

# Article Changes in Water-Use Efficiency of *Eucalyptus* Plantations and Its Driving Factors in a Small County in South China

Yuefeng Yao<sup>1</sup>, Jinjun Huang<sup>1</sup>, Wen He<sup>1,\*</sup>, Jiafu Zhu<sup>2</sup> and Yanyu Li<sup>2</sup>

- <sup>1</sup> Guangxi Institute of Botany, Chinese Academy of Sciences, Guilin 541006, China; yf.yao@gxib.cn (Y.Y.); jinjun.h@gxib.cn (J.H.)
- <sup>2</sup> Guangxi Huangmian State Owned Forest Farm, Liuzhou 545600, China; zjf78280976@163.com (J.Z.); liyy3836@163.com (Y.L.)
- \* Correspondence: hw@gxib.cn

**Abstract:** Ecosystem water-use efficiency (*WUE*) has been central in revealing the variability in terrestrial carbon and water cycles. Short-rotation plantations such as *Eucalyptus* plantations can simultaneously impact net primary production (*NPP*) and actual evapotranspiration ( $ET_a$ ), components of *WUE*, resulting in changes in terrestrial carbon and water cycles. However, there are few detailed studies on the changes in the *WUE* of *Eucalyptus* plantations at the catchment scale with high spatial remote sensing imagery. Here, we present the changes in the *WUE* of *Eucalyptus* plantations and its driving factors (i.e., *NPP* and  $ET_a$ ) using satellite-based models combined with 5-m spatial resolution RapidEye imagery in a small county in South China. The increases in  $ET_a$  of *Eucalyptus* plantations. The management practice used (short rotation in this study) can enhance the effect of climate warming on *WUE* by varying the *NPP* of *Eucalyptus* plantations. A high value of *NPP* leads to a high *WUE* of *Eucalyptus* plantations at the end of a short rotation, while a low value of *NPP* results in a low *WUE* at the beginning of another short rotation. Changes in the *WUE* of *Eucalyptus* plantations indicated large spatial and temporal variability, associated with climate warming and short-rotation practices.

**Keywords:** net primary production (*NPP*); actual evapotranspiration ( $ET_a$ ); climate warming; short rotation; RapidEye imagery

# 1. Introduction

Ecosystem water-use efficiency (WUE) has been central in revealing the variability in terrestrial carbon and water cycles and exploring the relationship between productivity and water use [1–3]. However, spatially significant differences in environmental factors can lead to different changes in WUE. Any disturbance of one element of WUE (i.e., photosynthesis or  $ET_a$ ) can cause the other to change [3]. Tree planting can constantly disturb the terrestrial carbon and water cycles. Tree planting is also considered as a successful strategy for achieving carbon neutrality targets in China [4] and a mitigated strategy for attaining the targets of the Paris Agreement in fighting climate change [5]. Therefore, there will be an increasing trend in establishing tree plantations in the future, which will have a significant impact on carbon and water cycles. Hence, to explore the relationship between tree plantations and WUE would improve our understanding of the coupling between terrestrial carbon and the water cycle under global warming.

Tree plantations usually increase both ecosystem productivity or carbon storage and  $ET_a$  simultaneously [6–8]. However, the different magnitudes, representing the sensitivity of different types of plantations to environmental disturbance, have not been fully explored. The presence of plantations is expanding steadily worldwide, especially in China [9], but they disrupt the water cycle as well [10]. For example, *Eucalyptus* is a fast-growing



Citation: Yao, Y.; Huang, J.; He, W.; Zhu, J.; Li, Y. Changes in Water-Use Efficiency of *Eucalyptus* Plantations and Its Driving Factors in a Small County in South China. *Water* **2023**, *15*, 2754. https://doi.org/10.3390/ w15152754

Academic Editors: Xinchun Cao and Ana-Maria Ciobotaru

Received: 7 June 2023 Revised: 14 July 2023 Accepted: 27 July 2023 Published: 29 July 2023



**Copyright:** © 2023 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). and preferred genus for plantations and has been planted worldwide due to its great commercial importance, specifically in South China. *Eucalyptus* plantations can increase carbon storage with increasing stand age [11], but they can consume more water than other forests [12], which may result in low *WUE*. The *WUE* of *Eucalyptus* plantations varies among genotypes [13–15]. These variations have also been commonly attributed to the environment [15] and management practices [16–18]. Therefore, the most important issue is how to sustainably manage plantations to attain carbon neutrality targets and reduce water stress under climate warming, as commercial forestry should be repudiated if it cannot benefit the environment [19].

Due to its large *Eucalyptus* plantation coverage, the Guangxi Zhuang Autonomous Region in South China is ideal for estimating *NPP* and  $ET_a$  and then exploring the changes in *WUE* of *Eucalyptus* plantations at the catchment scale. Here, we reveal a high spatial variability of *WUE* in *Eucalyptus* plantations by exploring the *NPP* and  $ET_a$  responses to short rotations and climate warming using RapidEye imagery with a 5-m spatial resolution. First, *Eucalyptus* plantations were classified using a classification and regression tree (CART) method for 2011–2019 in a small county in South China. Second, the *NPP* and  $ET_a$ of *Eucalyptus* plantations were calculated with modified satellite-based Carnegie–Ames– Stanford Approach (CASA) and Priestly–Taylor Jet Propulsion Laboratory (PT-JPL) models, respectively. In addition, changes in the *WUE* of *Eucalyptus* plantations and their driving factors were analyzed.

#### 2. Materials and Methods

## 2.1. Study Area

Huangmian, a small county covering approximately 499 km<sup>2</sup> in the Guangxi Zhuang Autonomous Region (Figure 1), South China, was chosen as the experimental site because *Eucalyptus* (mainly *Eucalyptus grandis*) has been cultivated in plantations there for at least 20 years [20]. *Eucalyptus* plantations currently occupy more than 30% of the total land area of Huangmian County. The digital elevation model (DEM) of Huangmian County shows elevations ranging from 60 to 845 m. The soil type is mainly Ach Haplic Acrisols according to the Soil and Terrain (SOTER) database obtained from the National Earth System Science Data Center (http://soil.geodata.cn (accessed on 30 June 2022)). Huangmian County has a monsoonal climate with an average annual precipitation ranging from 1750 to 2000 mm and an average annual temperature of approximately 21 °C.



**Figure 1.** Study site location and soil types. (**a**) Guangxi Zhuang Autonomous Region within China, and (**b**) Huangmian County located in the Guangxi Zhuang Autonomous Region. (**c**) Soil units of Huangmian County.

### 2.2. Datasets

# 2.2.1. RapidEye Imagery

The RapidEye multispectral satellite image data with a 5-m spatial resolution (https: //earth.esa.int/eogateway/missions/rapideye, accessed on 19 May 2022) was used in this study. We tried to separate *Eucalyptus* plantations from other forest types and then estimated their  $ET_a$  and transpiration with the PT-JPL model in late summer and autumn (mainly August to October) once every two years (biennially) from 2011 to 2019. As four RapidEye images were needed to cover the study area at each time slice, it required 20 RapidEye images for the full study period (Table 1). There was less than 0.2% cloud cover in images on 16 October 2011, but all clouds were located outside the Huangmian County territory. Approximately 0.5% of pixels with cloud cover in the northwest part of the study area in images on 24 August 2019 were omitted from image processing.

| No. | Images ID                          | Cloud Cover (%) | Date              |  |  |
|-----|------------------------------------|-----------------|-------------------|--|--|
| 1   | 4950409_2011-10-16_RE3_3A_Analytic | 0.16            |                   |  |  |
| 2   | 4950410_2011-10-16_RE3_3A_Analytic | 0               | 16 October 2011   |  |  |
| 3   | 4950509_2011-10-16_RE3_3A_Analytic | 0.05            | 16 October 2011   |  |  |
| 4   | 4950510_2011-10-16_RE3_3A_Analytic | 0               |                   |  |  |
| 5   | 4950409_2013-10-05_RE3_3A_Analytic | 0               |                   |  |  |
| 6   | 4950410_2013-10-05_RE3_3A_Analytic | 0               | 5 October 2012    |  |  |
| 7   | 4950509_2013-10-05_RE3_3A_Analytic | 0               | 5 October 2015    |  |  |
| 8   | 4950510_2013-10-05_RE3_3A_Analytic | 0               |                   |  |  |
| 9   | 4950409_2015-10-17_RE3_3A_Analytic | 0               |                   |  |  |
| 10  | 4950410_2015-10-17_RE3_3A_Analytic | 17 October 2015 |                   |  |  |
| 11  | 4950509_2015-10-17_RE3_3A_Analytic | 0               | 17 October 2015   |  |  |
| 12  | 4950510_2015-10-17_RE3_3A_Analytic | 0               |                   |  |  |
| 13  | 4950409_2017-09-16_RE4_3A_Analytic | 0               |                   |  |  |
| 14  | 4950410_2017-09-16_RE4_3A_Analytic | 0               | 16 Sontombor 2017 |  |  |
| 15  | 4950509_2017-09-16_RE4_3A_Analytic | 0               | 16 September 2017 |  |  |
| 16  | 4950510_2017-09-16_RE4_3A_Analytic | 0               |                   |  |  |
| 17  | 4950409_2019-08-24_RE3_3A_Analytic | 0               |                   |  |  |
| 18  | 4950410_2019-08-24_RE3_3A_Analytic | 0               | 24 August 2019    |  |  |
| 19  | 4950509_2019-08-24_RE3_3A_Analytic | 0               |                   |  |  |
| 20  | 4950510_2019-08-24_RE3_3A_Analytic | 3.2             |                   |  |  |

Table 1. Details of RapidEye multispectral images used in this study.

## 2.2.2. Meteorological Data

We collected data for eight key variables: daily mean air temperature; maximum and minimum air temperature; precipitation; air pressure; relative humidity; sunshine hours; and wind speed from four meteorological stations (Guilin, Liuzhou, Rong'an, and Mengshan: Figure 1b) from the China Meteorological Data Service Center (http://data.cma.cn (accessed on 10 July 2022)). Gridded meteorological data for all eight key variables from these four meteorological stations were generated with the inverse distance weighting (IDW) interpolation module of ArcMap (Esri Inc., Redlands, CA, USA, Version 10.3). Finally, the gridded net radiation (R<sub>n</sub>) and potential evapotranspiration (PET) were computed using the Food and Agricultural Organization (FAO) Penman–Monteith equation [21] combined with meteorological data.

#### 2.3. Methods

2.3.1. Classification and Regression Tree (CART)

CART was proposed by Breiman et al. [22]. It uses a Gini index for its impurity function [23]. First, it builds a large tree and then trims the tree to a smaller size with 10-fold (default) cross-validation to minimize the estimate error rates. This trimming procedure can solve underfitting and overfitting problems [24]. In image classification, CART analyzes all explanatory variables, including spectral and ancillary data, and determines the best binary division of a single explanatory variable for reducing the deviance in the response variable, such as the list of land use types [25].

The red edge spectral band can be used as a sensitive discriminator of *Eucalyptus* plantations [26]. We therefore applied the normalized difference red edge index  $(NDVI_{Re})$  [27] to enhance the differences in spectral information between *Eucalyptus* plantations and other forest types.

$$NDVI_{Re} = \frac{red \ edge - red}{red \ edge + red} \tag{1}$$

where *red edge* and *red* are the red edge and red bands of the multispectral RapidEye imagery, respectively.

Principal component analysis (PCA) was applied to transform the spectral information in the RapidEye imagery. Next, the spectral traits (i.e., mean, variance, contrast, dissimilarity, homogeneity, correlation, entropy, and second moment) were extracted to represent the texture information with the Co-occurrence Measures tool of ENVI, version 5.3 (Exelis Visual Information Solutions, Boulder, Colorado). Finally, the CART algorithm combined with vegetation indices and spectral and texture information was used to separate *Eucalyptus* plantations from all other forest types (Figure 2).



Figure 2. Flow chart illustrating the separation of *Eucalyptus* plantations from other forest areas.

2.3.2. Spectral Vegetation Indices and Fractional Green Vegetation Cover  $(F_c)$ 

As *NDV1*, ration vegetation index (*RV1*), soil adjusted vegetation index (*SAV1*), leaf area index (*LA1*), fractional green vegetation cover ( $F_c$ ), and other aforementioned meteorological variables are the main inputs of the CASA and PT-JPL models, we calculated

the *NDVI*, *RVI*, and *SAVI* with the near infrared (*NIR*) andred bands of multispectral RapidEye imagery as follows:

$$NDVI = \frac{NIR - red}{NIR + red}$$
(2)

$$RVI = \frac{NIR}{RED} = \frac{1+NDVI}{1-NDVI}$$

$$SAVI = \frac{1.5 \times (NIR - red)}{(NIR + red + 0.5)}$$
(3)

Next, *LAI* and  $F_c$  can be calculated based on the *SAVI* and *NDVI*, respectively, as follows:

$$LAI = \frac{\ln\left[\frac{0.69 - SAVI}{0.59}\right]}{0.91}$$
(4)

$$F_c = \frac{NDVI - NDVI_{min}}{NDVI_{max} - NDVI_{min}}$$
(5)

where the values of *NDVI<sub>max</sub>* and *NDVI<sub>min</sub>* are 0.95 and 0.05, respectively [28].

2.3.3. Carnegie-Ames-Stanford Approach (CASA) Model

The CASA model has been widely applied to address the spatial and temporal variability of *NPP* at different scales [29–31]. The *NPP* can be computed as:

$$NPP = LUE \times FPAR \times SOL \times 0.5 \tag{6}$$

where *LUE* is the light-use efficiency, *FPAR* is the fraction of absorbed photosynthetically active radiation, and *SOL* is the solar radiation.

FPAR can be calculated as follows:

$$FPAR_{NDVI} = \frac{NDVI - NDVI_{min}}{NDVI_{max} - NDVI_{min}} \times (0.95 - 0.001) + 0.001$$
(7)

$$FPAR_{RVI} = \frac{RVI - RVI_{min}}{RVI_{max} - RVI_{min}} \times (0.95 - 0.001) + 0.001$$
(8)

where  $FPAR_{max}$  and  $FPAR_{min}$  are 0.95 and 0.001, respectively, and have nothing to do with vegetation types.  $NDVI_{min}$  and  $NDVI_{max}$  are the values of 5% and 95% of the NDVI, respectively.  $RVI_{min}$  and  $RVI_{max}$  are the values of 5% and 95% of the RVI, respectively.

To overcome the overestimation and underestimation of *FPAR*, this value was set to the average of the *FPAR*<sub>NDVI</sub> and *FPAR*<sub>RVI</sub> values [32]:

$$FPAR = 0.5 \times FPAR_{NDVI} + 0.5 \times FPAR_{RVI} \tag{9}$$

LUE can be calculated as follows:

$$LUE = T_{\varepsilon 1} \times T_{\varepsilon 2} \times W_{\varepsilon} \times LUE_{max}$$
(10)

where  $T_{\varepsilon 1}$  is the temperature stress in production under high- and low-temperature conditions;  $T_{\varepsilon 2}$  is the temperature stress of changing from optimal temperature condition to highor low-temperature conditions; and  $W_{\varepsilon}$  is the water stress:

$$T_{\varepsilon 1} = 0.8 + 0.02 \times T_{opt} - 0.0005 \times T_{opt}^2$$
(11)

$$T_{\varepsilon 2} = \frac{1.1814}{1 + \exp\left(0.2 * (T_{opt} - 10 - T_a)\right)} \times \frac{1}{1 + \exp\left(0.3 * (-T_{opt} - 10 + T_a)\right)}$$
(12)

$$W_{\varepsilon} = 0.5 + 0.5 \times \frac{ET_a}{EPT} \tag{13}$$

where  $T_{opt}$  is the optimum temperature and was set to 25 °C [28];  $LUE_{max}$  is the maximum light-use efficiency and was set to 0.768 g C MJ<sup>-1</sup> according to Reference [33] in this study.

## 2.3.4. Priestly-Taylor Jet Propulsion Laboratory (PT-JPL) Model

The PT-JPL model was developed by Fisher et al. [34] for estimating  $ET_a$ . It partitions the evapotranspiration rate into canopy transpiration ( $T_r$ ), soil evaporation ( $E_{soil}$ ), and canopy interception evaporation ( $E_i$ ). These components can be computed as:

$$ET_a = (E_{soil} + E_i + T_r)/\lambda \tag{14}$$

$$E_{soil} = (f_{wet} + f_{SM} \times (1 - f_{wet})) \times \alpha \times \frac{\Delta}{\Delta + \gamma} \times (R_{ns} - G)$$
(15)

$$E_i = f_{wet} \times \alpha \times \frac{\Delta}{\Delta + \gamma} \times R_{nc}$$
(16)

$$T_r = (1 - f_{wet}) \times F_c \times f_T \times f_M \times \alpha \times \frac{\Delta}{\Delta + \gamma} \times R_{nc}$$
(17)

where  $\lambda$  is the latent heat of vaporization and is set to 2.45 MJ kg<sup>-1</sup>,  $\alpha$  is a constant and is set to 1.26 (unitless),  $\Delta$  is the slope of the saturation-to-vapor pressure curve (kPa °C<sup>-1</sup>),  $\gamma$  is the psychrometric constant (0.665 × 10<sup>-3</sup> × P kPa °C<sup>-1</sup>), *G* is the ground heat flux (W m<sup>-2</sup>) and can be ignored for daily time steps [21],  $R_{ns}$  is the net radiation to the soil (W m<sup>-2</sup>) calculated as  $R_{ns} = R_n \times (1 - F_c)$  [28], and  $R_{nc}$  is the net radiation to the canopy (W m<sup>-2</sup>) calculated as  $R_n \times F_c$ .  $f_{wet}$  is the relative surface wetness,  $f_{SM}$  is the soil moisture constraint,  $f_T$  and  $f_M$  are constraints for plant temperature and moisture, respectively.

 $f_{wet}$ ,  $f_{SM}$ ,  $f_T$ , and  $f_M$  can be calculated as follows:

$$f_{wet} = RH^4 \tag{18}$$

$$f_{SM} = R H^{VPD/\beta} \tag{19}$$

$$f_T = \exp\left[-\left(\frac{T_a - T_{opt}}{T_{opt}}\right)^2\right]$$
(20)

$$f_M = \frac{f_{APAR}}{f_{APAR_{max}}} \tag{21}$$

where *RH* is the relative humidity (%), *VPD* is the saturation vapor pressure deficit (kPa),  $\beta$  is the soil moisture constraint to *VPD* and is set to 1.0 kPa [34], *T<sub>a</sub>* is the air temperature (°C), *f<sub>APAR</sub>* is the fraction of photosynthetically active radiation (PAR) (unitless), and *f<sub>APARmax</sub>* is the maximum of *f<sub>APAR</sub>*.

Here,  $f_{APAR}$  is calculated as follows [35]:

$$f_{APAR} = 0.95 \times (1 - \exp(-0.5LAI))$$
(22)

2.3.5. Water-Use Efficiency (WUE) of Eucalyptus Plantations

We defined *WUE* of *Eucalyptus* plantations as the ratio of *NPP* to  $ET_a$  in this study, and it can be calculated with simulated *NPP* and  $ET_a$  values as follows (g C m<sup>-2</sup> mm<sup>-1</sup>):

$$WUE = \frac{NPP}{ET_a}$$
(23)

## 2.3.6. Validation of the Classification of *Eucalyptus* Plantations

To validate the classification results of *Eucalyptus* plantations based on CART, we used historical data of cultivated *Eucalyptus* plantations in Huangmian County from 2009 to 2018. These data were obtained from the Guangxi Huangmian State Owned Forest Farm.

The Kappa coefficient (*k*) test was used to evaluate the CART classification performance, and is defined as [36]:

$$k = \frac{P_o - P_e}{1 - P_e} \tag{24}$$

where  $P_o$  and  $P_e$  are the probabilities of the observed agreement and expected agreement by chance, respectively.

#### 3. Results

#### 3.1. Classification of Eucalyptus Plantations

Our evaluation of the classification results indicated a reasonably accurate separation of *Eucalyptus* plantations, as inferred from relatively high Kappa accuracy coefficients when using historical data of annual *Eucalyptus* plantation cultivation (Table 2). The total coverage of *Eucalyptus* plantations increased from approximately 152 km<sup>2</sup> in 2011 to 191 km<sup>2</sup> in 2019, reaching approximately 38% of Huangmian County territory, indicating that the area occupied by *Eucalyptus* plantations has increased over time.

| Table 2. Accuracy of | distinguishing Euc | <i>alyptus</i> plantations i | n the study region. |
|----------------------|--------------------|------------------------------|---------------------|
|                      |                    |                              |                     |

| Year | <i>Eucalyptus</i> plantation (km <sup>2</sup> ) | Kappa Accuracy Coefficient (%) |
|------|---|--------------------------------|
| 2011 | 152.79  | 70.93                          |
| 2013 | 189.49  | 75.97                          |
| 2015 | 184.87  | 74.46                          |
| 2017 | 181.65  | 69.81                          |
| 2019 | 191.67  | 72.03                          |

#### 3.2. NPP of Eucalyptus Plantations

The increasing trend of *NDVI* and  $F_c$  was similar to the change in the area of *Eucalyptus* plantations (Table 3), increasing during the study period. In contrast, the mean daily *NPP* peaked in 2017 and decreased to approximately 3.7 g C m<sup>-2</sup> in 2019, indicating that 2017 might be the end of a short rotation and that 2019 should be the beginning of another short rotation of *Eucalyptus* plantations. Correlation analysis confirmed that for all areas with *Eucalyptus* plantations, *NDVI*, and  $F_c$  did not have a significant impact on *NPP*. Therefore, information about stand ages and structure should significantly improve the accuracy in estimating productivity and its change trend in future studies.

**Table 3.** Change characteristics of *NDV1*, *F*<sub>c</sub>, and *NPP* of *Eucalyptus* plantations.

|                              | 16 October 2011 | 5 October 2013 | 17 October 2015 | 16 September 2017 | 24 August 2019 |
|------------------------------|-----------------|----------------|-----------------|-------------------|----------------|
| NDVI                         | $0.81\pm0.04$   | $0.83\pm0.05$  | $0.85\pm0.03$   | $0.83\pm0.07$     | $0.89\pm0.05$  |
| $F_c$                        | $0.84 \pm 0.05$ | $0.87\pm0.06$  | $0.89\pm0.03$   | $0.87\pm0.08$     | $0.93\pm0.05$  |
| $NPP\left(g C m^{-2}\right)$ | $3.68\pm0.52$   | $2.80\pm0.41$  | $3.99\pm0.34$   | $5.10\pm0.78$     | $3.77\pm0.41$  |

#### 3.3. Actual Evapotranspiration $(ET_a)$ and Transpiration of Eucalyptus Plantations

The daily  $ET_a$  of *Eucalyptus* plantations displayed different spatial patterns associated with different periods (Figure 3). The daily  $ET_a$  and transpiration of *Eucalyptus* plantations were highest on 24 August 2019, indicating that  $ET_a$  and transpiration might have been affected by other factors, especially by temperature (Table 4). Temperature had a significant impact on both  $ET_a$  (*p*-value = 0.009) and transpiration (*p*-value = 0.01) in *Eucalyptus* plantations according to correlation analysis. In contrast, neither the area of *Eucalyptus* plantations, *NDVI*, nor  $F_c$  had a significant impact on  $ET_a$  and transpiration. The ratio of transpiration to  $ET_a$  of *Eucalyptus* plantations was significantly high, higher than 66% for all study time slices, indicating that *Eucalyptus* plantations lose more water via transpiration to the atmosphere. In particular, we highlight that transpiration accounted for more than 82% of  $ET_a$  on 16 October 2011.



**Figure 3.** Spatial pattern of daily  $ET_a$  of *Eucalyptus* plantations on 16 October 2011 (**a**), 5 October 2013 (**b**), 17 October 2015 (**c**), 16 September 2017 (**d**), and 24 August 2019 (**e**).

**Table 4.** A high ratio of transpiration to  $ET_a$  was revealed in *Eucalyptus* plantations during late summer and autumn.

| Date              | <i>T<sub>r</sub></i> (mm) | $ET_a$ (mm)   | $T_r/ET_a$ (%) | Temperature (°C) |
|-------------------|---------------------------|---------------|----------------|------------------|
| 16 October 2011   | $2.40\pm0.27$             | $2.90\pm0.21$ | 82.76          | $22.31\pm0.03$   |
| 5 October 2013    | $2.36\pm0.32$             | $3.01\pm0.22$ | 78.41          | $23.64\pm0.05$   |
| 17 October 2015   | $2.32\pm0.15$             | $3.52\pm0.10$ | 66.91          | $22.73\pm0.08$   |
| 16 September 2017 | $3.04\pm0.44$             | $4.59\pm0.25$ | 66.23          | $28.18\pm0.05$   |
| 24 August 2019    | $3.93\pm0.46$             | $5.82\pm0.28$ | 67.53          | $30.32\pm0.12$   |

3.4. Water-Use Efficiency (WUE) of Eucalyptus Plantations

The *WUE* of *Eucalyptus* plantations also showed various spatial patterns associated with different periods (Figure 4). However, in contrast to  $ET_a$ , the *WUE* of *Eucalyptus* plantations was the lowest on 24 August 2019, indicating that high evapotranspiration or transpiration with low net primary production results in low *WUE* of *Eucalyptus* plantations in the late summer and autumn period (Table 5). Neither forest cover changes (including the area of *Eucalyptus* plantations, *NDVI*, and *F*<sub>c</sub>) nor climate warming had an impact on

9 of 13

the *WUE* of *Eucalyptus* plantations. Indirect effects of forest cover changes and climate warming on the *WUE* might occur by altering other vegetation properties (i.e., stand ages and structure) and evapotranspiration, respectively. Climate warming increased  $ET_a$  (Table 4) and then led to decreases in the *WUE* of *Eucalyptus* plantations.



**Figure 4.** Spatial pattern of the daily *WUE* of *Eucalyptus* plantations on 16 October 2011 (**a**), 5 October 2013 (**b**), 17 October 2015 (**c**), 16 September 2017 (**d**), and 24 August 2019 (**e**).

Table 5. Characteristics of the WUE of Eucalyptus plantations during late summer and autumn periods.

|  | 16 October 2011 | 5 October 2013 | 17 October 2015 | 16 September 2017 | 24 August 2019 |
|--|-----------------|----------------|-----------------|-------------------|----------------|
| $NPP\left(gCm^{-2}\right)$             | $3.68\pm0.52$   | $2.80\pm0.41$  | $3.99\pm0.34$   | $5.10\pm0.78$     | $3.77\pm0.41$  |
| $ET_a$ (mm)                            | $2.90\pm0.21$   | $3.01\pm0.22$  | $3.52\pm0.10$   | $4.59\pm0.25$     | $5.82\pm0.28$  |
| $WUE\left( \text{kg C m}^{-3} \right)$ | $1.26\pm0.09$   | $0.92\pm0.07$  | $1.13\pm0.07$   | $1.10\pm0.13$     | $0.65\pm0.04$  |

# 4. Discussion

*Eucalyptus* is not native to China. However, it has been widely planted and its plantation estate has expanded owing to its high wood productivity and economic benefits [6]. By the end of 2015, *Eucalyptus* plantations covered an area of 4.5 million hectares across

10 of 13

China [37]. This is expected to increase by 0.2 million hectares annually [38,39]. The Guangxi Zhuang Autonomous Region, as noted before, is the province in China with the largest extent of *Eucalyptus* plantations. The area has expanded to more than 1.8 million hectares in just the last decade and is predicted to increase in years to come. Huangmian, a small county in the Guangxi Zhuang Autonomous Region, witnessed an increase in the total area of *Eucalyptus* plantations from 2011 to 2019, accounting for at least 38% of the county's territory, which has come at the expense of declines in areas of other forest types. Such large-scale *Eucalyptus* plantations could have serious impacts, such as biodiversity reduction, soil degradation, and regional water security [38,40], consequently threatening the attainment of sustainable plantations. Hence, evaluating the relationship between *Eucalyptus* plantations and regional water cycles should be a priority for sustainable plantation forestry.

Accurately estimating evapotranspiration helps in achieving sustainable tree plantations and efficient water use management [8,41]. We analyzed the  $ET_a$  and transpiration of Eucalyptus plantations using a modified PT-JPL model combined with RapidEye multispectral images taken at a 5-m spatial resolution. We found that the value of daily  $ET_{a}$ , especially the transpiration of *Eucalyptus* plantations, was consistent with the transpiration of *Eucalyptus* plantations worldwide, ranging from 0.5 to 6 mm per day [8,42].  $ET_a$ and transpiration depend not only on vegetation growth dynamics but also on climatic factors and management practices [43]. Within a small county under the same site and climate conditions in South China, our study found that both the  $ET_a$  and transpiration of Eucalyptus plantations were significantly impacted by climate warming. Climate warming can indeed increase evapotranspiration [44,45], including in *Eucalyptus* plantations [46,47], and result in low WUE in Eucalyptus plantations. There was significant evidence of lower WUE in *Eucalyptus* plantations on 24 August 2019, with a high daily mean temperature of 30.32 °C, which was predominantly reflected by a higher  $ET_a$  and a lower NPP in *Eucalyptus* plantations. WhiteHead and Beadle [48] mentioned that when temperature extremes are high, the productivity (i.e., photosynthesis) of *Eucalyptus* plantations is much lower than expected, which may result in lower WUE. Hubbard et al. [15] also confirmed that high temperature could result in low growth, high transpiration, and low WUE in *Eucalyptus* plantations in Brazil. The lower net photosynthesis rate is primarily due to stomatal regulation, which could be a water-saving strategy to address the drier conditions induced by warming [49]. The daily mean temperature was higher than 30 °C on 24 August 2019, it was not extremely high but could still induced water stress in South China even with adequate water conditions. Therefore, management practice (i.e., short rotation in this study) enhanced the effect of climate warming on NPP and then decreased the WUE of Eucalyptus plantations. There was a higher WUE at the end of a short rotation (during 2017 in this study) and a lower WUE at the beginning of another short rotation (during 2019 in this study). A previous study confirmed that successive rotations decreases carbon storage in *Eucalyptus* plantations [50]. In addition, other management practices, such as fertilization, mixed-species plantations, and irrigation, could enhance the WUE of Euca*lyptus* plantations by promoting available resource use [51] and increasing photosynthetic capacity [16] to gain much more biomass and carbon stock per unit water use [18].

The *WUE* is not a constant for any species but varies according to the combination of stand age, growth dynamics, climate, and site conditions [52,53]. Therefore, in addition to management practices, stand ages, canopy structure, and physiological processes should be monitored to better evaluate productivity,  $ET_a$  and transpiration which will then improve accuracy when estimating the *WUE* of *Eucalyptus* plantations under future global warming. Other net productivity datasets such as forest inventory or airborne LiDAR productions, which could capture the aboveground forest biomass, should be considered to improve the accuracy of net primary production capturing and thus, *WUE* estimation. A previous study pointed out that plantations almost always had a higher water demand than the corresponding reference native forests [54]. Therefore, expanding short-rotation

*Eucalyptus* plantations should strive to reach a compromise between production goals and eco-environmental benefits under future global warming.

#### 5. Conclusions

We estimated the NPP with a modified CASA model,  $ET_a$  and transpiration of Eu*calyptus* plantations with a modified PT-JPT model combined with 5-m spatial resolution RapidEye imagery, and then explored the changes in the WUE of Eucalyptus plantations and its driving factors. Our results showed that high daily  $ET_a$  significantly decreased the WUE of Eucalyptus plantations. Both the daily  $ET_a$  and transpiration of Eucalyptus plantations were primarily impacted by temperature. Climate warming will increase evapotranspiration, decrease net photosynthesis, and result in low WUE in Eucalyptus plantations. Management practices (i.e., short rotation in this study) can enhance the effect of climate warming on WUE by varying NPP of Eucalyptus plantations. High NPP results in high WUE of Eucalyptus plantations at the end of rotations, while low NPP leads to low WUE at the beginning of successive rotations. However, some uncertainty remains as to whether there is interannual or growing season variation in the daily aboveground primary productivity of *Eucalyptus* plantations, which will result in different temporal and spatial patterns of WUE. Detection of changes in aboveground primary productivity using forest inventory data, LiDAR, or remote sensing-based primary productivity productions with high spatial resolution and subdividing species-specific stand levels will be helpful in improving the accuracy in exploring the WUE of Eucalyptus plantations. As both the  $ET_a$ and transpiration were high and WUE was low in Eucalyptus plantations under increased temperature conditions, any practices (i.e., intensive rotation or expanding) in changing the NPP of Eucalyptus plantations should balance production goals and sustainable water resource management under future global warming. This is particularly important in South China, especially in the Guangxi Zhuang Autonomous Region, since this region is the country's leader in terms of *Eucalyptus* plantation coverage.

**Author Contributions:** Conceptualization, Y.Y.; Data curation, Y.Y., J.H., W.H., J.Z. and Y.L.; Methodology, Y.Y. and W.H.; Writing—original draft, Y.Y.; Writing—review and editing, Y.Y., J.H., W.H., J.Z. and Y.L. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research was supported by the National Natural Science Foundation of China (No. 32060369), the Key Research and Development Program of Guangxi (No. GuikeAB22035060), the Basic Research Fund of the Guangxi Academy of Sciences (No. CQZ-D-1904) and the Fund of the Guangxi Key Laboratory of Plant Conservation and Restoration Ecology in Karst Terrain (No. 22-035-26).

**Data Availability Statement:** The datasets used in the present study are available from the authors' group on reasonable requested.

Conflicts of Interest: The authors declare no conflict of interest.

## References

- 1. Cai, W.; Ullah, S.; Yan, L.; Lin, Y. Remote sensing of ecosystem water use efficiency: A review of direct and indirect estimation methods. *Remote Sens.* **2021**, *13*, 2393. [CrossRef]
- Hatfield, J.L.; Dold, C. Water-use efficiency: Advances and challenges in a changing climate. *Front. Plant Sci.* 2019, 10, 103. [CrossRef] [PubMed]
- Yang, Y.; Guan, H.; Batelaan, O.; McVicar, T.R.; Long, D.; Piao, S.; Liang, W.; Liu, B.; Jin, Z.; Simmons, C.T. Contrasting responses of water use efficiency to drought across global terrestrial ecosystems. *Sci. Rep.* 2016, *6*, 23284. [CrossRef] [PubMed]
- Ge, J.; Zhang, Z.; Lin, B. Towards carbon neutrality: How much do forest carbon sinks cost in China? *Environ. Impact Assess. Rev.* 2023, 98, 106949. [CrossRef]
- United Nations Paris Agreement. Available online: https://unfccc.int/sites/default/files/english\_paris\_agreement.pdf (accessed on 1 May 2023).
- Wu, J.; Fan, H.; Liu, W.; Huang, G.; Tang, J.; Zeng, R.; Huang, J.; Liu, Z. Should Exotic Eucalyptus be Planted in Subtropical China: Insights from Understory Plant Diversity in Two Contrasting Eucalyptus Chronosequences. *Environ. Manag.* 2015, 56, 1244–1251. [CrossRef] [PubMed]

- Aguilos, M.; Sun, G.; Noormets, A.; Domec, J.C.; McNulty, S.; Gavazzi, M.; Prajapati, P.; Minick, K.J.; Mitra, B.; King, J. Ecosystem
  productivity and evapotranspiration are tightly coupled in loblolly pine (Pinus taeda l.) plantations along the coastal plain of the
  southeastern U.S. *Forests* 2021, *12*, 1123. [CrossRef]
- 8. Liu, W.; Wu, J.; Fan, H.; Duan, H.; Li, Q.; Yuan, Y.; Zhang, H. Estimations of evapotranspiration in an age sequence of Eucalyptus plantations in subtropical China. *PLoS ONE* **2017**, *12*, e0174208. [CrossRef]
- 9. Zhang, L.; Sun, P.; Huettmann, F.; Liu, S. Where should China practice forestry in a warming world? *Glob. Chang. Biol.* 2022, 28, 2461–2475. [CrossRef]
- 10. Liu, C.L.C.; Kuchma, O.; Krutovsky, K.V. Mixed-species versus monocultures in plantation forestry: Development, benefits, ecosystem services and perspectives for the future. *Glob. Ecol. Conserv.* **2018**, *15*, e00419. [CrossRef]
- 11. Du, H.; Zeng, F.; Peng, W.; Wang, K.; Zhang, H.; Liu, L.; Song, T. Carbon storage in a Eucalyptus plantation chronosequence in Southern China. *Forests* **2015**, *6*, 1763–1778. [CrossRef]
- 12. Jim, M.; Zhang, N.; Yang, Z.; John, C.; Xu, D. Water use by fast-growing Eucalyptus urophylla plantations in southern China. *Tree Physiol.* **2004**, *24*, 1035–1044. [CrossRef]
- Olbrich, B.W.; Le Roux, D.; Poulter, A.G.; Bond, W.J.; Stock, W.D. Variation in water use efficiency and δ13C levels in Eucalyptus grandis clones. J. Hydrol. 1993, 150, 615–633. [CrossRef]
- Rubilar, R.; Hubbard, R.; Emhart, V.; Mardones, O.; Quiroga, J.J.; Medina, A.; Valenzuela, H.; Espinoza, J.; Burgos, Y.; Bozo, D. Climate and water availability impacts on early growth and growth efficiency of Eucalyptus genotypes: The importance of GxE interactions. *For. Ecol. Manag.* 2020, 458, 117763. [CrossRef]
- 15. Hubbard, R.M.; Carneiro, R.L.; Campoe, O.; Alvares, C.A.; Figura, M.A.; Moreira, G.G. Contrasting water use of two Eucalyptus clones across a precipitation and temperature gradient in Brazil. *For. Ecol. Manag.* **2020**, 475, 118407. [CrossRef]
- 16. Forrester, D.I.; Theiveyanathan, S.; Collopy, J.J.; Marcar, N.E. Enhanced water use efficiency in a mixed Eucalyptus globulus and Acacia mearnsii plantation. *For. Ecol. Manag.* **2010**, *259*, 1761–1770. [CrossRef]
- 17. Hakamada, R.E.; Hubbard, R.M.; Moreira, G.G.; Stape, J.L.; Campoe, O.; Ferraz, S.F. de B. Influence of stand density on growth and water use efficiency in Eucalyptus clones. *For. Ecol. Manag.* **2020**, *466*, 118125. [CrossRef]
- Lopes, A.d.S.; Folegatti, M.V.; Júnior, E.D.F.; de Oliveira, G.Q.; de Oliveira, J.C.L.; Brito, K.M.R.; Rego, N.H. Volume, biomass, carbon stock and efficiency of water use in irrigated eucalyptus. *Cienc. Florest.* 2022, 32, 1047–1060. [CrossRef]
- 19. Hou, J.; Yin, R.; Wu, W. Intensifying Forest Management in China: What does it mean, why, and how? *For. Policy Econ.* **2019**, *98*, 82–89. [CrossRef]
- 20. Ouyang, L.; Zhao, P.; Zhou, G.; Zhu, L.; Huang, Y.; Zhao, X.; Ni, G. Stand-scale transpiration of a *Eucalyptus urophylla* × *Eucalyptus grandis* plantation and its potential hydrological implication. *Ecohydrology* **2018**, *11*, e1938. [CrossRef]
- 21. Allen, R.; Pereira, L.; Raes, D.; Smith, M. Crop Evapotranspiration: Guidelines for Computing Crop Requirements. Irrigation and Drainage Paper 56; FAO: Rome, Italy, 1998.
- 22. Breiman, L.; Friedman, J.H.; Olshen, R.A.; Stone, C.J. *Classification and Regression Trees*; Chapman & Hall/CRC: Boca Raton, FL, USA, 1984; ISBN 0412048418.
- 23. Loh, W.Y. Classification and regression trees. Wiley Interdiscip. Rev. Data Min. Knowl. Discov. 2011, 1, 14–23. [CrossRef]
- 24. Loh, W.Y. Fifty years of classification and regression trees. Int. Stat. Rev. 2014, 82, 329–348. [CrossRef]
- 25. Lawrence, R.L.; Andrea, W. Rule-based classification systems using classification and regression tree (CART) analysis. *Photogramm. Eng. Remote Sens.* **2001**, *67*, 1137–1142.
- Sibanda, M.; Buthelezi, S.; Ndlovu, H.S.; Mothapo, M.C.; Mutanga, O. Mapping the Eucalyptus spp woodlots in communal areas of Southern Africa using Sentinel-2 Multi-Spectral Imager data for hydrological applications. *Phys. Chem. Earth* 2021, 122, 102999. [CrossRef]
- 27. Gitelson, A.A.; Kaufman, Y.J.; Stark, R.; Rundquist, D. Novel algorithms for remote estimation of vegetation fraction. *Remote Sens. Environ.* **2002**, *80*, 76–87. [CrossRef]
- Yao, Y.; Liang, S.; Cheng, J.; Liu, S.; Fisher, J.B.; Zhang, X.; Jia, K.; Zhao, X.; Qin, Q.; Zhao, B.; et al. MODIS-driven estimation of terrestrial latent heat flux in China based on a modified Priestley-Taylor algorithm. *Agric. For. Meteorol.* 2013, 171–172, 187–202. [CrossRef]
- 29. Potter, S.; Randerson, T.; Field, B.; Matson, A.; Mooney, H.A. Terrestrial ecosystem production: A process model based on global satellite and surface data. *Glob. Biogeochem. Cycles* **1993**, *7*, 811–841. [CrossRef]
- Field, C.B.; Randerson, J.T.; Malmström, C.M. Global net primary production: Combining ecology and remote sensing. *Remote Sens. Environ.* 1995, 51, 74–88. [CrossRef]
- 31. Piao, S.; Fang, J.; Zhou, L.; Zhu, B.; Tan, K.; Tao, S. Changes in vegetation net primary productivity from 1982 to 1999 in China. *Global Biogeochem. Cycles* 2005, 19, 1–16. [CrossRef]
- Los, S.O. Linkages between Global Vegetation and Climate—An Analysis Based on NOAA Advanced Very High Resolution Radiometer Data; Vrije Universiteit: Amsterdam, The Netherlands, 1998.
- Zhu, W.; Pan, Y.; He, H.; Yu, D.; Hu, H. Simulation of maximum light use efficiency for some typical vegetation types in China. *Chinese Sci. Bull.* 2006, *51*, 457–463. [CrossRef]
- Fisher, J.B.; Tu, K.P.; Baldocchi, D.D. Global estimates of the land-atmosphere water flux based on monthly AVHRR and ISLSCP-II data, validated at 16 FLUXNET sites. *Remote Sens. Environ.* 2008, 112, 901–919. [CrossRef]

- 35. Ruimy, A.; Kergoat, L.; Bondeau, A. Comparing global models of terrestrial net primary productivity (NPP): Analysis of differences in light absorption and light-use efficiency. *Glob. Chang. Biol.* **1999**, *5*, 56–64. [CrossRef]
- 36. Cohen, J. A coefficient of agreement for nominal scales. Educ. Psychol. Meas. 1960, 20, 37–46. [CrossRef]
- 37. Xie, Y.; Arnold, R.J.; Wu, Z.; Chen, S.; Du, A.; Luo, J. Advances in eucalypt research in China. *Front. Agric. Sci. Eng.* 2017, 4, 380–390. [CrossRef]
- Chen, F.; Zheng, H.; Zhang, K.; Ouyang, Z.; Lan, J.; Li, H.; Shi, Q. Changes in soil microbial community structure and metabolic activity following conversion from native Pinus massoniana plantations to exotic Eucalyptus plantations. *For. Ecol. Manag.* 2013, 291, 65–72. [CrossRef]
- Liu, Z.; Wu, J.; Zhou, L.; Lin, Y.; Fu, S. Effect of understory fern (*Dicranopteris dichotoma*) removal on substrate utilization patterns of culturable soil bacterial communities in subtropical Eucalyptus plantations. *Pedobiologia* 2012, 55, 7–13. [CrossRef]
- Calviño-Cancela, M.; Rubido-Bará, M.; van Etten, E.J.B. Do eucalypt plantations provide habitat for native forest biodiversity? For. Ecol. Manag. 2012, 270, 153–162. [CrossRef]
- Ferraz, S.F.B.; Lima, W. de P.; Rodrigues, C.B. Managing forest plantation landscapes for water conservation. *For. Ecol. Manag.* 2013, 301, 58–66. [CrossRef]
- 42. Soares, J.V.; Almeida, A.C. Modeling the water balance and soil water fluxes in a fast growing Eucalyptus plantation in Brazil. *J. Hydrol.* **2001**, 253, 130–147. [CrossRef]
- Zhang, Z.; Zhang, L.; Xu, H.; Creed, I.F.; Blanco, J.A.; Wei, X.; Sun, G.; Asbjornsen, H.; Bishop, K. Forest water-use efficiency: Effects of climate change and management on the coupling of carbon and water processes. *For. Ecol. Manag.* 2023, 534, 120853. [CrossRef]
- Fan, J.; Wu, L.; Zhang, F.; Xiang, Y.; Zheng, J. Climate change effects on reference crop evapotranspiration across different climatic zones of China during 1956–2015. J. Hydrol. 2016, 542, 923–937. [CrossRef]
- 45. Dimitriadou, S.; Nikolakopoulos, K.G. Evapotranspiration trends and interactions in light of the anthropogenic footprint and the climate crisis: A review. *Hydrology* **2021**, *8*, 163. [CrossRef]
- 46. Martins, F.B.; Benassi, R.B.; Torres, R.R.; de Brito Neto, F.A. Impacts of 1.5 °C and 2 °C global warming on Eucalyptus plantations in South America. *Sci. Total Environ.* 2022, *825*, 153820. [CrossRef] [PubMed]
- Hakamada, R.E.; Hubbard, R.M.; Stape, J.L.; de Paula Lima, W.; Moreira, G.G.; de Barros Ferraz, S.F. Stocking effects on seasonal tree transpiration and ecosystem water balance in a fast-growing Eucalyptus plantation in Brazil. *For. Ecol. Manag.* 2020, 466, 118149. [CrossRef]
- Whitehead, D.; Beadle, C.L. Physiological regulation of productivity and water use in Eucalyptus: A review. *For. Ecol. Manag.* 2004, 193, 113–140. [CrossRef]
- Niu, S.; Xing, X.; Zhang, Z.; Xia, J.; Zhou, X.; Song, B.; Li, L.; Wan, S. Water-use efficiency in response to climate change: From leaf to ecosystem in a temperate steppe. *Glob. Chang. Biol.* 2011, *17*, 1073–1082. [CrossRef]
- 50. Li, X.; Ye, D.; Liang, H.; Zhu, H.; Qin, L.; Zhu, Y.; Wen, Y. Effects of successive rotation regimes on carbon stocks in eucalyptus plantations in subtropical China measured over a full rotation. *PLoS ONE* **2015**, *10*, e0132858. [CrossRef]
- Asensio, V.; Domec, J.C.; Nouvellon, Y.; Laclau, J.P.; Bouillet, J.P.; Jordan-Meille, L.; Lavres, J.; Rojas, J.D.; Guillemot, J.; Abreu-Junior, C.H. Potassium fertilization increases hydraulic redistribution and water use efficiency for stemwood production in Eucalyptus grandis plantations. *Environ. Exp. Bot.* 2020, 176, 104085. [CrossRef]
- 52. Albaugh, J.M.; Dye, P.J.; King, J.S. Eucalyptus and Water Use in South Africa. Int. J. For. Res. 2013, 2013, 852540. [CrossRef]
- 53. Hubbard, R.M.; Stape, J.; Ryan, M.G.; Almeida, A.C.; Rojas, J. Effects of irrigation on water use and water use efficiency in two fast growing Eucalyptus plantations. *For. Ecol. Manag.* **2010**, 259, 1714–1721. [CrossRef]
- Hua, F.; Bruijnzeel, L.A.; Meli, P.; Martin, P.A.; Zhang, J.; Nakagawa, S.; Miao, X.; Wang, W.; McEvoy, C.; Peña-Arancibia, J.L.; et al. The biodiversity and ecosystem service contributions and trade-offs of forest restoration approaches. *Science* 2022, 376, 839–844. [CrossRef]

**Disclaimer/Publisher's Note:** The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.