PROJECT

"Reconstruction and sustainable management of degraded forest based on the combination of inter-planting nitrogen fixation rare tree species and thinning"

FOREST ECOLOGICAL AND ECONOMIC ASSESSMENT REPORT

Bos Thom village, Knapor commune, Sotrnikum District, Siem Reap Province

30 July 2022

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1 Overview of the project

The project “Improvement and sustainable management of degraded forests based on replanting nitrogen-fixation precious tree species and thinning” was funded by APFNet from January 2019 to June 2022. This project was conducted in Bos Thom village, Knapor commune, Sotrnikum District, Siem Reap Province, Cambodia. This assessment report is to evaluate the forest ecological and economic benefits at the end of the project by monitoring the sampled plots in 50 hectares of degraded natural forest (referred to as "demonstration area”).

1.1 Natural condition

The demonstration area is in the northern Cambodia (40"11'104°E, 35"26'13°N), about 32 km away from Siem Reap City. The forest type of this region is a naturally mixed forest of evergreen and deciduous species, with a total area of 445 ha (194 ha forests with trees, 207 ha of sparse saplings, and 44 ha of grassland or vacant lot).

The climate is a tropical monsoon climate. The mean annual temperature is 28.2℃, and the annual rainfall is 1500~2000 mm. Rainy season is from May to October, which accounts for about 75% of the total annual rainfall, while dry season is from November to next April. The land is plain with an altitude of 50 ~ 80 m. Soil belongs to alluvial red-yellow Podzols. Soil is sandy and has poor abilities of water and nutrient conservation.

1.2 Forest management status

The demonstration forest is close to the community, about 1 km away in distance, and it is very convenient to enter the forest. Due to lack of scientific forest management techniques and forest protection policy and awareness, local people have cut down a large number of trees to obtain wood product and firewood. This leads to out-of-order development and utilization of community forest, declined forest quality , many large forest gaps and no wood to cut in forests. Furthermore, forest biodiversity decline and soil dry, harden or desertification appeared in some areas, forest ecosystem functions and productivity were heavy degraded, the number of large-sized and high-quality trees and the ecological and economic value declined dramatically.

1.3 Characteristics of three types of forest

According to forest macroscopic features, stand structure and intensities of human disturbance the forests in the demonstration area is divided into three forest management types: severely degraded forest, moderately degraded forest, and mildly degraded forest,. The structural characteristics of each forest type are as follows:

A Severely degraded forest (Type A): The forest is the most strongly disturbed by human activities. The trees in the community are almost cut down with a forest canopy density lower than 0.2. Regenerated low-growing trees, shrubs and heliophilous weeds are the main vegetation. The height of community is low with regenerated tree layer lower than 5 m. Plant diversity is not high, shrub and herb layers account for most of them and large glades formed **(Figure 1).** The soil is sandy, poor in water and fertilizer conservation, low organic matter content on the topsoil, mildly harden and short of potassium, sodium, calcium, magnesium and other cations.

Figure 1 Severely degraded forests

B Moderately degraded forest (Type B): The forest is greatly disturbed by human activities. It is sparse forests without no tall trees, which is formed after forest destruction. The community is mainly consisted of low-growing trees, regenerated s trees and shrubs from sprouts and seeds with a canopy density of 0.2-0.6. The vegetation species are relatively rich. The coverage density of herbaceous layer is significantly lower than that of severely degraded type **(Type A, Figure 2).** Soil degradation is not obvious and the organic matter content in topsoil is normal.

Figure 2 Moderately degraded

C Mildly degraded forest (Type C): The forest is less disturbed by human activities and rich in tree species. The forest structure is similar to that of virgin forests and developed lianas are observed in stand. Only a few large

Figure 3 Mildly degraded forests

trees with high wood utilization value are cut down in the community. The canopy density is higher and could reach 0.6~0.9 **(Figure 3).** Soil physical and chemical properties are not significantly different from those of virgin forests.

1.4 Management objectives and technical keys of the three types of forests

A. Management of severely degraded forest (Type A)

Dalbergia Cochinchinensis, Pterocarpus macrocarpus, Afzelia Xylocarpa, Cassia Siameca and other native and valuable nitrogen-fixation tree species were adopted to plant in sparse forests because of their faster growth and high economic value and benefits to the rapid improvement of forest structure and economic value.

Double-row strip planting method is used, and some native vegetation are retained in the strip during afforestation. The planting density is 1430 stems·ha^{-1} with a planting spacing 2 m × 2 m in the planting strip **(Figure 4).** The planting pit was 50 cm × 50 cm × 30 cm in size. This type of afforestation is completed in June 2019 with a total area of 5 ha.

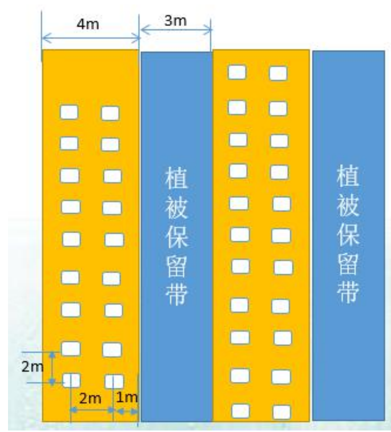

Figure 4 Schematic diagram of strip cleaning and planting site distribution

The purpose of such management is to make the bare land quickly restored by tree, shrub and grass and give play to the role of forest ecological service as soon as possible. Meanwhile, forest economic performance was improved and the goal of efficient and sustainable forest management and utilization are finally realized.

B. Management of moderately degraded forest (Type B)

A certain area of forest gaps is constructed, and some target tree species are replanted within the gaps for moderately degraded forests (the tree species selected for replanting was similar to type A).

Forest gaps are about 6 m in diameter and 10 m in

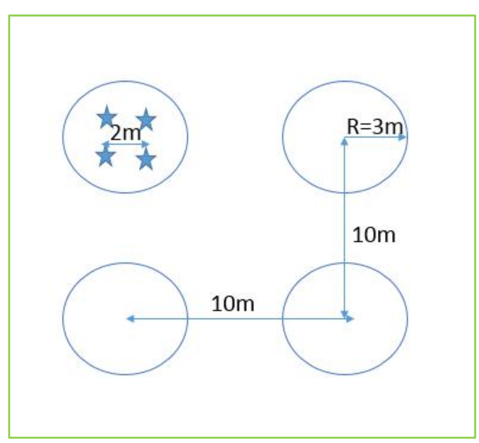

Figure 5 Schematic diagram of gap planting site configuration

distance between gaps **(Figure. 5).** Before replanting, the vegetation in forest gaps should be properly cleared, only trees with high value were retained. Land preparation method and specification are the same as type A, and 4 saplings are planted in each forest gap.

The purpose of such management is to adjust the structure and composition of low-quality forests, form a perfect community with multiple layers including tree, shrub and grass, restore the degraded forest gradually to a complex uneven-aged mixed forests, and then further improve the stand stability, quality and productivity.

C. Management of mildly degraded forest (Type C)

In the mildly degraded forests, three to five constructive tree species, including *Peltophorum dasyrrhachis, Anisoptera costata, Pterocarpus macrocarpus, and Sindora Cochinchinensis*, with high economic value are selected as crop trees for cultivation. Principles of not destroying the structure of present forests, increasing the proportion of high-value tree species gradually, and using natural resilience to realize the normal forest function are adopted in the management process.

The management objective is to conserve the construction and target tree species, promote the growth and development of crop trees, reduce the influence of non-crop tree species on the direction of forest succession, promote the restoration of degraded forest ecosystems and increase their economic utilization value.

2 Methods of investigation and assessment

At the beginning of the project, background investigation is conducted. The demonstration forest is divided into severely degraded forest type (hereinafter referred to as type A), moderately degraded forest type (hereinafter referred to as type B) and mildly degraded forest type (hereinafter referred to as type C) according to the degree of human disturbance, plant community structure, and composition of the forest.

In each type, three typical plots with three replicates (9 sample plots) are set up as representative stands for investigation. The sample plot is circular in shape, with a radius of 13.8 m and an area of 600 m^2. A PVC pipe is inserted at the center of the sample plot as a mark. The growth of replanted seedlings and remaining trees, stand structure and diversity, soil physical and chemical properties are investigated in December 2018 and January 2022, respectively.

2.1 Quality changes of forest resources

Tree height, DBH, survival rate and proportion of each replanted tree species are investigated after the project.

Tree height and DBH of each tree with DBH ≥5cm in the sample plot are investigated before and after the project, tree species composition, diameter class structure and stand volume are also calculated. Formula of stand volume was: $V=0.667054\times10^{-4}D^{1.84795450}H^{0.96657509}$.

In mildly degraded forest types, trees with obvious growth advantages, such as tall, straight, well-branched and high economic utilization value, are selected as crop trees, and a circle is marked at the breast height with red paint.

2.2 Changes in forest biodiversity

One sample plot (5 m × 5 m in size, for saplings and shrub layer) and four plots (2 m × 2 m in size, for herb layer) are set up at the beginning of the implementation of the project, mean height, abundance, coverage and plant diversity index are investigated in each sample plot, such as Margalef richness index, Shannon-wiener diversity index, Simpson dominance index and Pielou evenness index.

2.3 Variation of soil physical and chemical properties

In December 2018, a soil profile with a depth of 0.6 m was randomly dug in each plot, and then soil was collected at three layers of 0-20 cm, 20-40 cm and 40-60 cm. Soil physical properties (particle content of different particle sizes, water content and texture) and chemical properties (pH, organic matter, total carbon, total nitrogen, total phosphorus, available phosphorus, exchangeable potassium, sodium, calcium and magnesium) were determined. PH was determined by acidity meter, organic carbon was determined by Black&walkey method, soil total nitrogen was determined by Kessner method, total phosphorus was determined by Nitric acid digestion method, available phosphorus was determined by Bray 2 method and cation exchange capacity was determined by ammonium acetate exchange method.

In January 2022, a soil profile with the same depth was dug next to the above one for soil retest in all plots. Because the physical properties of soil were relatively stable, especially the composition of soil particles, only chemical properties were determined.

2.4 Carbon stock estimation of forest ecosystem

2.4.1 Carbon stock at tree layer

Carbon stock was estimated basing on tree biomass of all organs with a coefficient of 0.5. Since tree diversity was higher in natural forests, it was hard to develop biomass equations for all tree species. A representative tree species, *Magnoliaceae glance*, similar to most tree species in stand with well-developed biomass equations ($W_{stem} = 0.0274\ D^2H - 0.7035$； $W_{bark} = 0.0009\ D^2H - 0.1333$； $W_{branch} = 0.0031\ D^2H - 0.314$； $W_{leaf} = 0.0004(D^2H)1.1143$； $Wroot = 0.0043(D^2H)1.0428$) was used to estimate biomass of all tree species.

2.4.2 Carbon stock at shrub and herb layer

Five plots (2 m × 2 m in size) were set up at the middle and four corners of each sample plot, and a sub-plot was also set up in each plot. All the shrubs in the plots and herbs in the sub-plots were harvest for biomass measurement both for below and above ground. Dry biomass was calculated after dried in oven at 65℃. The conversion coefficient between biomass and carbon stock was also 0.5.

2.4.3 Carbon stock at soil layer

Three soil profiles were dug at a representative district in each plot, and about 200 g soil was collected at soil layers of 0-20, 20-40 and 40-60 cm, respectively. Meanwhile, soil was also collected for soil bulk density measurement. Soil collected from the same soil layer in each plot was mixed together, 200 g mixed soil was sampled by quartering method for soil organic carbon content measurement after air drying.

3 Results

3.1 Forest resource quality

3.1.1 Growth performance of replanted species

There were two types of forests, type A **(Figure 6)** and type B **(Figure 7),** replanted with nitrogen fixation species. The planting species was dominated by *Dalbergia Cochinchinensis*, which accounted for 67.3 % of the total number of plant trees in type A and 46.5% in type B. The second largest number of tree species was *Pterocarpus macrocarpus*, which accounted for 26.5% in type A and 32.2% in type B.

The survival rate of afforestation was high, and it reached 91.7% and 89.7% in type A and type B stands, respectively.

Tree height increment of all tree species was at a low level, and the annual increment of tree height was not higher than 0.5 m **(Table 1).** The lower growth performance in the primary period after planted was correlated with the local soil properties and seasonal drought climate.

Figure 6 Growth performance of newly planted saplings in type A forest

Figure 7 Growth investigation of saplings replanted in forest gaps in type B forest

Table 1 Survival and growth of replanted species in type A and type B plots

Forest type	Tree species	Tree age/ year	Survival number	Species ratio%	Total survival ratio%	Heig-ht/m	Annual increment of tree height/m
A	*Dalbergia Cochinchinensis*	3	185	67.3	91.7	1.09	0.36
	Pterocarpus macrocarpus	3	73	26.5		0.69	0.23
	Afzelia Xylocarpa	3	11	4.0		1.02	0.34
	Cassia Siameca	3	6	2.2		1.32	0.44
B	*Dalbergia Cochinchinensis*	2	125	46.5	89.7	0.87	0.44
	Pterocarpus macrocarpus	2	87	32.3		0.73	0.37
	Afzelia Xylocarpa	2	51	19.0		0.78	0.39
	Cassia Siameca	2	6	2.2		0.25	0.13

3.1.2 Structure variation of tree layer in different forest types

Since diameter of most trees in type A forest had not reach measuring diameter (5cm), the tree layer structure did not vary greatly with time, thus it was not investigated in type A. The variation of tree layer structure for type B and type C forests were shown as follows:

(1) **Species composition:** The number of tree species increased from 11 to 13, with an increase of 18.2% in type B stand; while only from 18.3 to 18.7, with an increase of 2.2% in type C stand **(Table 2).** The main reason was that some regenerated trees in type B forest grew up to the measuring diameter.

Table 2 Stand structure and tree growth variation of tree layer in type B and C forests

Factors	B type			C type		
Investigate time	2018.12	2022.1	increase rate %	2018.12	2022.1	increase rate %
Stand density/ha	656	1461	122.7	1356	1372	1.2
Canopy density	0.6	0.7	16.7	0.9	0.9	0.00
Species number	11	13	18.2	18.3	18.7	2.2
Mean DBH /cm	8.81±0.37	9.25±0.39	5.0	12.71±0.95	13.70±1.32	7.8
Mean tree height/m	7.93±1.49	8.16±1.54	2.9	14.77±1.48	15.51±1.56	5.0
Mean stand	18.8±8.1	29.57±8.5	57.3	128.96±13.5	157.69±19.5	22.3

volume/(m^3/ha)	5	6		6	1	

(2) Stand density: Stand density of type B forest increased from 656 ha to 1461 stems per ha with an increase of 122.7%. This indicated that lots of saplings reached the measuring diameter (≥5 cm) during the project implementation, the stand canopy density increased correspondingly, and stand structure developed to a positive direction of succession. Stand density in type C forest increased only from 1356 to 1372 stems per ha with an increase rate of 1.2% **(Table 2).**

(3) Tree diameter class: DBH of all forest types increased slightly. The mean DBH increased by 5.0% and 7.8%, and the mean annual DBH increment was 0.15 cm and 0.33 cm in type B and Type C forests, respectively **(Table 2).** Although the number of crop trees (DBH > 26cm) in type C forest only accounted for 4.3% of the total number of trees, the number of crop trees increased from 40 to 61 stems per ha. The DBH increment of crop trees was much higher than that of all trees in stand, which increased from 25.0 to 28.8 cm, with an annual increase of 1.3 cm. Therefore, it is believed that removal of disturbed trees had significant effects on DBH growth promotion of crop trees.

Tree diameter structure did not vary greatly among all forest types except for the number of trees in measuring diameter class. The proportion of large-diameter trees was low, and that of small-diameter trees was high. Taking type C forest as an example, the diameter class distributions belonged to normal distribution both at the beginning and end of the project **(Figure 8).**

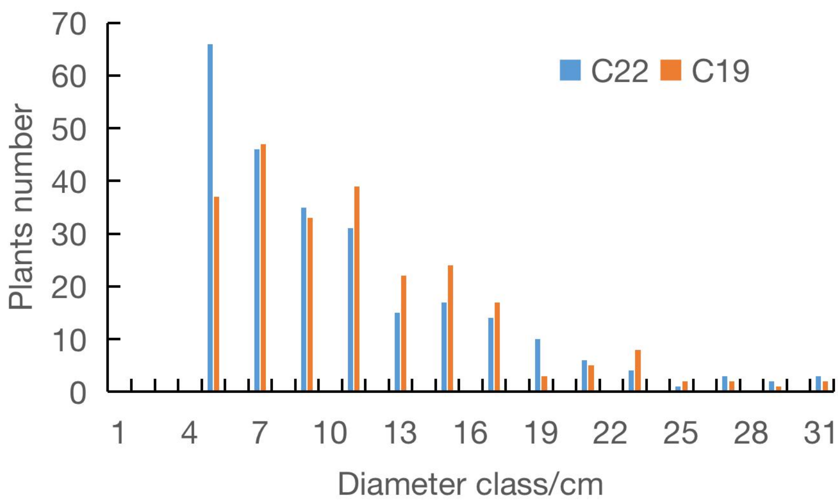

Figure 8. Diameter class distribution of type C forest

Note: C19 and C22 refer to the time of beginning and end of the project respectively

(4) Height increment

The stand tree height was low in sampled plots, and tree height increment was also at a low speed, the mean tree height at beginning and end of the project in type B forest was 7.93 m and 8.16 m respectively, it only increased by 2.9% in 3 years. In type C forest, they were just 14.77 m and 15.51 m, respectively, which increased by 5.0% in 3 years **(Table 2).**

(5) Stand volume increment

In type B forest, since the number of trees reaching the measuring diameter increased rapidly, the stand volume increased from 18.8 to 29.57 m^3 per ha, with an increase of 57.3% in 3 years. The high stand volume increment indicated that this forest type was in a relatively rapid growth speed **(Table 2).**

Stand volume in type C forest increased from 128.96 to 157.69 m^3 per ha, with an increase of 22.3% in 3 years. The mean annual stand volume increment was 9.58 m^3 per ha. This also indicated that this forest type was in a relatively vigorous growth period. Crop tree selection, disturbance trees and some lianas clearing as well as other forest management measures played a very important role in promoting forest growth, increasing forest stand volume and economic value of high-quality trees.

3.2 Forest community diversity

(1) Plant diversity among forest types

The species diversity and habitat diversity decreased with forest degradation degree, they were much higher in mildly degraded forest (type C), then followed by moderately degraded forest (type B) and severely degraded forest (type A) in turn.

Mildly degraded forest had a relatively stable and reasonable community structure, the dominant population in tree layer had strong natural regeneration ability and long-term succession potential. The disturbance degree (human disturbance and natural disturbance) in type A forest was the highest, and the stability, biodiversity, coordination and balance ability of forest community as well as natural restoration ability decreased. Meanwhile, the species and quantity of invasive shrub and grass increased correspondingly. These characteristics can be used as important indicators of forest community biodiversity, disturbance degree and forest health evaluation.

(2) Plant diversity before and after the project

After implementation of the project, there was a great change in biodiversity index of forest plant community. The diversity index increased the most in type A forest and then followed by type B, the diversity index in type C forest was relatively stable **(Table 3).**

The increase of species richness in tree layer was showed as follow, type A (18.2%) > type B (15.4%) > type C (5.9%). The species richness increment in grass, shrubs and lianas layers was presented as follow, type A (33.3%) > type B (9.1%) > type C (0) (Table 3). In type C forest, vegetation coverage of grass, shrubs and lianas as well as species richness decreased slightly due to the removal of disturbing trees and lianas. Furthermore, the increasing canopy density in the upper crown layer and the decreasing light in the lower crown layer were also the potential reasons.

Table 3 Plant diversity index of three forest types

Forest degradation type	Forest layer	Tree layer			Shrubs and grass layer		
Year	diversity index	2019	2022	Increase ratio%	2019	2022	Increase ratio%
A type	S/ Species richness index	11	13	18.2	12	16	33.3
	Shannon-Wiener index	2.21	2.3382	5.8	0.7039	0.7518	6.8
	Simpson index	0.87	0.9266	6.5	0.2669	0.2904	8.8
	Jsw/ evenness index	0.92	0.9642	4.8	0.2833	0.2989	5.5
	Rl/ Species richness index	3.11	3.3526	7.8	1.7378	1.8612	7.1
	λ/ Ecological dominance	0.09	0.0934	3.8	0.7326	0.7656	4.5
B type	S/ Species richness index	26	30	15.4	22	24	9.1
	Shannon-Wiener index	2.84	2.9678	4.5	2.0462	2.1280	4
	Simpson index	0.92	0.9678	5.2	0.8153	0.8544	4.8
	Jsw/ evenness index	0.87	0.9266	6.5	0.662	0.7083	7
	Rl/ Species richness index	5.24	5.4391	3.8	2.9827	3.1110	4.3
	λ/ Ecological dominance	0.07	0.0736	5.1	0.184	0.1928	4.8
C type	S/ Species richness index	34	36	5.9	31	31	0.0
	Shannon-Wiener index	2.94	3.0429	3.5	2.7337	2.6790	-2.0
	Simpson index	0.93	0.9672	4	0.8878	0.8656	-2.5
	Jsw/ evenness index	0.83	0.8765	5.6	0.7961	0.8359	5.0
	Rl/ Species richness index	6.03	6.2712	4	5.9715	6.0014	0.5
	λ/ Ecological dominance	0.07	0.0725	3.5	0.1063	0.1082	1.8

3.3 Physical and chemical properties of the soil

3.3.1 Soil physical and chemical properties before implementation of the project

Table 4 showed that the sand content in each soil layer of the soil profile was high for all forest degradation types, it was between 50.86 to 77.80%. Sand contents decreased significantly with the increment of soil depth, and there was an obvious phenomenon of sand surface aggregation (i.e., serious surface sanding). Sand content was the highest in 0-20cm soil layer, which was 64.78-77.80%, then followed by 20-40 cm and 40-60 cm soil layers, where sand content accounting for 54.54-65.99% and 50.86-65.99%, respectively. Since the soil was sandy soil for all soil layers, water retention in such soil was poor, the highest water content was only 12.30% and the lowest was 5.30%, water content of most soil layers was less than 10%, plant growth was easily suffered from water stress.

Organic matter and total nitrogen contents were high in all soil layers and only minor differences were observed among the three forest degradation types. It presents with the order of C>B>A as a whole. The total phosphorus content in soil was lower than 0.05%, while the available phosphorus content was very high and higher than 200 ppm. The exchange capacity of cation, such as potassium, sodium, calcium and magnesium, were extremely low, the total cation exchange of each soil layer was below 6 C mol/kg **(Table 5).** This indicated that the soil of the project area had poor capacity in fertilizer conservation and supply. In other words, the soil was lack in potassium, sodium, calcium, magnesium.

In conclusion, the soil in the project area was out of balance in nutrients and also easily suffered from water shortage, it was not beneficial for plant growth.

Table 4 Soil physical properties at different layers for the three degraded forest types before implementation of the project

Plot No.	Soil layer cm	Clay particle% <0.002mm	Fine silt % 0.002-0.02mm	Coarse dust % 0.02-0.05mm	Fine sand % 0.05-0.2mm	Coarse-grained sandt % 0.02-2mm	Total sand %	Soil texture
A-1	0-20	11.25	5.65	10.91	39.22	31.74	70.96	Heavy sand
	20-40	29.10	2.05	6.17	34.86	28.27	63.13	Moderate sand
	40-60	30.85	1.05	5.44	32.29	28.55	60.84	Moderate sand
A-2	0-20	11.05	8.05	6.79	34.32	37.84	72.16	Heavy sand
	20-40	31.35	5.00	4.39	25.58	32.79	58.37	Light sand
	40-60	35.45	7.90	4.22	22.72	29.76	52.48	Light sand
A-3	0-20	24.95	11.50	4.82	27.73	31.71	59.44	Light sand
	20-40	32.95	7.95	4.92	26.05	28.49	54.54	Light sand
	40-60	38.10	5.50	6.19	25.30	25.75	51.05	Light sand
B-1	0-20	8.15	8.85	3.36	23.50	54.30	77.80	Heavy sand
	20-40	21.35	4.25	4.41	21.54	47.35	68.89	Moderate sand
	40-60	24.80	3.15	4.68	19.64	46.35	65.99	Moderate sand
B-2	0-20	19.10	8.90	8.06	25.93	36.43	62.36	Moderate sand
	20-40	29.15	5.60	7.69	23.01	32.94	55.95	Light sand
	40-60	36.20	6.10	6.84	22.62	28.24	50.86	Light sand
B-3	0-20	10.55	5.25	5.94	30.98	46.34	77.32	Heavy sand
	20-40	28.40	4.10	5.57	25.76	33.87	59.63	Light sand
	40-60	36.95	3.28	5.15	21.90	32.62	54.52	Light sand
C-1	0-20	14.85	4.95	5.07	29.40	44.42	73.82	Heavy sand
	20-40	31.40	4.65	4.08	22.43	36.46	58.89	Light sand
	40-60	31.85	6.36	3.91	29.60	28.28	57.88	Light sand
C-2	0-20	12.15	4.65	4.28	25.80	50.85	76.65	Heavy sand
	20-40	19.01	8.10	8.78	25.54	39.12	64.66	Heavy sand
	40-60	26.70	5.35	3.81	20.07	42.33	62.40	Moderate sand

C-3	0-20	26.90	8.60	7.62	27.66	37.12	64.78	Moderate sand
	20-40	18.80	8.35	7.41	24.33	32.07	56.40	Light sand
	40-60	35.10	7.75	6.47	20.07	30.99	51.06	Light sand

Table 5 Soil chemical properties at different layers for the three degraded forest types before and after implementation of the project

Plot No.	Soil layer cm	Total carbon%		Increase ratio %	Total nitrogen %		Increase ratio %	Organic matter %		Increase ratio %	Total phosphorus %		Increase ratio %	available phosphorus ppm		Increase ratio %	pH value		Increase ratio %	Total cation exchange capacity c mol/kg		Increase ratio %
		2018	2022		2018	2022		2018	2022		2018	2022		2018	2022		2018	2022		2018	2022	
A-1	0-20	1.60	1.29	-19.38	0.14	0.16	14.29	2.76	2.22	-19.57	0.036	0.054	50.00	25	31	24.00	4.82	5.02	4.15	4.98	3.95	-20.68
	20-40	1.26	1.33	5.56	0.11	0.14	27.27	2.17	2.29	5.53	0.029	0.033	13.79	26	26	0.00	4.77	5.15	7.97	5.17	3.97	-23.21
	40-60	0.92	1.28	39.13	0.10	0.11	10.00	1.59	2.21	38.99	0.025	0.029	16.00	27	25	-7.41	4.75	5.20	9.47	4.36	4.17	-4.36
A-2	0-20	1.55	1.28	-17.42	0.18	0.15	-16.67	2.67	2.21	-17.23	0.041	0.051	24.39	49	30	-38.78	5.47	4.99	-8.78	5.26	3.76	-28.52
	20-40	1.12	1.36	21.43	0.14	0.12	-14.29	1.93	2.34	21.24	0.031	0.035	12.90	27	26	-3.70	5.14	4.93	-4.09	5.39	3.27	-39.33
	40-60	1.21	1.23	1.65	0.11	0.10	-9.09	2.09	2.12	1.44	0.025	0.029	16.00	25	26	4.00	6.62	4.89	-26.13	5.74	2.76	-51.92
A-3	0-20	1.36	1.27	-6.62	0.18	0.16	-11.11	2.34	2.19	-6.41	0.045	0.052	15.56	35	32	-8.57	4.88	4.70	-3.69	4.27	3.21	-24.82
	20-40	0.97	1.31	35.05	0.14	0.14	0.00	1.67	2.26	35.33	0.032	0.04	25.00	25	27	8.00	4.85	4.75	-2.06	4.63	2.77	-40.17
	40-60	1.05	1.24	18.10	0.11	0.11	0.00	1.81	2.14	18.23	0.025	0.029	16.00	24	26	8.33	4.84	4.73	-2.27	5.17	2.80	-45.84
B-1	0-20	1.55	1.60	3.23	0.15	0.14	-6.67	2.67	2.76	3.37	0.034	0.047	38.24	29	29	0.00	5.17	4.95	-4.26	4.8	3.55	-26.04
	20-40	1.40	1.42	1.43	0.11	0.14	27.27	2.41	2.45	1.66	0.032	0.038	18.75	26	26	0.00	4.78	5.02	5.02	4.16	3.94	-5.29
	40-60	1.23	1.38	10.87	0.08	0.12	50.00	2.12	2.38	10.92	0.027	0.039	44.44	25	29	16.00	5.30	4.86	-8.30	4.37	2.82	-35.47
B-2	0-20	1.88	2.21	17.55	0.16	0.14	-12.50	3.24	3.81	17.59	0.039	0.035	-10.26	32	28	-12.50	4.90	4.75	-3.06	4.77	3.22	-32.49
	20-40	1.44	1.63	13.19	0.10	0.14	40.00	2.48	2.81	13.31	0.029	0.031	6.90	26	22	-15.38	5.44	5.03	-7.54	4.73	2.72	-42.49
	40-60	1.30	1.31	0.77	0.10	0.10	0.00	2.24	2.26	0.89	0.027	0.032	18.52	27	26	-3.70	5.31	4.88	-8.10	5.53	2.59	-53.16
B-3	0-20	1.62	2.09	29.01	0.14	0.15	7.14	2.79	3.60	29.03	0.030	0.05	66.67	28	29	3.57	4.45	4.69	5.39	4.62	2.88	-37.66
	20-40	1.47	1.56	6.12	0.09	0.14	55.56	2.53	2.69	6.32	0.025	0.04	60.00	27	27	0.00	5.09	4.79	-5.89	4.2	2.87	-31.67
	40-60	1.26	1.26	0.00	0.11	0.13	18.18	2.17	2.17	0.00	0.023	0.03	30.43	28	26	-7.14	5.02	4.72	-5.98	4.17	2.67	-35.97
C-1	0-20	1.56	2.02	29.49	0.17	0.14	-17.65	2.69	3.48	29.37	0.026	0.054	107.69	29	29	0.00	4.91	4.93	0.41	4.69	3.30	-29.64

	20-40	1.50	1.49	-0.67	0.14	0.12	-14.29	2.59	2.57	-0.77	0.027	0.038	40.74	28	27	-3.57	4.76	5.04	5.88	4.4	3.74	-15.00
	40-60	1.39	1.45	4.32	0.14	0.12	-14.29	2.40	2.50	4.17	0.024	0.027	12.50	27	26	-3.70	4.85	4.63	-4.54	4.76	2.89	-39.29
C-2	0-20	1.66	1.85	11.45	0.16	0.16	0.00	2.86	3.19	11.54	0.034	0.053	55.88	29	29	0.00	4.47	4.75	6.26	4.6	3.45	-25.00
	20-40	1.35	1.53	11.76	0.14	0.14	0.00	2.33	2.64	11.74	0.027	0.039	50.00	27	30	11.11	5.10	4.72	-7.45	4.19	2.96	-29.36
	40-60	1.12	1.28	14.29	0.11	0.12	9.09	1.93	2.21	14.51	0.024	0.027	3.85	26	28	7.69	4.80	4.50	-6.25	4.08	2.69	-34.07
C-3	0-20	1.70	2.04	20.00	0.18	0.14	-22.22	2.93	3.52	20.14	0.034	0.034	17.24	28	30	7.14	4.74	4.87	2.74	4.82	3.55	-26.35
	20-40	1.60	1.84	15.00	0.16	0.13	-18.75	2.76	3.17	14.86	0.026	0.033	-13.16	30	29	-3.33	4.55	4.44	-2.42	4.64	2.67	-42.46
	40-60	1.45	1.56	7.59	0.14	0.10	-28.57	2.50	2.69	7.60	0.026	0.032	18.52	27	27	0.00	5.48	4.53	-17.34	4.73	2.57	-45.67

3.3.2 Soil chemical properties variation before and after implementation of the project

It can be seen from Table 6 that soil total carbon and organic matter contents had a consistent variation in each soil layer for the three forest degradation types both before and after the implementation of the project, this was mainly caused by the close positive correlation between soil total carbon and organic matter.

Soil total carbon and organic matter contents in 0-20 cm soil layer before afforestation were 19.38% and 19.57% higher than those after the project for type A forest ($P<0.05$, Table 6), the reason was that type A forest was almost new afforestation. Although the land preparation and forest tending would increase the amount of litter, low growth rate of young sapling and weeding lead to the long-time exposure of topsoil to sunlight, which resulted in higher soil temperature and increasing soil microbial and enzymatic activities. Furthermore, scarification further increased soil permeability. Therefore, the increased organic amount in the topsoil was lower than that of decomposed. However, there was no significant difference in 20-40 cm and 40-60 cm soil layers ($P > 0.05$) before and after implementation of the project.

Soil total carbon and organic matter contents were much higher after afforestation in type B forest, but significant differences were absent ($P > 0.05$, **Table 6**). The reason might be correlated with the insignificant increase in growth and litter.

Soil total carbon and organic matter contents in 0-20 cm soil layer were significantly higher in 2022 than that in 2018 for type C forest ($P<0.05$, **Table 7**). This was mainly related to accelerated tree growth after conducting the project, which lead to increased litter amount and organic matter at the surface layer. In addition, soil total carbon and organic matter contents in the other two soil layers both increased after the project, but the difference was not significant ($P > 0.05$).

Table 6 ANOVA analysis of soil chemical properties in different soil layers among three degraded forest types

type	Soil layer cm	year	Total carbon %	Total nitrogen %	Organic matter %	Total phosphorus %	Available phosphorus ppm	pH value	Total cation exchange capacity c mol/kg
A	0-20	2018	1.50±0.13※	0.17±0.02	2.59±0.22※	0.041±0.005	36.3±3.1	5.06±0.36	4.84±0.51※
		2022	1.28±0.01	0.16±0.01	2.21±0.02	0.052±0.002※	31.0±1.2	4.90±0.18	3.64±0.38
	20-40	2018	1.12±0.15	0.13±0.02	1.92±0.25	0.031±0.002	26.2±1.9	4.92±0.19	5.06±0.39※
		2022	1.33±0.03	0.13±0.01	2.30±0.04	0.036±0.004	26.3±0.8	4.94±0.20	3.37±0.60
	40-60	2018	1.06±0.15	0.11±0.01	1.83±0.25	0.025±0.00	25.3±1.6	5.40±1.05	5.09±0.69※
		2022	1.25±0.03	0.11±0.01	2.15±0.05	0.029±0.00	25.7±0.7	4.94±0.24	3.24±0.80
B	0-20	2018	1.68±0.17	0.15±0.01	2.90±0.30	0.034±0.005	29.7±1.8	4.84±0.36	4.73±0.10※
		2022	1.97±0.32	0.14±0.01	3.39±0.56	0.044±0.008	28.7±0.9	4.80±0.14	3.22±0.34
	20-40	2018	1.44±0.04	0.10±0.01	2.47±0.06	0.029±0.004	26.3±0.7	5.10±0.33	4.36±0.32※
		2022	1.54±0.11	0.14±0.00※	2.65±0.18	0.036±0.005	25.0±1.6	4.95±0.14	3.18±0.67
	40-60	2018	1.31±0.06	0.10±0.02	2.26±0.11	0.026±0.002	26.7±1.8	5.21±0.16	4.69±0.73※
		2022	1.27±0.04	0.12±0.02	2.18±0.07	0.034±0.005	27.0±1.7	4.82±0.09	2.69±0.12
C	0-20	2018	1.64±0.07	0.17±0.01	2.83±0.12	0.030±0.004	28.7±0.8	4.71±0.22	4.70±0.11※
		2022	1.97±0.10※	0.15±0.01	3.40±0.18※	0.047±0.011	30.0±0.0※	4.85±0.09	3.43±0.13
	20-40	2018	1.54±0.05	0.15±0.01	2.66±0.09	0.030±0.007	28.3±0.4	4.80±0.28	4.41±0.23※
		2022	1.56±0.25	0.13±0.01	2.69±0.43	0.037±0.003	28.7±1.5	4.73±0.30	3.12±0.55
	40-60	2018	1.32±0.18	0.13±0.02	2.28±0.30	0.026±0.002	26.7±0.7	5.04±0.38	4.52±0.38※
		2022	1.43±0.14	0.11±0.01	2.47±0.24	0.029±0.003	27.0±0.8	4.55±0.07	2.72±0.16

The total cation exchange in each soil layer was significantly higher in 2018 than that in 2022 ($P<0.05$, **Table 5-6**), since the increased tree number, tree growth and stand volume after the project resulted in increasing absorbed soil nutrients. This would reduce the concentrations of K^{+}, Na^{+}, Ca^{2+}, Mg^{2+} and other cations in soil. Cationic desorption would occur at the surface of soil colloid in order to maintain the balance between solid and liquid phases. However, the soil cation exchange capacity was too low in this study, and the buffer capacity was weak. It was hard to replenish the cation exchange in time.

Total phosphorus content in 0-20 cm soil layer was significantly higher in 2022 than that in 2018 for type A forest ($P<0.05$, **Table 5-6),** this may be caused by the increment of litter amount after afforestation. However, no significant difference was found in other soil layers. In addition, total nitrogen, available phosphorus contents and pH values showed no obvious regularity and there was no significant difference before and after the project ($P > 0.05$).

3.4 Forest carbon storage variation

3.4.1 Carbon storage variation in tree layer

This project only studied vegetation carbon storage in type B and type C degraded forests. There were mainly three reasons: **1)** Although the afforestation site located in the tropical areas and was of high temperature and rainy climate, and the trees selected for afforestation were all native and fast-growing nitrogen-fixation species, which should have a high growth rate, the present annual tree height increment was less than 0.5 meters, so the carbon storage increased from young forest was extremely limited. **2)** A large number of shrubs and grasses were removed every year in forest tending of young forests. Carbon emissions from litter and top soil would increase due to strong human disturbance, so it is impossible to accurately estimate the carbon loss caused by the young forest ecosystem. **3)** Carbon storage estimation error was high for young forests less than 3 years old and it made little sense. Additionally, disturbed trees or trees with low value, pressure and poor shape were cleared during the process in type B and C forests, which increased the amount of abnormal litter. Therefore, the carbon storage of litter layer was not studied either.

ANOVA results showed **(Table 7-8)** that the carbon storage of all organs for type C forest was significantly higher in 2022 than that in 2018 ($P < 0.05$), while there was no significant difference in type B forest ($P > 0.05$). For type C forest, the mean carbon storage increases of tree trunk, bark, branches, leaves and root were 5.80, 0.81, 0.54, 0.17 and 1.28 tons/ha, respectively, which was an increment of 20.16%, 20.08%, 20.29%, 20.01% and 20.14% in proportion.

In addition, the carbon storage increment in type C forest was much higher than that in type B forest, while the increasing proportion of carbon storage showed an opposite result. This is mainly due to the fact that type B forest was moderately degraded and the tree layer was severely damaged. Carbon storage of all organs in tree layer is generally low at beginning of the project. It was only about 1/7 of that in type C forest. Therefore, the increasing proportion in carbon storage was high because of the low carbon storage amount at beginning **(Table 7-8).**

Table 7 Carbon storage variation in each organ at tree layer for type B and C degraded forests

Forest type	Organ	Treatment	Carbon storage ton/ha		Carbon storage increment after afforestation	
			2018	2022	ton/ha	%
C type	Trunk	C1	28.54	35.28	6.74	23.62
		C2	28.77	34.61	5.84	20.30
		C3	28.98	33.78	4.80	16.56
		Average	**28.76**	**34.56**	**5.80**	**20.16**
	Bark	C1	3.99	4.93	0.94	23.56
		C2	4.02	4.83	0.81	20.15
		C3	4.05	4.72	0.67	16.54
		Average	**4.02**	**4.83**	**0.81**	**20.08**
	Branch	C1	2.66	3.29	0.63	23.68
		C2	2.68	3.23	0.55	20.52
		C3	2.70	3.15	0.45	16.67
		Average	**2.68**	**3.22**	**0.54**	**20.29**
	Leaf	C1	0.83	1.02	0.19	22.89
		C2	0.83	1.00	0.17	20.48
		C3	0.84	0.98	0.14	16.67
		Average	**0.83**	**1.00**	**0.17**	**20.01**
	Root	C1	6.31	7.80	1.49	23.61
		C2	6.36	7.65	1.29	20.28
		C3	6.41	7.47	1.06	16.54
		Average	**6.36**	**7.64**	**1.28**	**20.14**
	Total	C1	42.33	52.32	8.86	**20.93**
		C2	42.66	51.32	3.58	**8.39**
		C3	42.98	50.1	5.89	**13.70**
		Average	**42.66**	**51.25**	**6.11**	**14.43**
B type	Trunk	B1	4.97	8.34	3.37	67.81
		B2	2.41	3.56	1.15	47.72
		B3	3.97	6.55	2.58	64.99
		Average	**4.12**	**6.15**	**2.03**	**60.17**
	Bark	B1	0.83	1.17	0.34	40.96
		B2	0.34	0.64	0.30	88.24
		B3	0.55	0.91	0.36	65.45
		Average	**0.57**	**0.91**	**0.34**	**64.88**
	Branch	B1	0.56	0.78	0.22	39.29
		B2	0.23	0.43	0.20	86.96
		B3	0.37	0.61	0.24	64.86
		Average	**0.39**	**0.61**	**0.22**	**63.70**
	Leaf	B1	0.17	0.24	0.07	41.18
		B2	0.07	0.13	0.06	85.71
		B3	0.11	0.19	0.08	72.73

		Average	**0.12**	**0.19**	**0.07**	**66.54**
	Root	B1	1.32	1.84	0.52	39.39
		B2	0.53	1.01	0.48	90.57
		B3	0.88	1.45	0.57	64.77
		Average	**0.91**	**1.43**	**0.52**	**64.91**
	Total	B1	8.86	12.37	3.51	39.62
		B2	3.58	5.77	2.19	61.17
		B3	5.89	9.71	3.82	64.86
		Average	**6.11**	9.28	**3.17**	**55.22**

Table 8 ANOVA analysis of carbon storage before and after the project in different organs at tree layer for type B and C degraded forest types

Type	Organ carbon storage	Trunk	Bark	Branch	Leaf	Root	Total
C	2018	28.76±0.22	4.02±0.03	2.68±0.02	0.83±0.01	6.36±0.05	42.66±0.33
	2022	34.56±0.75※	4.83±0.11※	3.22±0.07※	1.00±0.02※	7.64±0.17※	51.25±1.11※
B	2018	4.12±1.78	0.57±0.25	0.39±0.17	0.12±0.05	0.91±0.40	6.11±2.65
	2022	6.15±1.89	0.91±0.27	0.61±0.18	0.19±0.06	1.43±0.42	9.28±2.81

Note: ※ represents significant differences of carbon storage between years within the same forest type ($P<0.05$)

3.4.2 Carbon storage variation in shrub layer

It can be seen from **Table 9** that the above-ground, underground and total carbon storage of shrub layer in type C forest increased by 6.61%, 6.37% and 12.98%, respectively, in 2022 compared with those in 2018. They increased by 8.16%, 9.85% and 18.00% in type B forest. However, there was no significant difference between the two years within the same type ($P > 0.05$, **Table 10).**

Total carbon storage of shrub layer was different between degraded types, which was 12.28% and 10.48% higher in type C forest than that of type B forests in 2018 and 2022, respectively. However, the annual carbon growth rate was much higher in type B forest **(Table 9).** This was mainly caused by the lower background value of type C forest compared to that of type B forest. In addition, type B was a moderately degraded forest type. The canopy density of such forest type was relatively low, which was conducive to the growth of shrub layer and then resulted in the carbon increase in shrub layer.

Table 9 Carbon storage variation in shrub layer for different degraded forest types

Type	Parts	treatment	Carbon storage ton/ha	Carbon storage increment after

		s			afforestation	
			2018	2022	tons/ha	%
C type	Above ground	C1	0.81	0.88	0.07	8.64
		C2	0.92	0.97	0.05	5.43
		C3	0.87	0.92	0.05	5.75
		Average	**0.87**	**0.92**	**0.06**	**6.61**
	Under ground	C1	0.45	0.48	0.03	6.67
		C2	0.39	0.41	0.02	5.13
		C3	0.41	0.44	0.03	7.32
		Average	**0.42**	**0.44**	**0.03**	**6.37**
	Total	C1	1.26	1.36	0.1	15.31
		C2	1.31	1.38	0.07	10.56
		C3	1.28	1.36	0.08	13.07
		Average	**1.28**	**1.37**	**0.08**	**12.98**
B type	Above ground	B1	0.83	0.91	0.08	9.64
		B2	0.71	0.76	0.05	7.04
		B3	0.77	0.83	0.06	7.79
		Average	**0.77**	**0.83**	**0.06**	**8.16**
	Under ground	B1	0.42	0.45	0.03	7.14
		B2	0.33	0.36	0.03	9.09
		B3	0.37	0.42	0.05	13.31
		Average	**0.37**	**0.41**	**0.04**	**9.85**
	Total	B1	1.25	1.36	0.11	16.78
		B2	1.04	1.12	0.08	16.13
		B3	1.14	1.25	0.11	21.10
		Average	**1.14**	**1.24**	**0.10**	**18.00**

Table 10 ANOVA analysis of carbon storage in shrub layer for different degraded forest types

Year	Type	Shrub above-ground	Shrub underground	Shrub layer	Grass above-ground	Grass underground	Grass layer
2018	C	0.87±0.06	0.42±0.03	1.28±0.03	0.23±0.04	0.11±0.04	0.34±0.08
2022		0.92±0.05	0.44±0.04	1.37±0.01	0.19±0.04	0.08±0.03	0.27±0.07
2018	B	0.77±0.06	0.37±0.05	1.14±0.11	0.42±0.07	0.19±0.04	0.61±0.07
2022		0.83±0.08	0.41±0.05	1.24±0.12	0.45±0.07	0.21±0.04	0.65±0.07

3.4.3 Carbon storage variation in grass layer

As seen from **Table 11,** above-ground, underground and total carbon storage of grass layer for type C forest decreased by 16.17%, 26.75% and 20.91% respectively from 2018 to 2022. While they increased by 6.49%, 8.92% and 7.14% for type B forest. However, no significant difference was observed between the two years in the same forest type ($P > 0.05$, **Table 12).**

Total carbon storage at grass layer was different between degraded forest types, the carbon storage in type B forest was79.41% and 144.44% higher than that of type C forest in 2018 and 2022 respectively. The reason was largely due perhaps to the fact that canopy density of type C forest was higher, light demanded herbs recessed or even died. The results indicated that forest canopy density was the main factor causing carbon storage variation in grass layer.

Table 11 Carbon storage variation in grass layer for different degraded forest types

Forest type	Part	Treatment	Carbon storage ton/ha		Carbon storage increment after afforestation	
			2018	2022	ton/ha	%
C type	Above ground	C1	0.19	0.15	-0.04	-20.05
		C2	0.27	0.23	-0.04	-14.81
		C3	0.22	0.19	-0.03	-13.64
		Average	**0.23**	**0.19**	**-0.04**	**-16.17**
	Under ground	C1	0.07	0.05	-0.02	-28.57
		C2	0.15	0.11	-0.04	-26.67
		C3	0.12	0.08	-0.03	-25.00
		Average	**0.11**	**0.08**	**-0.03**	**-26.75**
	Total	C1	0.26	0.20	-0.06	-23.08
		C2	0.42	0.34	-0.04	-19.05
		C3	0.34	0.27	-0.07	-20.59
		Average	**0.34**	**0.27**	**-0.07**	**-20.91**
B type	Above ground	B1	0.48	0.51	0.03	6.25
		B2	0.43	0.45	0.02	4.65
		B3	0.35	0.38	0.03	8.57
		Average	**0.42**	**0.45**	**0.03**	**6.49**
	Under ground	B1	0.16	0.18	0.02	12.50
		B2	0.23	0.25	0.02	8.70
		B3	0.18	0.19	0.01	5.56
		Average	**0.19**	**0.21**	**0.02**	**8.92**
	Total	B1	0.64	0.69	0.05	7.81
		B2	0.66	0.70	0.04	6.06
		B3	0.53	0.57	0.04	7.55
		Average	**0.61**	**0.65**	**0.04**	**7.14**

3.4.4 Carbon storage variation in soil layer

It could be seen from **Table 12** that soil carbon storage of the three degradation forest types all decreased with the increase of soil depth. The soil total carbon storage in type A forest decreased by 14.13 tons/ha from 2018 to 2022, which was a decrease of 10.97% in proportion. The decrease was 14.22 tons/ha in type C forest with a decrease of 10.62%, while there was no significant difference between the two years ($P>0.05$, **Table 13).**

Soil total carbon storage of type B forest increased by 22.23 tons /ha from 2018 to 2022, the increasing proportion was 22.37% and significant differences were observed between the two years ($P<0.05$, Table 14). This was mainly due to the fact that defective trees were felled during the management, which increased the amount of litter on the ground. In addition, management also improved light conditions, which accelerated the decomposition of litter on ground and then increased the amount of organic matter in soil.

Table 12 Soil carbon storage variation in different degraded forest types

Type		Soil layer cm	Soil carbon storage ton/ha		Carbon storage increment after afforestation	
			2018	2022	tons/ha	%
A	A1	0-20	43.2	44.01	0.81	1.87
		20-40	38.34	35.91	-2.43	-6.34
		40-60	33.21	34.56	1.35	4.07
	A2	0-20	59.67	43.2	-16.47	-27.60
		20-40	44.01	36.72	-7.29	-16.56
		40-60	35.37	33.21	-2.16	-6.11
	A3	0-20	56.43	42.39	-14.04	-24.88
		20-40	42.12	40.5	-1.62	-3.85
		40-60	34.02	33.48	-0.54	-1.59
	Subtotal	A1	114.75	114.48	-0.27	-0.24
		A2	139.05	113.13	-25.92	-18.64
		A3	132.57	116.37	-16.2	-12.22
		Average	128.79	114.66	-14.13	-10.97
B	B1	0-20	43.2	42.12	-1.08	-2.50
		20-40	34.02	40.5	6.48	19.05
		40-60	24.84	37.53	12.69	51.09
	B2	0-20	41.85	44.82	2.97	7.10
		20-40	30.24	41.31	11.07	36.61
		40-60	32.67	30.24	-2.43	-7.44
	B3	0-20	36.72	45.9	9.18	25.00
		20-40	26.19	43.2	17.01	64.95
		40-60	28.35	39.15	10.8	38.10
	Subtotal	B1	102.06	120.15	18.09	17.72
		B2	104.76	116.37	11.61	11.08
		B3	91.26	128.25	36.99	40.53
		Average	99.36	121.59	22.23	22.37
C	C1	0-20	54.54	41.85	-12.69	-23.27
		20-40	40.23	37.8	-2.43	-6.04
		40-60	39.15	37.26	-1.89	-4.83
	C2	0-20	49.95	50.76	0.81	1.62
		20-40	36.45	38.88	2.43	6.67
		40-60	34.56	35.1	0.54	1.56
	C3	0-20	55.08	43.74	-11.34	-20.59
		20-40	49.68	39.69	-9.99	-20.11
		40-60	42.12	34.02	-8.1	-19.23
	Subtotal	C1	133.92	116.91	-17.01	-12.70

		C2	120.96	124.74	3.78	3.13
		C3	146.88	117.45	-29.43	-20.04
		Average	133.92	119.70	-14.22	-10.62

Table 13 ANOVA analysis of soil carbon storage between years for different degraded forest types

Year	Degraded type		
	A	B	C
2018	128.79±12.58	99.36±7.14	133.92±12.96
2022	114.66±1.63	121.59±6.07※	119.7±4.37

3.4.5 Carbon storage variation in forest ecosystems

In 2018 and 2022, the carbon storage of type C forest ecosystem was much higher than that of type B forest ecosystem **(Table 14).** Carbon storage of tree layer, shrub layer, grass layer and soil layer for type B forest in 2018 and 2022 were 6.11 and 9.28 tons/ha, 1.14 and 1.24 tons /ha, 0.61 and 0.65 tons /ha, 99.36 and 121.59 tons/ha, respectively, and accounted for 5.70% and 6.99% 1.06% and 0.93%; 0.56% and 0.49%; 92.67% and 91.59% of carbon storage for the whole ecosystem, respectively **(Table 14).** The carbon storage in vegetation layer of type B forest was 7.86 tons/ha and 11.17 tons/ha in 2018 and 2022, respectively. It only accounted for 7.33% and 8.41% of carbon storage for whole ecosystem. The results indicated that the carbon storage in vegetation layer was low because of the serious damage of tree layer.

For type C forest, carbon storage of tree layer, shrub layer, grass layer and soil layer were 42.66 and 51.25 tons /ha, 1.28 and 1.37 tons/ha, 0.34 and 0.27 tons/ha; 133.92 and 119.07 tons/ha in 2018 and 2022, respectively, and accounted for 23.94% and 29.69%, 0.72% and 0.79%; 0.19% and 0.16%; 75.15% and 69.36% of ecosystem carbon storage, respectively **(Table 15).** In 2018 and 2022, carbon storage in vegetation layer of type C forest was 44.28 tons/ha and 52.89 ton/ha, which accounted for 24.85% and 30.64% of the whole ecosystem carbon storage, respectively. This indicated that tree performance in type C forest was much better than that of type B forest. However, the carbon storage in vegetation layer was lower both in type B and C forests.

Table 14 Carbon storage and its distribution in different degraded forest ecosystems

Type	B	C

Year	2018	2022	2018	2022
Tree layer	6.11±2.65 (5.70)	9.28±2.81(6.99)	42.66±0.33 (23.94)	51.25±1.11(29.69)
Shrub layer	1.14±0.11 (1.06)	1.24±0.12(0.93)	1.28±0.03(0.72)	1.37±0.01(0.79)
Grass layer	0.61±0.07(0.56)	0.65±0.07 (0.49)	0.34±0.08(0.19)	0.27±0.07(0.16)
Soli layer	99.36±7.14(92.67)	121.59±6.07(91.59)	133.92±12.96(75.15)	119.70±4.37(69.36)
ecosystem	107.22±9.97(100.00)	132.76±9.07(100.00)	178.20±13.40(100.00)	172.59±5.56(100.00)

Note: the data in brackets are the percentage of carbon storage in the ecosystem.

4 Discussion and conclusion

After implementation of the project, the stability of stand structure increased for all degraded forest types, the stand quality and economic value improved a lot, the main results and changes were as follows:

(1) Stand structure tended to be optimized.

Generally, the species diversity of type B forest increased obviously; the stand structure of type C stand tended to be stable. The number of increased tree species was the highest in type B forest, it increased from 11 to 13 with an increment of 18.2%. The increasing number of tree species was limited in type C forest, which increased only from 18.3 to 18.7, since some low-value disturbing trees and liana vegetation were cleared. Although the species diversity did not increase greatly, the economic value improved a lot in type C forest. The highest increment of stand density was observed in type B forest, the number of trees that larger than 5 cm increased by 122.7%. The increment of species richness was much higher in higher degraded forests. The structure of diameter class was not greatly improved, only the number of trees with diameter larger than 5 cm increased a lot in type B forests. It still existed the problem of more small-sized trees and less large-sized trees.

(2) Stand volume increased, high-quality individuals grew faster.

After valuable N-fixation tree species planted through opening forest gaps in type B forest and low value disturbing tree cleared as well as suitable tending in type C forest, stand volume and individual growth of high-value trees had a great improvement as a whole. During the three years of the project, the stand volume increased 57.9% for type B forest and 22.3% for type C forest. Meanwhile, the present stands were at the stage of vigorous growth, conducting crop tree selection, disturbing tree and liana clearing as well as other forest tending would have important effects on forest growth acceleration, stand volume improvement and economic value promotion of high-quality trees. Diameter growth of high-quality crop trees was much faster than that at stand level. However, the present stand volume was still not high, it was only 157.69 m^3/ha even though in type C forest, it was still far away from the level of local high yield stands. Therefore, forest tending should be intensified to improve the stand economic value by applying disturbing trees and liana clearing for crop trees.

(3) Management should be strengthened after the project to play the full role of replanted nitrogen-fixation species in enhancing stand value

For moderate and heavy degraded forests, valuable nitrogen-fixation species were replanted during the project. The preliminary results indicated that the survival rate of afforestation was higher and could reach 89.7%, while due to the fact that seasonal drought and sandy soil had negative effects on new planted seedlings, the annual increment of tree height for all tree species was lower than 0.5 m. For new planted trees, forest tending and management were needed to be reinforced, liana clearing and suitable pruning should be conducted on time. For type C forest, disturbing trees and liana clearing should be conducted every 5~8 years to improve forest ecological and economic values. In other words, forest tending and management should be continued and reinforced after the project for all degraded forest types to improve stand structure as soon as possible.

(4) Soil physical and chemical properties were improved, forest ecosystem services were promoted.

The soil belongs to sandy alluvial soil, the sand content in soil was high and reached 50.86-77.80%, it decreased with the increasing soil depth, with the highest sand content (64.78-77.80%) in soil layer of 0-20cm. The soil were all sandy soil in different soil layers, moisture and fertility preservation is poor, trees were easily suffered from water stress. Soil nutrients were unbalanced, the contents of organic matter, total nitrogen and available phosphorus were high and reached the middle to high levels, while the contents of total phosphorus, sodium, calcium, magnesium and other positive ions were poor. The imbalanced soil nutrients lead to the low tree growth increment. We suggested that measures. such as water-retaining agent, compound fertilizer and decomposed organic fertilizer implementations, should be conducted to improve soil moisture preservation, solve the problems of water depletion, shortages of total phosphorus, sodium, calcium, magnesium and other positive ions. and improve stand growth and ecological service function.

(5) Forest management should be reinforced and forest carbon storage was promoted.

In 2022, the mean diameter at breast height of type B forest was only 9.25 cm, diameter classes of most trees were lower than 10 cm, so did the diameter class in type C forest with the mean diameter at breast height of 13.70cm. Studies of carbon pool dynamics in tropical montane rain forests in Jianfengling indicated that the average carbon storage of tree layer in tropical mountain rainforest is 230.84±40.61 tons per hectare. Among all, trees with diameter larger than 10 cm contributed 90% of carbon storage in tree layer, especially for large-sized individuals (diameter≥45cm), with less than 1% of all trees contributed 32% of carbon storage reached of tree layer. This indicated that middle and large sized trees played the dominant role in determining carbon storage at tree layer. Although the climate conditions and forest types were similar to Jianfengling's, the carbon storage of tree layer in the present study was extremely low, the highest carbon storage was only 51.25 tons per hectare in type C stand. It was less than 1/4 of that in Jianfengling. The main reason was the extreme water shortage and imbalanced fertility, which lead to the poor growth performance and less large sized trees in forests. Therefore, scientific measures for soil improvement, water and fertilizer preservation as well as fertilizer replenishment should be conducted to solve the water and fertilizer stress and create suitable conditions for improving tree growth and the proportion of large-sized trees, and then promoting carbon sinks and other ecological services for tree layer.