ANALYZING THE TEMPORAL VARIATIONS OF NET PRIMARY PRODUCTIVITY OF TAIPEI CITY THROUGH REMOTE SENSING

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ABSTRACT: This study applies remote sensing to estimate the net primary productivity (NPP) of Taipei City. The objective is to analyze the temporal variation of NPP from 2002 to 2006 for the reference of Taipei's carbon planning. The research processes include the calculation of vegetation indices from SPOT images, the estimation of fraction of photosynthetically active radiation (FPAR) and photosynthetically active radiation absorbed by green plants (APAR), the estimation of NPP, and finally the temporal analysis of NPP variations from 2002 to 2006. The result indicates the mean of annual NPP in five years is 152 gC/m^2/yr and the mean of total NPP in five years is 4.10x10^4 ton/yr. Meanwhile, the temporal analysis of annual NPP variation illustrates the linear trend is decreasing from 2002 to 2006 and the annual NPP growth rate is -0.073x10^4 ton (R^2=0.31). The maximum NPP is in 2002 and the minimum NPP is in 2006. As for the temporal analysis of seasonal NPP variations, the NPP accumulation is mainly distributed between April and October. The NPP in seven months is about 77% of the annual NPP. The mean NPP in spring, summer, autumn and winter is 36.72 gC/m^2, 56.85 gC/m^2, 41.49 gC/m^2, and 16.78 gC/m^2, respectively. Obviously, four seasons have different fluctuation trends from 2002 to 2006. For example, the NPP in summer has an increasing trend. The annual NPP growth rate is 1.076 gC/m^2 (R^2=0.38). However, the decreasing trend is obtained from other three seasons. The annual NPP growth rates for autumn, winter and spring are -1.478 gC/m^2 (R^2=0.18), -1.378 gC/m^2 (R^2=0.37), and -0.913 gC/m^2 (R^2=0.20). From the above result, it can be concluded remote sensing is a timely, effective, feasible, and large scale approach to estimate the NPP for analyzing the temporal variation of NPP. The result obtained from this study can be extended for the reference of Taipei's carbon planning.

1. INTRODUCTION

The issues of greenhouse effect, global climate change, and carbon cycle have been causing growing concerns since the end of the 20th century. Among six greenhouse gases, the increasing amount of carbon dioxide is regarded as one of the important factors accelerating global warming and leading to global climate change. To resolve this issue, many countries signed the Kyoto Protocol (KP) in 2005 and made an agreement that participating nations are required to estimate their greenhouse gases and provide a national greenhouse gas inventory report. Since then, carbon sequestration has become an important issue in terms of absorbing and storing carbon dioxide. Meanwhile, forests play an important role in carbon sequestration because they yield the greatest potential for reducing greenhouse gas emissions.

It is well known that urban area have a serious problem with the increasing amount of carbon dioxide because of land use change, economic and industry development. Therefore, to achieve the objective of sustainable development in urban area, currently the reduction of carbon emission and the improvement of carbon sequestration become important topics for urban planning. As for the carbon sequestration in urban area, the priority task is the estimation of carbon sequestration. Several methods have been proposed to estimate carbon sequestration, including sampling of ground biomass, flux towers, model estimation, and the remote sensing technique (Zhu, 2005). Among these methods, remote sensing is suggested by International Panel on Climate Change (IPCC) because it is a timely, effective, economic, and large- scale technique to estimate carbon amounts for verifying national land use, land-use change, and forestry (LULUCF). As for the use of remote sensing, two approaches are commonly used. One is based on the regression model of forest stock and vegetation indices to estimate carbon stock or carbon sequestration (Wang, 2010). The other is the estimation of net primary productivity (NPP) (Monteith, 1972; Goetz and Prince, 1996; Gower et al., 1999; Zhu, 2005).

Due to the importance of carbon sequestration for urban planning and the IPCC suggestion on applying remote sensing to estimate carbon sequestration, this study focuses on the application of remote sensing to estimate the NPP of Taipei City. The objective is to analyze the temporal variation of NPP from 2002 to 2006 for the reference of Taipei's carbon planning.

2. MATERIALS AND METHODS

2.1 Study Area

Taipei City is located in the northern part of Taiwan. The area covers about 27000 hectares. The geological structure can be divided approximately into 3 topographies: volcanoes, hills and basin areas. The terrain is higher in the northeast and southeast regions. The climate is characterized as sub-tropical with seasonal monsoons. There are 12 administrative districts in Taipei City. The population is unevenly distributed due to the variation of topography and economic development.

2.2 Materials

(1) **Meteorological data:** Total monthly precipitation, mean monthly temperature, and total monthly solar radiation of Taiwan meteorological stations from 2002 to 2006 are provided by Taiwan Typhoon and Flood Research Institute. All data are then interpolated at the same scale with the SPOT image using the CoKriging method and digital terrain model under the geostatistical analysis of ArcGIS 10.2 software. Meanwhile, the paired t-test is used to compare the difference between the actual data and the interpolated data of meteorological stations. The result indicates there are no significant differences under the 99% significance level. After that, three kinds of Taipei's meteorological data are then extracted from Taiwan meteorological data.

(2) **Remote sensing data:** Taiwan's land cover map and SPOT image from 2002 to 2006 are provided by Aerial Survey Office, Taiwan Forest Bureau. The land cover map is classified into 6 types including woody plant, herbaceous plant, bare soil, water body, building ground, and road. The SPOT image with 20m×20m pixel size includes two periods. One is from February to April and the other is from August to October. Similar to the above meteorological data, Taipei's land cover map and SPOT image from 2002 to 2006 are then extracted.

3. METHODS

The method include two parts. The first part focuses on the estimation of NPP from 2002 to 2006. The steps include the calculation of vegetation indices from SPOT image, the estimation of fraction of photosynthetically active radiation (FPAR) and photosynthetically active radiation absorbed by green plants (APAR), and finally the estimation of NPP. The second part focuses on the temporal analysis of NPP variations from 2002 to 2006.

3.1 The Estimation of NPP

3.1.1 Calculation of Vegetation Index from SPOT images: The Normalized Difference Vegetation Index (NDVI) and Simple Ratio Vegetation Index (SR) are first calculated in this study. The reason is both indices are the primary parameters of FPAR estimation (Los et al. 1994). The NDVI as in equation (1) is calculated by near-infrared (NIR) and red (RED) bands. The range is between -1 and 1, which means there is high-density vegetation when it is close to 1. Meanwhile, the SR is calculated by the NDVI as equation (2). The index represents the richness of vegetation, but it is affected by the region and seasonality.

$$NDVI(x,t) = \frac{NIR(x,t) - RED(x,t)}{NIR(x,t) + RED(x,t)} \tag{1}$$

$$SR(x,t) = \left[\frac{1 + NDVI\,(x,t)}{1 - NDVI\,(x,t)}\right] \tag{2}$$

3.1.2 Estimation of FPAR and APAR: According to Hatfield et al. (1984), the relation between FPAR and NDVI was near-linear. Therefore, if linearity is assumed, the relation for FPAR and NDVI can be used to estimate the FPAR of NDVI (i.e., $FPAR_{NDVI}$) as in equation (3).

$$FPAR_{NDVI}\,(x,t) = \frac{\left(NDVI\,(x,t) - NDVI_{i,\min}\right) \times \left(FPAR_{\max} - FPAR_{\min}\right)}{\left(NDVI_{i,\max} - NDVI_{i,\min}\right)} + FPAR_{\min} \tag{3}$$

where $FPAR_{\max} = 0.950$, $FPAR_{\min} = 0.001$, and both are independent of vegetation types.

Meanwhile, Los et al. (1994) and Field et al. (1995) also indicated FPAR has a linear relationship with the SR. The relation between FPAR and SR (i.e., $FPAR_{SR}$) is as in equation (4)

$$FPAR_{SR}(x,t) = \frac{\left(SR(x,t) - SR_{i,\min}\right) \times \left(FPAR_{\max} - FPAR_{\min}\right)}{\left(SR_{i,\max} - SR_{i,\min}\right)} + FPAR_{\min} \quad (4)$$

where SR $_{i, max}$ and SR $_{i, min}$ respectively correspond to the NDVI $_{i, max}$ and NDVI $_{i, min}$.

In addition, Los et al. (1994) indicated the mean FPAR estimated by the $FPAR_{NDVI}$ and $FPAR_{SR}$ is suitable for the estimation of FPAR because of the smallest bias. Therefore, this study adopts equation (5) to estimate the $FPAR_{(NDVI+SR)/2}$ with α arbitrarily being set to 0.5.

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

To eliminate the problem of image acquisition in Taiwan, this study applies two periods of SPOT images to estimate the FPAR rather than single SPOT image. As for the estimation of APAR (MJ/m^2/month), it is the product of PAR and FPAR at each monthly time step. The PAR equals half of the total solar radiation (SOL) (MJ/m^2). The APAR is given by

$$APAR\ (x, t) = SOL\ (x, t) \times FPAR\ (x, t) \times 0.5 \quad (6)$$

3.1.3 Estimation of NPP: NPP (gC/m^2/month) is the product of APAR and the actual light use efficiency (ε) (gC/MJ) at each monthly time step.

$$NPP\ (x, t) = APAR\ (x, t) \times \varepsilon\ (x, t) \quad (7)$$

As for the actual light use efficiency in equation (7), Potter et al. (1993) indicated ε will be affected by temperature and water. It is the product of maximum light use efficiency ($\varepsilon_{\max}$) (gC/MJ) and the scales representing the availability of water (W) and the suitability of temperature (T_1,T_2), as shown in equation (8).

$$\varepsilon\ (x, t) = W(x, t) \times T_1\ (x, t) \times T_2\ (x, t) \times \varepsilon_{\max} \quad (8)$$

Here, $\varepsilon_{\max}$ means each vegetation type has a maximum light use efficiency in an ideal condition. The water scalar is a function of the ratio of estimated evapotranspiration to potential evapotranspiration at each monthly time step. The two temperature scalars represent the regulation of vegetation growth by temperature. Finally, equations (7) and (8) are then combined into the model as in equation (9).

$$NPP\ (x, t) = APAR\ (x, t) \times W(x, t) \times T_1\ (x, t) \times T_2\ (x, t) \times \varepsilon_{\max} \quad (9)$$

3.2 Temporal Analysis of NPP Variations

After the NPP estimation from 2002 to2006, this study further investigated the temporal analysis of NPP from annual variation and seasonal variation. To analyze the annual variation of NPP from 2002 to 2006, the linear trend analysis under the Excel software is then applied. The objective is to analyze the fluctuation trend of Taipei's NPP variation in five years. As for the seasonal variation of NPP from 2002 to 2006, the analysis focuses on the accumulation period of NPP and the variation of four seasons (i.e., spring, summer, autumn, and winter) in five years.

4. RESULTS AND DISCUSSION

4.1 Annual NPP from 2002 to 2006

Table 1 is the estimated monthly and annual NPP of Taipei City from 2002 to 2006. The annual NPP from 2002 to 2006 is 159.87 gC/m^2/yr , 149.30 gC/m^2/yr , 149.43 gC/m^2/yr , 159.10 gC/m^2/yr , 141.52 gC/m^2/yr, respectively. The mean NPP in five years is 152 gC/m^2/yr. In addition, the total NPP from 2002 to 2006 ranges from 3.821 x10^4 ton to 4.316 x10^4 ton and the mean NPP in five years is 4.1x10^4 ton/yr. Figure 1 is the distribution map of Taipei's NPP from 2002 to 2006. Obviously, the higher NPP is distributed in the northeast and southeast regions. To assess the feasibility of remote sensing on the estimation of NPP, the Taipei's NPP in 2005 (=4.30x10^4 ton/yr) is compared with the carbon sequestration of previous study (=4.45x10^4 ton/yr) which is based on field measured method in 2005 (Tsao et al., 2006). The result seems reasonable.

Table 1. Monthly and annual NPP of Taipei City from 2002 to 2006

Month Year	1	2	3	4	5	6	7	8	9	10	11	12	Annual NPP (gC/m^2)	Taipei's NPP (10^4 ton)
2002	4.83	6.53	10.37	11.23	16.44	17.00	20.29	18.42	18.41	16.61	10.77	8.99	159.87	4.316
2003	5.86	5.93	7.40	15.42	13.69	18.02	16.54	18.45	21.80	15.24	6.81	4.14	149.30	4.031
2004	4.42	9.13	5.85	13.49	17.85	16.04	21.71	19.95	13.74	11.18	9.36	6.71	149.43	4.035
2005	3.70	3.92	9.89	13.67	16.72	15.55	24.20	20.72	24.45	11.92	10.08	4.29	159.10	4.296
2006	4.66	5.54	7.54	10.14	13.91	15.77	20.57	21.02	14.15	13.59	9.36	5.27	141.52	3.821

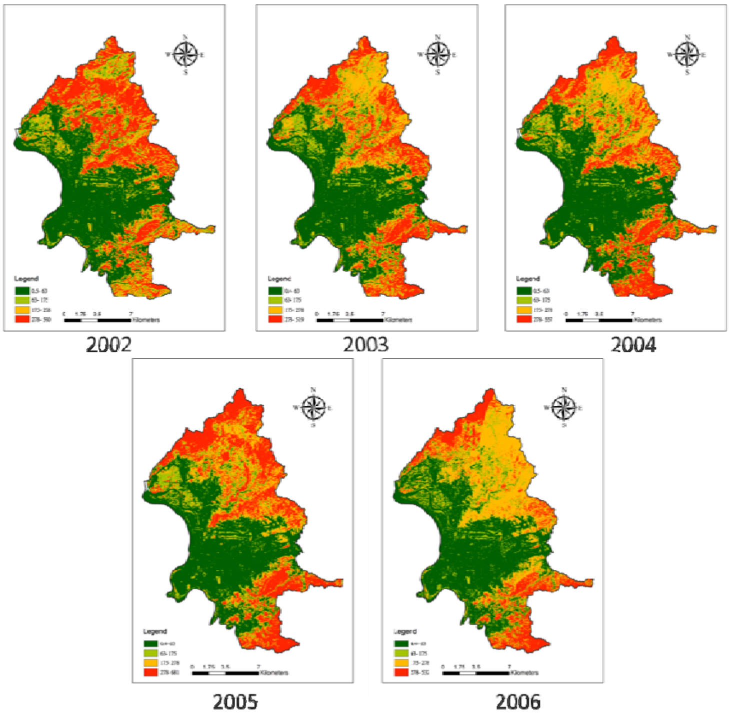

2002
2003
2004
2005
2006

Figure 1. The distribution map of Taipei's NPP from 2002 to 2006

4.2 Temporal Analysis of Total NPP Variation

According to the estimated Taipei's NPP, the temporal analysis of NPP variation from 2002 to 2006 is further analyzed by using the linear trend analysis of Excel software. The result is shown in Figure 2. Clearly, the linear trend of total NPP is decreasing in five years. The annual NPP growth rate is -0.073x10^4 ton/yr (R^2=0.31). The maximum NPP is in 2002 and the minimum NPP is in 2006.

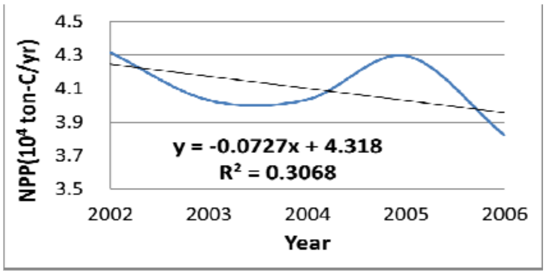


Figure 2. Temporal analysis of NPP variation from 2002 to 2006

4.3 Temporal Analysis of Seasonal NPP Variation

From Table 1, obviously the monthly NPP from January to December increases first and then decreases. This implies that the monthly NPP in a year is different. Therefore, this study further analyzes the seasonal NPP variation from 2002 to 2006, including the accumulation period of NPP and the variation of four seasons. The result is shown in Table 2 and Figure 3. Obviously, most NPP accumulation is distributed between April and October. The percentage from 2002 to 2006 is 74.1%~80.0%. The average is about 77.5%. As for the seasonal NPP variation in five years, the percentage in spring, summer, autumn and winter is about 24.2%, 37.5%, 27.3%, and 11.0%, respectively. The seasonal NPP variation is significant. The sequence of seasonal NPP variation from maximum to minimum is summer, autumn, spring, and winter.

Table 2 Temporal analysis of seasonal NPP variation from 2002 to 2006

Year	Annual NPP (gC/m^2)	April ~ October (%)	Spring (%)	Summer (%)	Autumn (%)	Winter (%)
2002	159.87	74.1	23.8	34.8	28.6	12.7
2003	149.30	79.8	24.5	35.5	29.4	10.7
2004	149.43	76.3	24.9	38.6	22.9	13.6
2005	159.10	80.0	25.3	38.0	29.2	7.5
2006	141.52	77.1	22.3	40.5	26.2	10.9

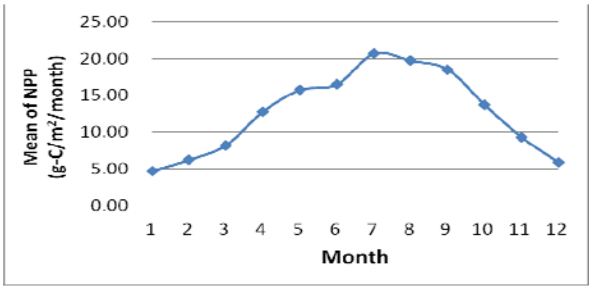
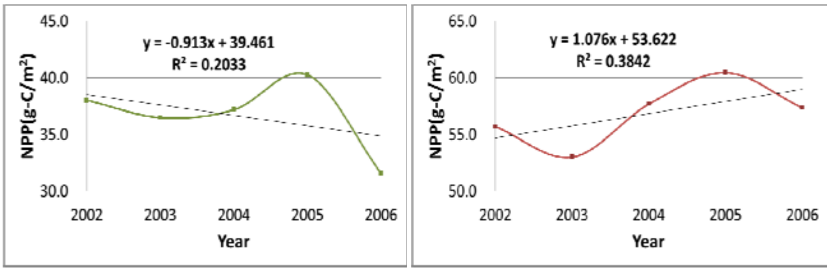
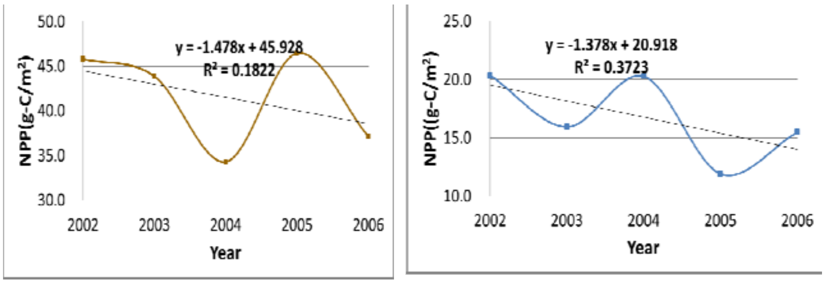


Figure 3. Temporal analysis of the monthly NPP variation in five years



(a) Spring

(b) Summer



(c) Autumn

(d) Winter

Figure 4. Seasonal NPP variation in (a) spring, (b) summer, (c) autumn and (d) winter

To further investigate the trend of seasonal NPP variation from 2002 to 2006, again the linear trend analysis for four seasons is applied by using the Excel software. The result is shown in Figure 4. Obviously, four seasons have different fluctuation trends from 2002 to 2006. For example, the NPP in summer has an increasing trend. The annual NPP growth rate is 1.076 gC/m^2 (R^2=0.38). On the other hand, other three seasons show the decreasing trend and the annual NPP growth rates for autumn, spring and winter are -1.478 gC/m^2 (R^2=0.18), -0.913 gC/m^2 (R^2=0.20), and -1.378 gC/m^2 (R^2=0.37), respectively.

5. CONCLUSION

The objective of this study is to apply remote sensing to estimate the net primary productivity (NPP) of Taipei City and analyze the temporal variation of NPP from 2002 to 2006 for the reference of Taipei's carbon planning. The research processes focuses on the estimation of NPP from 2002 to 2006, including the calculation of vegetation indices from SPOT image, the estimation of FPAR, APAR, and NPP; the temporal analysis of annual and seasonal NPP variations using the linear trend analysis. The result can be concluded as follows.

(1). Application of remote sensing on the estimation of Taipei's NPP: The Taipei's total NPP from 2002 to 2006 is 3.82 x10^4 ton ~ 4.32 x10^4 ton. The mean of NPP in five years is 4.10x10^4 ton/yr. To assess the feasibility of remote sensing on the NPP estimation, the NPP in 2005 (=4.30x10^4 ton/yr) is compared with the carbon sequestration of previous study (=4.45x10^4 ton/yr) which is obtained from field measured method in 2005. The result seems reasonable. Therefore, remote sensing is a timely, effective, economic and feasible approach to estimate the NPP of urban area.

(2). Temporal analysis of annual and seasonal NPP variation using remote sensing: The annual NPP variation from 2002 to 2006 illustrates the linear trend of Taipei's NPP is decreasing in five years. Meanwhile, the seasonal NPP variation indicates most NPP accumulation is distributed between April and October and the NPP in seven months is about 77.5% of the annual NPP. In addition, the seasonal NPP variation is significant in Taipei City. The sequence from maximum to minimum is summer, autumn, spring, and winter. Therefore, remote sensing is also an useful approach for temporal analysis of annual and seasonal NPP variation if compared with the traditional field measured approach.

The result obtained from this study can be extended for the reference of Taipei's carbon planning. However, several parameters play an important role during the NPP estimation, for example, the simulation of maximum light use efficiency for vegetation types and the use of SPOT seasonal image. Therefore, these parameters should be considered carefully when applying remote sensing to estimate the NPP.

6. ACKNOWLEDGEMENTS

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