

1 **Effects of land-use change and drought on decadal evapotranspiration and water balance**
2 **of natural and managed forested wetlands along the southeastern US lower coastal plain**
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40 **Abstract**

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43 Forested wetlands are important in regulating regional hydrology and climate. However, long-
44 term studies on the hydrologic impacts of converting natural forested wetlands to pine
45 plantations are rare for the southern US. From 2005-2018, we quantified water cycling in two
46 post-harvest and newly-planted loblolly pine (*Pinus taeda*) plantations (YP₂₋₇, 2-7 yrs old; YP₂₋₈,
47 2-8 yrs old), a rotation-age loblolly pine plantation (MP, 15-28 yrs old), and a natural
48 bottomland hardwood forest (BHF, > 100 yrs old) along the lower coastal plain of North
49 Carolina. We quantified the differences in inter-annual and seasonal water balance and trends of
50 evapotranspiration (ET) using eddy covariance over 37 site-years and assessed key climatic and
51 biological drivers of ET. We found that the rotation-age plantation (MP) had higher annual ET
52 (933 ± 63 mm) than the younger plantations (776 ± 74 mm for YP₂₋₇ and 638 ± 190 mm for YP₂₋₈),
53 and the BHF (743 ± 172 mm), owing to differences in stand age, canopy cover, and
54 micrometeorology. Chronosequence analysis of the pine sites showed that ET increased with
55 stand age up to 10 years, then gradually stabilized for the remainder of the rotation of 28 – 30
56 years. YP₂₋₈ was sensitive to water availability, decreasing ET by 30 – 43 % during the extreme
57 2007 – 2008 drought, but reductions in ET at MP were only 8 – 11 %. Comparing to BHF,
58 ditching with management enhanced drainage at YP₂₋₇ and YP₂₋₈, while drainage was lower at
59 the mature pine site. This study provides insight into land use-hydrology-climate interactions
60 that have important implications for forested wetland management in a time of rapidly changing
61 environmental conditions of the LCP of the southern US.

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63 **Keywords:** coastal plain forest, water balance, evapotranspiration, forested wetlands, managed
64 forests, drought

65 **1. Introduction**

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68 Wetland forests play a critical role in regulating regional ecohydrology (McNulty et al., 1997;
69 Sun et al., 2001), water quality (Moreno-Mateos et al., 2012; White and Kaplan, 2017), and
70 productivity of economically important crops, timber, and fishery resources (Bullock and
71 Acreman, 2003) in the southeastern U.S. Compared to upland forests, our knowledge of wetland
72 ecosystem hydrology is still inadequate to fully understand the regional roles of wetland
73 ecological functions and services (Amatya and Skaggs, 2001; Moreno-Mateos et al., 2012;
74 Noormets et al., 2010; Sun et al., 2002; Tor-ngern et al., 2018). In particular, large areas of
75 natural forested wetlands of the southeastern US lower coastal plain (LCP) were historically
76 cleared and drained for timber production (Campbell and Hughes, 1991). Timber companies in
77 the region lowered the water table and soil water content through construction of ditches and
78 canals to facilitate industrial tree farming (Amatya et al., 1996; Kelting et al., 2000; McCarthy et
79 al., 1991). These companies generally used bulldozers, bush hogs, back hoes and hydraulic
80 dredgers to construct the ditches (Burke, 1996). However, we know less about the impact of
81 forest management practices on the long-term impacts of this land use practice on energy, water,
82 and carbon cycling at the ecosystem, watershed, and regional scales (e.g., a forest rotation
83 period) (Sun et al., 2010; Tian et al., 2015).

84

85 Climate change projections suggest an increasing frequency of droughts in the southern US,
86 and at the same time an intensification of the hydrologic cycle (IPCC, 2013; Trenberth, et al.,
87 2007), bringing the risk of flooding. Therefore, a quantitative understanding of the effects of
88 climatic extremes on coastal wetland hydrologic function is a pressing research need to inform
89 LCP forest management.

90

91 Land use change, forest management practices, and climate fluctuations have the potential to
92 affect the regional hydrologic cycle and wetland ecosystem function directly by altering
93 evapotranspiration (ET) (Day et al., 2008; Ellison et al., 2017; Sun et al., 2010; White and
94 Kaplan, 2017). ET is recognized as a key hydrologic control (Sposito, 2017), returning 50–90 %
95 of the incident precipitation to the atmosphere in temperate forest ecosystems (Ford et al., 2007;
96 Gholz and Clark, 2002; Sun et al., 2002). ET links hydrology to biology and is strongly
97 associated with the primary productivity and biodiversity of terrestrial ecosystems (Jackson et
98 al., 2005; Noormets et al., 2006; Wilson and Baldocchi, 2000). ET is a particularly important
99 hydrologic flux under stresses caused by accelerating land-use and climate change (Jones et al.,
100 2012; Oishi et al., 2018; Woodward et al., 2014). Hydrologic and water quality models
101 developed for this coastal region are seldom validated with measured actual ET (Sun et al., 2010;
102 Tian et al., 2015). Large uncertainties remain therefore in watershed scale ET estimates because
103 it has been often derived as the residual of the water balance (Sun et al., 2002), and quantifying
104 ET of vegetated surfaces at a fine spatial and temporal scales (e.g. watershed, daily, monthly)
105 remains challenging. Improved estimation of ET, especially under extreme climate conditions
106 such as drought (Vose et al., 2016), is needed to project potential effects of management and
107 climate change on LCP forest water cycling. To advance this objective, researchers use eddy
108 covariance methodology to directly measure ET, energy, and carbon fluxes at the ecosystem
109 scale in recent decades (Wilson and Baldocchi, 2000; Baldocchi et al. 2001; Gholz and Clark,
110 2002; Sun et al., 2010).

111

112 To better understand the hydrology and C cycling of forested wetlands of the southeastern
113 U.S., we maintain a cluster of eddy covariance flux towers as part of the Ameriflux/FLUXNET

114 network at four sites along the LCP of North Carolina (Aguilos et al., 2020; Domec et al., 2010;
115 Miao et al., 2017; Minick et al., 2019; Mitra et al., 2019; Noormets et al., 2012; Sun et al., 2010;
116 Liu et al., 2019). The four sites are comprised of two young pine plantations (2-7 and 2-8 years
117 old), a rotation-age mature pine plantation (15–28 years old), and a natural, undisturbed forested
118 wetland (>100 years old).

119
120 In the current study, we were interested in how the conversion of wetland forest to managed
121 pine plantations, construction of ditches and extreme weather events (e.g. drought) impact the
122 water balance of these lower coastal plain forests. Specifically, we aimed to (1) examine the
123 seasonal and interannual variations in water balance; (2) determine the ratio of water leaving the
124 system as drainage (D) and ET relative to the amount of precipitation inputs (P); and (3) evaluate
125 the effect of drainage and land-use change, age, gross primary productivity (GPP) and climate
126 variation (including a severe drought in 2007-2008) on ET and water balance. We hypothesized
127 that (1) ET would be higher in rotation-age pine plantation than in young pine, owing mostly to
128 differences in canopy cover, and also higher than in the natural BHF that had lower NPP and
129 GPP (Aguilos et al., 2020); (2) ET increases with age commensurate with increases in GPP; (3)
130 Ditched landscapes for intensive pine plantation management would decrease the fraction of P
131 leaving the site as ET compared to a natural wetland forest; and (4) that a severe meteorological
132 drought in 2007-2008 would affect young plantations more than rotation-aged plantations due to
133 higher level of stress, shallower root systems and lower GPP, although ET and GPP would
134 remain tightly coupled even during extreme conditions.

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137 **2. Materials and Methods**

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139 *2.1 Study sites*

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141 Under the FLUXNET database, our sites are coded as US-NC3, US-NC1, US-NC2, and US-
142 NC4, herein referred to, respectively, as young loblolly pine YP₂₋₇ (2–7 years old) and YP₂₋₈ (2–
143 8 years old), rotation-age mature loblolly pine MP (15–28 years old), and a natural (undrained)
144 bottomland hardwood forest BHF (>100 years old; Fig. 1). The last numbers in the site
145 denominations correspond to the site’s actual age in 2018 except at YP₂₋₈ where it was 8 years
146 old when measurements ended in 2011.

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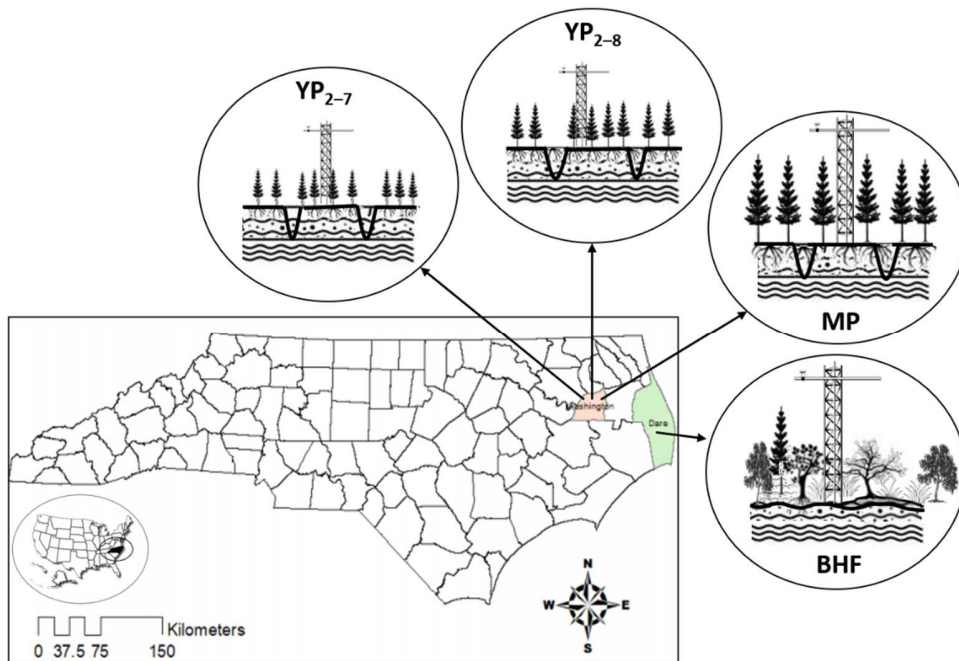
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Figure 1. Location of carbon and energy fluxes monitoring sites in the lower coastal plain of North Carolina.

163 The three loblolly pine plantations (YP₂₋₇, YP₂₋₈, and MP) are managed by Weyerhaeuser NR
 164 Company located in Washington County, North Carolina, USA (Noormets et al., 2010; Sun et
 165 al., 2010). The MP stand is now in its 5th rotation, which was established in 1992. The MP
 166 carbon, energy, and water flux monitoring tower was established when the plantation was 15
 167 years old in 2005. A thinning operation at the MP site occurred in 2009. Also in 2005, another
 168 nearby tower was built (YP₂₋₈) after a harvesting operation and replanting of 1-year old pine
 169 seedlings. Measurement at YP₂₋₈ ended in 2012, and it was replaced with YP₂₋₇ flux tower when
 170 another loblolly pine stand was harvested in 2012. The pine stands at the managed plantation
 171 sites are drained with a network of parallel ditches, 90-130 cm deep on 90-m spacing, and more

172 widely spaced roadside canals. Watershed yield (outflow) is monitored on the downstream end
173 of the drainage network using a V-notch weir. Parallel ditches and roadside canals divide the flat
174 landscape into a mosaic of regularly shaped fields and blocks of fields (Diggs, 2004).

175

176 The BHF flux tower was constructed in 2009 in a 100+ year-old natural coastal bottomland
177 hardwood forest at Alligator River National Wildlife Refuge in Dare County, NC, USA, to
178 establish a frame of reference for the managed plantation sites. It has had minimal human
179 disturbance since stand establishment. BHF is composed of mixed hardwood swamp forests
180 where ‘hummocks’ around tree bases are usually above the water table, and non-vegetated low-
181 lying ‘hollows’ are submerged for more than 70 % of the year (Miao et al., 2013; Minick et al.,
182 2019). This wetland forest site is approximately 108 km away from the managed plantations sites
183 (Fig. 1).

184

185 Pine plantation sites have elevations <5 m, while BHF was <1 m above sea level. At the
186 plantation sites, the mean annual precipitation was 1366 ± 57 mm (1971–2018), and the mean
187 annual temperature was 16.4 ± 0.4 °C (2005–2018). The BHF site had mean average
188 precipitation of 1239 ± 46 mm (1981–2018) and a mean annual temperature of 16.4 ± 0.6 °C
189 (2009–2018). A complete description of the sites is provided in Table 1 (Aguilos et al., 2020;
190 Domec et al., 2015; Miao et al., 2017; Noormets et al., 2012, 2010; Sun et al., 2011; Liu et al.,
191 2018).

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196 Table 1. Study site description of eddy covariance flux towers located along the lower coastal
 197 plain of North Carolina to monitor long-term evapotranspiration and forest water cycling.
 198

Location*/Parameters	YP ₂₋₇ ,	YP ₂₋₈	MP	BHF
Latitude	35.7990	35.8118	35.8030	35.7879
Longitude	-76.6560	-76.7119	-76.6685	-75.9038
Eddy covariance flux tower sensor height (m)	6.5 (2013) 9.0 (2016)	6.0 (2005) 11.6 (2008)	22.5 (2005) 28.7 (2017)	30.0 (2008) 33.3 (2012)
Management activities	Ditched, conversion to commercial forest with subsequent production cycle (e.g. thinning, fertilization, etc.)	Ditched, conversion to commercial forest with subsequent production cycle (e.g. thinning, fertilization, etc.)	Ditched, subsequent production cycles	None
Changes in hydrology due to ditch construction	Decreasing water table	Decreasing water table	Water table dependent on precipitation	Slight fluctuations in water table depth
Successional stage	Plantation stage	Plantation stage	Plantation stage	Natural stage
Structural attributes				
<i>Stand type</i>	Pine plantation	Pine plantation	Pine plantation	Natural hardwood
<i>Age (years, as of 2018)</i>	7*	8*	28*	>100
<i>Measurement period</i>	2013 – 2018	2005 – 2011	2005 – 2018	2009 – 2018
<i>Year of most recent harvest</i>	2012	2004	1992	Undisturbed
<i>Major species</i>	<i>Pinus taeda</i>	<i>Pinus taeda</i>	<i>Pinus taeda</i>	<i>Nyssa sylvatica</i> , <i>Nyssa biflora</i> , <i>Taxodium distichum</i> , <i>Acer rubrum</i> , <i>Liquidambar</i> <i>styraciflua</i> , pond pine
Soil type	Belhaven series (loamy, mixed, with highly decomposed organic matter layer underlain by loamy marine sediments)	Cape fear series (slightly higher water holding capacity and a surface loam layer)	Belhaven series (loamy, with highly decomposed organic matter layer underlain by loamy marine sediments)	Pungo series (poorly drained with highly decomposed muck and less decomposed peat layers; underlain by highly reduced mineral sediments)

199 *YP₂₋₇ is young pine 2-7 years of age; YP₂₋₈ is young pine 2-8 years of age; MP is mature pine 15-28 years of age;
 200 and BHF is natural bottomland hardwood forest, >100 years of age.
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2.2 Evapotranspiration measured by the Eddy Covariance System

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206 Following AmeriFlux protocols, latent heat (LE) and sensible (H) flux measurements were
207 made 9.0 m, 11.6 m, 28.7 m, and 33.3 m above the forest floor at YP₂₋₇, YP₂₋₈, MP, and BHF,
208 respectively. These variables were quantified along with the measurements of CO₂ exchange
209 using eddy covariance systems at all sites. An open-path analyzer (consisting of an LI-7500
210 infrared gas analyzer (LiCor, Lincoln, NE, USA), CSAT-3 sonic anemometer (Campbell
211 Scientific (CSI), Logan, UT, USA), or in the case of BHF, a Gill Windmaster (R-350; Gill
212 Instruments, Lymington, UK) was used to measure the ecosystem exchange of CO₂ and CR5000
213 dataloggers for the plantation sites and CR-1000 at the BHF site. The air temperature was
214 derived from sound speed measured by a sonic anemometer and was also obtained using a
215 thermocouple that was used for estimating H. A relative humidity and air temperature sensor
216 (model HMP-45C; Vaisala, Helsinki, Finland) was also installed at the same height as the IRGA
217 to quantify water vapor density.

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2.3 Data quality control and gap-filling

221

222 Following the data processing procedure as in previous studies (e.g., Aguilos et al., 2020;
223 Noormets et al., 2012, 2010; Sun et al., 2011), the 30-minute mean fluxes of H₂O were
224 calculated as the covariance of vertical wind speed and the concentration of H₂O, representing
225 the total water loss, including soil evaporation and canopy interception. Using the Eddypro

226 software (v. 6.1.0) (LICOR Inc, Lincoln, NE, USA), standard quality checks and corrections
227 were applied for spike detection (Vickers and Mahrt, 1997), planar fit coordinate rotation of
228 wind vectors (Wilczak et al., 2001), correction of the time lags between scalar concentrations
229 and wind speed (covariance maximization), air density fluctuation (Webb et al., 1980), and high
230 (Ibrom et al., 2007) and low pass filtering (Moncrieff et al., 2004). We flagged as 0 (high
231 quality), 1 (medium quality), and 2 (low quality) flux outputs (Mauder and Foken, 2006). Fluxes
232 with flags greater than 1 were discarded. Other sources of error and data losses were attributed to
233 low friction velocity, power losses, and instrument malfunction. After all data quality checks and
234 gap-filling procedures had been performed, the final data coverage of quality-controlled LE was
235 93 % for YP₂₋₇, 94 % for YP₂₋₈, 94 % for MP, and 97 % for BHF. Remaining gaps were filled
236 using empirical correlations between observed ET and grass reference evapotranspiration
237 calculated by the FAO Penman-Monteith method. Obvious outliers were removed on a 30-
238 minute timescale. For example, data points with $LE > 800 \text{ W m}^{-2}$ or $LE < -200 \text{ W m}^{-2}$ were
239 removed. For missing monthly precipitation data, we obtained the nearest US. Weather Service
240 station data or the automated or manual back-up rain gauge installed near the flux towers. The
241 total 30-min ET was converted from latent heat flux, LE (W m^{-2}) by the formula: $ET = LE \times$
242 $(0.01800/44000) \times 3600 \times 0.5$ (Sun et al., 2010). Daily ET was the sum of 30-min ET.

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244

245 *2.4 Other micrometeorological measurements*

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247 Additional micrometeorological parameters measured above the canopy at all sites included
248 photosynthetically active radiation (PAR, LI-190, LiCor Inc.), net radiation (CNR-1 and CNR-4,

249 Kipp & Zonen, Delft, the Netherlands), and precipitation (TE-525, Campbell Scientific Inc.,
250 Logan, UT, USA). Mean soil volumetric water content was measured for the top 30 cm using a
251 vertically inserted CS616 time domain reflectometry probe (Campbell Scientific Inc.). The depth
252 of the water table was monitored using ultrasonic water level datalogger (Infinites, Port Orange,
253 FL, USA). To compare across sites and to remove the influence of soil texture on soil water
254 content, drought intensity was quantified in the form of relative extractable water (REW) (Vicca
255 et al., 2012; Domec et al., 2015):

256

$$257 \quad REW = \frac{SWC - SWC_{wp}}{SWC_{fc} - SWC_{wp}} \quad (1)$$

258

259 where SWC is soil water content (SWC), and SWC_{wp} is the SWC at wilting point. The maximum
260 extractable water over the entire rooting zone is equal to SWC at field capacity (SWC_{fc}) less
261 SWC_{wp} . Soil texture was identified at the four sites, and SWC_{fc} and SWC_{wp} were obtained from
262 soil water estimates by texture and organic matter content (Saxton and Rawls, 2006). Anomalous
263 drought years were determined using an ecological drought indicator, the soil water stress index
264 (SWSI) (Granier et al., 1999), computed as the difference between the daily REW and 0.4 (a
265 threshold that induces stomatal closure in most trees), divided by 0.4.

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268 *2.5 The water balance equation*

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270 A simplified monthly and annual water balance equation for the study sites was developed as:

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272
$$P = ET + D + \Delta S$$

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274 where P is precipitation (mm), ET is ecosystem evapotranspiration (mm) that includes soil
275 evaporation, canopy interception or wet canopy evaporation and plant transpiration (i.e., dry
276 canopy transpiration); D is drainage (i.e., surface and shallow groundwater flowing out of the
277 watershed) (mm); and ΔS represents the change in water storage (mm) in both the unsaturated
278 and saturated soil zones.

279

280 The measured eddy fluxes are interpreted as representing the total ecosystem
281 evapotranspiration (ET) that includes both plant transpiration and evaporation from soil and plant
282 surfaces.

283

284 Change in storage (ΔS) was derived from change in water table depth at a monthly scale:

285

286
$$\Delta S = \Delta SWC \times WTD + \Delta WTD \times \theta_d$$

287

288 where SWC is the soil water content for the unsaturated zone measured at a soil depth of 30 cm,
289 WTD is the water table depth at the beginning the month, ΔWTD is the change in the water table
290 for the month, and θ_d is the drainable soil porosity (Sun et al., 2010). Drainage (D) was then
291 calculated as residuals after deducting ET and change in storage term from precipitation.

292

293
$$D = P - ET - \Delta S$$

294

295 P and ET were summed 30-minute data and compiled as daily, monthly or annual sums. D and
296 ΔS were derived monthly. It must be noted that systematic drainage system was constructed for
297 the managed plantation sites whereas the natural forest depended mostly on natural drainage
298 processes driven by local (shallow) topographic relief. Thus, the ‘ditching effect’ at the managed
299 sites is partially reflected in D as derived from the water balance equation.

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302 *2.6 Grass reference evapotranspiration (ET_0)*

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304 Grass Reference ET (ET_0) represents actual ET for a standard grass with a fixed leaf area
305 index and canopy conductance and without soil water stress (Allen et al., 1998). It was calculated
306 by the FAO (Penman-Monteith) method. ET_0 is controlled by atmospheric factors and offers a
307 convenient variable to compare actual forest ET across sites. In this study, ET_0 data were
308 obtained from the North Carolina State University climate database system at research stations
309 near our study sites. For the managed sites, we used the ET_0 data obtained from Tidewater
310 Research Station at Plymouth, NC. ET_0 data from Pamlico Aquaculture Field Laboratory in
311 Aurora, NC, was used for the BHF site since it was located in the same coastal setting.
312 Considering the completeness of data, we used turfgrass ET_0 from both field stations. Daily ET_0
313 were summed to derive monthly and annual ET_0 .

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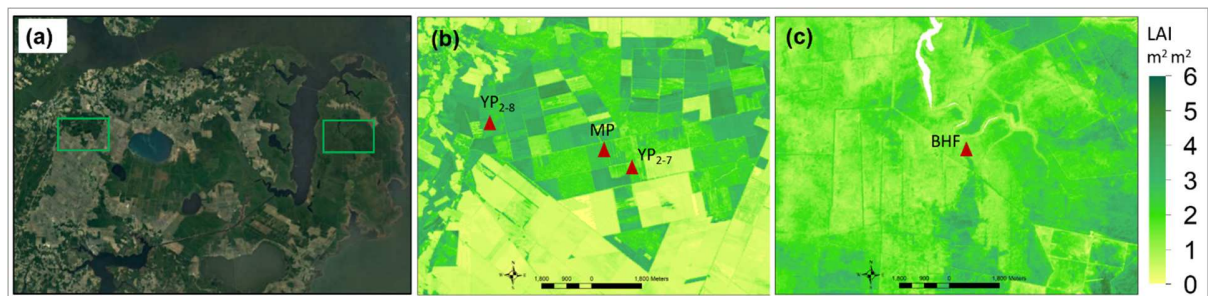
316 *2.7 Data analyses*

317 We used generalized additive models (GAMs) to explore the relationships of ET to climatic
318 variables such as net radiation (R_n), air temperature (T_{air}), relative extractable water (REW),

319 albedo, precipitation (P), and gross primary production (GPP; Aguilos et al., 2020). Leaf area
320 index (LAI) data were derived using two sources: 1) Landsat-scale LAI (Supplemental Fig. 1)
321 retrieved from Landsat shortwave surface reflectance data using MODIS LAI products as
322 reference using a regression tree analysis following the method developed in Gao et al., (2012);
323 2) A regression model developed from Albaugh et al., (2014) using LAI and basal area for pine
324 stands across the US Southeast, ranging from 3 to 14 years of age. We then used the resulting
325 regression equation to compute the LAI from YP₂₋₇, YP₂₋₈, and MP. We extended the equation
326 up to age 28 by adding data from the MP site. The basal area in 2013 at YP₂₋₇ (seedlings) was
327 considered negligible while missing LAI in 2014 and 2018 were filled using the stand age-LAI
328 regression equation obtained from years with available annual LAI computed for this site.

329

330



331

332 *Supplemental Figure 1. A sample of LAI images taken on November 16, 2016. Panel (b) is an*
333 *enlarged image of the green box on the left side of the panel (a), which shows the managed*
334 *plantations (YP₂₋₇, YP₂₋₈, and MP). The enlarged image of the green box on the right side of the*
335 *panel (a) is the natural forest (BHF) as shown in panel (c).*

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338

339 To predict the best drivers among climatic and biological variables, we built GAM models
340 with spline smoothers. To build the statistical models, we used the *mgcv* package, and used the
341 *MuMin* package to obtain the best smoothing dimension (Aguilos et al., 2018; Leonardi et al.,
342 2015; Shao et al., 2015). We used the Tukey HSD Test for inter-site comparison. Smoothed-
343 curve fitting and linear relationships were carried out with a locally weighted linear or
344 polynomial regression in the *ggplot2* package. All analyses were processed in R version 4.0.2 (R
345 Core Team, 2020).

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348 **3. Results**

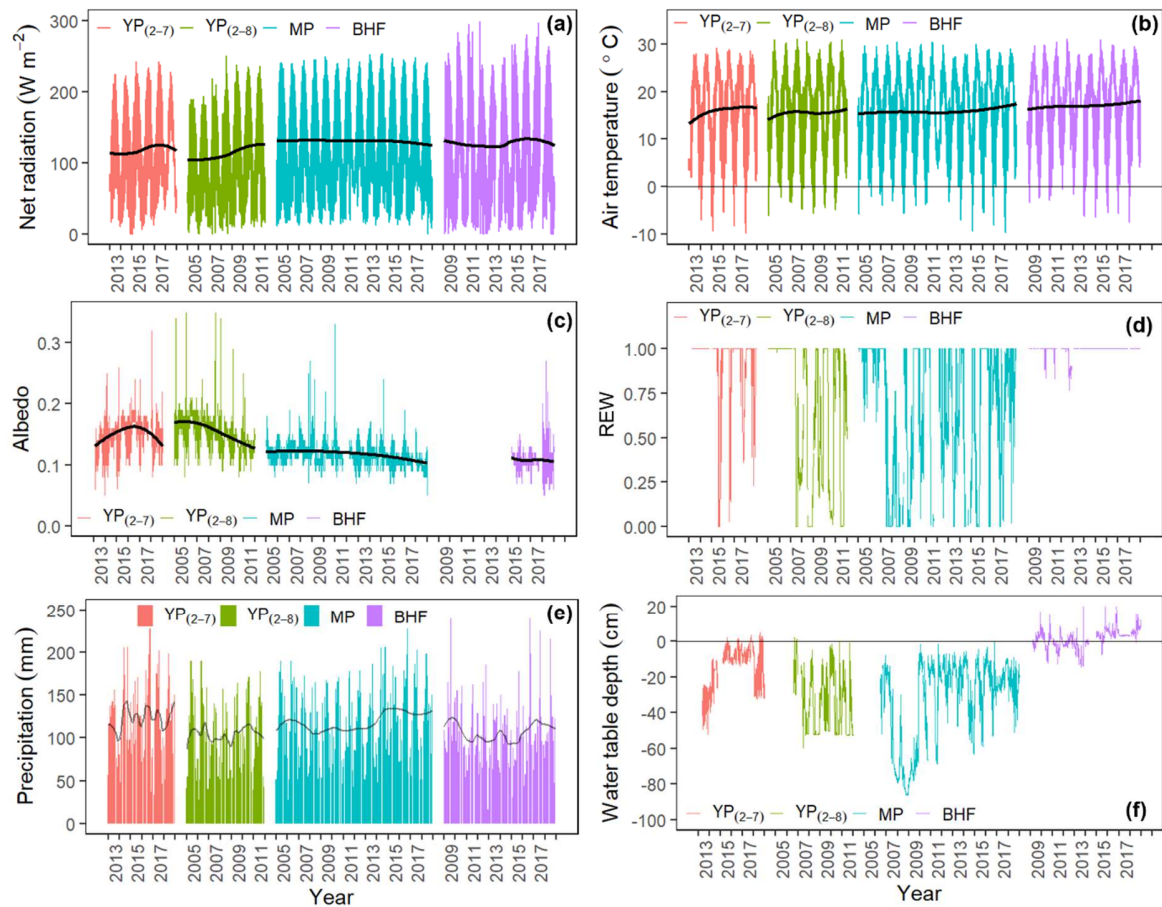
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350 *3.1 Micrometeorology, soil water, and water table depth*

351 Daily average micrometeorological data across the measurement periods (Fig. 2) revealed that
352 MP received higher net radiation (Rn) with a daily mean of 130 Wm^{-2} which was 10 – 14 %
353 higher than YP₂₋₇ (118 Wm^{-2}) and YP₂₋₈ (114 Wm^{-2}), respectively. This pattern was opposite to
354 that of albedo. MP had an albedo of 0.11, whereas YP₂₋₇ and YP₂₋₈ both had a higher value
355 (0.15). Interestingly, both MP and BHF had similar albedo (0.11) and Rn (130 Wm^{-2}) values.

356 Daily variation in REW and WTD indicate that the younger plantations had slightly
357 wetter soils than MP (Fig. 2 d, f). Annual precipitation (P) varied from 1282 – 1488 mm across
358 all sites and years. Annual average air temperature ranged from $\sim 15 - 18 \text{ }^\circ\text{C}$ at all sites and
359 followed a similar pattern to Rn, where seasonal highs (growing season) and lows (non-growing
360 season) were prominent throughout the study period (Fig. 2).

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366 *Figure 2. Daily variation of climate variables: (a) Net radiation, (b) Air temperature, (c) Albedo,*
 367 *(d) Relative extractable water (REW), (e) Precipitation, and (f) Water table depth. Each site was*
 368 *assigned with different vertical line colors. Thick horizontal lines are the smoothed curves.*

369 *Values are daily averages except for precipitation, where monthly sums were used in a bar plot.*
 370 *For interpretation of the references to color in the figure legend, the reader is referred to the*
 371 *web version of this article.*

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374 3.2 Water balances

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376 3.2.1 Seasonal variation in ecosystem water balance

377

378 Precipitation (P) and ET followed the same seasonal trend across all sites, increasing from
379 winter to spring, with a peak in summer and a gradual decline towards fall (Fig. 3 and
380 Supplemental Fig. 2). High ET during dry seasons indicated that soil water was generally not
381 limiting across sites. Among the managed sites, YP₂₋₈ had the lowest P and ET, while BHF had
382 the lowest P of all sites, especially during the growing season (April to August). However, the
383 capacity to release water through ET during the same period exceeded that of the young
384 plantations (Fig. 3).

385

386 Drainage (D) in young managed plantations was higher than MP and was relatively stable
387 year-round (Fig. 3). However, the seasonal fluctuations in D at BHF were pronounced, being
388 very low during the growing season (April to July), compared to the plantation forests. Yet, D at
389 the BHF site also exceeded D at the managed sites from September to December (Fig. 3),
390 suggesting lower ET in the BHF when deciduous trees dropped their leaves in the Fall.

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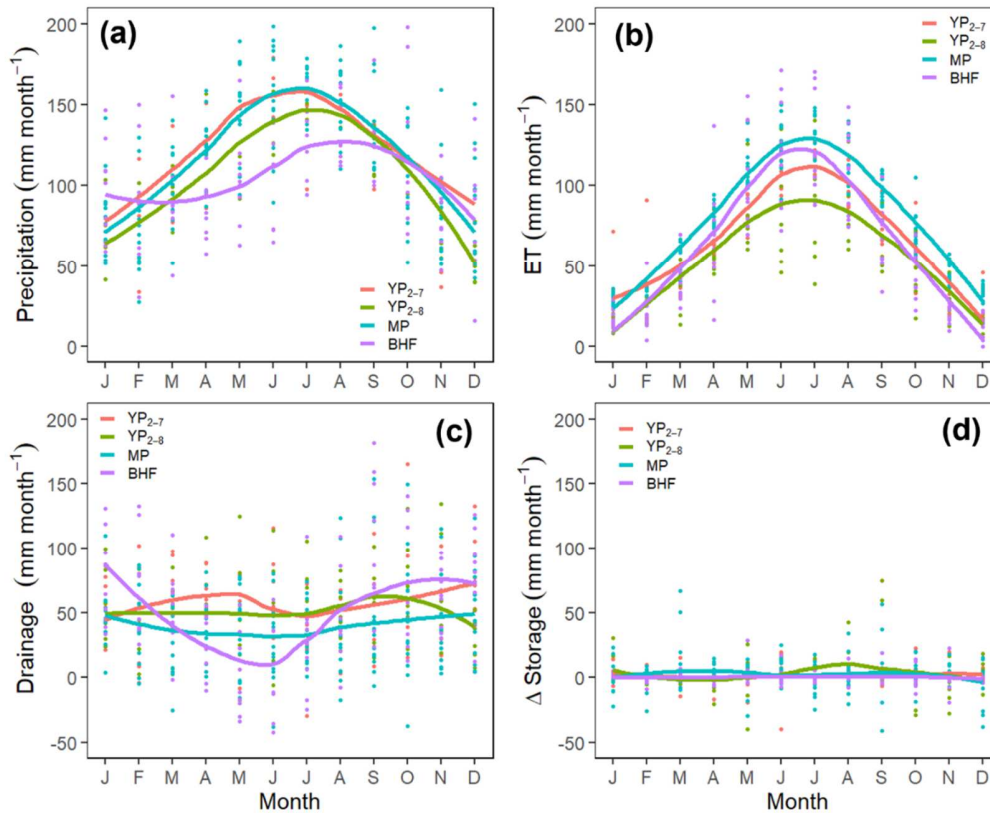
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406 *Figure 3. Seasonal variability in the water balance parameters of precipitation (P),*
 407 *evapotranspiration (ET), drainage (D), and change in soil water storage (ΔS) at YP₂₋₇, YP₂₋₈,*
 408 *MP, and BHF sites across the measurement period. Monthly data each year is represented by*
 409 *different colored circles. A thick solid line denotes the smoothed curves of each site.*

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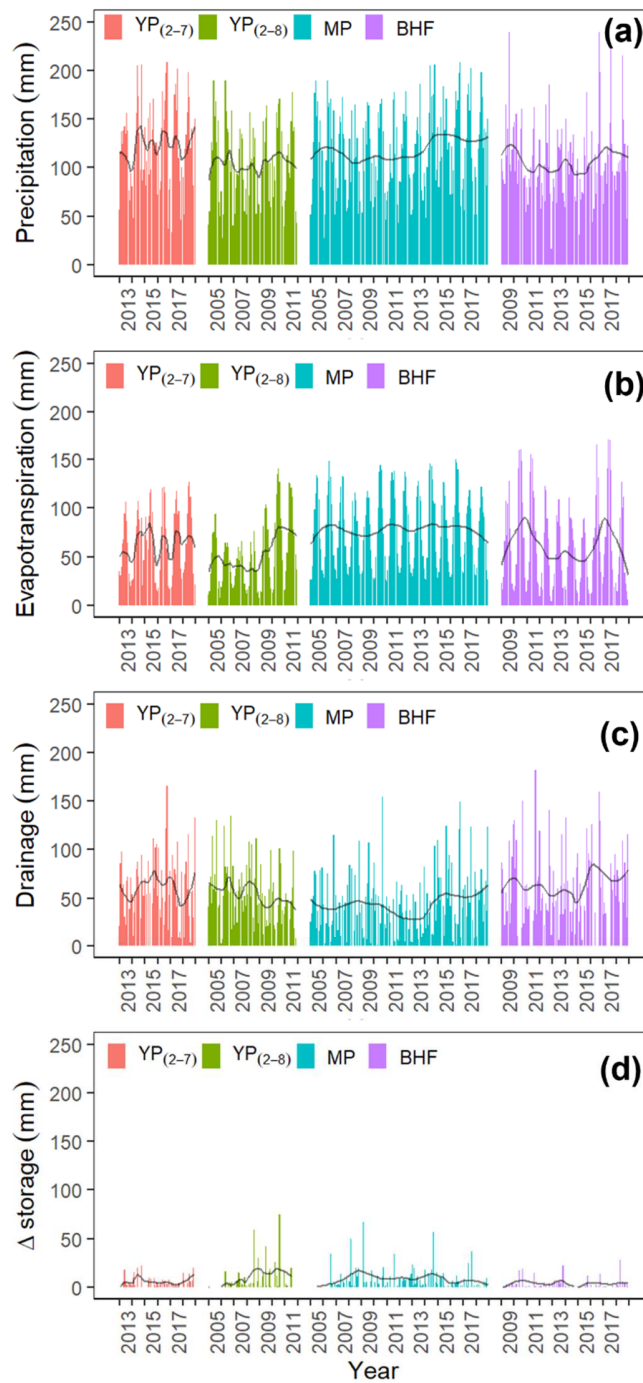
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420 *Supplemental Figure 2. Monthly trend in water balance parameters of precipitation (P),*
 421 *evapotranspiration (ET), drainage (D), and change in soil water storage (ΔS) water balance*
 422 *parameters (P, ET, D, and ΔS) at YP₂₋₇, YP₂₋₈, MP and BHF sites across the measurement*
 423 *period. Color-coded bars were assigned for each site. Trend lines were superimposed using thick*
 424 *curved lines across the measurement period.*

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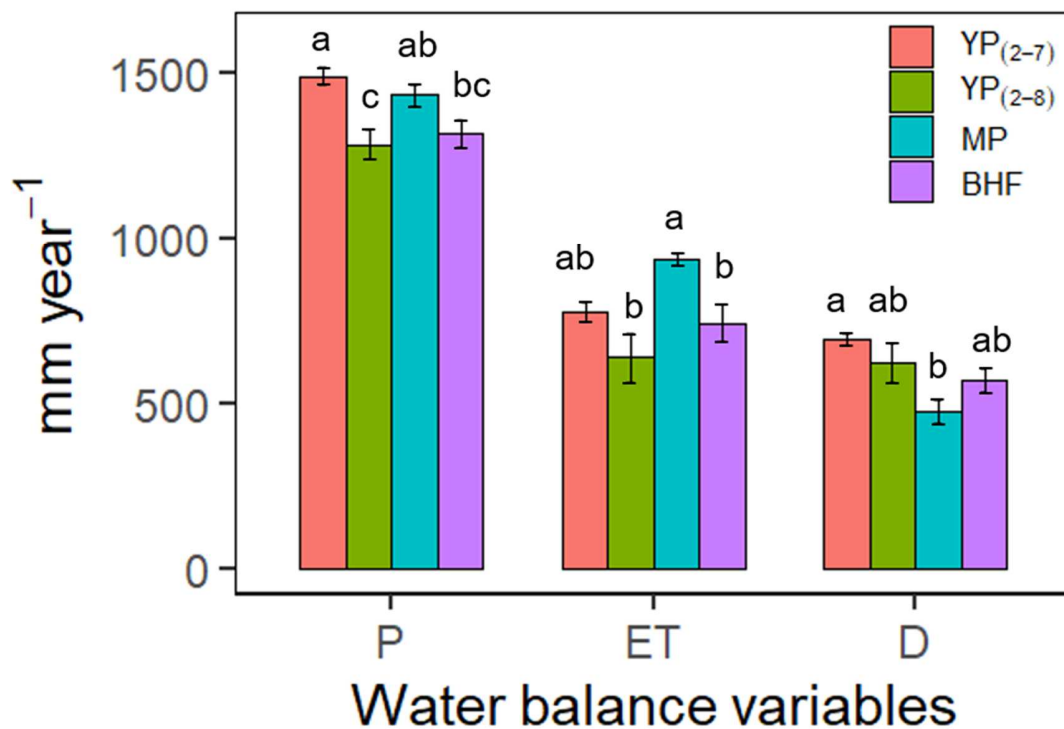
3.2.2 Interannual comparison of water balance

Annual P at managed plantation sites varied by 1 – 7 % within a site inter-annually (Table 2; Fig. 4 and 5). The rainfall amount at YP₂₋₇ and MP was statistically higher than YP₂₋₈ ($p < 0.05$). Precipitation at BHF was only statistically different from the younger forest YP₂₋₇ ($p < 0.05$), but not the other two plantation forests.

The MP site had the highest evapotranspiration with an overall annual average ET of 933 ± 63 mm compared to 776 ± 74 mm, 638 ± 190 mm, and 743 ± 172 mm for YP₂₋₇, YP₂₋₈ and BHF sites, respectively (Table 2; Fig. 4). Inter-annual variation in ET among younger managed sites was 1 – 44 % while the least variation occurred at the MP site (1 – 12 %; Fig. 5). Lower ET rates were observed in the first 3 – 4 years after harvest and subsequent plantation re-establishment at YP₂₋₇ and YP₂₋₈. Inter-annual variation in ET at MP was always higher than the younger plantations throughout the measurement period. Among the four sites, the BHF site had the most variation in inter-annual ET (3 – 49 %), compared to P variation at this site of only 2 – 15 %. (Fig. 5). The differences in ET between the managed MP and unmanaged BHF sites were statistically significant ($p < 0.05$).

448 Table 2. Interannual variations in precipitation, grass reference evapotranspiration, actual
 449 evapotranspiration, drainage and change in storage at YP₂₋₇, YP₂₋₈, MP, and the BHF site.

Site	Year	Precipitation (P, mm)	Grass reference ET (ET _o , mm)	Evapotranspiration (ET, mm)	Drainage (D, mm)	Δ Storage
YP ₂₋₇	2013	1380	1042	665	671	44
	2014	1508	1127	770	695	42
	2015	1518	1118	865	647	6
	2016	1533	1210	732	778	23
	2017	1437	1187	773	661	3
	2018	1552	1149	848	702	2
YP ₂₋₈	2005	1335	1059	568	767	0
	2006	1287	1156	513	749	25
	2007	1164	1219	490	627	47
	2008	1188	1194	444	795	-51
	2009	1234	1119	650	473	112
	2010	1505	879	897	570	38
	2011	1263	1037	903	385	-25
MP	2005	1486	1059	917	569	0
	2006	1398	1156	985	382	31
	2007	1305	1219	925	406	-26
	2008	1274	1194	859	382	33
	2009	1304	1119	852	469	-16
	2010	1525	879	949	538	38
	2011	1242	1037	1017	247	-22
	2012	1393	922	934	401	57
	2013	1349	1042	928	368	53
	2014	1585	1127	1049	426	110
	2015	1591	1118	885	730	-24
	2016	1571	1210	1015	538	18
	2017	1464	1187	890	546	28
2018	1552	1149	860	668	24	
BHF	2009	1490	954	720	770	0
	2010	1511	1089	982	516	13
	2011	1344	1107	930	420	-6
	2012	1174	979	606	581	-14
	2013	1173	950	597	556	20
	2014	1232	972	672	569	-9
	2015	1171	998	500	668	3
	2016	1367	1043	824	540	3
	2017	1355	1057	971	388	-5
2018	1345	1015	624	687	34	



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478 *Figure 4. Inter-site comparison of average annual precipitation (P), evapotranspiration (ET),*
 479 *and drainage flow (D) at YP₂₋₇, YP₂₋₈, MP, and BHF sites. Each site is represented by different*
 480 *colored bars. Different letters above each bar denote significant differences among sites ($p <$*
 481 *0.05) using the Tukey HSD test. Error bars indicate \pm SE. Annual data across the measurement*
 482 *period for each site was used.*

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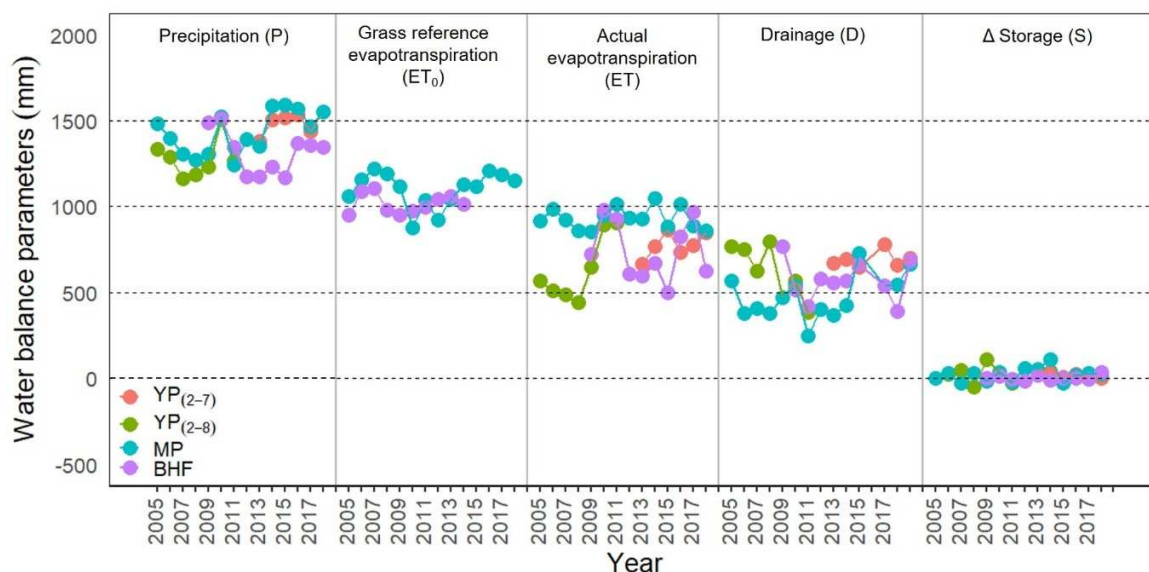
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 491 *Figure 5. Annual average water balance variables, including precipitation (P), reference grass*
 492 *evapotranspiration (ET₀), evapotranspiration (ET), drainage (D), and change in storage (ΔS) at*
 493 *YP₂₋₇, YP₂₋₈, MP and BHF sites. Each site is represented by different colored lines and circles*
 494 *across the measurement period.*

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 499
 500 Annual average drainage (D) in the managed sites ranged from 476 ± 129 mm to 692 ± 47
 501 mm, although young plantations (YP₂₋₇ and YP₂₋₈) drained 148 – 216 mm more water annually
 502 than MP (Fig. 4). D at young plantation sites was 46 – 48 % of overall P. In comparison, only 33
 503 % of P was drained from the MP site. Statistical differences were found between MP and YP₂₋₇
 504 ($p < 0.05$), reflecting the ability of the older pine plantation to release more water through ET
 505 than from D. Meanwhile, D at BHF was 43 % of overall P, amounting to 570 ± 116 mm of D
 506 annually (Fig. 4). Although the natural forest drained 94 mm more than the older pine plantation
 507 (MP), no statistically significant differences in D were found between the BHF and the managed
 508 plantation sites ($P > 0.05$). Ecosystem ET was always higher than D, but it did appear that young

509 plantations tended to drain comparable amounts of water as ET, with an annual difference of 14
510 to 84 mm at YP₂₋₇ and 14 mm at YP₂₋₈. The difference of 457 mm between ET and D at MP
511 illustrates that much more water was released to the atmosphere than drained away. Similarly,
512 BHF also had higher ET, 743 mm, compared to D, at 570 mm. The ΔS among sites did not
513 vary ($P > 0.05$). Interannual variation in S was only -51 mm to 110 mm (Fig. 5).

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516 3.3 *ET₀/P, ET/P, D/P, and ET/ET₀ ratios*

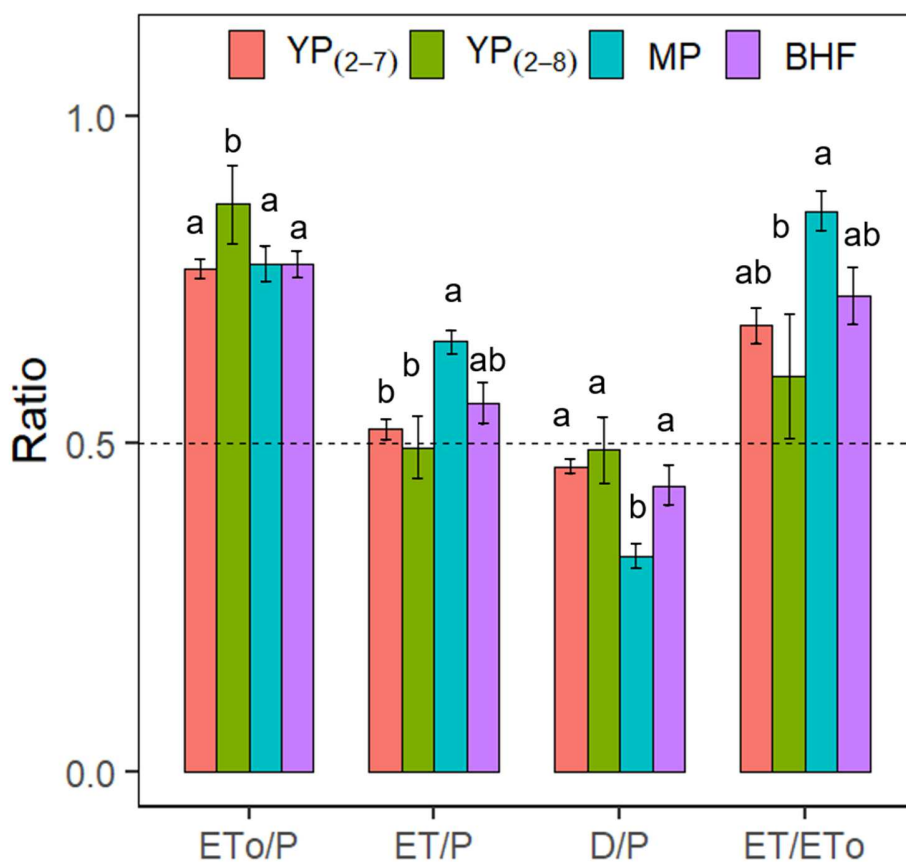
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518 MP had the highest ET₀/P ratio (0.87) that was significantly higher than the young plantations
519 and BHF, which had similar ET₀/P ratios (~0.77; Fig. 6). The annual ratio ranged from 0.58 to
520 1.02 at all sites (Fig. 8). ET₀ exceeded P only twice at YP₂₋₈ in 2007 and 2008. Overall mean
521 ET/P ratio varied from 0.49 – 0.65 among all sites. (Fig. 6). The long-term ET/P ratio at the
522 managed sites was ranked in the order MP > YP₂₋₇ > YP₂₋₈, with an average annual ET/P of
523 0.66, 0.52, and 0.49, respectively. At the BHF site, the annual average ET/P ratio was 0.56.

524

525 D was only about half of P (0.33 ~ 0.49) across all sites throughout the measurement period.
526 The lowest D/P occurred at MP, with the amount of D only 1/3 of the amount of P (0.33).
527 Interannually, D/P ranged from 0.26 ~ 0.67 (Fig. 7). Inter-site comparison of annual ET/ET₀
528 shows that only YP₂₋₈ and MP were statistically different (Fig. 6). The highest mean annual
529 ET/ET₀ occurred at MP, averaging 0.86 (ranging from 0.72 – 1.08, Fig. 7). The lowest was
530 observed at YP₂₋₈, at 0.60 but this site had high interannual variability, ranging from 0.37 to
531 1.02. Interannually, ET/ET₀ ratio at YP₂₋₇ ranged from 0.60 to 0.77, and ET and ET₀ were

532 strongly correlated ($R^2 = 0.75$). The correlation of ET to the grass reference ET_0 at MP was $R^2 =$
 533 0.73, but YP_{2-8} had the weakest relationship ($R^2 = 0.34$). Almost 80 % of the variation in ET at
 534 BHF was explained by ET_0 , with an annual average ratio of 0.73. These long-term observations
 535 demonstrate that ET on these coastal plain forests is almost always much lower than the potential
 536 water use of a reference grass.

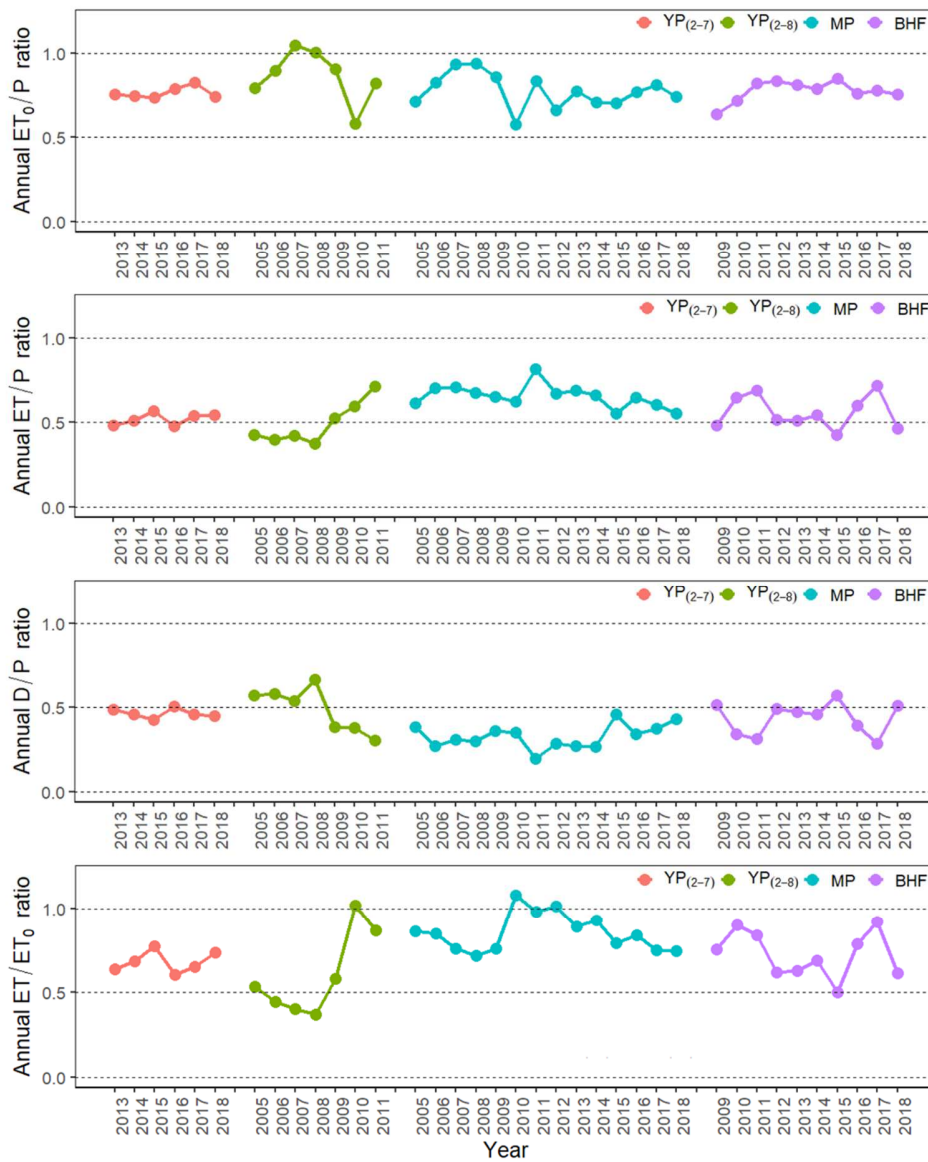


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539 *Figure 6. Inter-site comparison of ET_0/P , ET/P , D/P , and ET/ET_0 at YP_{2-7} , YP_{2-8} , MP, and BHF*
 540 *sites. Each site is represented by different colored bars. Different letters above each bar denote*

541 *significant differences among sites ($p < 0.05$) using the Tukey HSD test. Error bars indicate \pm*
 542 *SE. Based on annual data spanning the entire measurement period for each site.*
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550 *Figure 7. Interannual variation of ET_0/P , ET/P , D/P , and ET/ET_0 at YP_{2-7} , YP_{2-8} , MP , and BHF*
551 *sites across the measurement period. Thin color-coded lines per site connect monthly data.*

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555 *3.4 Effect of drainage and land-use change on water balance*

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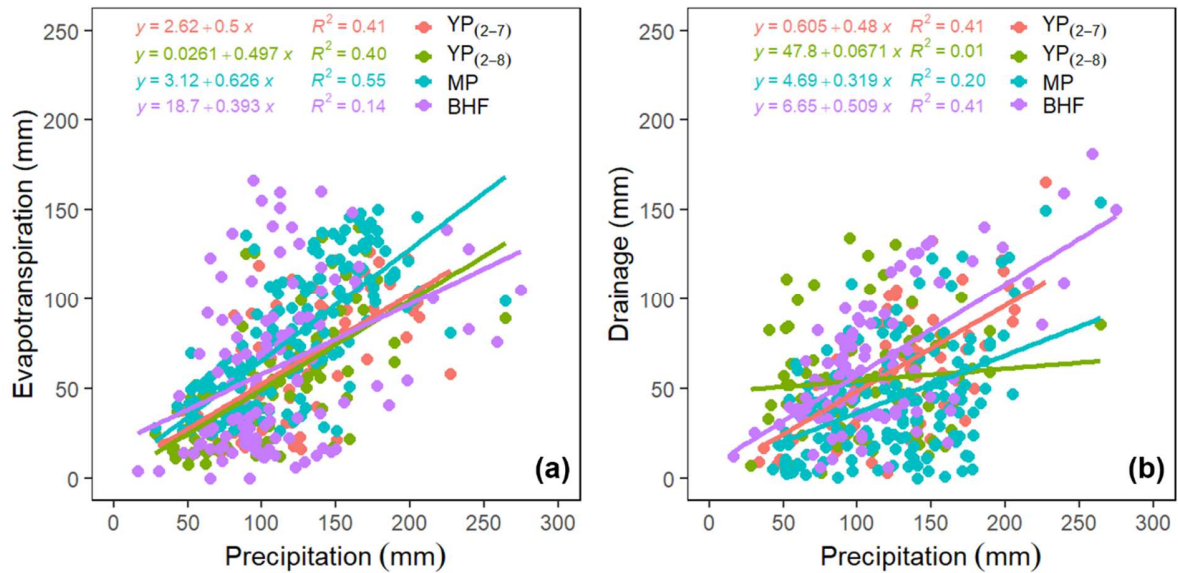
557 The present study found that 49 % – 65 % of P was lost to the atmosphere through ET, while
558 33 % – 48 % of P was removed through D in managed sites. The plantation sites had no apparent
559 difference with BHF site ($p < 0.05$; Fig. 4) in this regard, where 56 % and 43 % of P was lost
560 through ET and D, respectively. Although annual D in young managed plantations was
561 comparable with that of the natural forest, D at the MP site was the lowest among all sites.

562

563 We found a direct linear relationship between P and ET across managed sites ($R^2 = 0.40 -$
564 0.55) and a weaker relationship at the BHF site ($R^2 = 0.14$), suggesting a more pronounced
565 coupling of ET and P at the managed sites than in natural forest (Fig. 8). We also found that P-D
566 relationship in the YP_{2-7} and BHF sites were similar ($R^2 = 0.41$), and the relationship was
567 stronger than at the MP site ($R^2 = 0.20$), suggesting higher drainage occurred at relatively wetter
568 sites than in the mature plantation (Fig. 8).

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573 *Figure 8. Relationships between (a) P and ET and (b) P and D at YP₂₋₇, YP₂₋₈, MP, and BHF*
 574 *sites. Each circle indicates a monthly data colored according to the site. The colored lines*
 575 *indicate linear regression line.*

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578 3.5 Effect of stand age on ET

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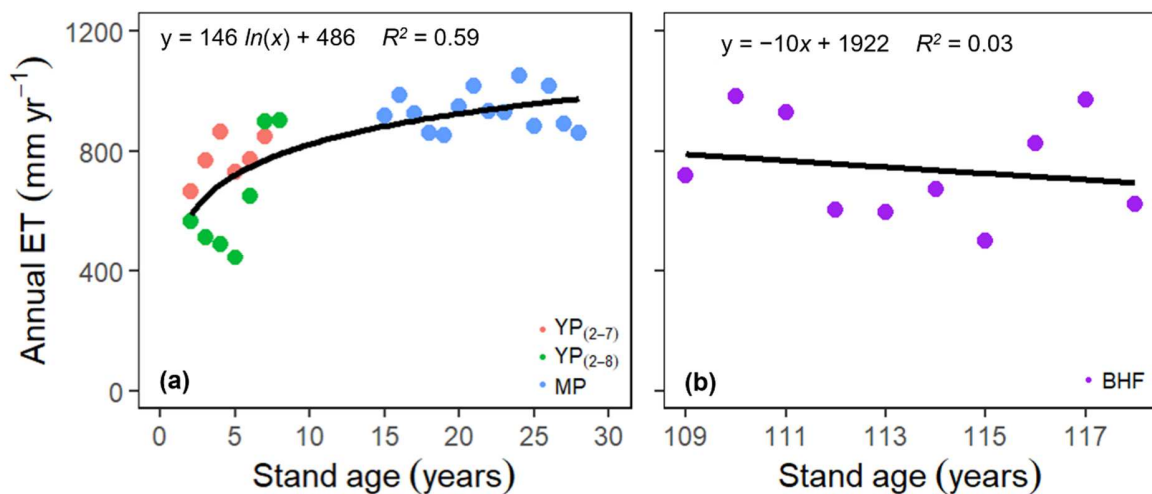
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581 ET increased with stand development of plantation forests (Fig. 9). ET correlated well with
 582 stand age ($R^2 = 0.59$), increasing rapidly from stand initiation stage (YP₂₋₇ and YP₂₋₈) to around
 583 10 years of age and then more slowly afterward. The stand age-ET relationship followed a
 584 similar trend of stand age-LAI relationship, with $R^2 = 0.57$ using the remotely sensed LAI, and
 585 $R^2 = 0.40$ using a ground-based regression model (Fig. 10). Annual average LAI at YP₂₋₇, YP₂₋₈,
 586 and MP sites was 1.46, 2.63, and 3.00, respectively, using the remotely-sensed LAI and 2.02,

587 1.55, and 2.55, respectively, using the ground-based regression equation (Supplemental Table 1).
 588 ET-LAI relationship is a little weaker with $R^2 = 0.27$ using the remotely sensed LAI and $R^2 =$
 589 0.46 using the ground-based regression model. In both LAI derivation cases, a sudden decline in
 590 LAI at 20 years old occurred due to thinning operations done during this year. After thinning,
 591 LAI gradually increased and slowly stabilized 3 – 5 years later (Fig. 10). BHF was a mature
 592 stand over the observation period with little change in LAI, averaging 2.30, and ranging from
 593 2.12 to 2.61 using remotely-sensed LAI data (Supplemental Table 1). Inter-annual variation in
 594 ET at the BHF site was, therefore, primarily driven by environmental factors.

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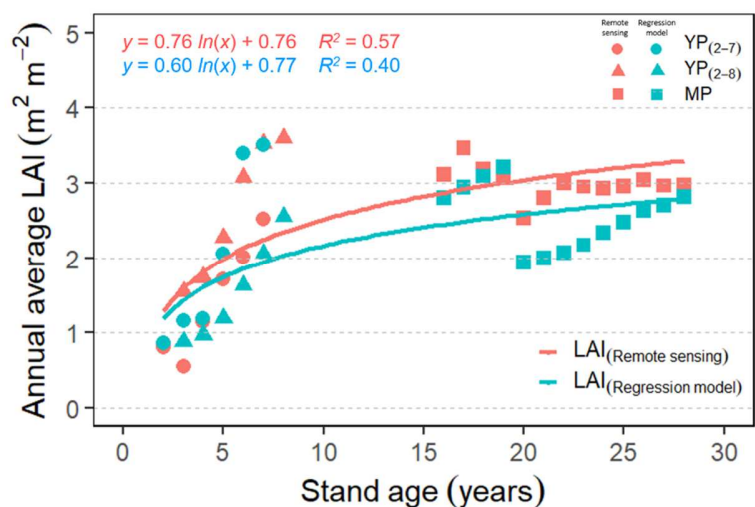
599 *Figure 9. Relationship between stand age and annual evapotranspiration (ET) at (a) managed*
 600 *sites and (b) BHF site. Each circle indicates an annual ET ratio colored according to the site.*
 601 *The black curve indicates the regression line.*

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608 *Figure 10. Relationship between stand age and annual average leaf area index (LAI) using*
609 *remote sensing and ground-based regression equation at YP₂₋₇, YP₂₋₈, and MP sites.*

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613 *Supplemental Table 1. Leaf area index (LAI) derived from remotely-sensed data from Landsat*
614 *available for the managed sites (YP₂₋₇, YP₂₋₈, and MP) and natural forest (BHF) and LAI*
615 *obtained from ground-based regression model only available for the managed sites.*

616

Year	YP ₂₋₇		YP ₂₋₈		MP		BHF	
	Remote sensing	Regression model	Remote sensing	Regression model	Remote sensing	Regression model	Remote sensing	Regression model
2005								
2006			1.54	0.88	3.12	2.80		
2007			1.74	0.97	3.46	2.94		
2008			2.27	1.19	3.18	3.09		
2009			3.07	1.63	3.08	3.21	2.41	
2010			3.53	2.06	2.53	1.93	2.61	
2011			3.60	2.55	2.80	2.00	2.27	
2012					3.00	2.06	2.28	
2013	0.81	0.86			2.95	2.17	2.24	
2014	0.55	1.15			2.93	2.33	2.12	
2015	1.14	1.19			2.96	2.47	2.35	
2016	1.72	2.06			3.04	2.63	2.35	
2017	2.01	3.40			2.96	2.70	2.15	
2018	2.51	3.51			2.97	2.81	2.16	

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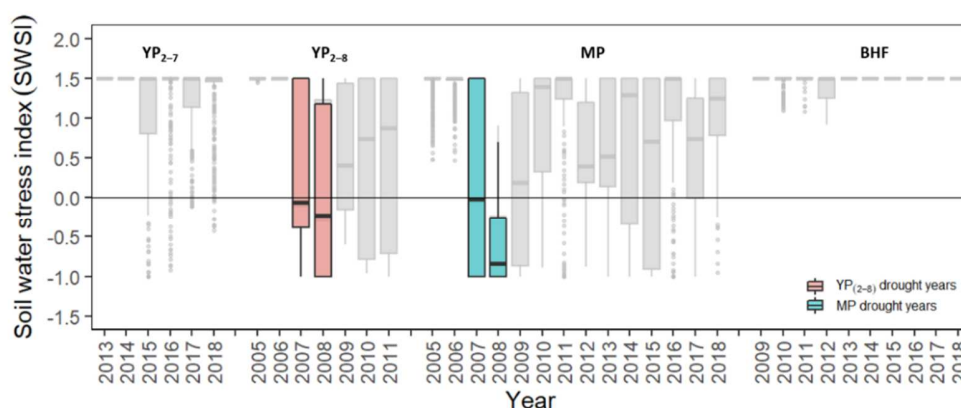
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619 3.6 Drought effects on ET

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621 In general, the SWSI was well above 0 at all sites for most years of the study, indicating these
622 lower coastal plain forests typically experienced very mesic conditions (Fig. 11). However, the
623 years 2007 and 2008 were exceptionally dry, as indicated by the daily SWSI median values
624 falling below 0 at YP₂₋₈ and MP (the only sites with data for those years), which means REW
625 levels were below 0.4, the threshold where plants suffer stress. During these years, the water
626 table depth dropped to 50 to 80 cm below the soil surface (Fig. 2). During drought periods, we
627 found an 8 – 11 % reduction in annual P at YP₂₋₈, with 1164 mm and 1188 mm in 2007 and
628 2008, respectively, compared to the long-term mean of 1282 mm. Annual ET declined by 30 –
629 43 % at YP₂₋₈ during this time, suggesting that ET responded proportionately greater than P (2-3
630 times the decrease).

631



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634 *Figure 11. Interannual variation in soil water stress index (SWSI). Daily SWSI values were used*
635 *during the measurement period at YP₂₋₇, YP₂₋₈, MP, and BHF sites. Drought years were*
636 *characterized by having an SWSI median falling below zero. These drought events occurring in*
637 *2007 and 2008 were highlighted with red color boxes for YP₂₋₈ and blue for the MP site. In the*

638 *box plot, the thick horizontal line shows the median, and the box extends to the upper and lower*
639 *quartiles, vertical dashed lines indicate the nominal range, open circles indicate points that lie*
640 *outside of the nominal range. SWSI at 0 indicates that REW = 0.4 (threshold value). The greater*
641 *SWSI above 0, the lower is the stress level.*
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645 A similar magnitude in P reduction was observed at MP (10 – 12 %) during the severe
646 drought of 2007/2008. Annual P was 1305 mm in 2007 and 1274 mm in 2008, which was 126
647 mm and 158 mm lower, respectively, than the long-term mean of 1431 mm. However, ET was
648 much higher at MP compared to YP₂₋₈, and the reduction in ET due to the drought was less
649 severe (1 – 9 %), possibly due to the older forest having greater stem capacitance and deeper
650 roots than the younger forest.

651

652 The drought was even more intense when only considering the growing season (June –
653 August) of 2007 and 2008, rather than the average growing season P over the entire
654 measurement period. YP₂₋₈ experienced a 15 – 26 % reduction in growing season P, representing
655 39 mm – 73 mm difference from the overall mean growing season P, while it decreased 7 – 26 %
656 at the MP (23 mm – 94 mm difference). We observed that the annual average available soil water
657 at YP₂₋₈ was REW = 0.49 and at MP REW = 0.40, both at the drought threshold, whereby trees
658 induce stomatal closure. At YP₂₋₈, the number of days where REW fell below the threshold of
659 0.40 was 179 in 2007 and 200 in 2008. MP had soil water content lower than the REW drought
660 threshold for 188 and 258 days in 2007 and 2008, respectively. The water table depth fell below
661 50 cm and was generally much lower than in other years during these drought periods.

662

663

664 The Generalized Additive Modeling (GAM) with the climatic factors R_n , T_{air} , water table
665 depth, albedo, and REW, and the biological control of gross primary production (GPP), revealed
666 that the combined effect of these variables ranked $R_n > \text{albedo} > \text{GPP} > T_{air} > \text{REW} >$
667 precipitation explaining 91 % of the variation in ET at YP_{2-8} during the drought period in
668 2007/2008. At MP, the predictors were ranked $R_n > \text{GPP} > T_{air} > \text{REW} > \text{albedo} >$
669 precipitation, with their combined effects explaining 88 % of the variation in ET. Light
670 availability was the best predictor of ET at both sites, with albedo the second key predictor at
671 YP_{2-8} . YP_{2-8} maintained the same amount of ET at albedo ranging from 0.10 – 0.20, whereas ET
672 declined as the albedo increased at MP within the range of 0.10 – 0.15. Maintaining high ET at
673 higher albedo during drought suggests that when the reflectance is high, the younger plantation
674 still loses significant amounts of water to the atmosphere. In contrast, the older plantation was
675 less responsive to an increase in albedo, suggesting that the mature forest better-conserved soil
676 water as the reflectance was getting higher. Surprisingly, neither REW nor precipitation held the
677 primary key to variation in ET during drought years when combined with other explanatory
678 variables, indicating the significant effect of other climatic or biological factors.

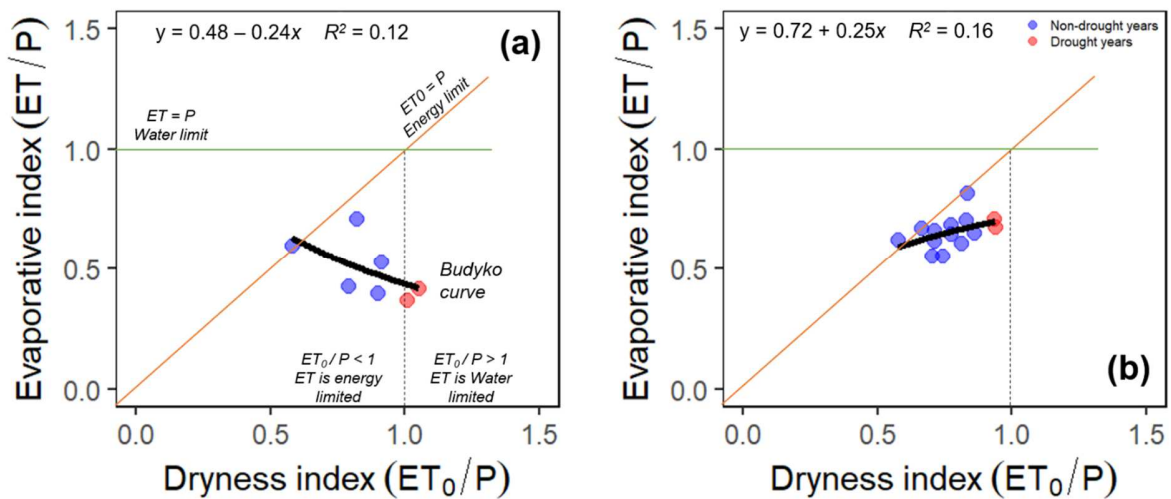
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680 We further analyzed the effect of the drought on ET using the Budyko framework, which
681 is widely used in hydrological studies (Budyko, 1974; Tor-ngern et al., 2018). The Budyko curve
682 is the relationship between the potential evapotranspiration (herein we use the grass reference
683 evapotranspiration, ET_0) and actual evapotranspiration (ET), each normalized by precipitation
684 (P). The Budyko curve is partitioned to conditions in which ET is limited by energy supply
685 ($ET_0/P < 1$), regulated by net radiation and vapor pressure deficit, or by water supply ($ET_0/P > 1$),
686 controlled by vegetation (canopy interception) and soil water storage. The larger the ET_0/P ratio,

687 the less P contributes to water yield. This analysis showed a weak negative response of ET/P
 688 with ET_0/P ($R^2 = 0.12$) at YP₂₋₈ (Fig. 12), wherein the evaporative index tended to decrease with
 689 the severity of dryness. In the case of MP, the severe 2007/2008 drought did not cause the
 690 rotation-age plantation to become water-limited.

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694 *Figure 12. The Budyko curves derived using annual data from YP₂₋₈ (a) and MP (b). Green and*
 695 *red lines show physical boundaries of the curve where dryness index (ET_0/P) increases with the*
 696 *evaporative index (ET/P) over the energy-limited region and where ET/P is independent of ET_0/P*
 697 *over the water-limited region. The blue circles correspond to non-drought years and red*
 698 *circles for drought years (2007 and 2008).*

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703 3.7 The ET-GPP relationship during drought period

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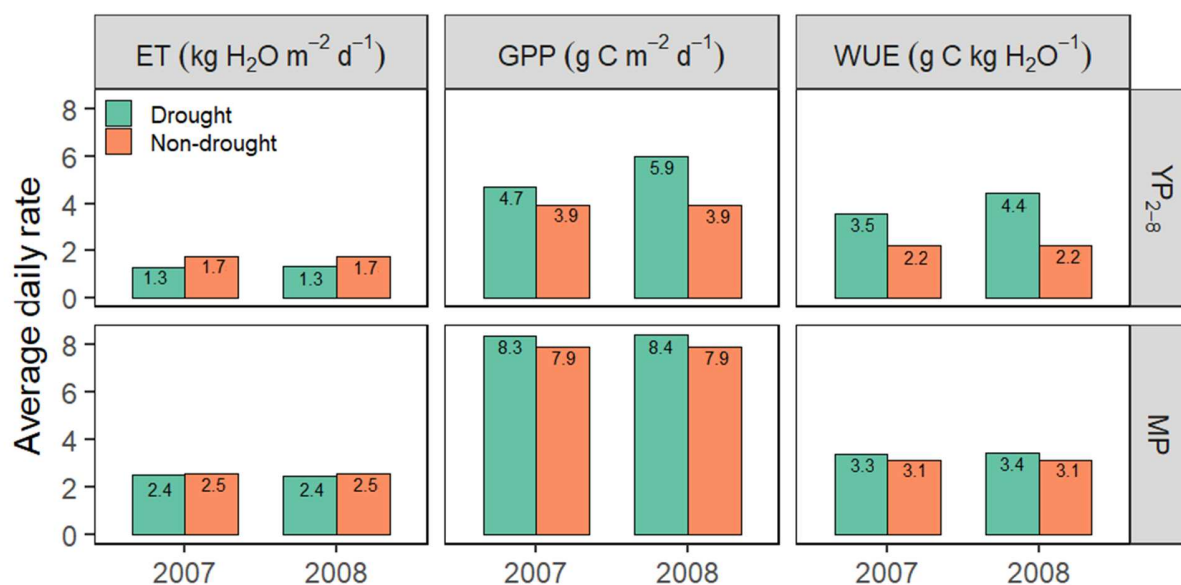
705 During the 2007/2008 drought period, we found a 6 – 9 % enhancement in GPP at the MP site

706 while the YP₂₋₈ site had 20 – 53 % increase (Fig. 13). In contrast, we found a slight reduction in

707 ET at YP₂₋₈ (30 – 43 %) and MP (8 – 11 %) thereby a higher water use efficiency (WUE) during
 708 drought period (Fig. 13). This inverse increase in GPP and reduction of ET during drought
 709 suggests a decoupling of ET and GPP during extreme dry conditions. The positive linear
 710 relationship between ET and GPP at MP and YP₂₋₈ sites during the drought period were
 711 relatively similar (Fig. 14). However, ET at YP₂₋₈ was sharply reduced, whereas GPP was not.

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717 *Figure 13. The average daily rate of evapotranspiration (ET), gross primary productivity (GPP),*
 718 *and water use efficiency (WUE) at the YP₂₋₈ and MP sites during the drought and non-drought*
 719 *periods in 2007 and 2008.*

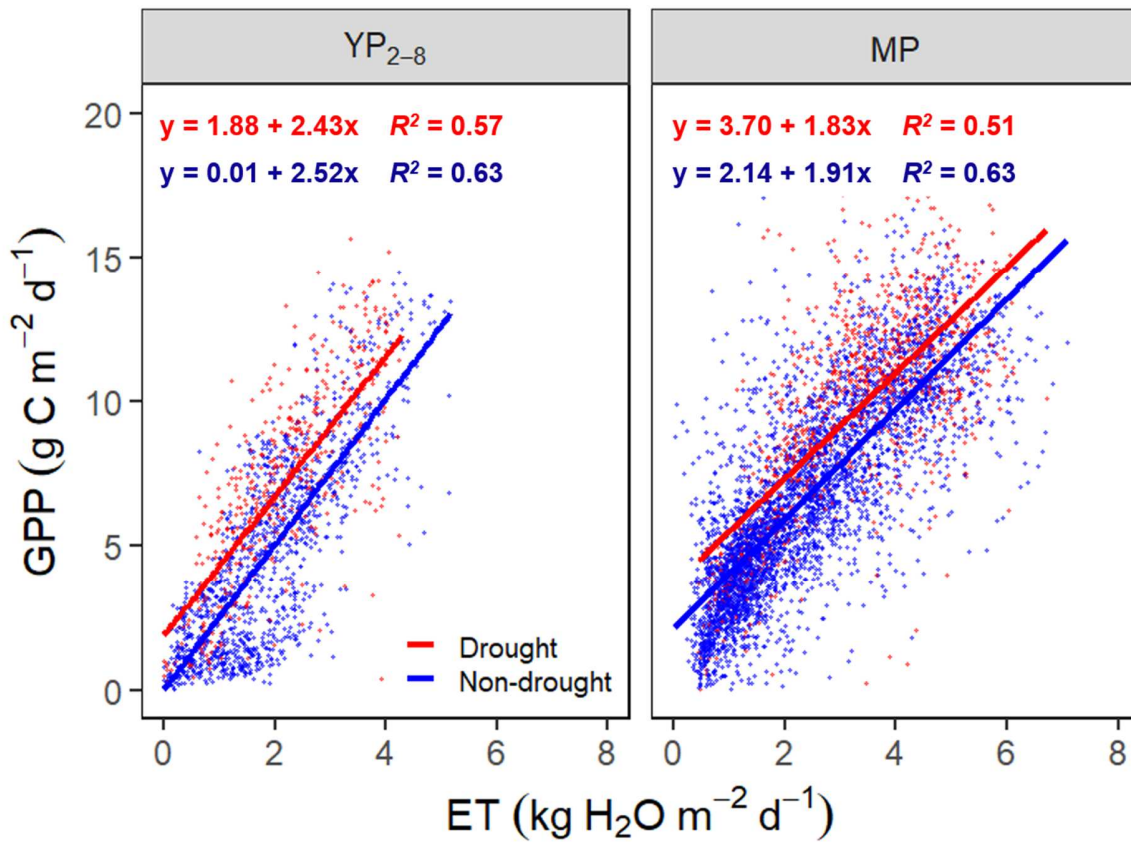
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728 *Figure 14. Relationship between average daily rate of evapotranspiration (ET) and gross*
729 *primary productivity (GPP) at the YP₂₋₈ and MP sites during the drought (red line and text) and*
730 *non-drought (blue line and text) periods in 2007 and 2008.*

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737 **4. Discussion**

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739 *4.1 Seasonal and inter-annual comparisons of site water balance*

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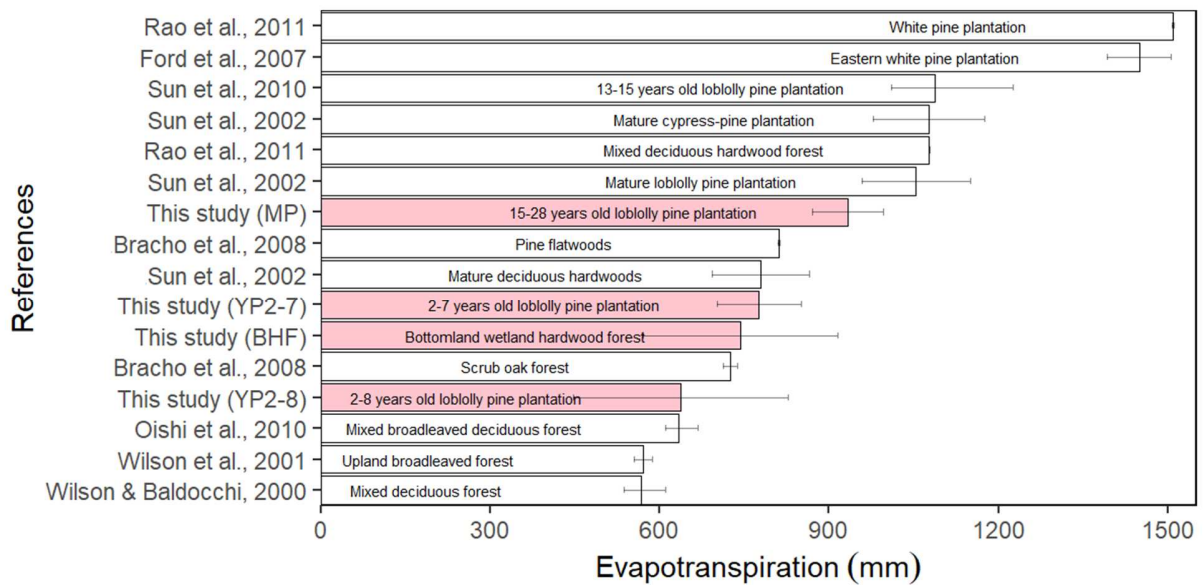
741 Overall, ET was lower than P during the late growing season (July – August) in all years and
742 sites, suggesting there is sufficient plant-available water in the soil to meet atmospheric demand
743 despite periods with no rain. This is in part due to adequate P throughout the year, but also, these
744 lower coastal plain systems receive groundwater from adjacent uplands. These physiographic
745 factors maintain the high water table and constrain D and ΔS components of the site water
746 balance. With little soil water limitation, the high solar radiation during the growing season
747 induces strong evaporative demand resulting in the high growing season ET. In dry periods
748 during the growing season, pine forests rely on deep, extensive root systems to access soil water
749 storage and groundwater (Domec et al., 2012; Luis et al., 2005; Vincke and Thiry, 2008).
750 Hydraulic redistribution and upward soil capillary water flux may also help sustain ET during the
751 growing season (Allen et al., 2010; Domec et al. 2010). These root-based mechanisms of soil
752 water access are consistent with the higher rates of ET at MP compared to YP sites, where ET
753 may be limited by smaller root systems (in addition to lower LAI, as shown in Supplemental
754 Table 1), along with lower stem capacitance, in the early stages of stand development.

755

756 Annual ET ranged from 638 – 933 mm in the managed plantations and 606 – 982 mm at the
757 natural wetland forest. ET for forest ecosystems in the southeastern US ranges from 486 to
758 1509 mm (Bracho et al., 2008; Ford et al., 2007; Oishi et al., 2010; Rao et al., 2011; Sun et al.,
759 2010, 2002; Wilson and Baldocchi, 2000; Domec et al. 2012) (Fig. 15). The ET rates found in

760 this study are within the mid-range when compared to other hydrologic studies conducted in
 761 other forest ecosystems worldwide, reporting annual ET ranging from 280 – 1029 mm (Aguilos
 762 et al., 2019; Brümmer et al., 2012; Humphreys et al., 2003; Li et al., 2010; Tang et al., 2014;
 763 Vourlitis et al., 2014; Wilson and Baldocchi, 2000).

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769 *Figure 15. Comparison of studies on annual evapotranspiration (ET) in major forest ecosystems*
 770 *in the southern United States.*

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773

774 Our data support the hypothesis that the rotation-age pine plantation would have higher ET
 775 than the two young plantations. Climatic controls, especially net radiation and albedo, and higher

776 leaf area, contributed to higher ET rates, consistent with a previous study at this site (Sun et al.,
777 2010). This is also consistent with a broader comparison to other southeastern US studies
778 (Figure 15), in which the primary drivers of ET were found to be Rn and albedo ((Rao et al.,
779 2011; Wilson and Baldocchi, 2000), LAI, and productivity (Bracho et al., 2008; Sun et al.,
780 2002), vapor pressure deficit (Oishi et al., 2010), and soil water availability (Bracho et al., 2008).
781 The data also support the hypothesis that MP ET would be higher than that of BHF, and here we
782 attribute that to biological and climatic effects.

783
784 The magnitude of inter-annual variation in ET at the rotation-age plantation, of 852 mm to
785 1049 mm, is within the range previously reported for the same site (Liu et al., 2018; Sun et al.,
786 2010; Tian et al., 2015; Yang et al., 2020). The small variation in annual ET has been attributed
787 to the shallow water table and deep root systems of this coastal plain setting (Domec et al.,
788 2012). We also found that ET differed between the two young pine plantations, even though
789 they were nearby. Differences between young plantations suggest that even in a single
790 geographical location, there can be multiple trajectories in ET during stand development due to
791 local differences in soil conditions, drainage, surrounding vegetation, inter-annual variation in
792 climate, etc. (Amiro et al., 2010; Borders et al., 2004; Noormets et al., 2012).

793

794

795 *4.2 ET, D ET₀/P, ET/P, D/P, and ET/ET₀ ratios*

796

797 Except for YP₂₋₈, where $ET/ET_0 = 0.34$, all other sites had high ET/ET_0 ratio of 0.73 ~
798 0.81, closer to what was previously reported (0.92) across North Carolina watersheds (Sun et

799 al., 2002, 2001), suggesting that our sites are generally not water-limited. Wetland-dominated
800 watersheds do not necessarily have a higher ET/ET_0 ratio (Sun et al., 2002).

801

802 Our data support the hypothesis that ET is always lower than P on an annual basis at these
803 wetland sites. However, the fact that ET can slightly exceed P in some months connotes
804 important implications for ecosystem water balance and its response to climatic variability. Both
805 growing season precipitation and soil water recharge in the non-growing season were necessary
806 to meet evaporative water demand in the growing season (Sun et al., 2011a). Therefore, any
807 shifts in seasonal precipitation patterns due to climate change (e.g., drought) could profoundly
808 affect ecosystem water use patterns during the growing season, thus affecting the sustainability
809 and productivity of lower coastal plain managed forest ecosystems.

810

811 Annual ET, averaged over 13 years at the managed sites, was lower than annual P by about
812 half (ratio 0.40 ~ 0.55), indicating that the overall effects of ET on water table depth are not
813 significant at lower coastal plain sites. This is consistent with another study that found lower ET
814 than P under similar conditions (Almeida et al., 2007). An ET of about half of P indicates that
815 the remainder of P contributes to watershed yield in this coastal plain area, typical of ecosystems
816 with very high soil water availability (Liu et al., 2018).

817

818

819 *4.3 Effects of ditching and land-use change on water balance*

820

821 The lower coastal plain is flat and poorly drained, resulting in a shallow water table. Ditching
822 was historically used in this region to drain excess water to improve site conditions for timber
823 production (Amatya et al., 1996).

824
825 Our study found no statistical difference ($p > 0.05$) between managed sites and natural forest
826 in terms of the amount of P being lost to the atmosphere through ET and removed through
827 drainage. This result contrasted our hypothesis that draining the landscape with ditches during
828 intensive forest management would decrease the fraction of P leaving the site as ET, as
829 compared to the natural wetland forest. In addition, our data suggest that land-use change and
830 ditching slightly enhances D at YP 2-7 and YP2-8, but ultimately decreases D when plantations
831 reach maturity. Differences in precipitation regimes and topographical characteristics (i.e.,
832 proximity to streams) between the plantation and BHF sites may also contribute to differences in
833 ET and D, making hydrologic comparisons difficult. However, the drainage pattern of BHF is
834 quite different from the drained, managed plantations, with extremes in both growing and non-
835 growing seasons (Fig. 2). This natural bottomland hardwood forest is occasionally submerged
836 and often experiences prolonged inundation during the non-growing season (Miao et al., 2013).
837 The water table at BHF is at full storage capacity during non-growing seasons, again due to the
838 low topographic setting, which receives water from adjacent uplands yet has impeded drainage
839 because of proximity to the sea. This poor drainage is characteristic of very diffuse lower coastal
840 plain watersheds with low topographic relief and poorly defined flow pathways for runoff,
841 decreasing the rate of overland flow. However, the water table became deeper at BHF during the
842 growing season during periods with no rain and high seasonal ET. Therefore, modeling studies

843 would benefit by considering the seasonal change in site water balance in such hydrologically
844 unique coastal plain settings.

845

846 Generally, studies suggest that forest harvesting results in increased drainage (Sun et al.,
847 2001), for at least 8 years afterwards (Arthur et al., 1998). In our study, YP₂₋₇ and YP₂₋₈, which
848 are recently clear-cut sites drained 122 mm – 216 mm more water (annual total = 624 mm – 692
849 mm) than MP (annual total = 476 mm), and 54 mm – 122 mm more than BHF (annual total =
850 570 mm). Thus, tree removal may raise the water table (Aust and Lea, 1992; Lockaby et al.,
851 1997) due to the reduction in ET, consistent with observations in our two young plantation sites
852 (Fig. 2). However, we caution that our study is not a paired watershed design, and thus
853 inferences must be considered with care.

854

855

856 *4.4 ET-stand age relationship*

857

858 The positive relationship between ET and stand age observed in our study is also consistent
859 with observations of others ((Jagodziński and Kałucka, 2008; Yang et al., 2020, 2017). Newly
860 established plantations tend to have low ET due to low leaf area (Supplemental Table 1, Fig. 10)
861 and developing root systems. However, ET increases with time commensurate with increases in
862 productivity (Aguilos et al., 2020). In the current study, the ET-GPP coupling was moderate at
863 the young pine plantations ($R^2 = 0.56$ at YP₂₋₇ and $R^2 = 0.73$ at YP₂₋₈). As the stands get older
864 (>15 years old), ET gradually stabilizes until it approaches the rotation age of ~28 – 30 years old,
865 the same period when GPP reaches a plateau. The ET-GPP relationship in our study was very

866 strong ($R^2 = 0.86$ at MP). Others observed LAI recovery following a disturbance until 15 years of
867 age, after which LAI gradually stabilized with increasing age (McMichael et al., 2004). LAI is
868 therefore a key component of the dynamics in productivity and evapotranspiration. However,
869 care must be taken in the use of allometric or remote sensing methods to obtain LAI. These
870 methods may underestimate or overestimate LAI (Albaugh et al., 2014; Arias et al., 2007; Liu et
871 al., 2015) due to overlapping or clumping between the leaves and light obstruction from
872 branches, boles, and stems (Zheng and Moskal, 2009).

873

874 The positive ET-stand age relationship has implications for forest management in that the
875 establishment of plantations of different age classes in parallel will result in reduced variation in
876 water table levels, thus reducing the effects of extreme water anomalies. However, the ET-stand
877 age relationship at BHF was insignificant despite a high ET-GPP correlation ($R^2 = 0.74$),
878 suggesting greater climatic control of ET at the natural forest rather than biological constraints in
879 this mature forest that does not undergo large changes in LAI from year to year.

880

881

882 *4.5 Effect of drought on ET*

883

884 A significant drop in precipitation in 2007 and 2008 resulted in increased depth to water table
885 and decreased drainage at YP₂₋₈ and MP (Aguilos et al., 2020; Noormets et al., 2010; Sun et al.,
886 2010), and corresponding decline in ET. The long-term data presented here support our
887 hypothesis that drought affects young plantations more severely than rotation-age plantations.

888 The decrease in ET at MP (9 %) was much smaller than occurred at the young pine sites, which
889 we attribute to the sharp increase in water table depth.

890

891 Typically, the high water table of these lower coastal plain sites provided abundant soil water
892 to meet the atmospheric evaporative demand. Also, hydraulic redistribution by deep roots might
893 have played a crucial role in replenishing soil water to the upper soil layers (Domec et al., 2010),
894 thus sustaining tree transpiration and ET. A slight reduction of ET during drought at MP can be
895 attributed to reductions in canopy interception, tree transpiration, understory transpiration, and
896 soil evaporation (Domec et al., 2012; Liu et al., 2018; Oishi et al., 2010). It has been observed
897 that a reduction in tree transpiration occurs with a decrease in soil water content, especially when
898 REW drops below the threshold of 0.4 (Almeida et al., 2007; Granier et al., 1999; Vincke and
899 Thiry, 2008). Prolonged soil water deficits in our study, with 177 – 188 days of REW falling
900 below 0.4 in 2007, which got worse in 2008 (200 – 258 days), indicate that trees might be under
901 constant water stress during these periods. However, trees at the MP site may have responded to
902 severe stress by partially closing stomata (Domec et al., 2009), improving water use efficiency.

903

904 Our results support the hypothesis that drought would decrease ET at the managed sites.
905 There was a higher proportional decline in ET, 30 – 43 %, at the young plantations compared to
906 the rotation-age plantation (8 – 11 %). This higher reduction in ET at the younger stands is
907 consistent with another remote sensing-based study, which reported that drought in this coastal
908 region had a more significant effect on young stands (Yang et al., 2020). Drought-induced
909 reduction in transpiration of young plantation forests might be due to low biomass/LAI, shallow

910 root systems, low stem capacitance, and reduced plant hydraulic conductivity (Domec et al.,
911 2012).

912

913 In addition to differences in roots and biomass among the four sites, net radiation, which is
914 influenced by canopy albedo, was also a key factor in explaining ET. Albedo significantly
915 affects net radiation and is highly dependent on the dynamics of plant growth patterns, and is
916 influenced by ‘greenness’ and ‘wetness’ of the land surface (Sun et al., 2010). Net radiation was
917 the primary climatic control on ecosystem ET during the observed drought period, consistent
918 with other studies (da Costa et al., 2018; Gaofeng et al., 2014; Stoy et al., 2006; Yu et al., 2008).
919 The discrepancy in Rn between young (mean = 104 W m⁻²) and rotation-age (134 W m⁻²)
920 plantations during the 2007/2008 drought was due to differences in surface albedo of 0.16 and
921 0.12 for the sites, respectively. Surface albedo has been shown to decrease with increasing
922 canopy height (Kuusinen et al., 2016), increasing leaf area index (Bright et al., 2015; Forzieri et
923 al., 2018), increasing biomass (Lukeš et al., 2014), and increasing age (Amiro et al., 2006; Bright
924 et al., 2013; Kuusinen et al., 2014), which characterize differences between MP and younger
925 plantations. Thus, MP absorbed more solar radiation, had lower reflectance, and thus lower
926 surface albedo. Any alteration in forest structure may affect albedo and thus Rn (Gaofeng et al.,
927 2014). Therefore, previous forest harvesting may have caused an increase in surface albedo at
928 YP₂₋₈. Further, the understory at young plantations was mostly herbaceous and deciduous woody
929 plants that lost leaves during the non-growing season, unlike with the evergreen canopy at MP,
930 where needles were present all year-round. Lower canopy cover leads to higher surface
931 reflectance and thus higher albedo at the younger pine forests.

932

933 Based on the Budyko's curve (Fig. 12), the ET_0/P ratio during the 2007/2008 drought years
934 was higher than 1.0, unlike at the MP site where ET_0/P remained less than 1.0. As drought
935 conditions became more severe, the sensitivity of transpiration to water deficit increased,
936 suggesting a down-regulation of stomatal conductance, which lowered tree transpiration under
937 extreme drought. This deviation from the theoretical Budyko's curve at the young plantation can
938 be attributed to a management intervention (e.g., harvest), which changed the vegetation cover
939 (Tor-ngern et al., 2018). Soil type (Wang et al., 2009), water storage capacity (Milly, 1994), the
940 timing of soil water recharge (Potter et al., 2005), and other factors such as incident radiation,
941 canopy leaf area, tree density, canopy conductance, and other micrometeorological conditions
942 also affect evapotranspiration, (Budyko, 1974; Tor-ngern et al., 2018).

943

944 Overall, annual ET/P (0.49 ~ 0.66), mean annual evaporative index, and ET_0/P (0.60 ~ 0.86),
945 mean annual dryness index, indicated that the young and mature plantations fell within the
946 theoretical Budyko (1974) space, and within the 1:1 line breakpoint, meaning that all sites were
947 more energy-limited rather than soil water deficient.

948

949

950 *4.6 The role of GPP to changes in ET during drought period at managed sites*

951

952 The positive ET - GPP relationship was more significant at MP compared to YP_{2-8} . Therefore,
953 higher net radiation and LAI (Supplemental Table 2) maintained higher ET (Fig. 13 and 14) and
954 higher GPP because there was little water stress due to more available groundwater and deeper
955 root systems in MP. In contrast, at YP_{2-8} , ET rates were sharply reduced, but GPP was not. It is

956 known that plants may delay bud break and leaf expansion with drought (Mijnsbrugge et al.,
957 2016), or roots of understory vegetation may exploit a higher soil volume that potentially
958 increases tolerance to drought (Warren et al., 2015). Further, ET response to drought at both
959 young and mature plantations may have also been influenced by varying tolerance to a drought
960 of different tree species or understory species that occurred at the sites, depending on drought
961 intensity levels (Maréchaux et al., 2018; Stahl et al., 2013). Overall, our results confirm that in
962 addition to available energy, biological controls (i.e., GPP, stomatal conductance, roots, LAI)
963 play a critical role in ET processes. Therefore ET is a good integrator of many physiological and
964 physical processes affecting forest water cycling (Ford et al., 2007; Stoy et al., 2006; Zhou et al.,
965 2008) and the tightly coupled water-carbon cycling (Sun et al., 2011b).

966

967 Interestingly, a 6 – 9 % enhancement in GPP at the MP site and 20 – 53 % increase in GPP at
968 YP₂₋₈ during the 2007/2008 drought period (Aguilos et al., 2020) were not accompanied by a
969 similar rise in ET at both sites (Fig. 13), suggesting increased WUE (Domec et al., 2015). We
970 found slight to moderate reductions in ET at YP₂₋₈ (30 – 43 %) and MP (8 – 11 %) during the
971 drought. This result does not support our hypothesis that ET and GPP will remain tightly,
972 positively coupled despite extreme climatic conditions (Fig. 14), and is inconsistent with the
973 widely reported coupling of ET and GPP (Brienen et al., 2011; Fisher et al., 2007; Huang et al.,
974 2015; Yu et al., 2008). Although we found that ET and GPP respond to the same primary
975 climatic drivers, the magnitude of response differs for the two processes during anomalous soil
976 water years. This asynchrony of the response represents a decoupling of carbon and water
977 cycling under extreme conditions. GPP is usually affected less during severe water depletion
978 since stomatal closure typically induces a stronger down-regulation of transpiration than

979 photosynthesis (Maréchaux et al., 2018), and transpiration is linearly related to stomatal
980 conductance. In contrast, photosynthesis may be limited by a variety of other factors and does
981 not respond linearly to instantaneous changes in stomatal conductance (Chaves et al., 2003).
982 Differences in sensitivity of ET and GPP to drought illustrate the challenges that must be
983 overcome for ecosystem models to accurately simulate these processes.

984

985

986 *4.7 Implications*

987

988 To our knowledge, the present study represents the longest direct measurement of ET and
989 forest water balance of lower coastal plain forested wetlands in the southeastern US, advancing
990 our understanding of the hydrologic responses to land-use change (drained vs. natural
991 hydrology), inter-annual variation in climate, and climate extremes (drought). Our results show
992 that water use (ET) by young drained plantation forests increases over time, as trees grow and
993 LAI stabilizes around age 10-15 years, the time of canopy closure. Mid-rotation plantation
994 forests that have higher biomass and productivity had similar or higher ET compared to
995 undisturbed natural forested wetlands. This has implications for drainage management in the
996 coastal plain at the landscape scale. Forest land managers can sustain ecological functioning to
997 extremes in water availability (drought or flooding) by using the relatively large ET of pine
998 plantations, or ‘biological drainage’ (Hao et al., 2015), to moderate watershed yield (more from
999 young plantations, less from mature), and water quality concerns from forest cutting and
1000 regeneration. The ditching practices of the past in coastal forested wetlands indeed increases
1001 flow and increases the risk of backflow and saltwater intrusion during storms and sea-level rise.

1002 Maintaining tree stocks may help mitigate the hydrological and climatic regulation functions
1003 (i.e., ET capacity) from disturbances such as land-use change (i.e., ditching). Our data suggest
1004 that these drained wetlands are resilient to extreme episodic droughts due to the shallow water
1005 table. Therefore, maintaining the water table through controlled drainage (Amatya et al., 2006)
1006 that alters ditch water levels based on-site hydrologic conditions can become increasingly
1007 important to mitigate drought effects on forest productivity under a changing climate. However,
1008 these wetlands are vulnerable to long-term climate change and sea-level rise, which likely alters
1009 the hydrology of the physiographic region of the southeast lower US coastal plain (Zhang et al.,
1010 2018), with implications for forest productivity, mortality and carbon storage (Aguilos et al.,
1011 2020). Watershed management in coastal plain regions should consider the potential combined
1012 effects of climate change, sea-level rise, and land-use dynamics on water balance. This study
1013 provides a long-term benchmark of forest water balance for both natural and managed
1014 conditions.

1015

1016 Our study also suggests that wetland forest ET/ET₀ values are somewhat variable depending
1017 on the stage of stand development. Annual forest ET rates are generally lower than ET₀ in this
1018 region but can exceed ET₀ in the peak of the growing season. Forest productivity is tightly
1019 coupled with ET. Thus forest ecosystem services of carbon sequestration and water supply have
1020 a tradeoff relationship (Jackson et al., 2005). However, this relationship varies among forest
1021 stands of different ages. Hydrological or regional climate models must consider the vegetation
1022 dynamics and the biological controls on hydrology to fully assess the role of wetland forests in
1023 regulating local and regional hydrology and climate.

1024

1025 **5. Conclusions**

1026

1027 Based on 37 site-years of monitoring, we found that total annual ET in plantation forests was
1028 more than half of precipitation. Poorly drained pine plantation forests with high leaf area had
1029 comparable ET compared to undisturbed forested wetland with low productivity and higher
1030 inundation. ET was quite resilient to changes in precipitation variability (e.g., drought) due to
1031 the flat topography and shallow water table. Annual variability in precipitation explained most of
1032 the variation in drainage in both intensively managed pine plantations and natural bottomland
1033 hardwood forest. Pine plantation ET increased sharply with stand age and leaf area index during
1034 the early years (0-10), but then gradually stabilized thereafter. This study improves
1035 understanding of the effects of land-use change and climate on ET and water balance of coastal
1036 forested wetlands. Forest structure (age, leaf area) and drainage patterns should be considered
1037 when parameterizing ecosystem models to accurately project responses of southern coastal plains
1038 to rapidly changing environmental conditions.

1039

1040

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1042

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1050

1051

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1053

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