# Water and carbon cycles are tightly coupled in loblolly pine (Pinus taeda L.) plantations along the coastal plains of southeastern U.S.

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**Abstract**

Forest water use efficiency (WUE), the ratio of gross primary productivity (GPP), and evapotranspiration (ET) is important variable to understand the coupling between water and carbon cycles, and to assess resource use, ecosystem resilience, and commodity production. Here, we determined WUE for managed loblolly pine plantation forests over the course of a rotation on the coastal plain of North Carolina in the eastern U.S. We found that forest annual GPP, ET, and WUE increased until age ten, which stabilized thereafter. WUE varied annually (2 - 44%), being higher at young plantation (YP, 3.12 ± 1.20 g C kg H2O d-1 ) compared to a mature plantation (MP, 2.92 ± 0.45 g C kg H2O d-1 ), with no distinct seasonal patterns. Stand age was strongly correlated with ET (R2 = 0.71) and GPP (R2 = 0.64). ET and GPP were tightly coupled (R2 = 0.86). Radiation and air temperature showed a significant effects on GPP and ET (R2 = 0.71 – R2 = 0.82) at a monthly scale, but not WUE. Drought affected WUE (R2 = 0.35) more than ET (R2 = 0.25) or GPP (R2 = 0.07). A drought enhanced GPP in MP (i.e., 6% – 9 %) and YP (i.e., 20% – 53%), but reduced ET (i.e., 8 – 11 %) and (i.e., 30 – 43 %) in MP and YP respectively, conferring that drought resulted in higher WUE by 8 – 30%. Minor seasonal and interannual variations in forest WUE of MP (age >10) suggested that forest WUE became stable as stands matured. Our study concluded that carbon and water cycles in loblolly pine plantations were tightly coupled with different characteristics in different ages and hydrologic regimes. WUE can be used to quantify water (carbon) flux from carbon (water) flux under varying environmental conditions. The tradeoffs between water and carbon resources should be recognized in forest management to achieve multiple ecosystem services (i.e., water supply and carbon sequestration).

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## Introduction

- Ecosystem water use efficiency (WUE) is expressed as the fraction of carbon gained through gross primary productivity (GPP) to water lost through evapotranspiration (ET) at the ecosystem level.
- Studying WUE is important to determine the carbon–water coupling amidst climate change and extreme weather events.
- However, multiple-year information about the response of forested wetland ecosystems to global warming and drought is scarce.
- Here, we investigated the WUE of converted forested wetlands in North Carolina, USA using the eddy covariance flux towers at two adjacent young (YP) and mature (MP) loblolly pine plantations.

**Objectives**

1) Determine the inter-annual and seasonal trends in GPP, ET, and WUE;
2) Evaluate the impact of age and climate, to include the 2007/2008 drought, on WUE and its components.

## Methods

**The Study Sites**

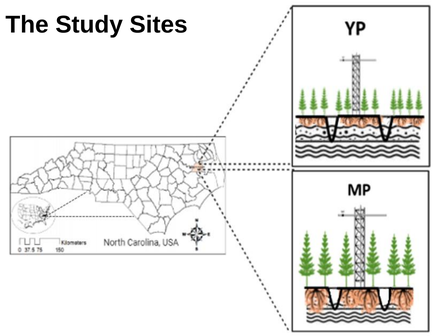


*Fig 1. Map showing the location of YP and MP flux towers established in North Carolina, USA.*

*Fig. 2 Registered under FLUXNET as (left) US-NC1 (herein (YP, 2–8 years old) ) and (right) US-NC2 (MP, 15 – 28 years old). Measurements covered from 2005 – 2011 at YP and 2005 – 2018 at MP.*

**Climate and Eddy Covariance Flux Monitoring**

- Atmospheric $CO_2$ and $H_2O$ concentrations
- Air temperature and humidity
- Global and infrared incident and reflected radiations
- Incident and reflected photosynthetic photon flux density
- Rainfall
- Wind direction and speed
- Atmospheric pressure
- Soil temperature
- Volumetric soil water content

## Results

**Interannual variation in GPP, ET, and WUE**

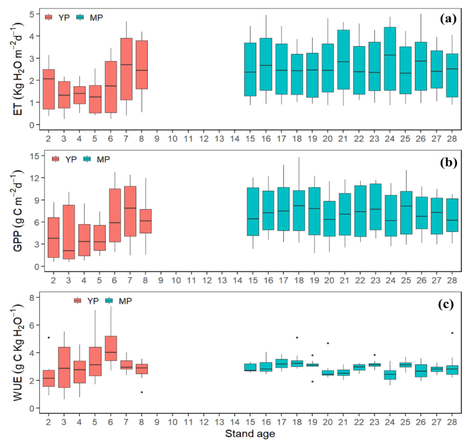


*Fig. 3 Inter-annual variation in ET, GPP, and WUE at different ages of the chronosequence (YP and MP). Monthly data were used in the analysis.*

**Monthly Variation in GPP, ET, and WUE**

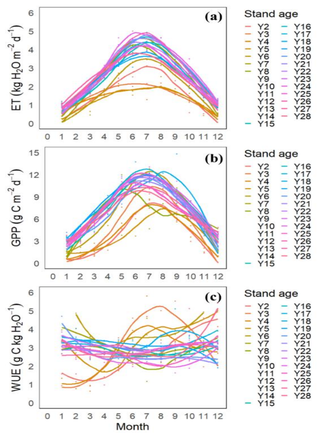


*Fig. 4 Seasonal trend in ET, GPP, and WUE across different age levels of the chronosequence sites (YP and MP) based on monthly smoothed values for each year.*

**Age-Dependency of GPP, ET, and WUE**

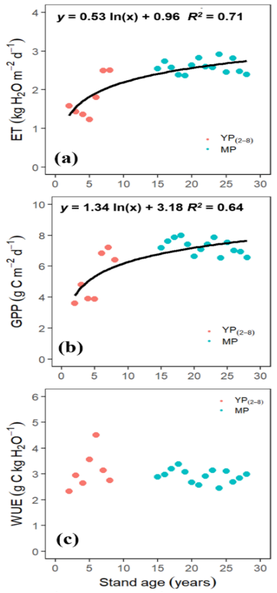


*Fig. 5 Regression curves between stand age and ET, GPP, and WUE*

**The Coupling of GPP and ET**

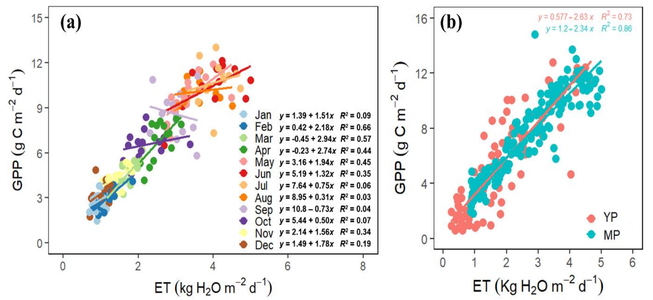


*Fig. 6 Panel (**a**) is the relationship between ET and GPP across all years in YP and MP with season as a factor. Panel (**b**) is the ET–GPP relationships across the entire period with site as a factor.*

**Environmental Effects on ET, GPP, and WUE**

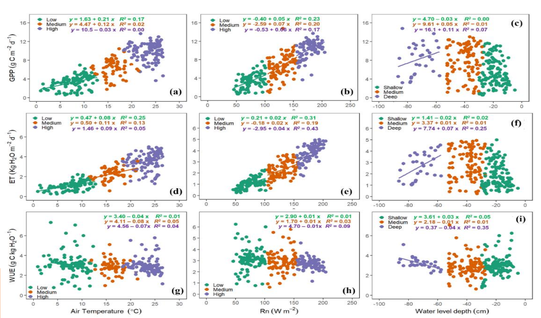


*Fig. 7 Relationship of clustered air temperature and net radiation (low, medium, high) and water table depth (shallow, medium, deep) on (**a**–**c**) ET, (**d**–**f**) GPP, and (**g**–**i**) WUE across all years at YP and MP combined.*

**Drought Effects on GPP, ET, and WUE**

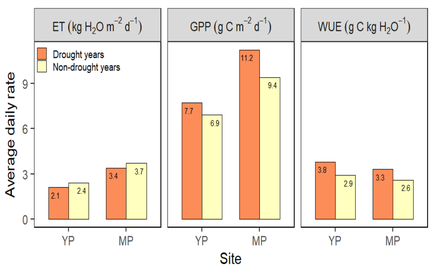


*Fig. 8 Daily average ET, GPP, and WUE at YP and MP. Daily values during the growing season (April – September) were averaged during 2007 and 2008 (drought years) and the rest of the years (non-drought years).*

## Conclusions

- The absence of distinct seasonal and inter-annual patterns in WUE for a mature stand (age > 10) confirms that carbon and water cycles are tightly coupled.
- Although the processes involved in $CO_2$ and $H_2O$ fluxes varied individually, they converged towards a relatively stable water use efficiency as the pine plantation matured.
- A stable WUE suggests that the pine ecosystem productivity can be readily predicted from ET and vice versa.
- Drought events in 2007/2008 affected little of pine plantation WUE suggesting an effective coping mechanism of pine plantations during drought.
- Our study presents aspects of improving ecosystem models to understand better the trade-off between the carbon absorbed and water released in vegetation–climate–hydrology feedback loops.

## Acknowledgement

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