

1 **The Brazil Eucalyptus Potential Productivity Project: Influence of water,**
2 **nutrients and stand uniformity on wood production**

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31 **Abstract.**

32 We examined the potential growth of clonal eucalyptus plantations at eight locations
33 across a 1000+ km gradient in Brazil by manipulating the supplies of nutrients and water,
34 and altering the uniformity of tree sizes within plots. With no fertilization or irrigation,
35 mean annual increments of stem wood were about 28% lower ($16.2 \text{ Mg ha}^{-1} \text{ yr}^{-1}$, about
36 $33 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$) than yields achieved with current operational rates of fertilization (22.6
37 $\text{Mg ha}^{-1} \text{ yr}^{-1}$, about $46 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$). Fertilization beyond current operational rates did not
38 increase growth, whereas irrigation raised growth by about 27% (to $30.6 \text{ Mg ha}^{-1} \text{ yr}^{-1}$,
39 about $62 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$). The potential biological productivity of the plantations was about
40 one-third greater than these values, if based only on the period after achieving full
41 canopies. The biological potential productivity was even greater if based only on the full-
42 canopy period during the wet season; the maximum biological productivity across the
43 sites (with irrigation, during the wet season) would be about $42 \text{ Mg ha}^{-1} \text{ yr}^{-1}$ ($83 \text{ m}^3 \text{ ha}^{-1}$
44 yr^{-1}). Stands with uniform structure (trees in plots planted in a single day) showed 13%
45 greater growth than stands with higher heterogeneity of tree sizes (owing to a staggered
46 planting time of up to 80 days). Treatments that increased growth also delayed by about
47 one year the point where current annual increment and mean annual increment
48 matched, indicating opportunities for lengthening rotations for more productive
49 treatments. The growth response to treatments at mid-rotation related well with full-
50 rotation responses, offering an early opportunity for estimating whole-rotation yields.
51 These results underscore the importance of resource supply, the efficiency of resource
52 use, and stand uniformity in setting the bounds for productivity, and provide a baseline
53 for evaluating the productivity achieved in operational plantations.

54 1.0 Introduction

55 Eucalyptus plantations in Brazil in 1970 typically grew at rates of about $15 \text{ m}^3 \text{ ha}^{-1}$
56 yr^{-1} (Queiroz and Barrichelo 2008). Over the next 35 years, intensive research and
57 improved operations tripled the average yields across 5.4 million ha, through improved
58 silviculture (site preparation, fertilization and control of ants and weeds), improved seed
59 selection, and the development of clonal propagation. Empirical analysis of growth
60 responses in experimental plantations guided management decisions, but the
61 ecophysiological factors behind these empirical patterns remained largely unexamined
62 until the late 1990s (Almeida et al. 2004 Stape et al. 2004a,b, Whitehead and Beadle
63 2004). To what extent is forest growth limited by the supply of nutrients, water, and
64 environmental constraints such as incoming light and vapor pressure deficit? The Brazil
65 Eucalyptus Potential Productivity (BEPP) Project was launched in 2001 to determine
66 potential growth rates when nutrient and water limitations are removed across a
67 geographic range of sites and clones, including the processes behind the responses in
68 wood growth (carbon allocation, resource use and efficiency). As part of this special
69 issue on Productivity in Tropical Plantations, this paper provides an overview of the
70 BEPP Project and summarizes the basic patterns of stand growth. Other papers in this
71 special issue examine carbon budgets (Ryan et al. 2010), patterns of resource use
72 efficiency by individual trees (Binkley et al., 2010), and water use (Hubbard et al., 2010).

73 The initial ideas tested in the BEPP Project developed from an earlier research
74 project on age-related decline in a *Eucalyptus saligna* plantation in Hawaii (Ryan et al.
75 2004). Wood growth and gross primary production declined substantially after mid-
76 rotation in that study, despite the high supply of water and repeated fertilization. A
77 decline in photosynthesis was the largest contributor to the decline in wood production,
78 with smaller contributions from increased partitioning to belowground and foliar

79 respiration. The growth decline was traced to a loss of efficiency of production per unit of
80 resource used, rather than to a decline in resource use. Dominant trees showed higher
81 efficiency of resource use (Binkley et al. 2002), leading to hypotheses about changes in
82 dominance and resource use efficiency as drivers of age-related decline (Binkley 2004).

83 A pilot experiment for the BEPP Project tested the effects of irrigation and
84 fertilization on maximum growth rates in a single plantation by Copener Florestal near
85 Alagoinhas, Bahia. The results from this individual site were designed to be
86 extrapolated to a broader landscape in Bahia with two approaches. Local
87 parameterization of the 3-PG forest growth model provided an opportunity for estimating
88 growth for different soils and environments in the region (Stape et al. 2004a). An
89 empirical approach to extrapolation was developed with a “twin-plot” approach that
90 joined routine forest inventory plots with simple stand treatments (Stape et al. 2004b).

91 The BEPP Project developed as a consortium of 5 (and eventually 8) companies,
92 the University of São Paulo, Colorado State University, and the USDA Forest Service,
93 coordinated through the Forestry Science and Research Institute (IPEF) in Piracicaba.
94 Each company installed a basic version of the potential productivity experiment (testing
95 irrigation and repeated fertilization). Routine measurements of stem growth were
96 supplemented with regular sampling of canopy leaf area, belowground carbon flux, and
97 other features needed for production ecology insights. The companies were responsible
98 for routine measurements, with training assistance from other BEPP collaborators.

99

100 **2.0 Methods**

101 2.1 Sites

102 The BEPP sites spanned a distance of more than 1000 km in southeastern Brazil
103 (Figure 1). The environmental gradients included three Soil Orders, an order of

104 magnitude in soil clay percent, and a 70% range in rainfall (Table 1, Table 2). The sites
105 ranged from warm tropical with low vapor pressure deficits to subtropical and marked
106 vapor pressure deficits. This paper analyzes patterns for a full rotation of 6 years for
107 three sites (ARA, IPB, and VER); 4 to 5 years of stand development were available for 4
108 other sites (CEN, SUZ, VIP and VLM), and just 3 years of development were obtained
109 for an 8th site (VCP) before a severe windstorm stopped the experiment.

110

111 2.2 Treatments

112 Goal #1 (determining potential production) was examined at all locations based
113 on typical current silvicultural operations as the baseline treatment for comparison.
114 These baseline treatments all included the use of clonal plantlets (chosen by each
115 company), initial fertilization (Table 3), and sustained weed control. Plot size was 30 x
116 30 m, with tree spacing near 3 x 3 m. With two rows of buffer trees, the interior
117 measurement subplots had 6 rows and 6 columns of trees. Irrigation treatments were
118 tested at all sites (Table 4) to remove any limitation of soil water supply on growth
119 (trenching between plots minimized any influence of adjacent treatments). Rates of
120 irrigation were tailored in each case to supplement rainfall and exceed potential
121 evapotranspiration each week. Current operational rates of fertilization may not
122 completely alleviate nutrient limitation, so all sites included a high fertilization treatment
123 with fertilizer applications twice annually for the first 3 years (with rates varying among
124 companies, Table 3). The influence of stand structure was examined at four sites, with
125 uniform plots (planted with clonal trees in a single day) and heterogeneous plots (planted
126 with the same clonal material but with 1/3 of the plantlets planted on Day 0, Day 40, and
127 Day 80 (Figure 2; design suggested by C. Giardina)). The range in planting times within

128 plots led to greater variation among tree sizes over time, similar to the stand structure
 129 that develops in seedling-origin stands (Boyden et al. 2008).

130

131 2.3 Measurements of tree mass and growth

132 Tree diameters and heights were measured every 3 months. Biomass
 133 regressions equations were developed separately for each site based on destructive
 134 harvesting (in spare plots) at about 1.5 years, 3 years, and 6 years. Stem wood mass
 135 correlated very highly with tree diameter and height for all sites and treatments (r^2
 136 greater than 0.98):

137 ARA: $0.0040 \times D^{1.959} \times H^{1.512}$ (n=128)

138 CEN: $0.0260 \times D^{1.174} \times H^{1.503}$ (n=53)

139 IPB: $0.0050 \times D^{1.751} \times H^{1.542}$ (n=169)

140 SUZ: $0.0090 \times D^{1.622} \times H^{1.515}$ (n=92)

141 VCP: $0.0170 \times D^{2.596} \times H^{0.427}$ (n=44)

142 VER: $0.0270 \times D^{2.221} \times H^{0.625}$ (n=264)

143 VIP: $0.0003 \times D^{1.592} \times H^{1.712}$ (n=36)

144 VLM: $0.0080 \times D^{1.778} \times H^{1.497}$ (n=35)

145 where D is diameter in cm at 1.3 m height, H is total tree height in m, and n is the
 146 number of trees used in each equation.

147

148 2.4 Statistical analysis

149 Within each site, the experiment was a completely randomized block design with
 150 four replicate plots (3 for ARA). Two levels of statistical inference were examined. The
 151 replication within each site provided for a population of inference of a few hectares, over
 152 the time span (and weather patterns) of the measurement periods. The results from

153 individual locations would probably provide reliable insights for plantations on similar
154 soils in nearby areas. The primary focus of this paper is the treatment response across
155 all sites, so the second level of inference uses the average results from each treatment
156 at a site as a unit of observation, and the population of inference would be a large
157 portion of the eucalyptus plantations in southeastern Brazil. All analyses were
158 performed with SAS 8.2 (SAS, 2000), using a P value of 0.05 for evaluating the likely
159 significance of treatment effects.

160

161 **3.0 Results**

162 Survival was very high across all treatments and sites, providing fully stocked
163 plots for evaluating the effects of treatments. The one exception was the VCP site that
164 was abandoned after 2.8 years following major breakage of trees in a severe windstorm
165 (up to 1/3 of trees damaged in irrigated plots, with almost no damage in non-irrigated
166 plots). The site index for the baseline treatment of traditional fertilization without
167 irrigation (TNU) ranged from 26 to 32 m at 5 years (Table 5), corresponding with mean
168 annual increments of 18 to 30 Mg ha⁻¹ yr⁻¹ (Table 6; about 37 to 62 m³ ha⁻¹ yr⁻¹).

169

170 3.1 Fertilization effect

171 All treatments influenced growth fairly consistently, from the time of plantation
172 establishment through the final measurement (Figure 3). The CNU treatment (no
173 fertilization, no irrigation, uniform structure) was tested at three sites, and led to a 28%
174 reduction in mean annual increment (MAI) relative to the baseline TNU treatment (Figure
175 4, Table 6). The effect was significant at the VIP and VCP sites, but not at the CEN site;
176 across all three sites, the P value for this treatment was 0.10 (or 0.05 for a one-tailed
177 hypothesis test (that CNU would grow less than TNU). Increasing fertilization rates from

178 current operational levels (TNU) to very high rates (FNU) had little marginal effect on
179 growth, with an average increase in MAI of just 4%; this effect was not significant within
180 any site, or across all sites together. Fertilization showed no significant interactions with
181 irrigation or stand structure.

182

183 3.2 Irrigation effect

184 The response to irrigation was far larger than fertilization (comparing all non-
185 irrigated and irrigate treatments), with MAI increasing by an average of 30%. The
186 irrigation effect was significant within all sites except CEN ($P = 0.28$). The growth
187 increase from irrigation ranged from a low of 7% ($1.7 \text{ Mg ha}^{-1} \text{ yr}^{-1}$, not significant) at the
188 cool, higher elevation CEN site to 67% ($15.2 \text{ Mg ha}^{-1} \text{ yr}^{-1}$) at the driest VLM site.
189 Irrigation did not show a significant interaction with stand structure.

190 The magnitude of the irrigation response related well to some of the climate
191 parameters, with stronger relationships with response as $\text{Mg ha}^{-1} \text{ yr}^{-1}$ than as percent.
192 The strongest relationships occurred between irrigation response and non-irrigated
193 water balance (rainfall minus potential evapotranspiration in Table 3), vapor pressure
194 deficit, and annual incoming radiation (all correlations $r^2 = 0.80$, $P < 0.02$). These three
195 environmental variables correlated highly with each other (r^2 0.62 to 0.83, P from 0.10 to
196 0.01).

197 Interestingly, the response to irrigation was strong in both the dry season (April to
198 September) and the wet season (October to March; Figure 5). Irrigation increased
199 growth in the dry season by an average of 34% ($9.5 \text{ Mg ha}^{-1} \text{ yr}^{-1}$ on an annual basis)
200 across all sites, and 23% during the wet season ($8.0 \text{ Mg ha}^{-1} \text{ yr}^{-1}$ on an annual basis).
201 Soil water apparently remains too low during at least some periods in the wet season
202 (without irrigation) to support maximum growth rates. The growth rate in irrigated

203 treatments was also lower during the dry season than the wet season, with the 19%
204 lower growth in the dry season matched by 19% lower incoming sunlight (data not
205 shown). Dry-season growth in the non-irrigated plots was 27% lower than wet-season
206 growth, combining the influence of lower incoming light and greater moisture stress.

207 Across sites, seasonal patterns of incoming light related well to seasonal growth
208 when irrigation removed water stress. However, daily, seasonal, and annual growth
209 were likely influenced by vapor pressure deficit (VPD; see review by Whitehead and
210 Beadle 2004), as evidenced by differences in photosynthesis and water use on a daily
211 basis (e.g. Hubbard 2010), by differences in growth among years with different average
212 VPD (e.g. Stape et al. 2006), and the key role of VPD in predicting regional patterns of
213 growth (e.g. Almeida et al. 2010).

214

215 3.3 Stand structure effect

216 Heterogeneous stand structure lowered growth by an average of 13% across the
217 5 sites that included this treatment (Table 6). The stand structure effect was significant
218 at all sites except ARA ($P=0.06$), as well as across all sites. The reasons for this effect
219 remain unknown. All stems (within a site) were genetically identical, as were all supplies
220 of resources. The interception of light did not differ at the plot scale (Ryan et al. 2010,
221 this issue), so the lower growth in the heterogeneous treatment resulted from lower
222 efficiency of light use rather than lower light interception. Binkley et al. (2010, this issue)
223 examined light use efficiency at the scale of individual trees, and found that non-
224 dominant trees used light less efficiently than dominant trees, and this effect was
225 accentuated by greater dominance in heterogeneous stands. The potential mechanisms
226 behind these patterns clearly need to be examined with further research.

227

228 3.4 Culmination of increment

229 Across the three sites that spanned a full rotation (ARA, IPB, VER), current
230 annual increment culminated between age 2 and 4 (Figure 6). The irrigated treatment
231 showed a higher peak (about 45 Mg ha⁻¹ yr⁻¹ for the uniform treatment) than the non-
232 irrigated treatment (about 33 Mg ha⁻¹ yr⁻¹). The irrigated plots also showed a greater
233 decline by year 6, with CAI dropping by about 13 Mg ha⁻¹ yr⁻¹ (uniform treatment)
234 compared with 5 Mg ha⁻¹ yr⁻¹ without irrigation. The pattern of CAI over time for the
235 heterogeneous stand structure was similar to the uniform structure, including the greater
236 decline for irrigated treatments. Contrary to the hypothesis of Binkley et al. (2002) and
237 Binkley (2004), high uniformity in stand structure did not prevent the decline in growth
238 after the stands reached full leaf area.

239

240 **4.0 Discussion**

241 What is the potential productivity of eucalyptus plantations in Brazil? This project
242 led to several sorts of answers. Based on the three sites that reached a full rotation, the
243 potential productivity based on current operational silviculture (applied with close
244 scrutiny under research conditions) averaged about 25 Mg ha⁻¹ yr⁻¹ (MAI for TNU
245 treatment in Figure 7), or about 51 m³ ha⁻¹ yr⁻¹. Removal of water limitation by irrigation
246 raised the ceiling on potential productivity to about 32 Mg ha⁻¹ yr⁻¹ (about 65 m³ ha⁻¹ yr⁻¹).
247 Operational-scale irrigation may be unlikely for most forests, but the gains from irrigation
248 underscore the potential value of intensive management of site water balance (including
249 control of competing vegetation). These MAI figures include the first 18 months of the
250 rotation before the trees full occupied the sites with full canopies and root systems, so
251 the biological potential productivity for fully established trees would be a current annual
252 increment (ages 1.5 through 6.0 years) of about 38 Mg ha⁻¹ yr⁻¹ (77 m³ ha⁻¹ yr⁻¹). The

253 biological productivity could also be considered for the portion of the year when climate
254 conditions are most favorable, with low vapor pressure deficits and high sunlight. The
255 current annual increment based on just the 6-month wet season reached about 41 Mg
256 $\text{ha}^{-1} \text{yr}^{-1}$ ($83 \text{ m}^3 \text{ ha}^{-1} \text{yr}^{-1}$). Higher rates of growth might be possible for some clones
257 during some years on some sites, but the potential productivity estimates from this
258 project probably represent the upper end of feasible rates for large areas for longer time
259 periods. These potential levels can serve as a benchmark for comparison with yields
260 obtained from operational silviculture.

261 The whole-rotation productivity for the treatments at the ARA, IPB and VER sites
262 were predicted well by the mid-rotation results (Figure 7), so these patterns may support
263 early decisions about the likely magnitude of full-rotation yields. Current annual
264 increment from year 2 to 3 accounted for 85% of the variation in whole-rotation MAI
265 across all treatments and sites. The MAI up to age 3 also predicted whole-rotation MAI
266 well ($r^2 = 0.68$). The effects of increased water supply (TIU and FIU in relation to TNU)
267 on biomass accumulation also related very well to the increase in site index ($r^2=0.87$)

268

269 4.1. Nutrition

270 Eight sites clearly cannot encompass the full range of conditions across this
271 broad region, so informed judgment is needed to extrapolate from our sample 8 sites to
272 the region of eucalyptus plantations in Brazil. For example, the growth response to very
273 heavy fertilization at the VIP and IPB sites were no larger than the response to the
274 traditional level of fertilization currently used by the Company (Table 6). Yet the average
275 response among 260 “twin-plot” fertilization trials on these Companys’ lands (at rates
276 similar to those used at this site) averaged 15-20% increase in wood growth (Stape et al.
277 2006, Ferreira and Stape 2009). About 20% of the plots did not respond to fertilization in

278 the twin-plot studies, so the VIP and IPB locations used in the BEPP Project would have
279 fallen among this minority of non-responsive plots. Alternatively, fertilizer applications in
280 operational treatments may be less precise than in research plots, so some of the
281 apparent difference between the BEPP plots and the regionally representative twin-plots
282 might illustrate differences between operations and research. This is a key point,
283 because the BEPP results indicated that current company prescriptions already attain a
284 maximum fertilizer response, and perhaps lower rates would provide a large response
285 with a substantially lower cost. In contrast, the twin-plot results indicate current
286 operations do fully alleviate nutrient limitation on a majority of sites, so this discrepancy
287 (an issue of real variation among sites, or in operational precision) needs to be
288 examined.

289

290 4.2. Water stress

291 How did irrigation lead to increased wood growth? Irrigated plots showed higher
292 levels of light use efficiency, expressed as wood growth per unit of light absorbed by the
293 canopy (Ryan et al. 2010). This increased efficiency of light use reflected an increase in
294 total gross primary production (and a constant efficiency of GPP per unit light absorbed),
295 coupled with a lack of change in total belowground carbon flux. Essentially the higher
296 total productivity of the irrigated plots was channeled into wood growth. The higher
297 efficiency of wood production per unit of light absorbed was consistent with the irrigation
298 response reported earlier for Copener Florestal site (Stape et al. 2008), as well as a
299 geographic rainfall gradient in Bahia (Stape et al. 2004b).

300 Increased wood growth in irrigated plots probably related primarily to increased
301 water use, rather than to a change in water use efficiency (wood growth/transpiration).
302 Hubbard et al. (2010) estimated transpiration in trees at the ARA and VER sites, and

303 concluded that the proportional increase in water use was matched by the proportional
304 increase in wood growth. This pattern contrasts with the estimated water use efficiency
305 at the Copener Florestal site, where the water balance for irrigated plots indicated higher
306 water use efficiency than in non-irrigated plots (Stape et al. 2008).

307 Water supply is clearly critical to plantation productivity. Several irrigation studies
308 have demonstrated strong relationships between water supply (and use) and wood
309 production for eucalyptus around the world, with stem growth responses of 15 to 35%
310 (Linder 1985, Madeira et al. 2002, Campion et al. 2006, Stape et al. 2008) or even
311 higher under arid conditions (Hunter 2001). The value of sites selected in the future for
312 plantations in Brazil will depend strongly on a range of water-related issues, including
313 rainfall, seasonality of rainfall, vapor pressure deficit, and soil water storage capacity
314 (Almeida et al. 2004, Stape et al. 2004a, Almeida et al. 2010). Intensive control of
315 competing vegetation may be particularly important in lowering water stress on trees in
316 some sites, and environmental issues of total water consumption and efficiency of water
317 use may shape silvicultural decisions as well as strategic planning by companies.
318 Consistent with other studies (e.g. Madeira et al. 2002, Campion et al. 2006), we found
319 no evidence of interactions between fertilization and irrigation, so issues of nutrition and
320 water stress may be managed separately.

321 Water supply is also critical when rainfall varies among years, and the responses
322 to these variations may differ substantially among clones. The next phase of the BEPP
323 Project will examine these interactions with a variety of clones tested across the region,
324 with rainfall exclusion treatments providing experimental manipulations of water supply
325 within an expanded set of sites.

326 Simple water budgets that contrast rainfall and potential evapotranspiration at
327 time scales of months (or years) would not capture the water limitations on eucalyptus

328 growth at our sites. Irrigation led to a 30% increase in stem growth, even though simple
329 water balance values in Table 2 indicate little if any water restriction on growth. Useful
330 predictions of the effects of water supply on eucalyptus growth probably require dynamic
331 process-based models with relatively short frames (daily or weekly; e.g. Almeida et al.
332 2004, Stape et al. 2004a).

333

334 4.3. Stand structure

335 Operational irrigation is not widespread in plantation forestry, but all plantations
336 develop a stand structure with low or high uniformity of tree sizes. The results of the
337 BEPP Project indicate that uniformity in stand structure can substantially influence wood
338 growth. Indeed, much of the higher yield that typically occurs in clonal eucalyptus
339 plantations relative to seed-origin plantations may result from higher uniformity of tree
340 sizes rather than other genetic aspects (Binkley et al. 2002). The interactions of
341 uniformity and genetics are probably complex. For example, Boyden et al. (2008)
342 examined the competitive effects of neighbors on the growth of individual trees. A
343 medium sized focal tree (75 kg wood mass) tree of clonal origin (surrounded by trees of
344 the same clone) grew better than the same size tree from seed origin (surrounded by
345 other seed-origin trees), when the overall size of neighbors offered little competition. As
346 competition pressure increased with increasing size of neighboring trees, the growth of
347 the clonal tree (with clonal neighbors) dropped below the level of the seed-origin tree
348 (with seed-origin neighbors). A 50% increase in the completion index from 0.4 to 0.6
349 lowered the growth of the clonal tree by 20 to 30%, compared with a reduction of less
350 than 10% in the seed-origin tree.

351 Silvicultural opportunities for promoting high uniformity in stand structure are
352 clearly important, and more research is warranted on the mechanisms behind these

353 responses as well as the interactions with genotypes. Dominant trees in the BEPP
354 plantations showed higher light use efficiency than non-dominant trees (Binkley et al.
355 2010). It seems likely that this higher efficiency also reflects a pattern of allocation
356 among tissues within trees, with higher allocation to wood growth relative to
357 belowground by dominant trees. However, we have no information on belowground
358 carbon flux on an individual tree basis, and other explanations remain possible.

359 The initial period of stand development shows low rates of stem growth as the
360 canopy increases to a maximum. The period of time required for full canopy
361 development may be reduced by increasing planting density, but the value of rapidly
362 developing canopies may depend in part on the overall hydrology of a site. Following
363 harvesting, soil water storage may increase while stand leaf area remains low; rapidly
364 developing leaf area in high-density stands may begin to tap this stored water sooner
365 than lower-density stands. However, rapid reduction in stored soil water may not lead to
366 higher MAI for the whole rotation, so the interactions of stand density, rate of canopy
367 development, and drawdown of stored soil water may lead to interesting interactions.

368

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375 **5.0 References**

- 376 Almeida, A.C., Landsberg, J.J., Sands, P.J., 2004. Parameterisation of 3-PG model for
377 fast-growing *Eucalyptus grandis* plantations. For. Ecol. Manage. 193, 179-195.
- 378 Almeida, A.C., Siggins, A., Batista, T.R., Beadle, C., Fonseca, S, and Loos, R. 2010.
379 Mapping the effect of spatial and temporal variation in climate and soils on
380 *Eucalyptus* plantation production with 3-PG, a process-based growth model. For.
381 Ecol. Manage., this issue.
- 382 Binkley, D. 2004. A hypothesis about the interaction of tree dominance and stand
383 production through stand development. For. Ecol. Manage. 190:265-271.
- 384 Binkley, D., Stape, J.L., Ryan, M.G., Barnard, H. and Fownes, J. 2002. Age-related
385 decline in forest ecosystem growth: an individual-tree, stand-structure
386 hypothesis. Ecosystems 5:58-67.
- 387 Binkley, D., Stape, J.L., Bauerle, W.L., and Ryan, M.G. 2010. Explaining growth of
388 individual trees: Light interception and efficiency of light use by *Eucalyptus* at four
389 sites in Brazil. For. Ecol. Manage., this issue.
- 390 Boyden, S., Binkley, D. and Stape, J.L. 2008. Competition among *Eucalyptus* trees
391 depends on genetic variation and resource supply. Ecology 89:2860-2867.
- 392 Campion, J.L., Nkosana, M., and Scholes, M.C. 2006. Biomass and N and P pools in
393 above- And below-ground components of an irrigated and fertilized *Eucalyptus*
394 *grandis* stand in South Africa. Aus. For. 69:48-57.

- 395 Ferreira, J.M. de A., and Stape, J.L. 2009. Productivity gains by fertilization in
396 *Eucalyptus urophylla* clonal plantations across gradients in site and stand
397 conditions. Southern Forests, in press.
- 398 Hubbard, R.M., Stape, J.L., Ryan, M.G., Almeida, A.C., and Rojas, J. 2010. Effects of
399 irrigation on water use and water use efficiency in two fast growing eucalyptus
400 plantations. For. Ecol. Manage., this issue.
- 401 Hunter, I. 2001. Above ground biomass and nutrient uptake of three tree species
402 (*Eucalyptus camaldulensis*, *Eucalyptus grandis* and *Dalbergia sissoo*) as affected
403 by irrigation and fertiliser, at 3 years of age, in southern India. For. Ecol.
404 Manage. 144:189-200.
- 405 Linder, S., 1985. Potential and actual production of Australian forest stands. In:
406 Landsberg, J.J., Parsons, W. (Eds.), Research for Forest Management. CSIRO,
407 Melbourne, pp. 11–35.
- 408 Madeira, M.V., Fabião, A., Pereira, J.S., Araújo, M.C., and Ribeiro, C. 2002. Changes in
409 carbon stocks in *Eucalyptus globulus* Labill. plantations induced by different
410 water and nutrient availability. For. Ecol. Manage. 171:75–85.
- 411 Ryan, M.G., Binkley, D., Fownes, J., Giardina, C., and Senock, R. 2004. An
412 experimental test of the causes of age-related decline in forest growth. Ecol.
413 Mon. 74:393-414.
- 414 Ryan, M.G., Stape, J.L., Binkley, D., 2010. Whole-rotation production ecology in the
415 Brazil Eucalyptus Potential Productivity Project. For. Ecol. Manage., in review,
416 this issue.
- 417 SAS Institute (2000) SAS Software version 8.2. SAS Institute Inc., Cary, NC.

- 418 Stape, J.L., Binkley, D., and Ryan, M.G. 2004b. *Eucalyptus* production and the supply,
419 use and the efficiency of use of water, light and nitrogen across a geographic
420 gradient in Brazil. For. Ecol. Manage. 193:17-31.
- 421 Stape, J.L., Binkley, D., and Ryan, M.G. 2008. Production and carbon allocation in a
422 clonal *Eucalyptus* plantation with water and nutrient manipulations. For. Ecol.
423 Manage. 255:920-930.
- 424 Stape, J.L., Ryan, M.G. and Binkley, D. 2004a. Testing the 3-PG process-based model to
425 simulate *Eucalyptus* growth with an objective approach to the soil fertility rating
426 parameter. For. Ecol. Manage. 193:219-234.
- 427 Stape, J.L., Binkley, D., Jacob, W.S. and Takahashi, E.N. 2006. A twin-plot approach to
428 determine nutrient limitation and potential productivity in *Eucalyptus* plantations
429 at landscape scales in Brazil. For. Ecol. Manage. 223:358-362.
- 430 SYSTAT. 2004. SYSTAT 11.0. SPSS Science, Chicago.
- 431 Thornthwaite, C.W., and Mather, J.R. 1957. Instructions and tables for computing
432 potential evapotranspiration and the water balance. Publ. Climat. 10:185-311.
- 433 Queiroz, R.D.S. and Barrichelo, G. 2008 The eucalyput: a century in Brazil. Duratex
434 S.A., São Paulo.
- 435 Whitehead, D. and Beadle, C.L. 2004. Physiological regulation of productivity and
436 water use in *Eucalyptus*: a review. For. Ecol. Manage. 193:113-140.

437 Table 1. Site and plantation descriptions. Soil attributes for a depth of 0 to 40 cm.

Site code,location	Latitude (S), Longitude (W)	Elevation (m)	Soil Order	pH (0.1	Sum Base	Clay (%)	Genetic clone	Planting date
				<i>M</i> CaCl ₂)	cations mmol.kg ⁻¹			
ARA- Aracruz, ES	19° 49', 40° 05'	12	Ultisol	4.0	23	37	3918	March 2001
CEN- Guanhaes, MG	18° 46', 42° 55'	220	Oxisol	4.0	21	65	57,13,74,86	April 2004
IPB- Mogi Guacu, SP	22° 21', 46° 58'	312	Oxisol	6.0	75	45	H13	October 2000
SUZ- T.Freitas, Bahia	18° 02', 39° 52'	84	Ultisol	4.4	27	21	10	December 2001
VCP- L.Antonio, SP	21° 32', 48° 22'	680	Entisol	3.9	8	34	37	March 2000
VER- Eunapolis, Bahia	16° 21', 39° 34'	187	Ultisol	4.3	35	37	53	March 2001
VIP- L.Antonio, SP	21° 32', 48° 22'	680	Entisol	3.9	12	28	41	August 2003
VLM- Bocaiuva, MG	17° 20', 43° 50'	900	Oxisol	5.5	42	48	1,3,4,63	February 2005

438 Table 2. Climate characteristics for the sites (site codes in Table 1). Values are annual averages across years, measured or estimated at
 439 each site. Values for the wet season are October to March, those for the dry season are April to September. Potential evapotranspiration
 440 based on equations from Thornthwaite and Mather 1957).

	ARA	CEN	IPB	SUZ	VCP	VER	VIP	VLM
Average Annual Temperature (°C)	23.6	19.4	21.6	23.1	22.0	23.0	22.7	23.6
(Dry season; wet Season)	(22.3; 24.9)	(18.3; 20.6)	(19.6; 23.2)	(20.4; 25.1)	(20.8; 24.2)	(21.3; 24.5)	(21.8; 23.6)	(20.5; 25.0)
PAR (MJ m ⁻² yr ⁻¹)	2752	2555	3055	2921	3063	3114	2949	3474
(Dry season; wet Season)	(1184; 1568)	(1150; 1405)	(1375; 1680)	(1286; 1635)	(1348; 1715)	(1339; 1775)	(1445; 1504)	(1772; 1702)
Rainfall (mm yr ⁻¹)	1360	1108	1317	1351	1307	1433	1247	848
(Dry season, wet season)	(870; 490)	(920; 188)	(1067; 250)	(905; 446)	(1072; 235)	(888; 545)	(1047; 200)	(772; 76)
Vapor pressure deficit (kPa)	0.78	0.63	1.05	0.76	1.06	0.78	1.05	1.30
Irrigation water (mm yr ⁻¹)	701	1116	796	1715	1045	846	440	1554
Total water for irrigated treatment (mm yr ⁻¹)	2061	2224	2113	3066	2352	2279	1687	2402
Potential evapotranspiration (mm yr ⁻¹)	1204	876	1024	1255	1087	1144	1124	1221
Average available soil water with and (without) irrigation (mm to 2 m depth)	100 (88)	100 (60)	100 (72)	100 (79)	100 (59)	100 (95)	95 (58)	100 (32)

441 Table 3. Total fertilization amounts added (kg of element per hectare) through the end of the rotation, or to the last measurement in 2009
 442 (see site codes in Table 1).

443

444 Treatment
(T = traditional,
 445 F = high fertilization)

SITE	Treatment	Nitrogen	Phosphorus	Potassium	Calcium	Magnesium	Boron
ARA	F	967	374	753	634	40	6
446 ARA	T	77	54	89	585	40	1
447 SUZ	F	510	219	409	229	-	2
SUZ	T	52	44	66	112	-	5
CEN	F	732	145	570	918	180	8
CEN	T	86	40	171	705	120	3
IPB	F	640	238	498	996	180	5
IPB	T	33	44	27	-	-	2
VLM	F	444	160	369	280	60	8
VLM	T	79	55	66	280	60	6
VER	F	1,012	374	797	1,074	180	5
VER	T	12	46	18	62	-	-
VIP	F	594	33	546	620	120	2
VIP	T	21	33	136	396	72	2
VCP	F	724	284	669	776	60	-
VCP	T	14	14	109	240	24	-

448 Table 4. Production ecology treatments applied at each site (see Table 1 for site codes). Three-letter treatment codes (in bold) denote in
 449 sequence Nutrient treatment, Water treatment, Stand structure treatment.

	Uniform stand structure (U)			Heterogeneous stand structure (H)	
	No fertilization (Control)	Traditional fertilization (T)	High fertilization (F)	Traditional fertilization (T)	High fertilization (F)
	Code: CNU	Code: TNU	Code: FNU	Code: TNH	
Not Irrigated (N)	CEN, VCP, VIP	ARA, CEN, IPB, SUZ, VCP, VER, VIP, VLM	ARA, CEN, IPB, SUZ, VCP, VER, VIP, VLM	IPB, SUZ, VER	
		Code: TIU	Code: FIU	Code: FIH	
Irrigated (I)		CEN, IPB, VCP, VER, VIP, VLM	ARA, CEN, IPB, SUZ, VCP, VER, VIP, VLM	ARA, IPB, SUZ, VCP, VER	

450 Table 5. Tree and stand values by treatment and site at the end-of-rotation or last measurement in 2009; site codes from Table 1,
 451 treatment codes from Table 4. Values are means with standard deviations given in parentheses (n = 4 for all sites. or n = 3 for ARA). For
 452 each site and variable, values followed by different letters differ at $P = 0.05$.
 453

Site Age (years)	Stocking (tree ha ⁻¹)	DBH (cm)	Height (m)	Site Index (m. 5 yr)	Basal Area (m ² ha ⁻¹)	Wood (Mg ha ⁻¹)	MAI (Mg ha ⁻¹ yr ⁻¹)
ARA (6.0 years)							
TNU	1100 (17) a	14.9 (0.4) b	22.7 (0.2) ab	25.2 (0.4) b	20.1 (1.2) c	109.9 (5.3) c	18.3 c
FNU	1100 (17) a	15.0 (0.3) b	22.8 (1.4) ab	26.3 (1.4) a	20.4 (0.7) c	115.1 (12.0) c	19.2 c
FIU	1111 (0) a	16.7 (0.6) a	24.4 (1.1) a	27.3 (0.7) a	26.2 (1.5) a	169.1 (13.3) a	28.2 a
FIH	1069 (17) b	15.2 (0.8) b	21.1 (1.1) b	28.1 (0.4) a	22.9 (1.6) b	144.5 (14.8) b	24.1 b
IPB (6.0 years)							
TNU	1153 (42)	17.0 (0.4) c	27.9 (0.5) b	29.9 (0.6) d	27.2 (1.9) c	153.8 (13.8) d	25.6 d
FNU	1161 (101)	17.2 (0.6) c	28.0 (0.6) b	29.8 (0.6) cd	28.1 (1.6) b	159.4 (12.5) c	26.6 c
TIU	1186 (17)	18.8 (0.9) a	29.1 (1.0) a	31.4 (0.3) ab	34.4 (2.6) a	205.8 (18.5) a	34.3 a
FIU	1161 (43)	18.2 (0.6) b	27.8 (1.4) b	31.4 (0.4) ab	32.5 (2.9) a	190.6 (20.5) b	31.8 b
TNH	1085 (84)	16.2 (0.3) d	26.0 (0.1) c	29.9 (0.4) bc	24.7 (0.8) d	137.2 (5.1) e	22.9 e
FIH	1136 (42)	17.2 (0.4) c	25.8 (0.6) c	31.5 (0.3) a	30.0 (1.2) b	173.0 (8.0) c	28.8 c
VER (6.0 years)							
TNU	1087 (29) a	18.8 (0.8) b	30.9 (0.6) bc	32.0 (0.9) c	31.1 (2.3) ab	178.7 (18) bc	29.8 bc
FNU	1064 (31) a	19.4 (1.9) ab	31.0 (1.7) bc	32.8 (1.3) bc	32.5 (6.8) ab	190.5 (49.9) ab	31.8 ab
TIU	1072 (29) a	20.5 (0.4) a	32.6 (0.6) a	33.6 (0.9) ab	36.3 (2.5) a	220.2 (16) a	36.7 a
FIU	1080 (25) a	20.3 (0.4) a	32.1 (0.3) ab	33.4 (0.8) bc	35.9 (2.1) a	214.8 (12.7) a	35.8 a
TNH	1103 (15) a	16.0 (1.3) c	26.9 (0.8) d	32.5 (1.4) bc	25.3 (4.4) c	144.4 (31.2) c	24.1 c
FIH	918 (81) b	19.3 (0.4) ab	29.9 (0.9) c	33.6 (0.5) a	29.1 (2.4) bc	176.6 (12.9) bc	29.4 bc
SUZ (5.5 years)							
TNU	1111 (0) a	15.2 (0.3) b	25.7 (0.5) b	27.1 (0.9) b	20.6 (0.8) b	117.8 (5.2) b	21.4 b
FNU	1087 (15) ab	15.5 (0.1) b	25.8 (0.1) b	26.3 (0.2) b	20.9 (0.6) b	118.7 (3.4) b	21.6 b
FIU	1041 (58) bc	17.0 (0.4) a	27.0 (1.0) a	29.4 (0.5) a	24.4 (0.8) a	145.3 (4.2) a	26.4 a
TNH	1087 (29) ab	14.5 (0.2) c	24.4 (0.4) c	27.0 (0.2) b	18.9 (0.7) c	103.9 (4.8) c	18.9 c
FIH	1018 (56) c	16.8 (0.5) a	26.2 (1.1) a	29.6 (0.8) a	23.7 (0.5) a	138.2 (8.6) a	25.1 a

CEN (5.3 years)

CNU	1111 (0)	16.8 (1.1) c	26.0 (2.2) b	28.4 (1.3) b	25.5 (3.3) b	111.9 (19.2) b	21.3 b
TNU	1095 (31)	17.8 (1.3) b	27.5 (2.9) ab	29.3 (2.7) a	27.9 (3.3) ab	127.3 (24.8) ab	24.3 ab
FNU	1111 (0)	18.1 (1) b	27.3 (2.7) ab	29.8 (2.1) a	29.5 (3.5) a	131.0 (22.6) ab	25.0 ab
TIU	1095 (31)	18.7 (1) a	27.7 (2.7) a	30.5 (0.7) a	31.2 (3.7) a	138.9 (24.8) a	26.5 a
FIU	1041 (139)	19 (1.3) a	28.3 (2.2) a	30.8 (1.0) a	30.8 (6.9) a	137.6 (29.7) a	26.2 a

VIP (4.8 years)

CNU	1318 (25) a	12.3 (0.9) d	21.6 (2.2) c	26.0 (2.0) c	16.6 (2.8) d	68.7 (25.1) c	14.5 c
TNU	1210 (22) b	15.3 (0.4) c	24.4 (1.2) ab	28.6 (0.7) b	23.3 (1.2) c	114.1 (15.0) b	24.0 b
FNU	1266 (76) ab	15.4 (1.0) c	23.0 (3.2) bc	29.0 (1.1) b	24.9 (2.4) c	114.1 (31.2) b	24.0 b
TIU	1310 (25) ab	16.5 (0.3) b	24.7 (1.5) ab	30.8 (0.8) a	30.0 (1.0) a	150.7 (18.8) a	31.7 a
FIU	1088 (92) c	17.3 (0.9) a	25.0 (1.9) a	31.3 (0.5) a	27.6 (3.4) b	133.3 (35.3) a	28.1 a

VLM (4.5 years)

TNU	1018 (185)	14.3 (0.7) b	21.6 (1.7) b	26.5 (1.4) c	16.3 (1.6) c	93.7 (12.2) b	20.8 b
FNU	1080 (62)	14.5 (0.6) b	22.1 (2) b	28.0 (2.0) b	18.2 (1.1) b	108.1 (18.5) b	24.0 b
TIU	1056 (108)	17.2 (0.4) a	24.8 (1.9) a	30.0 (1.6) a	24.8 (2.1) a	168.1 (24.2) a	37.4 a
FIU	1056 (89)	17.3 (0.5) a	24.9 (1.8) a	30.8 (2.2) a	25.1 (1.5) a	171.0 (21.0) a	38.0 a

VCP (2.8 years)

CNU	966 (170) ab	11.1 (0.9) c	17.2 (0.9) c	26.0 (1.1) b	9.7 (1.3) d	31.2 (5.3) d	11.4 d
TNU	1041 (52) a	12.4 (0.1) b	18.3 (0.5) b	26.8 (0.7) b	12.8 (0.4) c	43.7 (0.9) c	15.9 c
FNU	1056 (68) a	12.5 (0.2) b	18.0 (0.5) b	26.4 (0.8) b	13.2 (0.5) c	45.2 (2.3) c	16.5 c
TIU	948 (29) ab	14.2 (0.2) a	20.0 (0.7) a	29.2 (0.5) a	15.4 (0.4) b	59.7 (2.7) b	21.7 b
FIU	1080 (35) a	14.3 (0.3) a	20.2 (0.7) a	29.9 (0.5) a	17.7 (0.4) a	69.8 (3.0) a	25.4 a
FIH	894 (90) b	14.5 (0.3) a	19.5 (0.2) a	29.5 (0.6) a	15.2 (0.7) b	60.3 (2.4) b	22.0 b

454 Table 6. Mean annual increment of stemwood biomass at the end-of-rotation (6 years-old) or at the last measurement by site (codes in
 455 Table 1) and treatment or factor (treatment codes from Table 4). Values inside parenthesis are standard errors of the mean; for the
 456 irrigation (N and I) and stand structure (H and U), values followed by the same letter do not differ at $P = 0.05$ (see Table 5 for the other
 457 treatments comparisons).
 458

Site (Age)	Mean Annual Increment ($\text{Mg ha}^{-1} \text{ yr}^{-1}$)								
	CNU	TNU	FNU	TIU	FIU	N	I	H	U
ARA 6.0y		18.3(0.5)	19.1(1.1)		28.1(1.2)	19.1(1.1) b	28.1(1.2) a	24.0(1.4)	28.1(1.2)
VER 6.0y		29.7(1.5)	31.7(4.1)	36.7(1.3)	35.8(1.0)	30.7(2.0) b	36.2(0.8) a	26.7(1.6) b	32.7(1.4) a
IPB 6.0y		25.6(1.1)	26.5(1.0)	34.3(1.5)	31.7(1.7)	26.1(0.7) b	33.0(1.1) a	25.8(1.1)	28.7(1.5)
SUZ 5.7y		21.4(0.4)	21.5(0.3)		26.4(0.3)	21.5(0.3) b	26.4(0.3) a	22.0(1.2)	23.9(0.9)
CEN 5.3y	21.3(1.8)	24.2(2.3)	24.9(2.1)	26.4(2.3)	26.2(2.8)	24.6(1.4)	26.3(1.7)		
VIP 4.8y	14.4(3.0)	24.0(1.5)	24.0(3.2)	31.7(1.9)	28.0(3.7)	24.0(1.6) b	29.9(2.0) a		
VLM 4.5y		20.8(1.3)	24.0(2.0)	37.3(2.6)	38.0(2.3)	22.4(1.2) b	37.6(1.6) a		
VCP 2.8y	11.3(1.1)	15.9(0.1)	16.4(0.4)	21.7(0.5)	25.4(0.5)	16.1(0.2) b	23.5(0.7) a	21.9(0.4) b	25.4(0.5) a
Average	16.2(1.7)	22.6(0.8)	23.7(1.0)	31.3(1.3)	30.0(1.0)	23.5(0.7) b	30.6(0.8) a	24.4(0.7)	28.0(0.8)
Gain/Loss	-28%	--	+ 4%	+ 32%	+ 27%	--	+ 30%	-13%	--

459

460 Figure 1. Location of the 8 BEPP sites (site codes in Table 1).



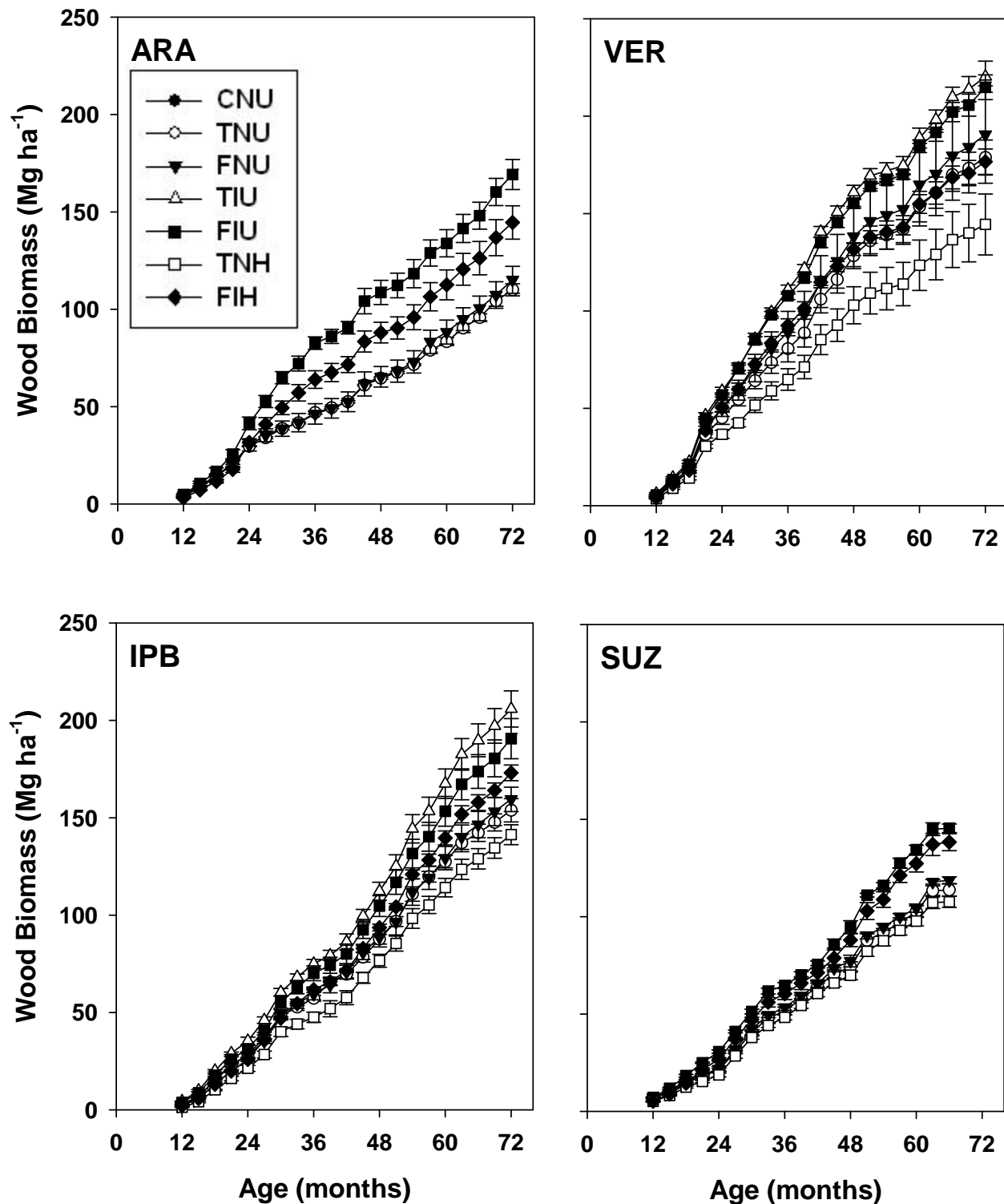
461



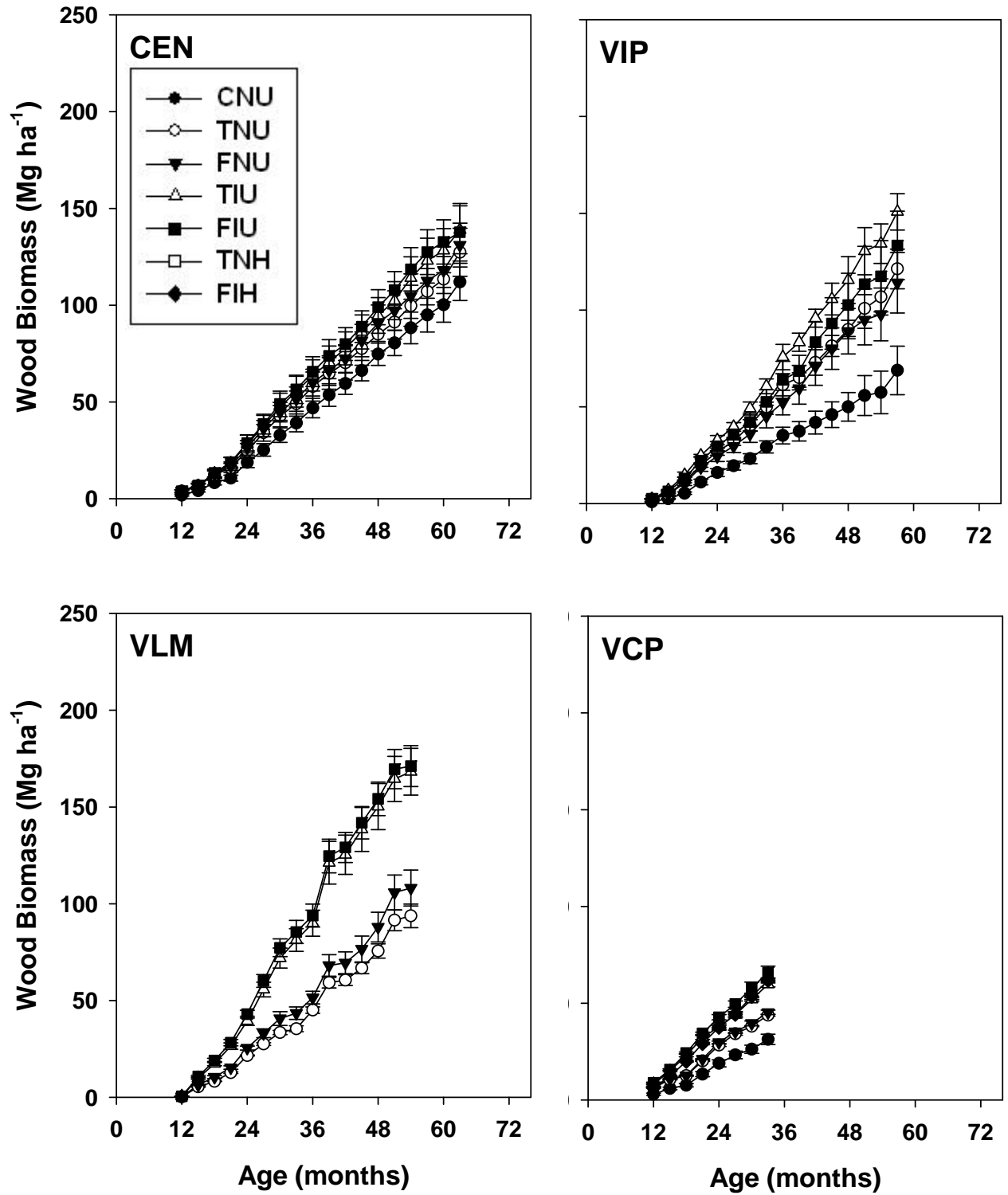
462

463 Figure 2. Upper: Aerial photograph of one of the BEPP site (IPB), at Mogi Guacu, SP at
464 4 months old (with lines traced on the photo to show plot boundaries). Notice the
465 uniform plots and the heterogeneous plots developing in response to staggered planting
466 times within plots. Lower: Boundary between uniform and heterogeneous treatment at
467 the IPB site at 2.5 yr.

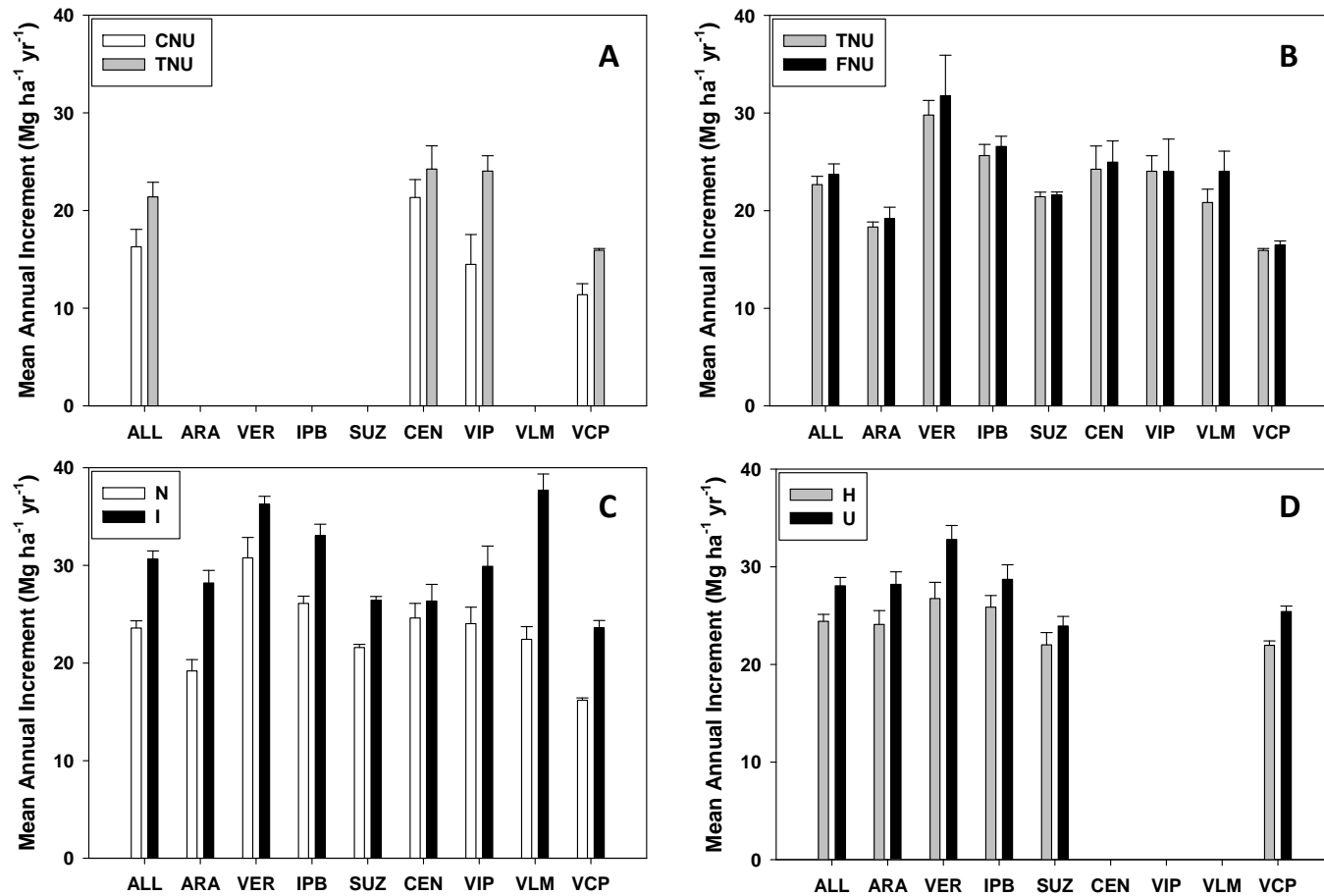
468 Figure 3. Wood mass accumulation for each site (codes in Table 1) in relation to
469 treatments (codes in Table 4). Error bars are standard errors of the means of 4
470 plots/site (3 for ARA).



471 Fig. 3, (continued)

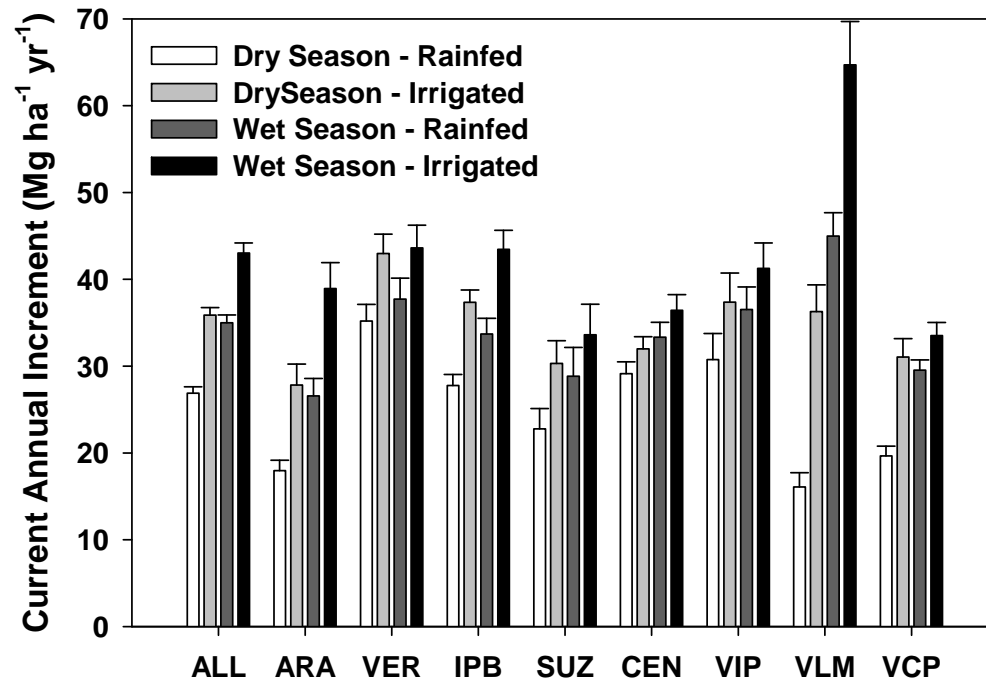


472 Figure 4. Mean annual increment effect (for the entire period) for no fertilization versus traditional (current operational) fertilization without
 473 irrigation (A); traditional fertilization versus high fertilization without irrigation (B); the overall effect of irrigation (C), and the overall effect of
 474 stand structure (D). In all graphs, the first pair of bars presents the grand mean across sites (site codes in Table 1, treatment codes in
 475 Table 4). Error bars for the sites are the standard errors among plots within sites, and for the grand means the error bars are the standard
 476 variance among sites.



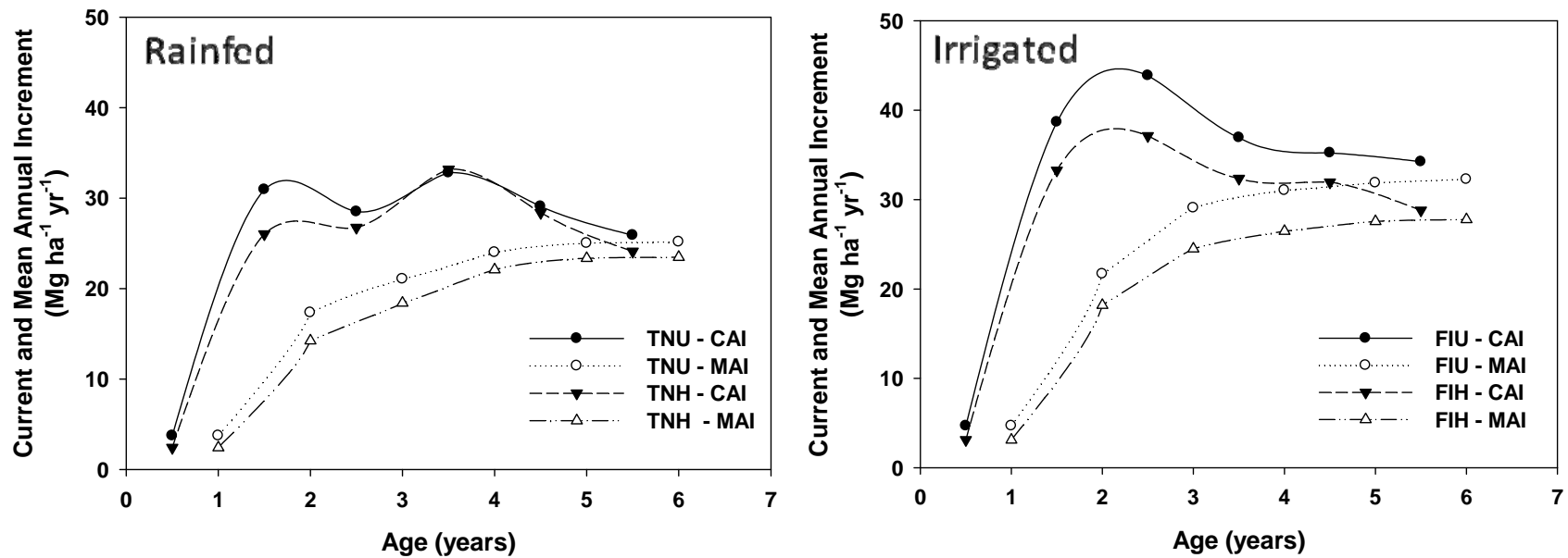
477 Figure 5. Annualized rate of growth for comparing dry season and wet season patterns (site codes in Table 1). With irrigation, wet-season
 478 growth was 19% greater than in the dry season, matching the difference in incoming light. Without irrigation, the wet season grew 27%
 479 more than the dry season. Bars are standard errors of the mean within each site (n=4 except ARA = 3; and for grand mean (all), bars are
 480 standard errors of the mean for 8 sites.
 481

482

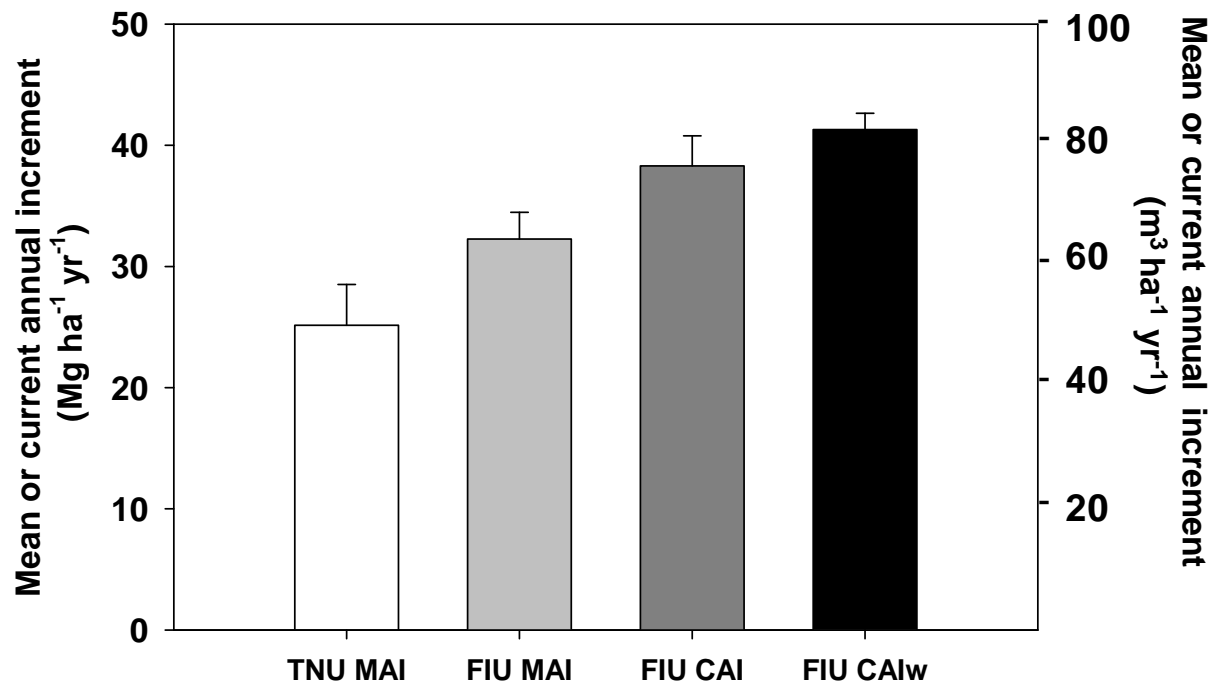


483 Figure 6. Current and mean annual wood increments for the three sites (ARA, IPB, and VER) with a full rotation of measurements. The
 484 expected decline after reaching full canopy development was apparent in all four treatments (left), but relatively minor; uniform stands did
 485 not show less decline (as predicted by Binkley et al. 2002, Binkley 2004).

486



487 Figure 7. Potential productivity may be characterized in various ways. These bars represent the growth for the three sites that completed a
488 full rotation (ARA, IPB, VER). The first bar is the mean annual increment for current operational silviculture (TNU MAI), and the second bar
489 (FIU MAI) shows the rotation-long gains that may be obtained from irrigation. The third bar represents average annual growth for the
490 period once full canopies have developed (18 months), and the final bar represents the biological maximum based on the full-canopy
491 portion of the rotation, just for the wet, high-sunlight season.
492



493 Figure 7. Changes in full-rotation yields estimated from mid-rotation responses; MAI for
494 the entire rotation (ARA, IPB, VER sites) related very strongly to CAI from year 2 to 3
495 (upper), as well as to MAI at year 3 (middle; the relationship with CAI was stronger), and
496 the increase in site index also corresponded well with biomass gains (bottom).
497

498

