xishuangbanna area from 1990 to 2015, the regional ecological pattern is fragmenting (more eco-patches but smaller in the average size), with an increase of farmlands and a decline of forests. Among these changes, the reclamation of lands for agriculture and rubber plantation has significantly encroached on the original forest ecosystem. For instance, the 2,470-square-kilometer forest in the Xishuangbanna National Nature Reserve is now separated into 5 areas, which heavily weakens the ecological value of rainforests as the diversity of native rainforest species is diminished, impeding gene flows as well. In the larger ecological pattern of Xishuangbanna, Sanda Mountain is a key linkage connecting the Wild Elephant Valley Nature Reserve and Xishuangbanna Primeval Forest Park (Fig. 2) yet suffering from ecological damages in ecological corridor connectivity and vegetation community structure caused...
2 Targets and Technical Framework of Rainforest Ecological Restoration Planning

Tropical rainforest restoration is a time-consuming and complicated process\(^2\), which requires a dynamic adaptation to the changing environment. The core of this process is to restore the structure and services of ecosystems, instead of recovering its appearance. Widely reviewing related practices at home and abroad, the project team proposed a diversified and dynamic restoration roadmap, ranging from individual patch restoration to eco-corridor re-establishment, to realize an overall ecological improvement by reconstructing rainforest vegetation community basing on the existing habitat conditions and increasing species diversity. Considering the complex and changing tropical rainforest habitat conditions, the team proposed to dynamically evaluate and monitor the ecological restoration efficiency along the implementation process, in order to adjust technical methods constantly (Fig. 5).

3 Ecological Restoration Strategies

3.1 Exploration of Diverse Restoration Methods

The methods applied in tropical rainforest restoration differ from each other as they have to suit the site locality that is impacted by several ecological factors such as topography, landform, climate, altitude, soil, vegetation, humidity, and human interventions\(^3\). Therefore, the project team first evaluated the site with weighting analyses on the ecological...
Factors, according to which the study area was divided into four zones and treated with different restoration methods, i.e., introducing constructive plant species, introducing pioneer plant species, introducing mixed plant species, and facilitating the natural regeneration of vegetation community (Fig. 6)\(^6\).

### 3.1.1 Introducing Constructive Plant Species

Constructive plant species can be used to dominate the tropical rainforest community structure and help re-establish a rainforest ecosystem within a short time. This approach was adopted to the valleys where the existing slope, soil, and humidity conditions are suitable to a quick growth of constructive species. Specifically, the upper layer included typical tree species, such as *Parashorea chinensis*, *Pometia tomentosa*, and *Terminalia myriocarpa*, and the lower layer may also constitute a diverse vegetation structure, as well as ground-covering species. Through a precise planning design, the valley rainforest is expected to get gradually restored with rich plant species, multiple layers, and high-density canopy in a relatively short period of time (Fig. 7).
覆被
Vegetation covering

空地
Open area

修复区域
Area under restoration

新林
New formed forest

季风常绿阔叶林
Monsoon evergreen broad-leaf forest

热带果园
Tropical orchard

橡胶林
Rubber forest

新生境
New formed habitat

荒地
Wasteland

2017

2018

2019

2020

2022

2027

2047

74% 覆被 Vegetation covering
24% 新林 New formed forest
2% 空地 Open area

50% 覆被 Vegetation covering
24% 新林 New formed forest
25% 修复区域 Area under restoration
1% 空地 Open area

40% 覆被 Vegetation covering
60% 新林 New formed forest

22% 季风常绿阔叶林
Monsoon evergreen broad-leaf forest

5% 热带果园 Tropical orchard

47% 橡胶林 Rubber forest

24% 新生境 New formed habitat

2% 荒地 Wasteland

24% 季风常绿阔叶林
Monsoon evergreen broad-leaf forest

4% 热带果园 Tropical orchard

22% 橡胶林 Rubber forest

24% 新生境 New formed habitat

25% 修复区域 Area under restoration
1% 空地 Wasteland

32% 季风常绿阔叶林
Monsoon evergreen broad-leaf forest

3% 热带果园 Tropical orchard

5% 橡胶林 Rubber forest

60% 新生境 New formed Habitat
3.1.2 Introducing Pioneer Plant Species

Pioneer plant species, such as Betula alnoides, Acacia mangium, and Paramichelia baillonii, were selected in the restoration of the ridges, steep terrains, and other areas of poor growing conditions, to shade other tropical rainforest plants later introduced and facilitate the succession from pure rubber forest to a mixed forest on the ridges. In such areas, human interference such as rubber tapping and deforestation should be restricted. Planting other species of trees, vines, and groundcovers when the local climate and soil conditions are suitable may also help increase the forest stands and ultimately restore the mountain ridge rainforests (Fig. 8).

3.1.3 Introducing Mixed Plant Species

The mixed-species planting mode of restoration was employed in the areas with high-yielding orchards (Mangifera indica, Camellia sinensis, etc.) and rubber forests. Using methods such as eco-agriculture and vertical planting, part existing orchards can be replaced with valuable economic trees while remaining rubber forests to establish compound ecological forest communities. This approach will significantly enhance the local biodiversity, improve ecological services, and increase economic benefits in a short period of time (Fig. 9).

3.1.4 Facilitating the Natural Regeneration of Vegetation Community

The method of facilitating the natural regeneration of vegetation community is to protect forest competent to realize self-recovery and accelerate the succession towards the desired vegetation community with proper human interference. This method may also help alleviate the competition between trees with weeds and avoid disturbance. To the areas of better water and humidity conditions and more secondary forests, the project team took measures of closing hillsides to protect existing forest and planting individual or a cluster of tropical rainforest saplings (e.g., Dipterocarpus gracilis and Dipterocarpus tonkinensis) in gaps to promote positive succession. Though time-consuming, this method is superior to others for its low cost and low-tech practice (Fig. 10).

3.2 Dynamic Restoration and Succession

An overarching tropical rainforest restoration strategy that covered specific objectives at varied scales aimed to realize an overall ecological improvement, with consideration of the rugged and steep geographic features of Sanda Mountain. The first step was to supplement tropical rainforest tree species in part of the existing tropical rainforest to improve the forest stand structure. Secondly, restoration priority was given to areas with better site conditions so as to restore simple ecological chains and vegetation communities in forms of scattered small tropical rainforest patches. Next, these patches could be connected with valleys to form the ecological spine, establish a holistic ecological chain, and recover eco-corridors in the tropical rainforests, which could promote wildlife migration and exchange between habitats. Finally, an ecological network was created by linkage patches, valleys, and eco-corridors.
### 表1: 规划近期碳储量变化（2020~2025年）

| 用地类型       | 地上碳库（MgC） | 占比（%） | 地下碳库（MgC） | 占比（%） | 土壤有机碳（MgC） | 占比（%） | 死亡有机碳（MgC） | 占比（%） | 总碳储量（MgC） |
|-----------------|----------------|----------|----------------|----------|------------------|----------|----------------|----------|----------------|
| 水系及建筑用地 | 0              | 0        | 0              | 0        | 0                | 0        | 0              | 0        | 0              |
| 荒地            | 0              | 0        | 0              | 0        | 0                | 0        | 0              | 0        | 0              |
| 农业用地       | 4.96           | 0.02     | 0.31           | 0.01     | 6.10             | 0.03     | 0.17           | 0        | 11.54          |
| 灌木林         | 2808.69        | 13.40    | 464.91         | 18.65    | 3719.26          | 17.07    | 291.67         | 16.60    | 7284.53        |
| 经济林         | 4880.01        | 22.56    | 494.16         | 19.82    | 5806.39          | 26.65    | 418.91         | 24.50    | 11599.46       |
| 热带雨林       | 4738.60        | 31.20    | 11148.00       | 46.05    | 6084.41          | 27.93    | 716.55         | 38.10    | 14487.56       |
| 新植幼林       | 7099.95        | 32.82    | 385.60         | 15.47    | 6169.70          | 28.32    | 367.29         | 20.80    | 14022.55       |
| 总碳储量       | 21532.21       |          | 2492.98        |          | 21785.86         |          | 1794.59        |          | 47605.64       |

### 表2: 规划远期碳储量变化（2020~2050年）

| 用地类型       | 地上碳库（MgC） | 占比（%） | 地下碳库（MgC） | 占比（%） | 土壤有机碳（MgC） | 占比（%） | 死亡有机碳（MgC） | 占比（%） | 总碳储量（MgC） |
|-----------------|----------------|----------|----------------|----------|------------------|----------|----------------|----------|----------------|
| 水系及建筑用地 | 0              | 0        | 0              | 0        | 0                | 0        | 0              | 0        | 0              |
| 荒地            | 0              | 0        | 0              | 0        | 0                | 0        | 0              | 0        | 0              |
| 农业用地       | 4.96           | 0.01     | 0.31           | 0.01     | 6.09             | 0.02     | 0.31           | 0.01     | 11.66          |
| 灌木林         | 2808.65        | 7.93     | 464.92         | 11.52    | 3719.39          | 14.40    | 533.64         | 13.63    | 7526.41        |
| 经济林         | 4879.79        | 13.78    | 494.16         | 12.25    | 5806.11          | 22.48    | 766.41         | 19.57    | 11946.81       |
| 热带雨林       | 27710.56       | 78.27    | 3075.92        | 76.23    | 16302.02         | 63.10    | 2614.94        | 66.79    | 49703.77       |
| 总碳储量       | 35403.95       |          | 4035.31        |          | 25834.27         |          | 3915.32        |          | 69188.85       |
providing routes for the flora and fauna to inhabit. With all these strategies, tropical rainforests of a high biodiversity can successfully return from the single-structure rubber forests (Fig. 11 ～ 13).

4 Benefit Assessment after the Restoration
Considering the significant role of tropical rainforest ecosystem played in maintaining global carbon balance and regional biodiversity, the project team quantitatively estimated the changes in carbon storage, habitat quality, and ecosystem service value before and after ecological restoration to evaluate the ecological benefits of restoration.\(^{[7][8]}\)

4.1 Assessment of Carbon Storage Changes
4.1.1 Calculation Methods and Processes
Adopting the Carbon Storage and Sequestration Model of InVEST (Integrated Valuation of Ecosystem Services and Tradeoffs) jointly developed by Stanford University, World Wide Fund for Nature, and the Nature Conservancy\(^{[9]}\), the team estimated the changes and spatial distribution of carbon storage of the study area before and after the planning, to inform the follow-up protection and restoration measures. Four carbon pools, i.e., aboveground biomass, underground biomass, soil, and dead organic matter, were selected to evaluate the carbon storage of different land use types within the study area.

With the Carbon Storage and Sequestration Model, the capacity of carbon storage is calculated by multiplying the area of classified land use and its corresponding carbon density; and the total capacity of carbon storage will be obtained by summing them up. Following this rule, the study determined seven land use types in both the short-term (2020-2025) and long-term (2020-2050)\(^{[3]}\) planning according to the data of the Planning and Design of Forest Resources Inventory of Jinghong City\(^{[10]}\) and interviews, fieldwork, and literature review; the carbon densities of four carbon pools were identified basing on the carbon density of forest ecosystem in Yunnan Province estimated by Yan Teng et al.\(^{[11]}\) After inputting these two types of initial data to the InVEST Model and processing the raster data in ArcGIS, the project team obtained an assessment of each grid’s carbon storage and weighted each land use type with their corresponding valuation. Finally, the total carbon storage and their changes before and after implementing the short-term or long-term planning were simulated.

4.1.2 Result Analyses
The simulation results indicated that the carbon storage of current rubber forest is about 42,259.32 MgC, accounting for 83.5% of the total carbon storage in the planning area. Once completing the patch restoration, the area of tropical rainforest will double with about 5 square kilometers of restored rainforest. Meanwhile, the total carbon storage of the economic forests will decrease sharply from 50,609.60 MgC to 47,605.64 MgC (Table 1, Fig. 14). In the long-term planning, when the saplings grow into a mature rainforest with complex biological structure, the total carbon storage will reach 69,188.85 MgC, 36.4% higher than the current level (Table 2, Fig. 14).\(^{[12]}\)

4.2 Habitat Quality Assessment
4.2.1 Calculation Methods and Processes
The habitat quality reflects the suitability extent of an

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③ Usually, the succession cycle of a tropical rainforest is around 5 years, while the succession from a planted rubber forest and other forest stands would take a much longer time that is usually witnessed around 30 years. Thus, this study prepared a short-term planning and a long-term planning for five and thirty years respectively. Meanwhile, after interviewing with local experts in tropical rainforest and substantial literature review, the team formulated the land use types in the short- and long-term planning, which differed from the land use types in conventional land use planning.
ecosystem for human living and production activities in a certain time period and spatial range. With the land use data in short-term and long-term planning, the project team employed the Habitat Quality Model of InVEST to calculate the habitat quality index of the two time spans, to reveal the impacts of land use changes on the habitat quality\(^{[13]}\).

The mapping of habitat quality, according to the data of land use and the threatening factors in the Habitat Quality Model, is conducted to evaluate the habitat quality by examining the threatening factors’ scope and weight of impact (Table 3), the sensitivity coefficient of habitat to threatening sources, etc. (Table 4). Six categories of data were used in this model: the current and planned land use coverage, threatening factors (cities, villages, roads, mines, and projected roads) and their impact scope and habitat sensitivity coefficients, and the maps of forest protection level by the Planning and Design of Forest Resources Inventory of Jinghong City\(^{[10]}\).

4.2.2 Result Analyses

According to the simulation result which evaluated the five ecological threatening factors and their impact scopes, the high- and low-quality habitats within the study area were identified. Comparatively, the planned roads may largely impact the habitat quality index in that the area of high-quality habitat decreased by 7.84 km\(^2\) to 12.02 km\(^2\) and the area of medium- and low-quality habitats increased from 10.32 km\(^2\) to 11.55 km\(^2\). However, the habitat quality index of the northeast and the central areas of less rural construction was significantly improved, seeing an increase of original rainforest area from 5.82 km\(^2\) to 12.42 km\(^2\). As a result, the overall habitat quality may witness an improvement through the long-term restoration (Fig. 15).

4.3 Ecosystem Service Evaluation

4.3.1 Calculation Methods and Processes

The value of ecosystem services refers to the benefits that human beings get directly or indirectly from the ecosystem, mainly including material and energy input to human socio-economic systems, the absorbance and transformation of waste from the systems, and the services directly provided to human societies.\(^{[14]}\)

Adopting the evaluation methods from the assessment of the forest ecosystem services evaluation in China by Lu Shaowei et al.\(^{[15]}\), seven indicators, including provisioning service, water conservation, carbon sequestration and oxygen release, nutrient accumulation, soil conservation, air...
purification, and biodiversity improvement, were selected to evaluate the ecosystem service value of each land use type before and after restoration, in accordance with the research findings from Dynamic evaluation on ecosystem service values of Xishuangbanna, Yunnan, China by Yu Xiaoxin et al.\textsuperscript{[16]} Moreover, the research on the correlation between ecological asset changes and rainforest restoration processes in medium- and micro-scale areas may provide scientific evidence for the decision-making on ecosystem management and ecological compensation in the study area.
4.3.2 Result Analyses

According to the evaluation of ecosystem services of different land use types (Table 5), as well as the corresponding area proportion, the existing total ecosystem service value of the study area is CNY 201.52 million. In the later stage of restoration, this number might increase to 245.57 million (Table 6) while the indicators of water conservation, carbon sequestration and oxygen release, and nutrient accumulation may increase considerably as the extension of tropical rainforest[17].

5 Discussion and Conclusions

Through this restoration planning practice, the project team corroborate that ecological restoration, compared with single-purpose ecological conservation, environmental management, and ecological improvement, is a time-consuming, complicated, and dynamically evolving process which requires continuous efforts in forest cultivation and monitoring. This planning project at present has just finished its preparation of planning schemes; as the ecological restoration implements and monitoring starts, associated data will be collected to inform the adjustment of the technical framework and roadmaps. Still, this project shows an exploratory significance in large-scale rainforest ecological restoration, either in China or globally, and may provide illumination for other explorations of tropical rainforest areas in Southeast Asia.

(1) Stages of Tropical Rainforest Ecological Restoration

Generally, the process of forest restoration includes the Gap Phase, Building Phase, and Maturity Phase according to the theory of Restoration Ecology. However, considering the ecosystem’s extremely high biodiversity and complex community structure, the project team proposed a five-stage restoration process — closing the hillsides for afforestation, removing non-rainforest components, re-establishing communities, facilitating succession, and improving the ecosystem — to deal with the unknown challenges in ecological restoration from planted rubber forests (Fig. 16).

First, the strategy of closing the hillsides for afforestation may prevent tropical rainforest ecosystem from human interference in order to minimize disturbance for the restoration. Secondly, through a scheduled removal of planted rubber forests and non-tropic rainforest components with topographical considerations, preliminary rainforest habitats will be created. Thirdly, constructive or key species necessary for vegetation community establishment should be introduced and maintained to form a sound structure
of tropical rainforest habitats. After years of succession, these vegetation communities will grow into rich-layered and stable tropical rainforests. Finally, actions should be taken to improve and manage the tropical rainforests by introducing more tree species to improve the structure of these rainforest communities.

(2) Creating New Habitats through Dynamic Restoration Methods

Tropical rainforest often undertakes irreversible ecosystem changes. Under the risks of climate change, key species loss, and species invasion, it is impossible to restore the ecosystem to any historical state. Instead, practices should constantly adjust the restoration methods on ecosystem structures and services to create new habitats so as to achieve a new dynamic balance within the ecosystem.

(3) Restoration Evaluation and Management Mechanism

A monitoring system is also essential to evaluate and manage tropical rainforest restoration on each stage, ranging from overall assessments on the ecosystem stability and sustainability to single-factor examination on soil conditions. For instance, it took about 190 years for Colombia to restore its tropical rainforest back to an ecosystem with a primeval-forest-like community structure. Thus, a long-term monitoring and research onto the tropical rainforest should cover the preliminary investigation and planning, the implementation and management of restoration methods, and finally the maintenance and evaluation on the restoration performance.

PROJECT INFORMATION

LOCATION: Jinghong City, Dai Autonomous Prefecture of Xishuangbanna, Yunnan Province, China
AREA (SIZE): 85 km²
CLIENT: Jinghong Municipal Housing and Urban-Rural Development Bureau
LANDSCAPE ARCHITECTURE: China Academy of Urban Planning & Design Shenzhen
CHIEF PLANNER: Zhu Rengyu
PROJECT TEAM: Lao Bingli, Zhuo Weide, Ren Jing, Chen Kan, Wang Zejian
COLLABORATOR: Shenzhen Long Chace Region Planning & Design Co., Ltd.
PLANNING PERIOD: 2017 to present

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