SPATIO-TEMPORAL VARIATION OF NET PRIMARY PRODUCTIVITY IN A RAPIDLY EXPANDING ARTIFICIAL WOODLAND AREA BASED ON REMOTE-SENSING DATA

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With 4 figures and 5 tables
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Summary: The expansion of artificial woodlands in China has contributed significantly to regional land-cover changes and changes in the regional net primary productivity (NPP). This study used Ximeng County in the Yunnan Province as a case study to investigate the overall changes, associated amplitude, and spatio-temporal distribution of NPP from 2000–2015.The Carnegie-Ames-Stanford approach was used in the rapidly expanding artificial woodland area based on MODIS-NDVI data, meteorological data, and Landsat 5 TM data to calculate the NPP. The results show that (1) artificial woodlands experience a 10fold increase and account for 93 % of the land cover transfer, which was mainly from woodland areas. (2) The NPP was 906.2×10^9 $gC\cdot yr^{-1}$ in 2000 and 972.0×10^9 $gC\cdot yr^{-1}$ in 2015, presenting a total increase of 65.8×10^9 $gC\cdot yr^{-1}$ and a mean increase of 52.4 $gC\cdot m^{-2}\cdot yr^{-1}$ in Ximeng County. (3) The most notable NPP changes take place in the central and the western border regions, with the increasing NPP of artificial woodlands and arable land offsetting the negative effects of the decrease in woodland NPP. (4) The total NPP in the study area kept increasing, primarily due to the growing area of artificial woodlands as well as the stand age of the woods, whereas the mean value change of the NPP is mostly related to the increasing stand age. (5) The artificial woodlands increase the NPP value more than natural woodlands. While protecting and promoting ecologically valuable natural forests at the same time, it seems quite advantageous to establish regional plantations and coordinate their development on a scientific basis with a view to increasing NPP, economic development, but also the ecological stability of this mountain region. Our study reveals the changes in NPP and its distribution in a rapidly expanding area of artificial woodland in southwest China based on remote-sensing data and the CASA model, providing a decision-making basis for rational land-use management, the optimal utilization of land resources, and a county-scale assessment approach.

Zusammenfassung: Die Zunahme der künstlich angelegter Wälder in China hat erheblich zu regionalen Veränderungen der Bodenbedeckung und der regionalen Nettoprimärproduktivität (NPP) beigetragen. In dieser Studie wurde der Bezirk Ximeng in der Provinz Yunnan als Fallstudie herangezogen, um die Gesamtveränderungen, die damit verbundene Amplitude und die räumlich-zeitliche Verteilung der NPP von 2000-2015 zu untersuchen. Der Carnegie-Ames-Stanford-Ansatz wurde in dem sich schnell ausbreitenden Kunstwaldgebiet auf der Grundlage von MODIS-NDVI-Daten, meteorologischen Daten und Landsat 5 TM-Daten zur Berechnung der NPP verwendet. Die Ergebnisse zeigen, dass (1) die künstlichen Wälder um das zehnfache zunahmen und 93 % der Landbedeckungsveränderung ausmachen, die hauptsächlich von Waldgebieten ausging. (2) Die NPP betrug $906{,}2\times10^9$ $gC\ yr^{-1}$ im Jahr 2000 und $972{,}0\times10^9$ $gC\ yr^{-1}$ im Jahr 2015, was einen Gesamtanstieg von $65{,}8\times10^9$ $gC\ yr^{-1}$ und einen mittleren Anstieg von 52,4 $gC\ m^{-2}\ yr^{-1}$ im Bezirk Ximeng bedeutet. (3) Die bemerkenswertesten NPP-Veränderungen finden in den zentralen und westlichen Grenzregionen statt, wobei die zunehmende NPP von angelegten Wäldern und Ackerland die negativen Auswirkungen des Rückgangs der NPP von Wäldern ausgleicht. (4) Die Gesamt-NPP im Untersuchungsgebiet nimmt weiter zu, was in erster Linie auf die wachsende Fläche der angelegten Wälder und das Bestandsalter der Wälder zurückzuführen ist, während die Mittelwertänderung der NPP hauptsächlich mit dem zunehmenden Bestandsalter zusammenhängt. (5) Die künstlichen Wälder erhöhen den NPP-Wert stärker als die natürlichen Wälder. Bei gleichzeitigem Schutz und Wiederherstellung ökologisch wertvoller Naturwälder erscheint es durchaus vorteilhaft, regionale Plantagen anzulegen und deren Entwicklung auf wissenschaftlicher Grundlage zu koordinieren, um die NPP, die wirtschaftliche Entwicklung, aber auch die ökologische Stabilität dieser Bergregion zu fördern. Unsere Studie zeigt die Veränderungen der NPP und ihrer Verteilung in einem sich rasch ausdehnenden Gebiet künstlicher Wälder im Südwesten Chinas auf der Grundlage von Fernerkundungsdaten und dem CASA-Modell auf und liefert damit eine Entscheidungsgrundlage für ein rationales Landnutzungsmanagement, die optimale Nutzung von Landressourcen und einen Bewertungsansatz auf regionaler Ebene.

Keywords: net primary productivity, land cover change, artificial woodland, Carnegie-Ames-Stanford approach, Southwest China

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1 Introduction

Plantation crops like tea, rubber, coffee, and eucalyptus are artificially planted all over China owing to their short production cycles, quick growth, high market demand, and economic benefits. Planting trees is considered to be a cost-effective measure for controlling desertification and conserving the environment (Yang et al. 2006). However, large areas of artificial woodlands can change the biodiversity (Begotti et al. 2018), soil quality, net primary productivity (NPP), ecosystem structure (Tererai et al. 2013), and ecosystem functions (Martello et al. 2018) at various scales. Under the current conditions of global climate change and increasing human activity, the multi-dimensional vulnerability and risks (Chen et al. 2014) of social-water (Chen et al. 2019; Vörösmarty et al. 2000) and ecosystems in large artificial woodland areas are of significant concern.

NPP is an important indicator of the social-ecosystem sustainability. It refers to the total amount of organic dry matter per unit area and per unit time produced by green plants (Tripathi et al. 2017). As a key variable representing vegetation vitality, NPP can directly reflect the production capacity of plant communities under natural conditions. It is also the main indicator that measures the carbon fixation capacity of vegetation, and the sensitivity indication factor can be used to determine carbon sinks/sources and adjust the ecological process (Jiang et al. 2016). On the other hand, it can also indirectly represent the impact of land-use cover change on ecosystem sustainability. It has a certain feedback effect on the quality state, carbon balance, and climate change of the ecosystem (Xu et al. 2020). In recent years, NPP has garnered significant research interest as climate change and changes in the associated water resources are affecting vegetation growth. For instance, a study in South India found that changes in fine-root biomass and NPP follow the conversion of tropical forests into forest plantations and agroecosystems (Sundarapandian and Swamy 1998). Runyon et al. (1994) evaluated how climate constrains NPP by limiting the utilization of intercepted photosynthetically active radiation. Beyond these physical factors, previous studies have also shown that the extensive planting of artificial woodlands has a large impact on regional NPP. Laclau et al. (2008) applied nonlinear regression to obtain the fraction of photosynthetically active radiation (FPAR) assimilated by green plants, and Vassallo et al. (2013) further determined that the annual average amount of the aboveground NPP nearly quadruples after the replacement of grasslands with alpine-ashes. Guo et al. (2010) employed the quadrat harvesting method and regression analysis, concluding that the annual average NPP of a three-year *Jatropha Curcas* plantation reached approximately 10.827 $t \cdot hm^{-2}$ in the Red River basin of Yunnan, China. Since the mid-1970s, China's afforestation and forestry management, grassland protection, agricultural system reform, and conservation farming practices have greatly changed the methods used to approach land restoration (Zhao et al. 2021), which have proven to be an important way to change regional carbon storage. Many studies use the NPP as a forest ultimate carbon sequestration technique to assess the value of solid carbon–oxygen release services. In addition to changes in area change, the changes in the annual carbon fixation capacity of various land-use types are also affected by spatial changes in NPP (Cheng et al. 2017). DeFries et al. (1999) found that the global NPP decreases by about 5 % per year due to land-use changes. In China, the implementation of ecological restoration projects plays the role of carbon fixation; 56 % of these carbon sinks are caused by the implementation of ecological restoration projects (Zhao et al. 2021).

With recent developments in remote-sensing technology, models for estimating large-scale NPPs are receiving significant research interest. Among these, the representative Carnegie–Ames–Stanford Approach (CASA) (Potter et al. 1993) has been applied widely at different spatial scales (the regional scale and the global scale) (Ruimy et al. 1994; Lobell et al. 2002; Wei and Wang 2014) for various types of ecosystems (grasslands, forests, farmlands, etc.), and has also been validated by experimental data (Geng et al. 2012; Lei et al. 2013; Zhang et al. 2014). Currently, it is very common to apply measured data to study the impacts of artificial plantations on the regional ecological environment on the mesoscale. However, remote-sensing data has rarely been used in this field, especially at the county scale (Potter et al. 2012; Hicke et al. 2002).

Ximeng County is a relatively poor county at the border of Myanmar and China, with mountainous terrain (the Hengduan Mountains) and a tropical to sub-tropical climate. The main industry in this region is forestry and agriculture. To develop the forestry and economy, determining the conditions of artificial woodlands is important for governmental decision-making and farmers' livelihoods. Further, agroforestry – based on planted trees – provides productive and protective forest functions such that local communities can ensure sustainable forest management (Van et al. 2003). In addition, this border area is the main observation site for biodiversity, animal transfer, and forest cover change (Giri et al. 2003; William et al. 2011). Many farmlands hare have been converted to forestland by the 'Grain for Green' policy and some forestland has been reclaimed by crop cultivation (Zhao et al. 2018a). Therefore, to assess and monitor the changes in land cover/use, particularly from the perspective of NPP, is imperative.

Since 2000, forestry had been one of the most important industries in Ximeng County of the Yunnan Province, and the pace of construction of commercial forest bases has consequently sped up. Thus, the artificial woodland area (rubber plantations, eucalyptus plantations, tea plantations, etc.) of the county grew from 20 km^2 in 2000 to 223 km^2 in 2015. The rapid expansion of plantations in this region inevitably led to changes in the land cover type, regional NPP, and distribution pattern. However, only a few studies have focused on the county-scale NPP in southwestern China to date. Dong and Ni (2011) simulated the NPP of vegetation in the karst areas of southwest China using a CASA model. Their results show that the NPP in the southwest Yunnan province is greater than 480 gC·m^{-2}·yr^{-1}. He and Zhang (2006) applied a climate model to research the NPP in Yunnan province from 1960 to 2000, indicating an average NPP of 795.8g C·m^{-2}·yr^{-1} in Ximeng County. Qiu (2013) used a process model (CEVSA) to study the vegetation NPP in southwestern China and determined that the average NPP in Yunnan Province is less than 1000 gC·m^{-2}·yr^{-1}. The spatial distribution pattern of NPP in Ximeng County is related to the distribution characteristics of water and heat resources, along with the land cover change in Ximeng County. The spatial changes in NPP in Ximeng County are mainly concentrated in the artificial garden planting areas (Zhao et al. 2018a). However, the extent, magnitude, and mechanism of its impact on NPP have not been studied adequately yet. Therefore, this study aims to determine the spatio-temporal distribution of NPP within rapidly expanded artificial woodland areas, along with the impacts of rapid artificial woodland changes on NPP in complex topographic areas at the regional scale. Moreover, the appropriate means and methods used for NPP research in complex topographical areas at the county scale are also proposed. Remote sensing data and meteorological data are applied jointly to drive the CASA model and to analyse the spatio-temporal variation patterns of NPP in Ximeng County from 2000 to 2015. The study further explored the effect of land cover change due to rapidly expanding artificial woodlands on regional NPP variations.

2 Materials and methods

2.1 Study area

Ximeng County, located in the southwestern region of Yunnan province, is at the border of Myanmar and China and covers a total area of 1258 km^2 (Fig. 1). As part of the southern section of the Hengduan Mountains, the entire county has mountainous terrain. Its elevation is higher in the northeast and lower in the southwest, ranging from 590.0 m to 2458.9 m above sea level, which is a significant difference in terms of elevation-related landscapes. A few river valleys criss-cross the middle and low areas, which provide areas for major human settlements and limited agriculture.

The climate types in the county include tropical, subtropical, and temperate monsoon climates, associated with the altitude, affected by the southwestern warm and moist airflow from the Bay of Bengal throughout the year. The average yearly precipitation in Ximeng County can reach 2758.3 mm, which is the highest in the Yunnan Province. Ninety percent of the precipitation occurs as rain in summer and autumn. Owing to the unstable climate, various soil types have developed, such as lateritic, lateritic red, red, and yellow-brown soil. Moreover, the annual mean temperature is 15.30 ℃, with the highest temperature reaching 23.9 ℃ in June and the lowest at 13.4 ℃ in January. Local climate and soil conditions are favourable for the growth of seasonal rainforests, monsoon forests, and monsoon evergreen broad-leaved forests, providing a habitat for diverse wildlife. Overall, the internal and external conditions for developing a forestry economy are significant in this region.

From 2000 to 2015, the population of Ximeng County grew from 86,600 to 94,400. The per capita gross domestic product (GDP) increased from 1,109 RMB to 11,777 RMB, classifying the county as 'poor' and eligible for support in terms of poverty alleviation. The local government has been continually adjusting the structure of the agriculture industry since 2000 by promoting forest, fruit, and tea production. Consequently, large areas of the Simao pine forest, eucalyptus forest, tea plantations, and rubber plantations were developed in the county, particularly rubber gardens, tea gardens, and eucalyptus forests. Thus, the regional woodlands and land cover changed significantly throughout this process. Therefore, relevant scientific concerns and far-reaching agricultural and forestry development policies have become crucial issues in recent years.

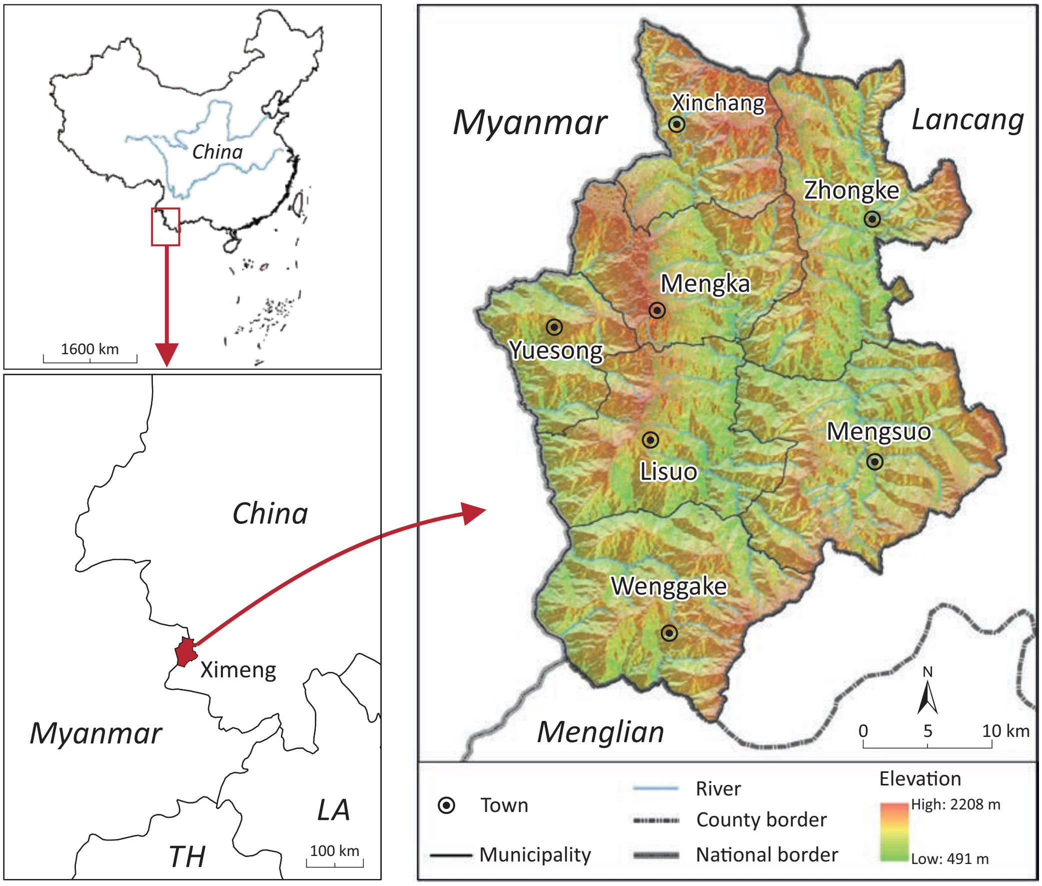

Fig. 1: Location, landforms, and administrative divisions of Ximeng County

Usually, changes in NPP are related to the local temperature, precipitation, solar radiation intensity, and human activities (Wang et al. 2018). However, the values of the physical factors of temperature, precipitation, and solar radiation intensity exhibit only slight variations during 2000, 2005, 2010, and 2015 in Ximeng County, which indicates that the local NPP is primarily impacted by human activities, such as the implementation of agriculture and forestry policies, and the associated land cover changes (Du 2015). Thus, this study aims to investigate how the agriculture and forestry development changed the spatio-temporal variation characteristics of NPP in Ximeng County.

2.2 Materials

The materials used in the study include normalized difference vegetation index (NDVI) data, meteorological data, Landsat 5 TM data, and statistical data. NDVI data are collected from Global Inventor Modeling and Mapping Studies (GIMMS). The MODIS-NDVI data composites of 2000, 2005, 2010, and 2015 had a spatial resolution of 250 m. The maximum value composite (MVC) was used to acquire the monthly value of MODIS-NDVI data and to calculate the fraction of photosynthetically active radiation (FPAR).

Meteorological data is collected from 14 weather stations spread over Ximeng County and the two adjacent counties, Lancang County and Menglian County. The data involves daily sunshine duration, monthly mean temperature, and total monthly precipitation. To compare the analysis results with existing relevant research, depending on the climatic data from nine neighbouring meteorological stations of Ximeng county, the same inverse distance weighting (IDW) is applied for interpolation calculations, to obtain the values of surface solar radiation, temperature stress indexes, and water stress indexes to reconstruct the surface variation data (Bartier and Keller 1996; Du et al. 2015).

The classification data of vegetation types are extracted from four sets of Landsat 5 TM data, with a spatial resolution of 30 m, in February of 2000, 2005, 2010, and 2015. The land covers of Ximeng County are classified into six types: woodlands (trees and shrubland), grasslands, arable land, artificial woodlands (rubber plantations, tea plantations, and eucalyptus plantations, herein), construction land, and water areas. In combination with site surveys, a precise evaluation is carried out on the classified images using the confusion matrix, which shows that the overall accuracy of the confusion matrix of land classification over four periods is more than 70 %, and the kappa coefficient is greater than 0.75. Because a portion of the radiation spectrum of rubber plantations is similar to that of tea plantations, both rubber and tea are classified as artificial woodlands; although there are certain spectral similarities among artificial woodlands, woodlands, and arable land, these similarities are few. The spectral similarities between other land-use types are few, and the classification accuracy is generally in line with the given requirements.

2.3 Methods for NPP evaluation

A method for estimating plant productivity was proposed by Monteith (1972) using the photosynthetically active radiation absorbed by plants and the light-use efficiency. Based on their algorithm, Heimann and Kelling established an NPP model in 1989, which was further developed into the Carnegie–Ames–Stanford Approach (CASA) by Potter (1993). Since then, the CASA model has been widely used for evaluating the dynamic changes and spatiotemporal variability of NPP at the regional and global scale (Yu et al. 2009). The model takes the stress factors' impact on vegetation NPP into consideration, including the solar radiation, temperature, and moisture:

$$NPP(x,t) = APAR(x,t) \times \varepsilon(x,t) \tag{1}$$

where $APAR(x,t)$ is the photosynthetically active radiation absorbed by plants within pixel x at time t (gC·m^{-2}·month^{-1}) and $\varepsilon(x,t)$ is the actual utilization efficiency of solar energy (gC·MJ^{-1}). In this study, we convert the NPP calculated in formula (1) to the annual mean value of NPP (Li 2004), and then multiply it by the land area to obtain the total value of NPP in the region:

$$APAR(x,t) = SOL(x,t) \times 0.5 \times FPAR(x,t) \tag{2}$$

$$SOL(x,t) = (a_n + b_n \times n/N) \times S_0 \tag{3}$$

where $SOL(x,t)$ is the total amount of solar radiation within pixel x at time t (MJ·m^{-2}·month^{-1}), which can be calculated using empirical formula (3) (Li 2004). n is the actual number of sunshine hours. S_0 is the atmospheric external emission. a_n is the amount of atmospheric external radiation that reaches the surface on cloudy days (n=0), while b_n is the amount of atmospheric external radiation reaching the surface on fine days (n=N). *0.5* is a constant coefficient that indicates the percentage of the solar effective radiation available for the plant (at wavelengths of 0.4–0.7 μm) to the total solar radiation (McCree 1981). $FPAR(x, t)$ is the FPAR absorbed by the plants. There is a linear relationship among the FPAR, NDVI, and ratio vegetation index (RVI), which can be used to calculate the value of FPAR in each grid (Chen et al. 2011):

$$\varepsilon(x,t) = T_{\varepsilon 1}(x,t) \times T_{\varepsilon 2}(x,t) \times W_{\varepsilon}(x,t) \times \varepsilon^{*} \tag{4}$$

where, $T_{\varepsilon 1}(x,t)$ and $T_{\varepsilon 2}(x,t)$ represent the stress effects of low temperatures and high temperatures on the utilization of the light energy of vegetation, respectively. $T_{\varepsilon 1}(x,t)$ represents the restriction on photosynthesis by the biochemical processes inherent in plants at high or low temperatures, while $T_{\varepsilon 2}(x,t)$ represents the effect of temperature changes on the light energy conversion rate from the optimum temperature to high or low temperatures; and $T_{\varepsilon}(x,t)$ represents the water stress index. The estimation of $T_{\varepsilon 1}(x,t)$, $T_{\varepsilon 2}(x,t)$, and $T_{\varepsilon}(x,t)$ follows the methods described in a previous study (Du 2010), and is, therefore, not introduced here. ε^{*} represents the maximum conversion rate of solar energy (gC·MJ^{-1}), which reflects the maximum utilization efficiency of solar energy under ideal conditions. Different vegetation species have different ε^{*} values. We adopted the method used by Zhu et al. (2007) to assign ε^{*} values of different land-use types in Ximeng County.

FPAR is primarily affected by the vegetation type and coverage rate, which can be calculated using formula (5) (Los 1998):

$$FPAR(x,t) = \alpha FPAR_{NDVI} + (1-\alpha) FPAR_{SR} \tag{5}$$

where $FPAR_{NDVI}$ is the value of FPAR calculated from NDVI data. $FPAR_{SR}$ is the value of FPAR calculated from RVI data. α is the coordination factor between $FPAR_{NDVI}$ and $FPAR_{SR}$, which can be determined according to the actual conditions in the study area, and a value of 0.5 was used in this study (Los 1998):

$$FPAR_{NDVI} = \frac{(NDVI(x,t) - NDVI_{i,\min})}{(NDVI_{i,\max} - NDVI_{i,\min})} \times (FPAR_{\max} - FPAR_{\min}) + FPAR_{\min} \quad (6)$$

where $NDVI\ (x,t)$ represents the NDVI within pixel x at time t ($MJ \cdot m^{-2} \cdot month^{-1}$). $NDVI_{i,\ max}$ and $NDVI_{i,\ min}$ correspond to the maximum and minimum NDVI values of vegetation type i, respectively. $FPAR_{max}$ and $FPAR_{min}$ are not dependent on the vegetation type, the values of which were taken as 0.95 and 0.001, respectively (Ruimy et al. 1994):

$$FPAR_{SR} = \frac{(SR(x,t) - SR_{i,\min})}{(SR_{i,\max} - SR_{i,\min})} \times (FPAR_{\max} - FPAR_{\min}) + FPAR_{\min} \quad (7)$$

where, $SR_{i,max}$ and $SR_{i,min}$ correspond to the 95th and 5th percentile of the NDVI value of vegetation type i, respectively. Based on NDVI data, the simple ratio vegetation index (SR) was calculated using formula (8) (Ruimy et al. 1994):

$$SR(x,t) = \frac{1 + NDVI(x,t)}{1 - NDVI(x,t)} \quad (8)$$

3 Results

3.1 Artificial woodland development and land cover changes

From 2000 to 2015, the most prominent change in land cover in Ximeng County was the expansion of artificial woodlands, which increased from 20 km^2 to 223 km^2. Further, the woodland area decreased by a total of 180 km^2, while the other types of land cover did not exhibit remarkable changes (Fig. 2). In

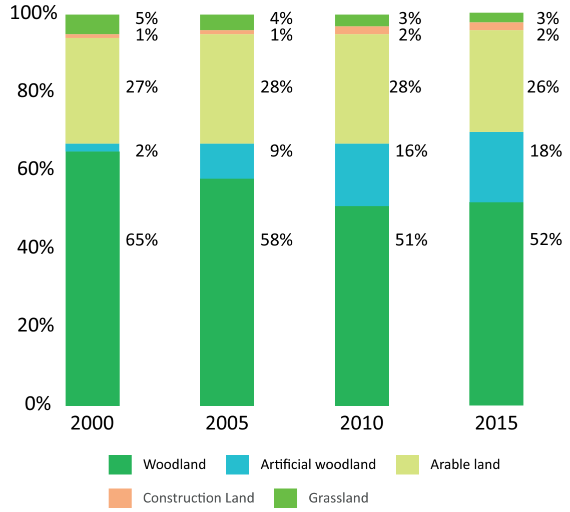

Fig. 2: Percentage of the area of land-use types in Ximeng County

general, the increasing trend of artificial woodland corresponds to the decreasing trend of natural woodland. In recent years, to improve the economic development in Ximeng County, the county has increased the development of the forest industry and animal husbandry. Consequently, artificial woodlands grew rapidly from 2000 to 2015, where the area of rubber plantations increased the most (134 km^2). It is clear that the conversion of land cover types from natural land to artificial woodlands is affected by the development of agriculture and animal husbandry in Ximeng County.

Table 1 shows the detailed conversion rates among land cover types in Ximeng County. An inward transfer refers to newly added areas of certain land cover types converted from other types of land cover, and an outward transfer means that the area

Tab. 1: Transferred areas [km^2] of different land cover types from 2000 to 2015

Land cover types	2000-2005			2005-2010			2010-2015		
	Inward Transfer	Outward Transfer	Net Transfer	Inward Transfer	Outward Transfer	Net Transfer	Inward Transfer	Outward Transfer	Net Transfer
Artificial woodland	117.55	3.00	113.65	100.41	11.32	89.09	51.95	31.09	20.86
Arable land	97.87	87.69	10.18	99.79	106.63	-6.85	90.47	104.79	-14.2
Grassland	5.08	41.51	-36.44	2.06	7.57	-5.51	17.16	12.4	4.76
woodland	59.50	149.1	-89.61	54.88	132.4	-77.52	114.16	126.96	-12.8
Construction land	3.75	1.50	2.25	2.55	2.09	0.45	4.22	4.18	0.04
Water area	0.10	0.13	-0.03	0.37	0.04	0.33	0.33	0.01	0.32

of a certain land cover type is converted to another. From 2000 to 2005, the largest area of inward transfer was artificial woodlands, followed by arable lands and natural woodlands. Construction lands exhibited slight changes, while water areas were relatively stable. Accordingly, the most significant outward transfer is that of woodland areas, followed by arable land and grassland areas. These trends were maintained throughout 2005–2010. Although the arable land area changed frequently and significantly, it remained relatively stable in terms of its total area, while the woodlands decreased significantly and artificial woodlands increased remarkably. From 2010 to 2015, woodlands comprised the largest area in terms of both inward and outward transfers. However, the net transfer quantity is small. Further, the areas of arable land inward and outward transfers ranked second among these types of land cover. According to the net transfer data, the change in woodland areas in Ximeng County is most significant.

A significant land cover transfer that occurred during the studied period was the rapid expansion of artificial woodlands. The estimation – at the township scale – shows that a large area of woodland, grassland, and arable land had been converted into artificial woodlands. From 2000 to 2005, the most notable increase took place in the southeast of Lisuo and south of Wenggake along the Nankang River valley, with areas of 57.1 km^2 and 28.3 km^2, respectively (Fig. 3a). Xinchang, at the north of Ximeng County, exhibited the smallest increase. From 2005 to 2010, the biggest change occurred at the central part of Lisuo (67.1 km^2) and Mengka (63.1 km^2), while Xinchang was still the region with the least change. From 2005 to 2010, artificial woodlands in both Lisuo and Zhongke increased most significantly among all township areas (Fig. 3b–c). From 2010 to 2015, the distribution of artificial woodlands changed less, and the spatial production pattern was relatively constant (Fig. 3c–d). According to these data, the overall land cover conversion in the 15 years was dominated by a substantial increase in artificial woodlands, particularly along the China–Myanmar border regions in the west and along the Nankang River valley in the middle of Ximeng County (Fig. 3a–d). Additionally, during the study period, the artificial woodlands plantation area below 1100 m increased 10.67 times, which was mainly due to the planting of rubber forests; the planting area increased 1.45 times between 1400–1900m, mainly due to the planting of eucalyptus forests and tea gardens; and other planting areas increased 1.45 times. Overall, the artificial woodlands are distributed in mountainous areas with good traffic accessibility.

3.2 Changes of the total NPP during the period of 2000–2015

The total value of NPP in Ximeng County in the year 2000 was 906.2×10^9 $gC\cdot yr^{-1}$ (Tab. 2). It decreased to 844.5×10^9 $gC\cdot yr^{-1}$ in 2005 and then continuously increased to 972.0×10^9 $gC\cdot yr^{-1}$ in 2015. In these 15 years, the NPP increased by a total of 65.8×10^9 $gC\cdot yr^{-1}$, with a mean increase of 52.4 $gC\cdot m^{-2}\cdot yr^{-1}$. The county's NPP decreased from 2000 to 2005 and increased thereafter. From 2000 to 2005, the mean NPP values and total NPP values for all land cover types decreased in spite of various transfers occurring. However, the NPP values increased when other land cover types were converted into woodlands, including artificial woodlands. Based on the overall period from 2000-2015, the two land use types arable land and woodland show a net loss of NPP of a similar magnitude, while the NPP of artificial woodland in particular has increased significantly. It is also noteworthy that, in addition, not only the NPP of grassland has increased, but even (albeit to a very small extent) the NPP of construction land and water areas (Tab. 2). The reason for this increase in NPP when farmland is converted to construction land is that the NPP of the original farmland is not high. After the conversion into construction land, green trees are planted on the land and nurseries are cultivated, which increases the NPP. After the transformation of construction land into water areas, the NPP increased only slightly, primarily owing to the growth of phytoplankton, emergents plant and floating plant. From 2000 to 2005, the area where the construction land was transformed into water areas was in Longtan, Ximeng County. The area of the lake increased and aquatic vegetation increased; therefore, NPP increased.

The area and NPP value of natural woodlands are the highest among all other land use types in the period from 2000 to 2015. While the area share and total net primary production decreased sharply until 2010 and then showed a slight increase, the area of artificial woodlands increased continuously and the total NPP value rose to 123×10^9 $gC\cdot yr^{-1}$.

The share of grassland has decreased by about one third over the entire period and the value of the total NPP has decreased accordingly; however, it is noteworthy that the mean NPP has increased slightly. The share of farmland fluctuated over the study period, but shows a slightly

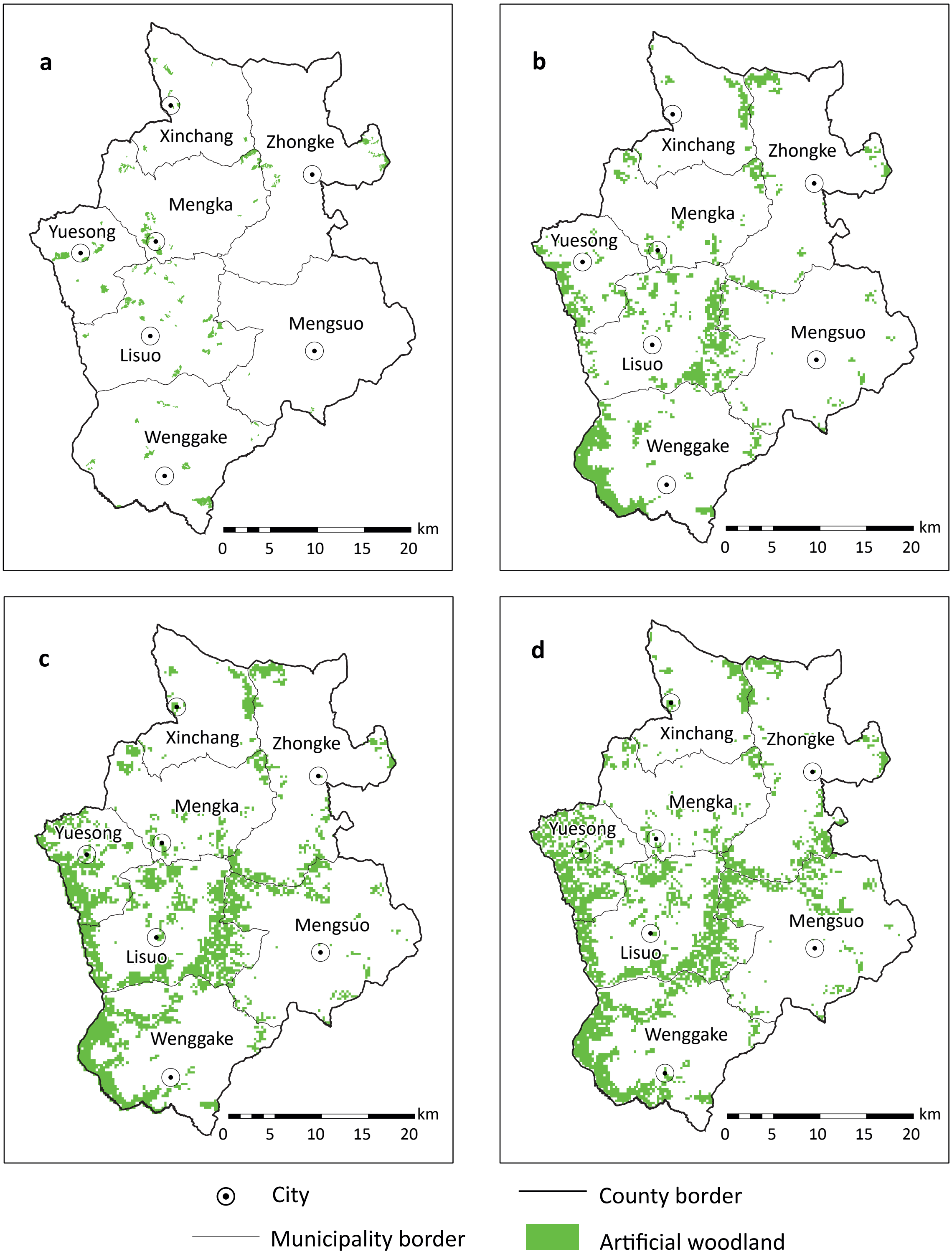

Fig. 3: The distribution of artificial woodlands in 2000 (a), 2005 (b), 2010 (c), and 2015 (d)

decreasing trend overall; however, the total NPP also increased slightly for this land use type. Contruction land and water areas are spatially of minor importance in the study area; this is also reflected in very low total NPP values. These results demonstrate that the changing trends of

Tab. 2: NPP of different land cover types and their change from 2000 to 2015

Land cover types	2000			2005			2010			2015			Changes 2000-2015		
	Area	MV	TV	Area	MV	TV	Area	MV	TV	Area	MV	TV	Area	MV	TV
Woodland	815	875	713	701	873	612	626	1015	635	656	958	628	-159	83	-85
Artificial woodland	21	704	14	138	457	63	221	547	121	223	615	137	202	-89	123
Grassland	63	473	30	46	440	20	41	513	21	36	559	20	-27	87	-10
Arable land	341	422	144	354	407	144	350	452	158	321	551	177	-20	129	33
Construction land	17	291	5	18	282	5	19	316	6	19	472	9	2	181	4
Water area	1	309	0.2	1	298	0.2	1	321	0.4	3	398	1	2	89	0.8
Total	1258	720.3	906.2	1258	671.3	844.2	1258	748.1	941.4	1258	772.7	972	0	52.4	65.8

Note: MV - mean value of NPP [$gC \cdot m^{-2} \cdot yr^{-1}$]; TV - total value of NPP [$10^9 \cdot gC \cdot yr^{-1}$]; area [$km^2$].

the mean and total NPP were basically consistent for different land cover types from 2000 to 2015, decreasing from 2000 to 2005 and increasing thereafter (cf. Tab. 2). The factors influencing the NPP changes mainly involve vegetation types, their growth status, climatic factors, and the degree of human interference. From 2000 to 2005, the newly added plantation tress were immature, and their utilization efficiency of solar energy and output levels were low, which led to a low mean NPP value. Additionally, massive artificial woodlands around the cities and rural settlements were converted to other land cover types alongside the rapid urbanization process. Therefore, the NPP mean values of all land-use types in 2005 were smaller than those in 2000. Notably, the planting of artificial woodlands increased very rapidly during this period. The area of artificial woodland in 2005 reached 5.54 times that in 2000, which enhanced the total NPP of artificial woodlands in 2005 (significantly exceeding the level in 2000).

From 2005 to 2015, the NPP of most land-use types exhibited an increasing trend, other than woodland and grasslands in 2015. It is important to note that, along with the continuous expansion of artificial woodlands and the growth of plantation plants, the total and mean NPP values of artificial woodlands increased distinctly during this period. By 2015, the mean NPP of artificial woodlands surpassed that of arable land, but was smaller than that of woodlands. This indicates that, after a period of growth, the productivity per unit area of artificial woodlands was higher than that of arable land, but still lower than that of woodlands. Furthermore, the total NPP of artificial woodlands increased from less than 10 % of arable land in 2000 to nearly 80 % in 2015. In other words, the impacts of artificial land on regional ecosystem services are becoming increasingly severe.

3.3 Spatial distribution of NPP

From 2000 to 2005, a significant decrease in NPP can be observed, as NPP values in all seven municipalities showed a negative development. However, in the following five years, the NPP value increased in a large part of the region, so that the total NPP also increased significantly. From 2010 to 2015, the areas with increased and decreased NPP values were approximately equal in size, so that the total NPP value increased slightly in comparison (Fig. 4a-c).

Most decreases in NPP from 2000 to 2005 were concentrated at the central and western parts of the county (Fig. 4a). The NPP value decreased up to 1306.6 $gC \cdot m^{-2} \cdot yr^{-1}$ in many areas, including the townships of Lisuo, Wenggake, and Yuesong, as well as the areas bordering Myanmar (Fig. 4a). The greatest changes in land cover took place in these areas, where cropland and natural forests were converted into artificial forests (Table 3). Initially, the intensive use of arable land led to an increase in cropping density and NPP. However, with the introduction of the 'Grain to Green' policy, some cropland was abandoned and converted into artificial woodland. During the juvenile phase, the NPP at first remained low because the

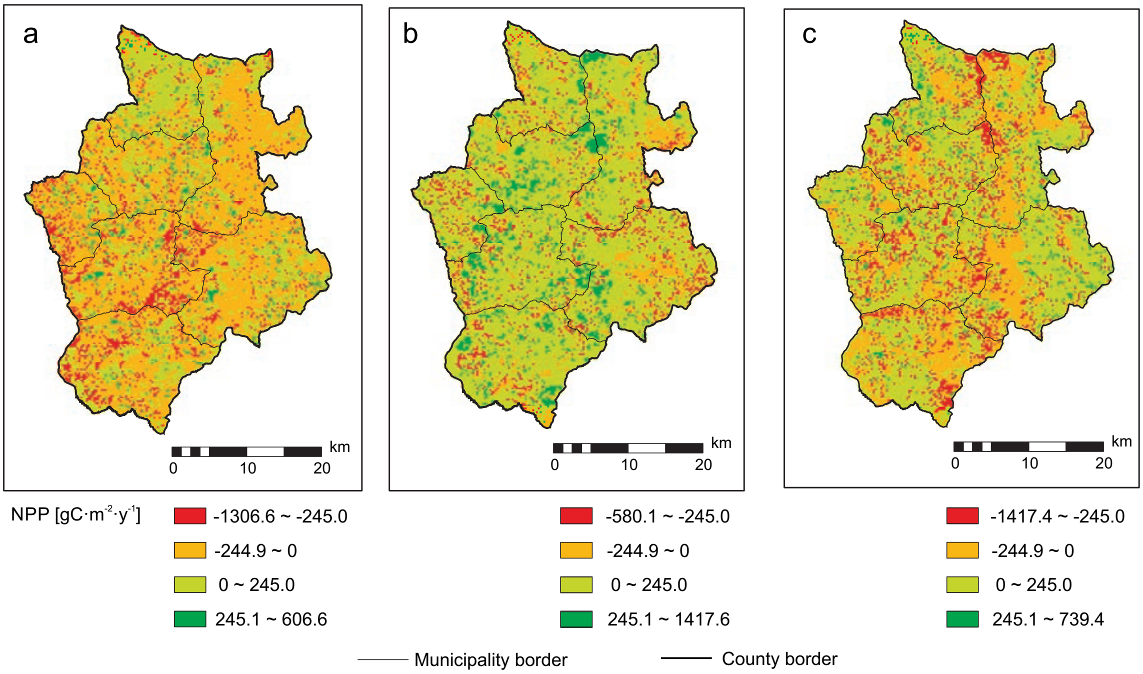

Fig. 4: Distribution of NPP changes in 2000–2005 (a), 2005–2010 (b), and 2010–2015 (c)

canopy of the artificial forest initially developed only slowly and the photosynthetic intensity was not as high as that of the former vegetation. In many areas of these municipalities, artificial forests have become the most important land use type, although natural forests and farmland continue to occupy large areas. Overall, two-way conversions between these land use types can be observed.

Compared to the western areas, the NPP changes in the eastern municipalities (Mengsuo and Zhongke) appear at first glance to be much smaller and indeed the peak values are largely absent here, but in the total area the decrease in NPP also dominates for the period 2005-2010, with values in the range of up to 245.0 gC·m^{-2}·yr^{-1}); only very small sub-areas show an increase in NPP (Fig. 4a). Basically, the land use types woodland, arable land and artifical woodland dominate here as well. The lower intensity of NPP change may be due, among other things, to the fact that land conversion had already begun earlier here and that more fragmented land use patterns have emerged overall.

Tab. 3: Variation of NPP values according to land cover changes from 2000 to 2005

Land Cover types	Artificial woodland		Arable land		Grassland		Woodland		Construction land		Water area	
	MV	TV	MV	TV	MV	TV	MV	TV	MV	TV	MV	TV
Artificial woodland	-35	-0.57	-54	-0.129	0	0	93	0.185	0	0	0	0
Arable land	-43	-1.70	-19	-4.83	-52	-0.140	40	1.84	-7	1.76×10^{-4}	0	0
Grassland	143	0.287	-17	-0.10	-28	-1.16	176	2.32	low	low	0	0
Woodland	-195	-10.6	-177	-15.1	-137	-0.316	-32	-21.2	-121	-0.034	-687	-0.043
Construction land	-41	-0.02	-163	-0.031	0	0	low	low	-10	-0.016	28	0.021
Water area	-49	-0.0031	low	low	low	low	low	low	low	Low	-7	-0.005

Note: MV - mean value [gC·m^{-2}·yr^{-1}]; TV - total value [10^9·gC·yr^{-1}]

From 2005 to 2010, some areas of the county exhibited increased NPP values, particularly in the mid-southern and northern regions. However, a few parts at the western frontier and in the east still exhibited obvious decreases in NPP (Fig. 4b). The areas with the most significant NPP increase – of up to 1417.6 gC·m^{-2}·yr^{-1} – were concentrated in the central, northern, and southern regions. This includes the townships of Lisuo, Mengka, Yuesong, Wenggake, and Zhongke. This conspicuous increase in NPP occurred mainly in woodlands, arable lands, and early planted artificial woodlands (rubber plantations). Over these five years, the land cover changed significantly in the five municipalities, mainly converting from woodlands and arable land to artificial woodland (Tab. 4). Throughout this period, the number of plants in the woodlands increased obviously, and the photosynthesis rate of artificial woodlands continually increased with stand age. As a result, the mean values of NPP in most types of land cover rose rapidly. However, the NPP values decreased slightly (up to 580.1 gC·m^{-2}·yr^{-1}) in a few small areas of Mengsuo and Zhongke owing to the rapid expansion of construction lands in these areas, in combination with the loosely distributed arable lands and the local agriculture planting structures. The strong NPP decreases in the mid-western parts of the county during the period 2000-2005 contrast sharply with NPP increases in the following period of 2005-2010. While land conversion caused NPP decrease in the first phase, a delayed increase in biomass production led to the rising NPP values in the next phase. In comparison to 2010, the NPP increased in some areas of Ximeng County in 2015; however, large areas in the middle of the county experienced declines in NPP (Fig. 4c). The increases reached 739 gC·m^{-2}·yr^{-1} in Yuesong and Mengsuo, and the decreases reached a maximum of 1417.4 gC·m^{-2}·yr^{-1} in Xinchang, Zhongke, Lisuo, and Wenggake. The large decrease of NPP values in the central region was mainly due to the drastic conversions of woodlands to cultivated land, construction land, and artificial woodlands (Tab. 5). For municipalities in the western and eastern parts of the county, the land area was mainly arable land and artificial woodland, where the NPP increased significantly from 2005 to 2015 owing to human cultivation and planting.

From 2005 to 2015, with the exception of water areas, all land cover types exhibited increases in their NPP mean values and total values (Tab. 3 -Tab. 5). Under this overall trend, the NPP values had decreased in cases of the conversion of forest land into other land cover types, and the conversion of other land cover types into construction land (Tab. 5). Given this fact, it becomes clear that land cover change is an important factor affecting the variation of NPP, especially for expanded artificial lands. Typically, the southwest border areas and the central areas of the county, where the artificial woodlands expanded rapidly, experienced the most significant spatio-temporal changes in terms of NPP (Fig. 2 and Fig. 4). During the same period, the mean and total NPP values for artificial woodlands decreased first and then gradually increased (2005–2010), primarily owing to the number of conversions and the stand age of the woods. This is understandable as the plants were not yet mature and had low-efficiency photosynthesis in the early stages after planting, which resulted in a low NPP.

Tab. 4: Variations in NPP values with land cover changes from 2005 to 2010

Land Cover types	Artificial woodland		Arable land		Grassland		Woodland		Construction land		Water area	
	MV	**TV**	**MV**	**TV**	**MV**	**TV**	**MV**	**TV**	**MV**	**TV**	**MV**	**TV**
Artificial woodland	167	13.7	73	0.192	0	0	498	3.20	-70	-0.035	0	0
Arable land	86	6.93	48	11.9	0	0	468	20.3	-90	-0.0904	-151	-0.019
Grassland	89	0.006	44	0.191	67	2.68	119	4.96	low	low	-43	-0.0027
Woodland	-267	-9.91	-287	-27.0	0	0	117	69.7	-368	-0.322	-551	-0.103
Construction land	low	low	135	0.051	0	0	511	0.671	35	0.609	48	0.003
Water area	low	low	low	low	0	0	low	low	low	low	-4	-0.0024

Note: MV - mean value [gC·m^{-2}·yr^{-1}]; TV - total value [10^9 gC·yr^{-1}]

Tab. 5: Variations in NPP with land cover changes from 2010 to 2015

Land Cover types	Artificial woodland		Arable land		Grassland		Woodland		Construction land		Water area	
	MV	TV	MV	TV	MV	TV	MV	TV	MV	TV	MV	TV
Artificial woodland	-21	-3.59	-25	0.169	-410	-0.618	17	0.369	25	0.0097	7	0.0051
Arable land	136	4.58	137	30.2	79	0.64	193	0.0014	208	0.376	-289	-0.0942
Grassland	58	0.017	81	0.365	38	0.706	77	0.584	low	Low	0	0
Woodland	-211	-3.71	-167	-12.9	-225	-0.384	-100	-54.2	27	0.0533	-201	-0.118
Construction land	27	0.011	227	0.464	0	0	202	0.345	234	3.47	0	0
Water area	low	low	low	low	0	0	low	low	low	Low	0	0

Note: MV - mean value, unit: $gC·m^{-2}·yr^{-1}$; TV - total value; unit: 10^9 $gC·yr^{-1}$

Along with the growing stand age, the forested area gradually increased in size and the photosynthesis ability was strengthened, which began to promote the regional NPP.

4 Discussion

4.1 Combination of multiple data sources and the CASA model to meet the requirements of accurate NPP assessment

Estimating NPP mainly involves measurement and model simulation methods. Relying on remote-sensing and meteorological data, the representative CASA model in the light-energy utilization model has been successfully implemented for NPP estimation in large and mesoscale regions. In this case, Ximeng county is close to Myanmar and has complex terrain, diverse vegetation types, and strong human influence; in addition, remote-sensing technology is the most effective for obtaining vegetation cover information, with MODIS data and Landsat 5 TM image data being accessible and free to download. This indicates that the CASA model can be used for NPP calculation in an adaptive and straightforward manner.

The given topographical relief could lead to local heat–moisture redistribution, and influences the growth of plants. Li et al. (2019) extracted the elevation, slope, and aspect information based on DEM, and corrected the CASA model to study the NPP of the Hexi Corridor, finding that the influence of these factors on NPP evaluation results is variable. The estimated values of all kinds of land use – without considering the influence of topography – are about 3 % higher than those after correction. However, Chen et al. (2013) found similar results in the southwest region of the Qinling Mountains in China. Based on this understanding, the main focus of this study was the variations in NPP features in the entire area of Ximeng County over time; the effect of topography has not yet been explored in depth. Significant research attention should be paid to the influence of terrain factors on NPP estimation in follow-up research. In addition, higher temporal and spatial resolutions of the image and observed data will improve the accuracy of NPP assessment and model validation considerably.

4.2 Comparison of the NPP assessment results

In this manuscript, the mean values of NPP in Ximeng County are 720.3 $gC·m^{-2}·yr^{-1}$, 748.1 $gC·m^{-2}·yr^{-1}$, and 772.7 $gC·m^{-2}·yr^{-1}$ in 2000, 2010, and 2015, respectively. These values are consistent with those found by Qiu (2013), and are close to 795.8 $gC·m^{-2}·yr^{-1}$, which is the average NPP from 1960 to 2000 across this county, found by He and Zhang (2006). Another study found that the average NPP in the southwest region of the Yunnan Province was more than 480 $gC·m^{-2}·yr^{-1}$ (Dong and Ni 2011). The present study provides evidence as to where the causes for these partly very different values are to be found. As a result of changing phases and intensities of land use change on different spatio-temporal scales, significant fluctuations in NPP occur.

Since the comparative studies (He and Zhang 2006; Dong and Ni 2011; Qiu 2013) differ from the present study in terms of timing, research period and spatial scale, the differences seem plausible. The comparison with these works shows general similarities in NPP magnitudes, but the results of this study are more precise at the spatio-temporal level. Consequently, the research approach presented offers precise and nuanced applicability to county-level NPP estimates.

4.3 Dual advantages of ecological compensation and the direct economic income caused by regional artificial woodlands

The complex and diverse terrain and climate at the border of southwest China endow it with forest resources, but is also an obstacle to local economic development. Relying on agricultural income cannot make local farmers self-sufficient; the expansion of artificial woodlands has improved local residents' income and is in line with the inevitable trend of the 'Grain to Green' ecological restoration policy. The ecological effect value of the natural woodland is the largest, that of eucalyptus forest is second, and the ecological effect per unit area of the rubber forest is better than that of arable land, paddy fields, paddy gardens, and tea gardens (Zhao et al. 2018b). As the research area is characterised by steep topography and has widespread arable land, grassland and bare land, agroforestry is important with regard to the carbon cycle, the water balance and soil protection (Zhao and Yi 2018) As a fast-growing tree species, eucalyptus has high productivity. Considering the great demand for wood and to protect the native forest from destruction, eucalyptus was introduced locally. Zhao and Yi (2018) suggest that eucalyptus has carbon-fixation and oxygen-release properties, environmental purification, forest protection, climate regulation, and other ecological functions; however, owing to its short growth cycle, excessive consumption of nutrients and water, and its effect of reducing biodiversity, its further development has been hindered. Instead of thinning, eucalyptus management in Ximeng County has been using block logging, which has a negative impact on environmental quality. In recent years, eucalyptus planting areas have been strictly controlled. Considering the negative impact of eucalyptus on regional ecological conditions, its distribution and planting should be rationally planned on the basis of increased scientific research in order to fully realise its optimal ecological and economic production value. Today, Yunnan Province has the highest rubber yield per unit area in China, and can be used as an experimental base (Zhao et al. 2021). Rubber forests are sustainable artificial ecosystems, and one of the best ecosystems found on dry land, further, the community diversity of rubber forests is significantly higher than that of eucalyptus forests (Chen et al. 2019). The diversity of rubber forests is similar to that of natural secondary forests in the seedling and juvenile stages, but with increasing forest age, the plant species diversity will gradually become lower than that of secondary forests (Xing et al. 2012). A study by Moazzam et al. (2014) found that the optimum carbon fixation cycle for rubber forests is 40 years, which indicates that rubber forests planted in the county in the past 20 years have great production potential. While rubber forests are tall, developing small trees and shrubs such as coffee, konjac, and other cash crops can increase the biodiversity and further increase the NPP. As the forest ages, the diversity of the rubber forest community will gradually decrease, along with its productivity; the transpiration will also increase year by year (Lin et al. 2016; Luo et. al 2018). Therefore, in the future, the reasonable management and control of the age of local rubber forests is an effective measure to increase the dual benefits of ecological and economic sustainable development.

The contrast between the forestry and planting industry is not limited to the output value, but also affects ecological security (Ren and Liu 2013). When selecting the trade-off between food crops and cash crops, and economic woodlands and ecological woodlands, we should not only concentrate on the market economic income, but also the plant's ecological effects in terms of the regional ecological sustainability. Further, the 'Grain to Green' project should be promoted, mountains sealed, and forests cultivated according to local conditions. Provided that the restoration and renewal of natural secondary forests is not threatened, scientific research has shown that artificial forests should be introduced and management enhanced to increase income from forestry production (Zhao and Yi 2018). This can also be accomplished by combining direct cash crop income with potential ecological assets. This can help the regions undertake sustainable development planning and regulation more effectively.

5 Conclusions

This study used the CASA model to analyse the spatio-temporal changes in land cover in Ximeng County. Further, it evaluated the related regional NPP changes based on meteorological data, and the Landsat 5 TM image data in 2000, 2005, 2010, and 2015. The following conclusions could be drawn:

(1) Artificial woodland was the land cover type that increased the most, from 20 km^2 in 2000 to 223 km^2 in 2015, accounting for 93 % of the land cover transfer. Accordingly, the woodlands had reduced by a total of 180 km^2, while other types of land cover did not exhibit significant changes.

(2) The NPP increased from 906.2×10^9 $gC\cdot yr^{-1}$ in 2000 to 972.0×10^9 $gC\cdot yr^{-1}$ in 2015 in Ximeng County, reflecting a total of 65.8×10^9 $gC\cdot yr^{-1}$ increase and a mean increase of 52.4 $gC\cdot m^{-2}\cdot yr^{-1}$. The NPP value decreased over the first five years and then increased gradually, with a changed value of -61.7×10^9 $g\ C\cdot yr^{-1}$, 96.9×10^9 $g\ C\cdot yr^{-1}$, and 30.6×10^9 $g\ C\cdot yr^{-1}$ in each five-year period.

(3) The spatial changes in the regional NPP values are significant. The most notable NPP changes occur in the central and the western border regions, with a variation range of -1417.4 $gC\cdot m^{-2}\cdot yr^{-1}$ and 1417.6 $gC\cdot m^{-2}\cdot yr^{-1}$. In comparison, the areas with slight NPP changes were relatively small and dispersed throughout the county. The main reason for this distribution of NPP changes is the large transfer of forest land and arable land to artificial woodlands along the western boundary and the central parts of the county.

(4) The total NPP of artificial woodlands continuously increased, which was a result of the increased planting area and the stand age of plants over the years. However, the mean value change of NPP was more dependent on the increasing stand age of plants.

(5) In comparison to natural woodlands, plantations can rapidly increase the NPP. To realize the economic benefits of forestry and the sustainable development of the ecological economy in Ximeng County, the scale of eucalyptus planting should be strictly controlled; it is necessary to further study the scientific distribution of different plantations and understand the thinning and afforestation density of eucalyptus. The planting of cash crops under the rubber forest canopy should be determined scientifically according to differences in age. Further, to increase the heterogeneity and diversity of the regional landscape, the natural regeneration of the mountainous natural secondary forests should be maintained.

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