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Dynamics of ecosystem services provided by subtropical forests in Southeast China during succession as measured by donor and receiver value

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Abstract

The trends in the provision of ecosystem services during restoration and succession of subtropical forests and plantations were quantified, in terms of both receiver and donor values, based on a case study of a 3-step secondary succession series that included a 400-year-old subtropical forest and a 23-year history of growth on 3 subtropical forest plantations in Southeastern China. The ‘People’s Republic of China Forestry Standard: Forest Ecosystem Service Valuation Norms’ was revised and applied to quantify the receiver values of ecosystem services, which were then compared with emergy-based, donor values of the services. The results revealed that the efficiencies of subtropical forests and plantations in providing ecosystem services were 2 orders of magnitude higher than similar services provided by the current China economic system, and these efficiencies kept increasing over the course of succession. As a result, we conclude that afforestation is an efficient way to accelerate both the ability and efficiency of subtropical forests to provide ecosystem services. The ability of different ecosystems to provide services depends on the concentration of available natural resources in the system at a large scale, but also on the ability of the ecosystems to capture natural resources in the same or similar environments.

Keywords

dynamic of ecosystem services; donor and receiver values; emergy; subtropical forests

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1. Introduction

Ecosystem services research has become a focal area of investigation over the past decade (Fisher et al., 2009), as a result of the increasing severity of environmental problems and their associated negative effects on socioeconomic activities and human wellbeing. Ecosystem valuation is the principal step needed to put ecosystem services into socioeconomic valuation and policy making. Valuing the ecosystem's contributions to socioeconomic wellbeing can help resource managers assess the effects of market failures, by measuring the cost of ecosystem losses to society in terms of the associated loss in economic benefits. Research establishing this connection has raised public awareness of the valuable services provided by nature, including those of forests (Li, 2008). However, due to the significant difference in assessment indicators, calculation approaches and reference prices among various case studies, the research results of ecosystem services studies often cannot be easily compared or studied dynamically (Pimental et al., 1997; Li, 2008; Zhang et al., 2010a). Furthermore, based on anthropocentrism, most of the ecosystem services valuation studies are focused on the receiver value of the goods and services to human beings, and lack a donor-side consideration of the problem (Campbell and Brown, 2012). However, donor and receiver values are two basic aspects of value and need to be accounted for in comprehensive strategy-making; furthermore, their integration is essential for clarifying a system's efficiency in producing receiver value. Biophysical process analysis, emergy evaluation and other methods used in ecosystem services valuation could shed light on these issues from the donor side perspective, and consequently reflect the transition from anthropocentrism towards ecocentrism, which calling for humanity to establish partnerships with nature, where nature is not only preserved for its present and future benefits to humanity (i.e., stewardship), but is given equal weight in determining what is best for the entire system (Odum, 2007; Liu et al., 2016). The complementary aspects of emergy analysis and environmental economics based ecosystem services valuations are getting more and more attention from scientists and governments at all scales (Patterson et al., 2006; Campbell, 2009; Lee and Huang, 2011; Campbell and Brown, 2012; Coscieme et al., 2014; Campbell and Tilley, 2014; Liu et al, 2014; Fang et al., 2015), but a comprehensive accounting system for ecosystem services evaluated from both the donor and receiver perspectives is still under development, as is integrated ecological-economic cost-benefit analyses, which is needed for comparison among different options for providing ecosystem services, which is fundamental for strategic decision- making.

In addition, most past ecosystem services studies have been isolated snapshots mainly focused on concepts and theories or on policies and compensation standards, and as a result dynamic and systematic studies are lacking for the most part. Such studies have been identified as a key factor for the further development of knowledge about ecosystem services and for their application in both the development of long-term ecological conservation and restoration practices (Liu et al., 2007; Yu and Peng, 2010). However, the dynamic trends of all ecosystem service functions develop within the structures of ecological networks are nonlinear; therefore, the relationships among them are complex and hard to predict, without the support of long-term monitoring studies (Yu and Bi, 2011). To normalize and guide forest ecosystem services assessment in China, in May 2008 the State Forestry

Administration of China issued the 'People's Republic of China Forestry Standard: Forest Ecosystem Service Valuation Norms' (referred to as 'Norms' in the following text), which proposed a suite of assessment formulae for 14 indices accompanied by reference prices for each service (Appendix Table 1, 2). Although there are still many controversies, deficiencies and problems that need further study, the Norms document developed the first general framework for forest ecosystem services assessment and provided guidance for the evaluation of forest ecosystem services research in China (Zhang et al., 2010a; Zhang et al., 2010b). In most cases, 'Norms' represents the cost to replace an ecosystem service with an equivalent service performed through human work. It is important to note that by these replacement costs the values generated likely do not represent the marginal cost or benefit of forest loss or gain, i.e. the actual change in wellbeing when a forest expands or contracts. The values represent a maximum value, assuming that all ecosystem service loss would need to be replaced with human work.

Low latitude subtropical forests play an essential role in establishing an ecological balance and improving environmental quality in southeast China, which has been seriously degraded under heavy population pressure and rapid development of local economies over the past few decades (Yu and Peng, 1996). Both government and scientists have paid special attention to the conservation and restoration of lower subtropical forests since the 1950s, with the goal of enhancing regional environmental quality and sustainability and some advancements in our understanding have been made both through the exploration of ecological theory and through observing the behavior of subtropical forests (Zhou et al., 2006). Specifically, the selection and implementation of a suite of forest restoration modes has been shown to be outstanding in providing some specific ecosystem services, such as water and soil conservation, carbon fixation and oxygen release, and biodiversity conservation *etc.* (Peng, 2001, 2003). However, the dynamic patterns determining ecosystem service values in subtropical forests and in classical subtropical forest plantations have not been explored yet, although this is essential information needed for forest management on both spatial and temporal scales.

The trends of the ecosystem service values of subtropical forests and plantations, following succession and restoration, were disclosed in this study based on a long-term field measurement program at two national forest field research stations in Guangdong Province, Southeast China, *i.e.* Heshan and Dinghushan Forest Ecosystem Research Stations. The formulae and prices given by the 'Norms' document were applied and adjusted to assess the receiver values[1] of 8 ecosystem services, *i.e.* water regulation, water purification, soil fixation, soil fertilizer conservation, carbon sequestration, oxygen release, nutrient accumulation in biomass, and biodiversity conservation on three subtropical forest plantations in southeast China, *i.e.*, a conifer plantation (CP), an acacia plantation (AP), and a mixed native species plantation (NP); and a three-stage long-term secondary succession series of subtropical forest, *i.e.*, a pine forest (PF), a mixed conifer and broad-leaved forest (MF), and a monsoon evergreen broadleaf forest (EF). Simultaneously, the biophysical donor value of these ecosystem services was quantified by the emergy method. Then, a

[1] receiver value, value based on the willingness to pay or receive payment for a good or service. It can also be measured by alternative methods, such as the replacement cost of an item as found in 'Norms'

comparison was done between the environmental economic receiver values and the emergy values to obtain a more holistic view of the different dimensions of value. This comparison quantified the efficiencies of subtropical forests and plantations in providing ecosystem services relative to the current Chinese economic systems for providing the same services.

2. Location and methods

2.1. Location and sites

All three forest plantations located at Heshan National Field Research Station of Forest Ecosystems (HNFRSFE, 22°40′N, 112°53′E) were planted in 1984 on grassy slopes that were formerly regional monsoon evergreen broadleaf forest, for the purpose of studying forest restoration. This area is located on low hills with an altitude of less than 100m. This location is controlled by a typical monsoonal climate, with mean annual precipitation of 1800 mm and mean annual temperature of 21.7ºC. The soil in HNFRSFE is composed mainly of lateritic red earth and mountain yellow-brown earth in a vertical distribution. The main species planted in NP was *Schima wallichii*, whereas, *Pinus massonina* and *Cunninghamia lanceolata* dominated in CP, and *Acacia mangium* dominated in AP. Measurements and studies showed a significant development of both community structure and function of the three plant communities during over 20 years of self- organization, without the application of specific management activities after planting (Li et al., 2013; Lu et al., 2015).

A three-stage long-term secondary succession series of subtropical forest was monitored and measured in the Dinghushan Biosphere Reserve (23°10′N, 112°32′E), a UNESCO MAB site (No. 17) 100 km away from HNFRSFE. The Dinghushan Biosphere Reserve was first established in 1950 as the first national nature reserve in China with the purpose of protecting the regional climax forest, i.e., a natural monsoon evergreen broadleaved forests, which is approximately 400 years-old (EF, Zhou et al., 2006). In Dinghushan, the pine forest (PF) is about 55 years old, and the mixed pine and broad-leaved forest (MF) is about 75 years old. All three forests are located at an elevation of 200–300 m above sea level on south-facing slopes.

2.2. Methods

2.2.1. Ecosystem services measurement—Eight of the 14 indices, i.e. water regulation, water purification, soil fixation, soil fertilizer (N, P, K and organic carbon, OC) conservation, carbon sequestration, oxygen release, nutrient (N, P, and K) accumulation in biomass, and biodiversity conservation, were calculated using the formulas proposed in ‘Norms’. Then, the first six indices were combined into 3 integrated indices, i.e. water conservation (water regulation and purification), soil conservation (soil fixation and fertilizer conservation) and carbon sequestration and oxygen release (Table 1).

For the three forest plantations in Heshan station, most of the ecological factors needed for the calculation of the indices, such as the content of N, P, K and OC in both soil and plants, soil density, biomass and Shannon-Wiener Index of plant community diversity were taken from field monitoring and investigation data (Fu, 2010). The evapotranspiration and Net

Primary Productivity (NPP) data were taken from a simulation based on the Biome-BGC model (Li et al., 2013). Erosion factors for forest land and non-forest land were from published studies conducted in the same region (Peng, 2001). For the three forests in Dinghushan station, all data were from published studies based on field investigations and measurements at the station (Peng, 2001; Yan, 2001; Mo, 2003; Zhou, 2005; Tang, 2006; Tang et al., 2006; Zhang, 2011).

2.2.2. Environmental economic assessment—The reference prices proposed in 'Norms' were not all based on the same year's price, e.g. the prices for oxygen, fertilizers and water purification were from 2007, while the price for hydrological regulation was the price in 2005, and the price for air pollution treatment was the price as determined in 2003. All of the reference prices were adjusted to their price in 2000 through applying the appropriate GDP deflators (Table 1). Furthermore, to improve the sensitivity and accuracy of the valuations, linear interpolation was applied to the valuation of species conservation, which was given in 'Norms' as 7 levels of value based on Shannon-Wiener Index (SWI).

2.2.3. Emergy evaluation—The Planetary emergy baseline captures the global environmental resources driving the geobiosphere and serves as a unified basis for the calculation of emergy in all studies of systems on the planet. The baseline is needed for determining the unit emergy values (UEVs) of all available energy and material storages and flows of the geobiosphere. After the calculation of the baseline in Odum (1996) a value of 9.44E24 sej/y prevailed for about 5 years. Subsequently a debate about the value and significance of the baseline became a fundamental issue in the field of emergy studies, with several updates presented in the literature by different researchers over time (Odum, 2000; Campbell, 2000; Campbell et al., 2005; Brown and Ulgiati, 2010). Various values of the baseline were calculated using different quantification methods or including different methods of combining and weighting the emergy sources driving the geobiosphere. Finally, the baseline has been updated by synthesizing the results of two rigorous studies that produced values of the baseline (11.6E24seJ/yr and 12.1E24seJ/yr) close enough for an agreement after considering their uncertainties (Campbell, 2016; Brown and Ulgiati, 2016). The agreed upon value of 12E24seJ/yr for the planetary baseline is expressed in solar equivalent joules (seJ) since the planetary baseline can only be established through the estimation of equivalences. Once estimated as a solar equivalent input to Earth's geobiosphere the baseline can be used to determine the solar emergy required for all flows generated from Earth processes (Brown et al., 2016). The 12E24seJ/yr baseline was applied in this study.

It is difficult to divide ecosystem services into independent production processes for calculating their emergy, because of the complex relationships between ecosystem structure and function, as well as the higher interdependency among different ecosystem services. However, the efficiency of an ecosystem in providing services as a whole can be measured by calculating the ratio of the receiver value of the ecosystem services to the emergy flows used by the ecosystem to support those services, taking a kind of black box approach.

For a long time, the emergy inputs to, instead of emergy used by, systems were taken to be empower (emergy per time) of the system. However, not all inputs, like precipitation, are

used by systems with a portion flowing out, e.g. run off. Here, evapotranspiration was considered as the part of rainfall being used in the forests, instead of all of the precipitation. A comparison between annual precipitation and evapotranspiration was given to quantify the difference between the two emergy accounting methods. Furthermore, the accumulation of nitrogen and carbon in the three forest plantations by both the soil and plants were quantified, and compared with the emergy of evapotranspiration. Then, the maximum emergy of the renewable inputs was counted as the environmental basis for the system.

Besides environmental inputs to the 3 plantations, the system also received purchased inputs to support forest restoration in the form of chemical fertilizer, seedlings and labor to start the system. Purchased emergy inputs were considered to contribute to the whole growth period of the trees and so they were divided equally over the growth period as 3.29E14 sej/ha/yr (294.32 RMB in 2000/ha/yr), under the assumption that the growth period of trees is 40 years (Yu and Peng, 1996; Peng, 2003; Lu et al., 2011). To compare with the environmental economic values in yuan, the emergy cost of ecosystem services was divided by the emergy/money ratio of China in 2000 (Yang et al., 2010) to get the Emvalue in emyuan.

3. Results

3.1. Dynamics of environmental economic values

3.1.1. Adjusted replacement value of forest ecosystem services—The real prices of forest ecosystem services in China in 2000 and 2010 are shown in Table 1. The prices can be converted to any other year's real price based on the GDP deflators, which can be deduced from the Statistical Yearbook of China (http://www.stats.gov.cn/tjsj/). Then prices can be calculated in other units, such as US$, based on the money exchange rates in the year of interest (http://www.x-rates.com/cgi-bin/hlookup.cgi).

After adjustment, the relative prices of some ecosystem services (water quantity regulation and purification, soil fixation, and carbon fixation) were increased compared with the other services.

3.1.2. Dynamics of environmental economic ecosystem service values following succession—The function of water conservation (i.e. water regulation and purification) quickly developed in all three forest plantations in the first 10 years after planting (Fig. 1). It increased about 2.45 times on average with AP having the best performance of this indicator most of the time. After 10 years, the water conservation function of the three plantations fluctuated with variations in annual precipitation. At 23 years old, the mean water conservation function of the three plantations was about 9% higher than that of the 55 year-old secondary succession pine forest (PF), 93% that of the 75 year-old mixed pine and broadleaf forest (MF), and 86% that of the 400 year-old monsoon evergreen broadleaf forest (EF). Development from PF to MF marks a second acceleration period of the water conservation function in subtropical forest succession; however, after this time the rate on increase of this function decreased.

In contrast to the development trend of water conservation, the soil conservation function (i.e. soil fixation and fertilizer conservation) developed slowly in the first 15 years in all

three subtropical forest plantations, then speeded up, with CP having the highest performance, followed by NP and AP (Fig. 2). The function of soil conservation in the three forest plantations increased about 3.3 times on average over the period of observation (23 years) exceeding that of PF by 1.5 times. However, this value was still lower than that of MF and EF. Over the long-term during secondary succession, the soil conservation function in the subtropical forests quickly increased during succession from PF to MF, then slowly increased from MF to the climax state, EF. During this succession from mixed pine and broad-leaved forest (MF) to the regional climax, EF, the soil conservation function only increased 28% in over 300 years.

The Acacia plantation (AP) had the best performance with reference to the function of carbon sequestration and oxygen release, followed by NP and CP (Fig. 3). The function of carbon sequestration and oxygen release of the three forest plantations quickly increased in the first 5 years after planting to a value similar to that of the 55-year PF, then all 3 plantations fluctuated along a decreasing path. Over the period of observation, the carbon sequestration and oxygen release function of the three subtropical forest plantations had a mean that was 89% that of PF, 41% that of MF, and 32% that of EF. Succession from PF to MF constitutes a second period of rapid development of carbon sequestration and oxygen release in the subtropical forest. After that, this function kept increasing, but at a slower speed toward the climax condition, EF.

The development of nutrient accumulation in biomass of the three subtropical forest plantations showed a similar trend to that of carbon sequestration and oxygen release, i.e., it quickly increased in the first 5 years after planting, followed by a period of steady decline that lasted about 20 years (Fig. 4). The succession from PF to MF was a period of rapid change with a precipitous rise in the accumulation of nutrients in forest biomass. After that, the speed of nutrient accumulation decreased, but continued at a rate faster than that of carbon sequestration and all the other functions examined so far. Finally, the function of nutrient accumulation in biomass of the regional climax, EF, was, respectively 1.43 and 4.23 times that of the 75 year-old mixed forests, MF, and the 55 year-old pine forest, PF.

The mean SWI of the three subtropical forest plantations quickly increased about 2.76 times in the first 20 years after planting (Fig. 5). Twenty-three years after planting, the mean SWI or biodiversity conservation function of the three plantations was 1.33 times that of the approximately 55 year-old PF, 1.54 times that of the approximately 75 year-old MF, and 94% that of the approximately 400 year-old EF. The SWI of MF was lower than that of the PF, although its species richness was higher.

Mainly driven by the development of the ecosystem services of water conservation, carbon sequestration and oxygen release, and biodiversity conservation, the total ecosystem service function of subtropical forest plantations developed rapidly after planting, especially over the first 5 years (Fig. 6). After 23 years, the total value of ecosystem services of the three subtropical forest plantations was 1.11 times that of the 55 year-old PF, 80% that of the about 75 year-old MF, and 64% that of the 400 year-old EF at Dinghushan. The secondary succession process from PF to MF is a period of rapid development of subtropical forest ecosystem services as a whole, during which the total value of ecosystem services increased

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39% in about 25 years. After that, the speed of development of total ecosystem services in subtropical forest slowed down, but it still kept increasing toward the climax, EF, mainly due to the further development of biodiversity conservation.

3.2. Dynamics of the emergy-based donor values

The annual precipitation at Heshan Station varied during the 23-year period (1546±382mm/yr), but evapotranspiration increased in the first 10 years after planting and then varied a little as the consequence of the variations in annual precipitation (Fig. 7).

The percentage of ET in precipitation, increased from only 12% at the beginning to over 32% in the first 10 years, then varied between 32% and 72%, with the percentages being relatively higher in dry years and lower in wet years (Fig. 8). This figure quantitatively explores the possible range of overestimate due to taking annual precipitation as the empower of the forest ecosystem instead of evapotranspiration, i.e., between 28% to 68% for subtropical forest plantations over 10 years old, and which can be up to 88% greater for forests shortly after planting.

The emergy of ET of the 3 forest plantations was 1 to 2 orders of magnitude larger than the emergy storage increase of N and C (Fig. 9). Assuming N and C are from natural biogeochemical process, instead of specific external sources, only the largest input among water and elements should be counted in emergy synthesis to avoid double counting, since all of them were driven by the same planetary biogeochemical cycles. Thus, ET was taken as the environmental input to the subtropical forests and plantations under study here.

The emergy captured by the three forest plantations quickly doubled in the first 10 years after planting, and then fluctuated with annual precipitation (Fig. 10). After 23 years, the ET of the three plantations was 37%, 33% and 32% of the ET of PF, MF and EF, respectively. After accounting for the initial purchased inputs (294.32 RMB in 2000/ha/yr) the trends remained the same, but the rate of increase slowed to only 56% of that in the first ten years. And, after 23 years of development, the emergy required for the ecosystem services produced by of the three plantations was 54%, 48% and 46% of that absorbed by PF, MF and EF, respectively.

During succession from PF to MF, the ability of the subtropical forest to capture environmental resources as shown by the ecosystems’ ET increased 39% in about 20 years (7% per year). After reaching the MF stage the rate of increase in emergy capture slowed down to about 0.3% per year from MF to the climax stage, EF.

3.3. Dynamics of ecosystem efficiency in providing services

Afforestation is an efficient means of restoring ecosystem services, as shown by the fact that the mean environmental economic value/Emvalue ratio increased 83% in the first 2 decades of forest plantation development (Fig. 11). In addition, this ratio rose to be over 20% higher than that of MF after the 2nd year after planting. Also, it exceeded EF by 39% after 23 years of development. At the scale of long-term secondary succession, the efficiency of subtropical forests in providing ecosystem services kept increasing over the whole period, but the rate of increase slowed considerably after the MF stage. At the current level of

technology in providing economic ecosystem services, all subtropical forests and forest plantations under study here were efficient providers of ecosystem services, i.e., the environmental economic values of the ecosystem services provided were between 48 to 99 times greater than that of the respective donor values of the service (the Emvalue).

4. Discussion

4.1. Conserving and restoring subtropical forests for maximizing ecosystem services

Among terrestrial ecosystems, tropical and subtropical forests have superior ability to provide ecosystem services, due to their relatively high biodiversity and NPP. However, the rapid loss and degradation of these forests is a serious problem that is now gaining public attention (Kremen et al., 2000; Agrawal et al., 2008; FAO, 2014). Forest restoration is considered to be one of the most efficient tools to deal with some environmental problems, e.g. global climate change and soil erosion etc. (Liu et al., 2008), but these problems have been perceived by some conservationists and economists, as a diversion, a delusion, or far worse a waste of money (Aronson et al., 2006). Such attitudes make it vital to incorporate ecosystem services and the efficiencies with which they are provided into economic analyses by considering their fundamental ecological economic characteristics and origin in biophysical processes.

Many scientists believe that when ecosystem services are considered to be free subsides an increase in scarcity will not be felt until an ecosystem service becomes limiting to an economic activity, at which point the cost to the social economy would likely be much more than if an investment in natural capital had been made prior to economic limitation (Coscieme et al., 2014; Campbell and Tilley, 2014b). This is true because after over 3 thousand million years of evolution and selective pressure following the maximum empower principle (Odum, 1996) nature is more likely to be much more efficient in producing ecosystem services than current technologies. Environmental economic assessment of ecosystem services highlights the essential contributions of nature to human economic and social systems at all scales from a specific ecosystem to the world as a whole. However, due to the lack of a straightforward link between the assessments of ecosystem services and ecosystem processes, the applicability of the assessment results to develop ecosystem management strategies and to evaluate ecological economic trade-offs is still weak.

Pulselli et al. (2011) showed that the ratio of the emergy flow supporting the entire biosphere to the world ecosystem services value based on Costanza et al. (1997) is one order of magnitude lower than traditional emergy to money ratios (EMRs) calculated for national economics. After that, Coscieme et al. (2014) also showed that the ecosystems in a national territory provide a unit of receiver value using less emergy than the national economy.

Based on long-term monitoring, the results of this study showed that the ratios of environmental economic value/Emvalue of ecosystem services provided by three subtropical forests in China ranged from 56 to 92, which illustrates the superior efficiency of subtropical forests in providing ecosystem services compared to the technologic systems of the economy. Furthermore, the environmental economic valuation results indicated that afforestation is an efficient way to speed up the recovery of ecosystem services, as shown by

the fact that the mean total ecosystem services value of the three subtropical forest plantations developed 99% of the functionality of a 55 year-old pine forest PF in only 23 years. Based on the case studies examined here, we demonstrated that re- forestation can not only speed up the restoration of ecosystem services, but also improve the efficiency with which they are provided, confirming the hypothesis made by Coscieme et al. (2011).

4.2. Emergy-based ecosystem services evaluation and its integration with environmental economic valuation

Defined as ‘the available energy of one kind that is used up in transformations directly and indirectly to make a product or service’ (Odum, 1996), emergy is a tool that is able to evaluate the convergence of matter and energy to a system on a common basis, and therefore, it is an ideal tool to identify, quantify and weight the inputs that feed a system. As a biophysical donor side valuation method, emergy-based evaluation is an empirical, but also a conceptual, basis upon which the value of nature’s contributions to society can be determined. This approach can increase our knowledge about the production of ecosystem services from the perspective of donor value. Donor value and receiver value are two fundamental aspects of value, and their ratio (output/input ratio) is a basic indicator of the efficiency and benefits gained from different systems and processes. The ratio has the form of benefits received as evaluated in money to emergy cost either expressed as emjoules or as Emvalue (emdollars), which is a quantity relating the energy base for an economy to the money circulating in the economy in a given year. Thus, emergy evaluation is not an alternative method to environmental economic assessment, but rather a complementary and systemic approach to highlight the mechanisms of service production by different systems. Not all of the emergy inputs that support a system can be converted into ecosystem services (Pulselli et al., 2011), thus the environmental economic value/Emvalue of ecosystem services can be taken as the minimum output/input ratio for ecosystems at the macroscopic system level for providing ecosystem services. Although donor and receiver values are two different concepts, they are believed to be correlated with each other in some way. Coscieme et al. (2014) documented a significant correlation between the available renewable emergy and ecosystem service values aggregated at a national scale, which suggests that ecosystem services are somehow dependent on energy and natural resource concentration in ecosystems. For a long time, the emergy of the largest available renewable natural resources (generally the chemical potential energy of rain) was taken as the renewable emergy input to the system under study. However, not all available natural resources are used by ecosystems, and only the part that is actually used should be counted in the cost for ecosystem development/production and maintenance (Li et al., 2014). The comparison in this study showed that although the annual precipitation varied a lot during the 23 year study period, the evapotranspiration of the three forest plantations developed smoothly. Setting aside the large variation or noise in the precipitation signal, the overestimate possible by taking annual precipitation as the renewable input to subtropical forest plantations instead of ET can be up to 88%.

Statistical analysis based on SPSS 21.0 showed that, the environmental economic values of ecosystem services provided by subtropical forests and plantations is significantly correlated with both their ET (P=0.000) and regional precipitation (P=0.006), while the latter two are

not correlated with each other (P=0.377). Combined with the results of Coscieme et al. (2014), we can see that the ability of ecosystems to provide services is dependent on the available natural resource concentrations in ecosystems at the large scale (e.g., precipitation at the regional and national scales), but also on the ability of the ecosystems (in this study, ET is a proxy for the ability to concentrate the chemical potential energy of precipitation) to concentrate natural resources in the same or similar environments.

4.3. Dynamics of biodiversity following succession and its evaluation

Biodiversity is a multidimensional concept and its description and therefore its measurement takes many forms, and the measure of biodiversity that is the best predictor of ecosystem service quality or quantity, varies widely according to the ecosystem services being considered. There are three aspects of biodiversity in which we are primarily interested, i.e., number of species, overall abundance, and species evenness, which are generally measured by Species Richness (SR), Simpson's Diversity Index (SDI) and Shannon-Wiener Index (SWI).

Among the above biodiversity indices, species richness is the most widely measured and reported one, and therefore has been commonly used in ecosystem services studies (Balvanera et al., 2006; Costanza et al., 2007; Naidoo et al., 2008). The mater-analysis of Balvanera et al. (2006) explored that biodiversity (88% SR) has positive effects on regulating and supporting services, which was strengthened by Cardinale et al. (2012) based on the searching through of ISI Web of Knowledge. Despite indications of a strong association between SR and ecosystem service production, the Shannon-Wiener index (SWI) was employed by 'Norms' to monitor forest ecosystem service due to biodiversity conservation, because it is an indicator of both the richness and evenness of species distributions (Shannon, 1948; Chen and Zhang, 1999).

Detailed correlation analyses using SPSS 21.0 showed that significant correlations exist among ecosystem services (without accounting for biodiversity) and the two biodiversity indices (SWI and SR) with all three Pearson ratios less than 0.001. However, detailed analysis showed that SR declines in the three forests plantations from 10 to 15 years old (Fig. 12), but this was not seen in the dynamics of SWI (Fig. 5). Furthermore, an even larger difference in the trend of biodiversity development was shown between SWI and SR, *i.e.* although the SR of the three plantations increased 6.8 times 23 years after planting, the mean SR at 23 years was still less than that of PF and MF (Fig. 12). The SR of PF (42 species) was 72% that of MF (58 species), but its SWI (3.52) was 1.06 times that of MF (Fig. 6b, Fig. 12). Based on the above differences, we can see that SWI covered some of the characteristics of SR, but not all, and sometimes the unclosed part of SR can show a different picture of biodiversity. Consequently, we recommend adding SR in 'Norms', as a complimentary index for measuring biodiversity conservation as a forest ecosystem service.

4.4. Other methodological options

The emergy value of ecosystem services can be calculated in different ways. This work largely follows Pulselli et al. (2011) where the emergy value of the production of ecosystem services is attributed to renewable empower, a black box method. Campbell and Tilley

(2014a) suggest that this method underestimates the emergy required to provide ecosystem services, because some "historical" emergy, such as species genetic information *etc.*, is also necessary to provide the services. Furthermore, the emergy driving each service should be evaluated independently to allow comparisons between services. However, it is a time and data intensive process and using renewable emergy can be seen as a minimum estimate of the emergy value of ecosystem services.

As described in the introduction, the 'Norms' document is predominately a measure of the replacement cost for ecosystem service with human generated alternatives (the exception being the cost of carbon which is assumed to be equivalent to the tax on carbon in Sweden in 2007). This approach is similar to many previous studies (Costanza et al., 1997; Weber, 2007) which propose that the economic value of human work is equivalent to similar work being done in the ecosystem. However, these values do not necessarily reflect the marginal cost, or any particular benefit, of losing or gaining forest. The values suggested here would not be appropriate to be used in a Payment for Ecosystem Services (PES) market or tax, as they largely reflect potential rather than experienced gains or losses in utility. To establish a reasonable PES scheme, an assessment of the particular trade-offs associated with the loss or gain of a certain area of forest must be made. For example, a forest area needed to satisfy the potential need for additional water treatment infrastructure might be evaluated by equating the marginal values from the costs or benefits of the trade-offs, and the outcome of this analysis could be used to suggest a value to be used in a PES scheme. In the future we suggest the 'Norms' document use values specific to China, and its regions (if possible) and be updated to include a range of values for each ecosystem service, in order to better reflect uncertainty in ecosystem service value.

5. Conclusions

1) Subtropical forests are two orders of magnitude more efficient in producing ecosystem services than the current technologic economic systems of China.

2) Afforestation is an efficient way to speed up the restoration of ecosystem services.

3) Emergy evaluation is not an alternative method to the environmental economic assessment, but a complementary and systemic approach to highlight the donor-side value of ecosystem services, and the efficiency of the production of services by ecosystems.

4) The ability to provide ecosystem services is dependent on the available natural resources present in ecosystems at large scale (e.g., at regional and national scales), but also on the ability (i.e., ET as a proxy in this study) of the ecosystems to capture natural resources in the same or a similar environment.

5) Although SWI is generally an indicator of both the richness and evenness of a species distribution, a quite different trend of development and succession of biodiversity in subtropical forests and plantations was shown by SR compared to SWI. Considering that both are significantly correlated with ecosystem services,

joint use of these indices might be a better solution for the measurement of biodiversity conservation.

Acknowledgement

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Appendix A. Equations and factors to quantify forest ecosystem services suggested by Norms

Function	Index	Equation and factors	
Water conservation	Water regulation	G_{WR}=10A(P-E-C) G_{WR}- The quantity of regulated water in m^3/yr, P-annual precipitation in mm/yr, E- Evapotranspiration in mm/yr, C- runoff in mm/yr, A-Area of forest in ha.	
Soil conservation	Soil fixation	$G_{SF}=A(X_2-X_1)$, $G_{SN}=AN(X_2-X_1)$, $G_{SP}=AP(X_2-X_1)$, $G_{SK}=AK(X_2-X_1)$ GSF- annual fixed soil in t/yr, X_1- erosion factor at forest area in t/yr, X_2- erosion facto at non-forested area in t/yr, GSN- avoided nitrogen erosion in t/yr, GSP- avoided phosphorus erosion in t/yr, GSK- avoided potassium erosion in t/yr, N- nitrogen content in soil in %, P- phosphorus content in soil in %, K- potassium content in soil in %, A- area of forest in ha.	
	Fertilizer conservation		
Carbon fixation and oxygen release	Carbon fixation	Carbon fixation in plants	$G_{PC}=1.63R_CAB_{yr}$ G_{PC}- carbon fixed in plants in t/ha/yr, R_C- carbon content in air, 27.27%, B_{yr}-net primary productivity (NPP) of forest in t/ha/yr, A- area of forest in ha.
		Carbon fixation in soil	GSC=AFS GSC- carbon fixed in soil in t/yr, FS- carbon fixed in united area of soil in t/ha/yr, A- area of forest in ha.
	Oxygen release	$G_O=1.19AB_{yr}$ G_O- oxygen released by forest in t/yr, B_{yr}-net primary productivity (NPP) of forest in t/ha/yr, A- area of forest in ha.	
Nutrients accumulation	Nutrients accumulation in plants	Nitrogen accumulated in plants	$G_{PN}=AN_{NU}B_{yr}$, $G_{PP}=AP_{NU}B_{yr}$, $G_{PK}= AK_{NU}B_{yr}$, G_{PN}- nitrogen accumulated in plants in t/yr, G_{PP}- phosphorus accumulated in plants in t/yr, G_{PK}- potassium accumulated in plants in t/yr, N_{NU}-nitrogen content in plants in %, P_{NU}- phosphorus content in plants in %, K_{NU}- potassium content in plants in %, B_{yr}-net primary productivity (NPP) of forest in t/ha/yr, A- area of forest in ha.
		Phosphorus accumulated in plants	
		Potassium accumulated in plants	

Appendix B. Equations and factors to value forest ecosystem services suggested by Norms

Function	Index	Equation and factors
Water conservation	Water regulation	U_{WR}=10C_RA(P-E-C), U_{WP}=10KA(P-E-C) U_{WR}- value of regulating water in yuan/yr, U_{WP}- value of purifying water in yuan/yr, P-annual precipitation in mm/yr, E- Evapotranspiration in mm/yr, C- runoff in mm/yr, C_R- investment needed for constructing unite reservoir, K-price of water purifying in yuan/yr, A-Area of forest in ha.
	Water purification	
Soil conservation	Soil fixation	U_{SF}=AC_S((X_2-X_1)/ρ, U_{SF}=A(X_2-X_1)(NC_1/R_1+PC_1/R_2+KC_2/R_3+MC_3) U_{SF}- vluae of soil fixation in yuan/yr, U_{SF}- value of fertilizer conservation in yuan/yr, X_1- erosion factor at forest area in t/yr, X_2- erosion facto at non-forested area in t/yr, C_S- price for digging and transport soil in yuan/m^3, A-Area of forest in ha, ρ- soil density in t/m^3, N-nitrogen content in soil in %, P- phosphorus content in soil in %, K- potassium content in soil in %, M- organic matter content in soil in %, R_1- nitrogen content in chemical fertilizer, $(NH_4)_2HPO_4$, in %, R_2- phosphorus content in chemical fertilizer, $(NH_4)_2HPO_4$, in %, R_3- potassium content in chemical fertilizer, KCl, in %, C_1-price of chemical fertilizer, $(NH_4)_2HPO_4$, in yuan/t, C_1- price of chemical fertilizer, KCl, in yuan/t, C_3- price of organic matter in yuan/t.
	Fertilizer conservation	
Carbon fixation and oxygen release	Carbon fixation	U_C=AC_C(1.63$R_C$$B_{yr}$+$F_S$) U_C- value of carbon fixation in yuan/yr, B_{yr}-net primary productivity (NPP) of forest in t/ha/yr, C_C- price of carbon fixation in yuan/t, R_C-carbon fraction in CO_2, 27.27%, F_S- carbon fixation in forest soil in t/ha/yr, A- area of forest in ha.
	Oxygen release	U_O=1.19C_OAB_{yr} U_O- value of carbon release in yuan/yr, B_{yr}-net primary productivity (NPP) of forest in t/ha/yr, C_O- price of oxygen in yuan/t, A- area of forest in ha.
Nutrients accumulation	Nutrients accumulated in plants	U_{NU}=AB_{yr}($N_{NU}$$C_1$/$R_1$+$P_{NU}$$C_1$/$R_2$+$K_{NU}$$C_2$/$R_3$) U_{NU}- value of nutrients accumulation in yuan/yr, P_{NU}- phosphorus content in plants in %, K_{NU}- potassium content in plants in %, B_{yr}-net primary productivity (NPP) of forest in t/ha/yr, R_1- nitrogen content in chemical fertilizer, $(NH_4)_2HPO_4$, in %, R_2- phosphorus content in chemical fertilizer, $(NH_4)_2HPO_4$, in %, R_3- potassium content in chemical fertilizer, KCl, in %, C_1- price of chemical fertilizer, $(NH_4)_2HPO_4$, in yuan/t, C_1- price of chemical fertilizer, KCl, in yuan/t, B_{yr}-net primary productivity (NPP) of forest in t/ha/yr, A- area of forest in ha.
Biodiversity conservation	Species conservation	U_{bio}=S_{bio}A U_{bio}- value of species conservation in yuan/yr, S_{bio}-opportunity cost of species lost in yuan/ha/yr, A- area of forest in ha.

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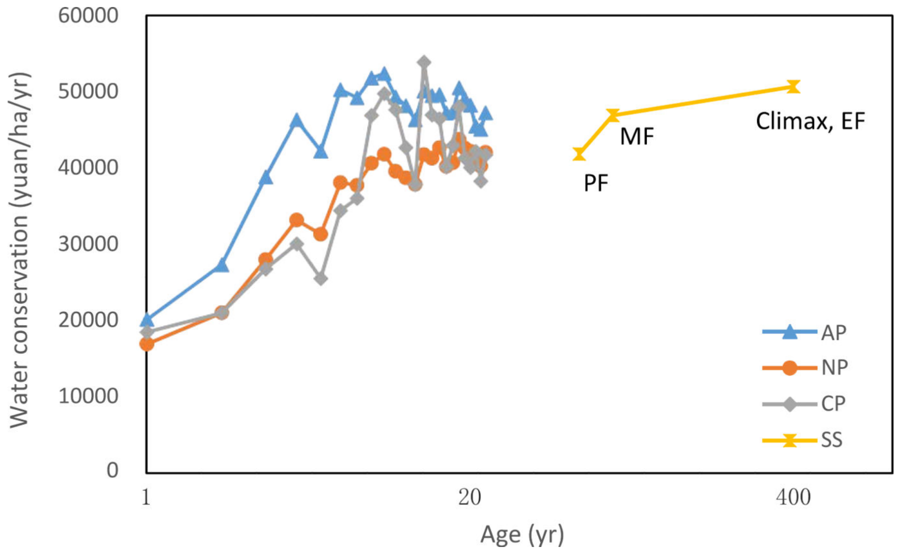

Fig. 1.

Development of the function of water conservation during restoration and succession of subtropical forests

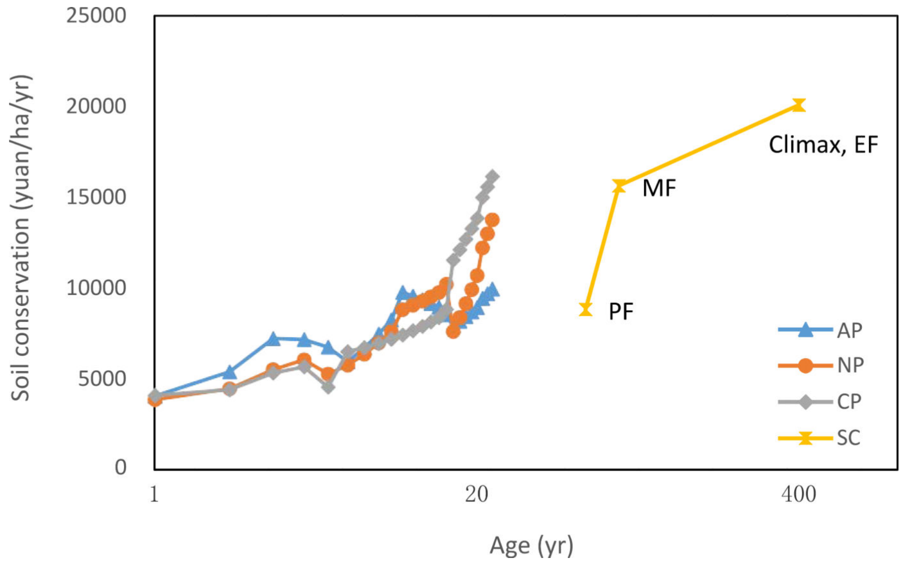

Fig.2.

Development of the function of soil conservation during restoration and succession of subtropical forests

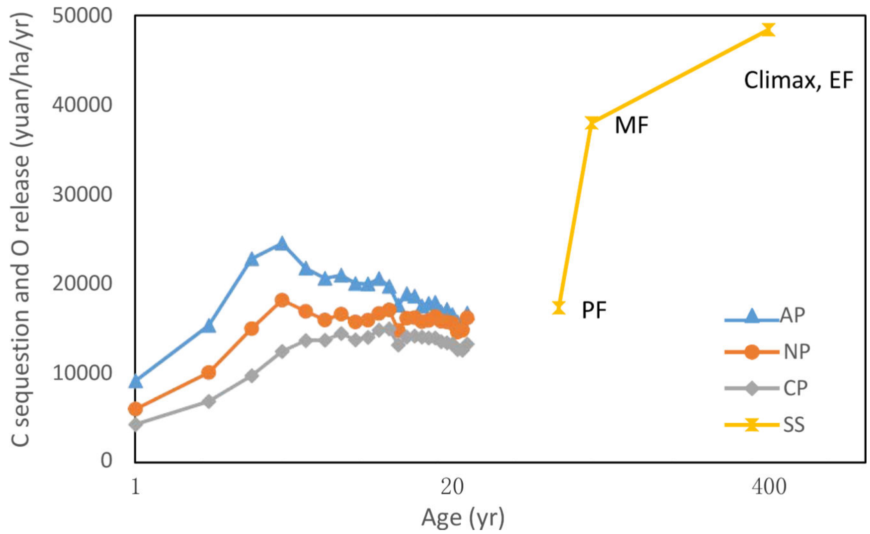

Fig.3.

Development of the function of carbon sequestration and oxygen release during restoration and succession of subtropical forests

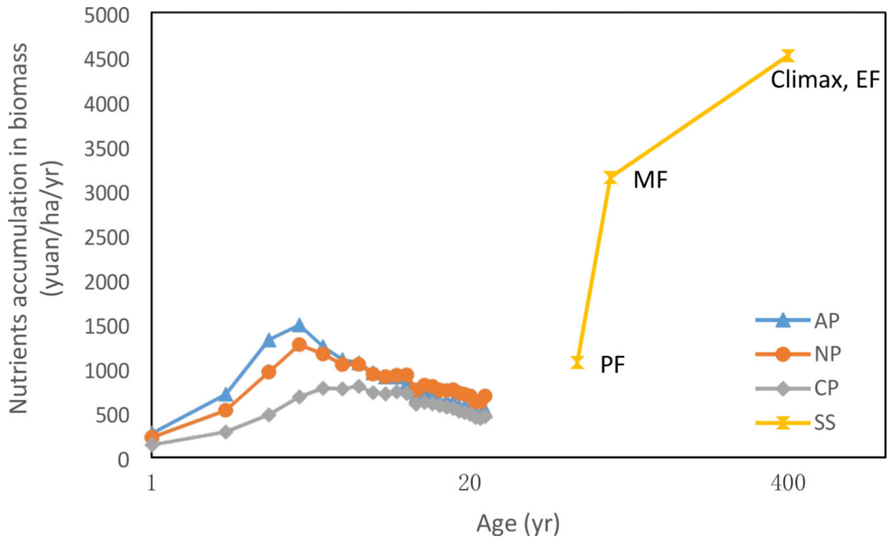

Fig.4.

Development of the function of nutrient accumulation in biomass during restoration and succession of subtropical forests

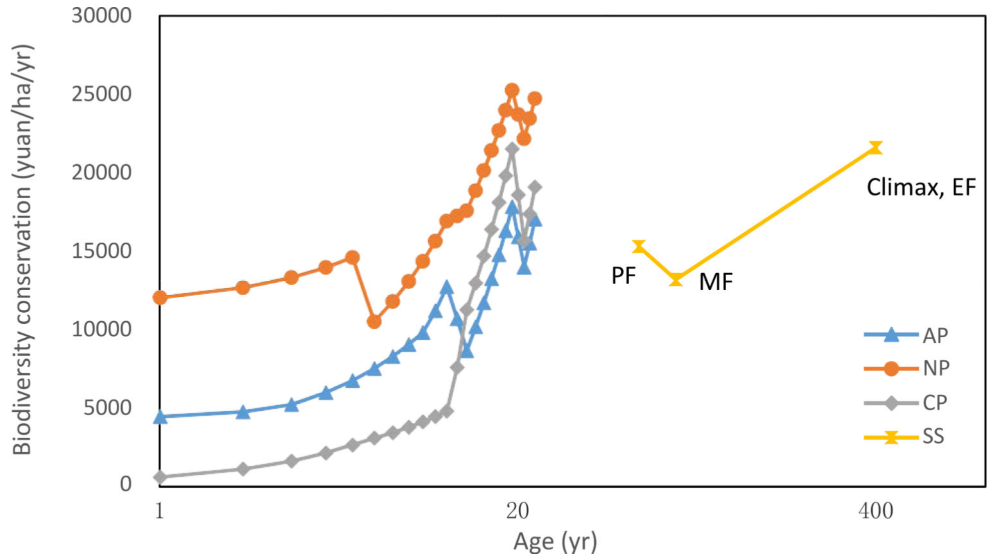

Fig.5.

Development of the function of biodiversity conservation during restoration and succession of subtropical forest

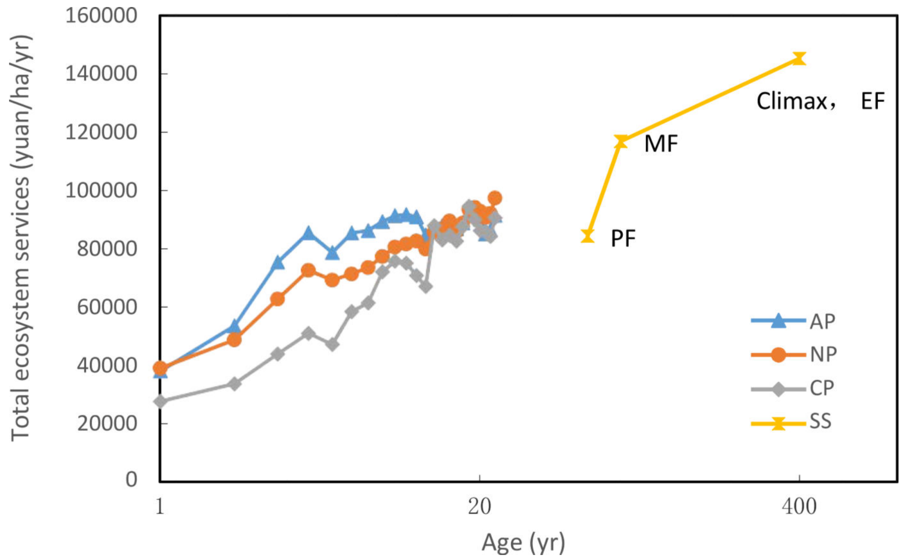

Fig.6.

Development of total ecosystem services during restoration and succession of subtropical forest

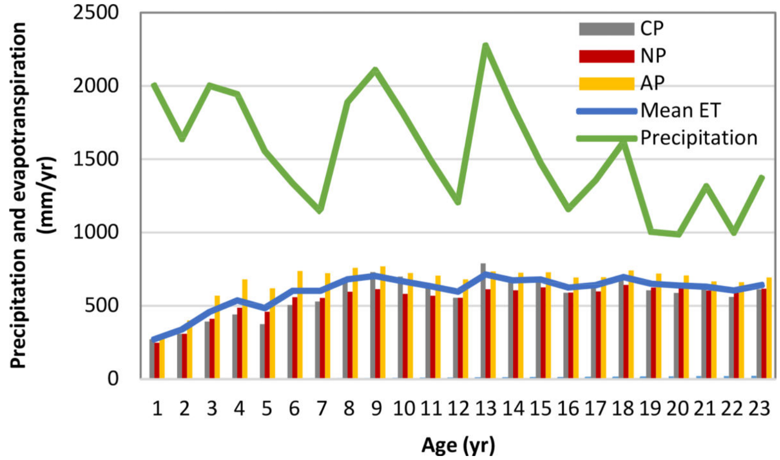

Fig.7.

Annual precipitation at Heshan Station and evapotranspiration of the 3 forest plantations

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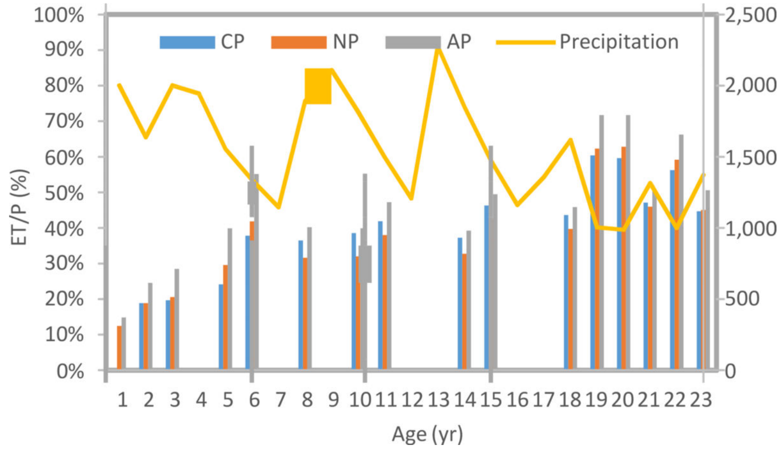

Fig.8.

Annual precipitation and evapotranspiration of the three forest plantations in Heshan station from 1985 to 2007

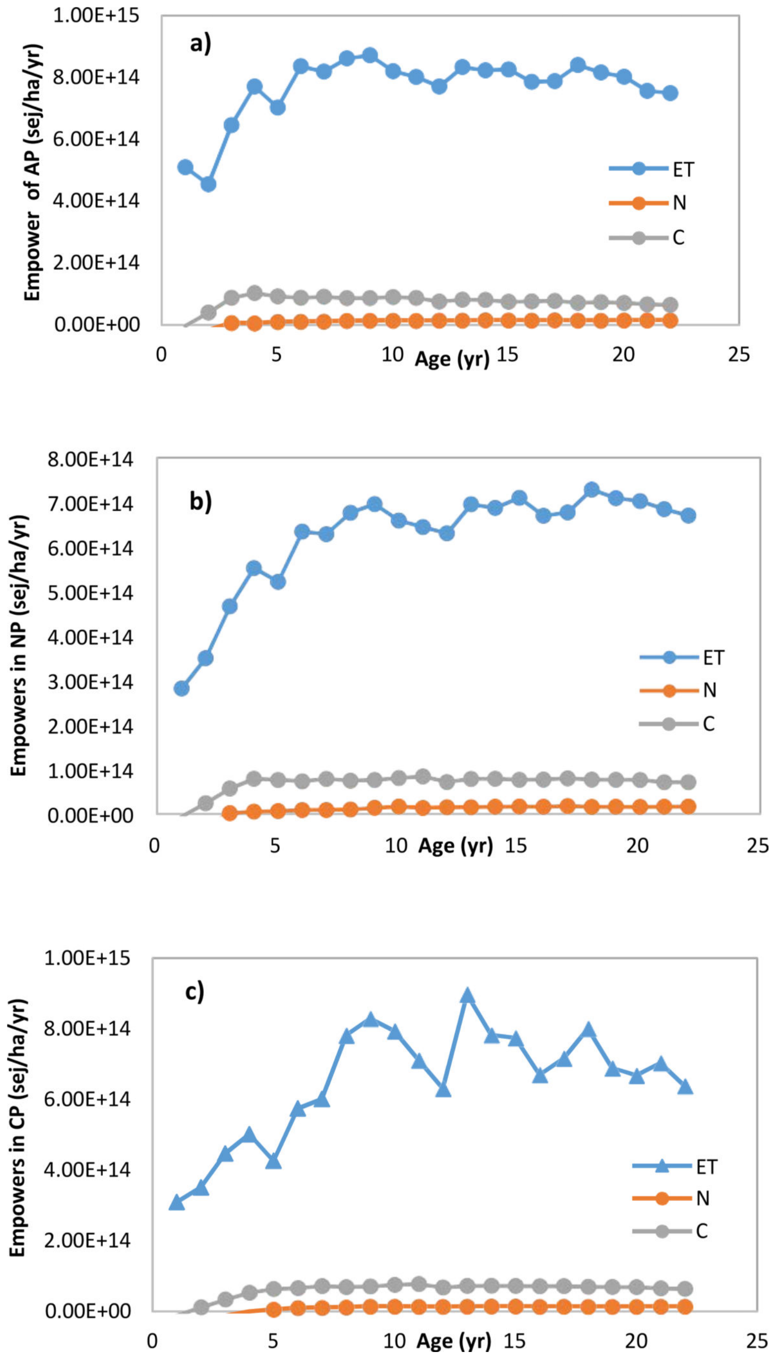

Fig.9.

Emergy flows of evapotranspiration, nitrogen, and carbon through the three forest plantations

a) Emergy flows of evapotranspiration, nitrogen, and carbon through AP

b) Emergy flows of evapotranspiration, nitrogen, and carbon through NP

c) Emergy flows of evapotranspiration, nitrogen, and carbon through CP

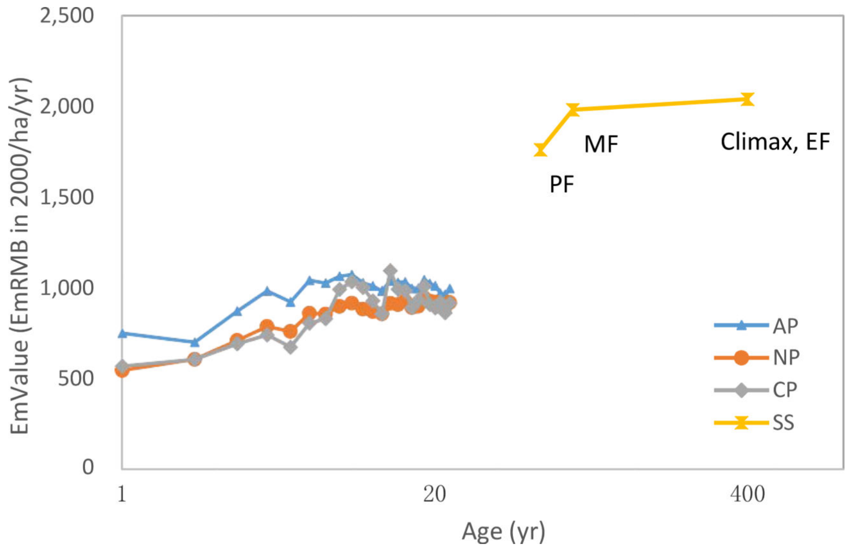

Fig.10.

Emergy based cost of ecosystem services provided during restoration and succession of subtropical forests

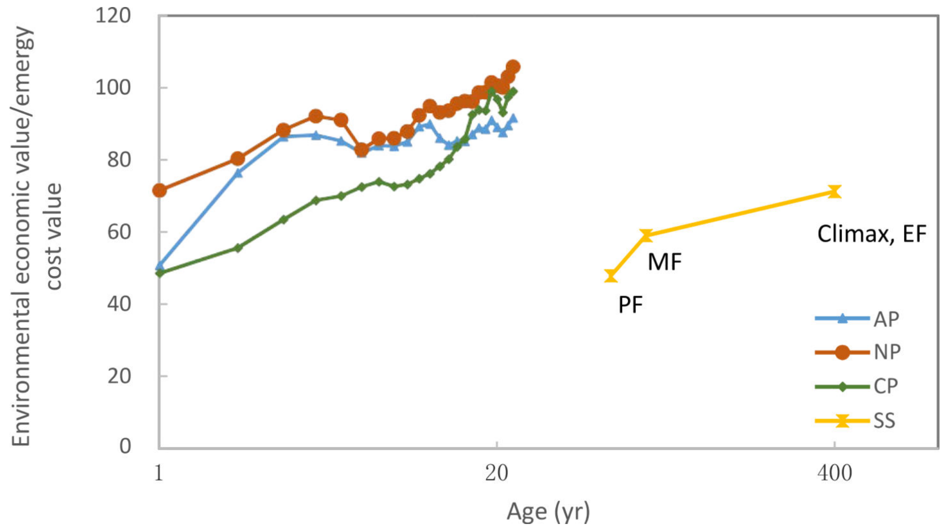

Fig.11.
Development of the efficiency in providing ecosystem services during restoration and succession of subtropical forests

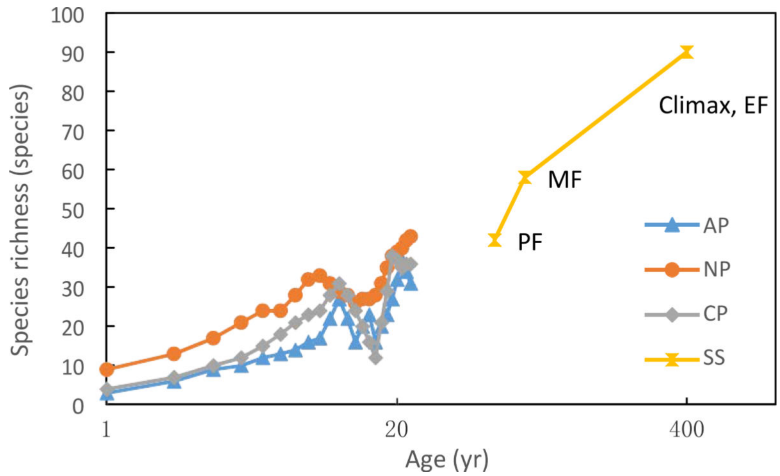

Fig. 12.
Development of plant species richness during secondary succession of subtropical forests

Table 1

Recommended prices for forest ecosystem services proposed in LY/T 1721–2008 (i.e., 'Norms') and their adjustment

Item		Proposed price	Unit	Explanation of the proposed price	Real price in 2000**	Real price in 2010**
Water conservation	Water regulation	6.11	Yuan/MT	Mean price of water reserve construction during 1993 to 1999 (2.17yuan/MT), multiplied by price index of 2005 (2.816)	5.22	7.80
	Water purification	2.09	Yuan/MT	Mean municipal water price in middle and big cities in China in 2007	1.60	2.39
Soil fixation	Soil fixation	12.6	Yuan/m3	MWRC. 2002. Hydrology Engineer Budget Norms for soil excavation	12.27	18.33
Nutrients accumulation	Chemical fertilization with Ammonium phosphate	2400	Yuan/MT	Average price of similar chemical fertilizers in China in 2007	1835.31	2740.71
	(DAP,$(NH_4)_2HPO_4$) Chemical fertilization with potassium chloride (KCl)	2200	Yuan/MT	Average price of similar chemical fertilizers in China in 2007 spring	1682.37	2512.32
	Soil organic matter	320	Yuan/MT	Average price of organic fertilizers in China in 2007 spring	244.71	365.43
Carbon fixation and Oxygen release	Carbon fixation	1200	Yuan/MT	Carbon tax in Sweden ($150/MT) multiplied by the exchange ratio of US$/RMB=8 which is the mean ratio in 2006	987.74	1475.01
	Oxygen release	1000	Yuan/MT	Average price of O2 gas in China, spring 2007	764.71	1141.96
Biodiversity conservation	Species conservation	3000*	Yuan/ha/yr	SWI=<1	2294.14	3425.89
		5000*	Yuan/ha/yr	1< SWI=<2	3823.57	5709.81
		10000*	Yuan/ha/yr	2< SWI=<3	7647.13	11419.62
		20000*	Yuan/ha/yr	3< SWI=<4	15294.27	22839.24
		30000*	Yuan/ha/yr	4< SWI=<5	22941.40	34258.86
		40000*	Yuan/ha/yr	5< SWI<=6	30588.54	45678.48
		50000*	Yuan/ha/yr	6=< SWI	38235.67	57098.10

MWRC--Ministry of Water Resources of China; NDRC--National Development and Reform Commission;

* The time of the price is not mentioned in the standard, considering the last time that price is mentioned in the standards is 2007, we assume that these are 2007 prices.

** The exchange ratios of US$ to RMB in 2000 and 2010 were respectively 8.28 and 6.75.