A twin-plot approach to determine nutrient limitation and potential productivity in Eucalyptus plantations at landscape scales in Brazil

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Abstract

Many forest experiments test for nutrient limitation in replicated fertilization trials at one or several locations, providing a poor basis for extrapolation across large landscapes. We present an experiment that paired control and treated plots at 127 locations (with similar initial wood biomass, “twin-plot”), providing no experimental replication within sites, but strong replication within the population of stands across the landscape. This twin-plot approach, with 6-month period re-measurements, showed that forest productivity increased from 19.6 to 24.4 Mg ha⁻¹ yr⁻¹, representing an average response to heavy application of fertilization of 4.8 Mg ha⁻¹ yr⁻¹ (10 m³ ha⁻¹ yr⁻¹) for 2 years. The response in stands derived from clonal plantlets and seedlings was the same, although the fertilized clonal stands were 48% more productive than stands derived from seedlings. Older stands of both types were more responsive than younger stands, with a 0.6 Mg ha⁻¹ yr⁻¹ increase in growth for each additional year of age. Coarse-textured Entisols showed twice the response that developed in more-productive, fine-textured Entisols. The growth response was much smaller during the dry season (4.5 Mg ha⁻¹ yr⁻¹) than in the rainy season (9.4 Mg ha⁻¹ yr⁻¹). Analysis of growth by treatment and season allowed us to estimate the potential productivity of the sites, which averaged 29.1 Mg ha⁻¹ yr⁻¹ (62 m³ ha⁻¹ yr⁻¹). The twin-plot design is relative simple and inexpensive, and can be used in conjunction with routine inventory designs to guide decisions about overall stand silviculture.

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Forest productivity is limited by the supplies of one or more nutrients in almost all forests, and forest nutrition management is a key issue in the management of commercial forests. Many forests are also limited by the supply of water. The potential response of forests to fertilization is typically assessed using experimental applications of one or more nutrients (at one or more rates) in a replicated blocked design within one or several stands. This design tests whether the growth of trees in fertilized plots is higher than the growth in control plots, or if the rate of growth response increases with increasing rates of fertilizer application. Classic experimental designs (such as described in Cochran and Cox, 1978) might provide a strong basis for evaluating some of the processes that underlie the overall growth response of the stand (such as changes in leaf area or belowground production). However, the classic design of replication within a single site provides no statistical basis for estimating the degree of nutrient limitation across a landscape, or the economics of operational fertilization. This limited design of experiments is a widespread problem in forest research; we tallied the number of experiments reported in volumes 200, 202, and 203 of Forest Ecology and Management, and found that one-third of stand-level experiments had no replication beyond a single stand.

If the population of interest is a landscape of forests across a range of soil types, stand ages, and other factors, then experimentation on nutrition management needs to sample this
population representatively. High precision in the results of an experiment at a single stand may be of little value in estimating the response of across a population of stands. We describe a “twin-plot” approach for determining nutrient limitation in forest landscapes (Stape et al., 2004), and illustrate the value of the approach with a case study from Eucalyptus plantations in Brazil. The twin-plot method entails the establishment of many pairs of plots, with one control and one treatment plot at each location. The control plot is the normal permanent plot of the inventory network, which measures the real productivity of the forest under the traditional company management. The nearby twin-plot will be under intensive management (high fertilization, weed and pest controls) in other to remove, or minimize, the constraints to forest productivity. This design provides no degrees of freedom for testing the growth response within each individual stand, but many degrees of freedom for estimating the response across the population of stands in the landscape. The twin-plot method also provides opportunities for combining information on nutrient limitation and fertilization response with geographic information systems, and may provide a basis for parameterization of production models (Landsberg, 2003).

The potential productivity of plantations may also be constrained by the supply of water, and the calibration of productivity models such as 3-PG, ProMod and Cabala (Landsberg and Waring, 1997; Almeida et al., 2004; Dye et al., 2004; Battaglia and Sands, 1997; Battaglia et al., 2004) requires information on the degree of soil nutrient limitation and the maximum potential rate of photosynthesis. The twin-plot approach can provide a robust dataset for parameterizing and testing physiologically based models of productivity by providing a quantitative estimate of soil fertility (Stape et al., 2004), and maximum potential growth rates during periods of high water availability.

In this paper, we used a twin-plot approach to examine the extent and degree of nutrient limitation across large region of Eucalyptus plantations. We also evaluated the maximum potential productivity of these plantations by examining the growth rates during the 6-month rainy season.

1. Site description and methods

A total of 131 twin-plots were installed at Votorantim Pulp and Paper Company (VCP) in Eucalyptus plantations in São Paulo state, based on a random sample of 1875 inventory plots arrayed across 40,500 ha of plantations (Fig. 1). The twin-plots were located 15–20 m from the control (inventory) plots, using the same plot layout. By October 2001, all twin-plots were installed. Four pairs of plots were disturbed over the following 2 years, leaving 127 pairs of plots for our analysis. The span of randomly selected plots included from 9 to 44 plots in each annual age class (<2.5, 3.5, 4.5 and >5.5 years old), 7–40 plots in each of six soil classes (three Entisols and three Oxisols), and 12–42 plots in each 2-m class of site index (dominant height at 5 yr basis, <21, 23, 25, 27 and >29 m). Each plot consisted of 7 × 10 rows of trees; the spacing between trees varied from 3 m × 2.5 m, 3 m × 3 m or 6 m × 1.5 m spacing, yielding a range in plot sizes from 388 to 767 m², and 29–84 trees per plot. Twenty-eight of the plantations originated from seedlings (E. grandis), and 99 from clonal plantlets (E. grandis × urophylla). The treatment plot in each pair received an initial application, by October 2001–February 2002, of 180 kg N ha⁻¹, 50 kg P ha⁻¹, 150 kg K ha⁻¹, 800 kg Ca ha⁻¹, 180 kg Mg ha⁻¹, 180 kg S ha⁻¹, as well as 5 kg B ha⁻¹, 27 kg Zn ha⁻¹, 3 kg Cu ha⁻¹, 9 kg Fe ha⁻¹, 6 kg Mn ha⁻¹, and 0.3 kg Mo ha⁻¹. After this initial application, each treated plot received three additional doses (December 2002, April 2003 and October 2003) of 180 kg N ha⁻¹, 35 kg P ha⁻¹, and 150 kg K ha⁻¹. Control of weeds (with glyphosate) and pests (leaf-cutting ants, sulfluramid) were included in the intensive twin-plot treatment. However, VCP has a very intensive weed and pest control system, and we expect that almost all of the twin-plot response related to improved nutrition.

Tree measurements were done every 6 months, from April 2002 (plantation ages ranged from 26 to 87 months) to April 2004. We measured all tree diameters and 20% of tree heights; heights of other trees were estimated with a site-specific hypsometric regression (ln(H) = a + b/DBH). Tree volume was
estimated by applying a local generated volume (m$^3$) regression equation to tree diameter (DBH, in cm) and height (H, in m):

$$\text{volume} = 0.000053 \times DBH^{1.9088} \times H^{0.9544}$$

$$\text{(n = 198, } r^2 = 0.994, P < 0.0001)$$

Volume was converted to mass based on the specific density of wood for each species or clonal variety, which ranged from 0.450 to 0.572 Mg/m$^3$. Wood biomass increment, per hectare per year, was the sum of the net increment of each tree during the year, expanded to a hectare basis based on the plot area.

The maximum potential productivity was determined as the average wood increment for the two wet seasons (October–April) in the treated plots, assuming that any nutrient limitation was alleviated by the fertilization treatment, and water limitation was absent during the rainy season (with typical precipitation of >100 mm/month, Fig. 2).

Linear regressions were used to test for initial differences in wood mass between the control (inventory) and treated (twin) plots; for the difference in increment over the following 2 years; and for the relationship between initial stand age and treatment response. Analyses of variance were used to test for the effect of soil type (testing both soil orders and texture classes within orders), and tree type (seedling or clone). All analyses were performed with SYSTAT version 6.0.

2. Results and discussion

As expected, the control and treatment plots did not differ within each pair before treatment (77.1 Mg ha$^{-1}$ versus 77.6 Mg ha$^{-1}$, as twins, Fig. 3), and heavy fertilization led to large increases in wood increment, from 19.6 to 24.4 Mg ha$^{-1}$ yr$^{-1}$, representing an average response of 4.8 Mg ha$^{-1}$ yr$^{-1}$ for 2 years. With an average wood density of 0.47 Mg/m$^3$, the increase in volume increment was about 10 m$^3$ ha$^{-1}$ yr$^{-1}$ for the 2 years. The response was lower in stands with higher increments in control plots ($P < 0.001$; Fig. 4). Stands that averaged 10 Mg ha$^{-1}$ yr$^{-1}$ without fertilization responded with about 7 Mg ha$^{-1}$ yr$^{-1}$ of increased growth, compared with just 2.5 Mg ha$^{-1}$ yr$^{-1}$ for stands that averaged 30 Mg ha$^{-1}$ yr$^{-1}$ without fertilization.

Growth response did not differ on average between Entisols and Oxisols ($P = 0.31$, Fig. 4, Table 1), though within Entisols, plantations on coarse soils responded more strongly than finer textured soils ($P = 0.04$, Fig. 5, Table 1). Seedlings versus clonal plantlets differed strongly in average increment ($P < 0.0001$), but not in response to fertilization ($P = 0.66$). However, the effect of genetic origin contributed marginally ($P = 0.07$) to the relationship between increment and fertilization response; with increasing control-plot increment, clones were more likely to decline in response. The increment of the plantations declined strongly with stand age, averaging 28 Mg ha$^{-1}$ yr$^{-1}$ at 30 months, and just 16 Mg ha$^{-1}$ yr$^{-1}$ at 70 months (Fig. 6, Table 1). The response to fertilization may have been influenced by plantation age at the time fertilization began ($P = 0.06$), with the response of 30-month-old stands averaging 3.5 Mg ha$^{-1}$ yr$^{-1}$ compared with 5.3 Mg ha$^{-1}$ yr$^{-1}$ for 70-month-old stands (response = 2.1 + 0.05 age, Fig. 6). However, the plantation age is partially confounded with silvicultural technology, as VCP Company increased its operational rates of fertilization in recent years. Nevertheless, the results can be used immediately for operational purpose in
similar sites. The density of trees in the plantations, ranging from 679 to 1377 trees/ha, did not influence increment in control plots ($P = 0.32$) or fertilization response ($P = 0.24$).

The profitability of silvicultural practices may depend strongly on the distribution of responsiveness among stands, rather than on the mean response (Fisher and Binkley, 2000). Twenty percent of all plots showed double the average response to fertilization (Fig. 5). Among the Entisols, about 20% of the coarse-textured sites responded with more than double the average response, and 24% of these sites fell below the average. The fine-textured Entisols, in contrast, had only 14% of sites showing double the average response and 71% showing less than average response. This type of information can be analyzed with formal approaches for making decisions under known uncertainty, and for estimating the likely value of research that increase the accuracy of identifying highly responsive and weakly responsive sites.

Our estimates of maximum potential productivity averaged 10 Mg ha$^{-1}$ yr$^{-1}$ greater than the increment in control plots (a 50% increase, Fig. 7). The maximum productivity correlated strongly with the increment in control stands ($r^2 = 0.33$, $P < 0.0001$), and older stands showed lower maximum potential productivity than younger plots ($r^2 = 0.13$, $P < 0.0001$). The average for 30-month-old stands was 35.0 Mg ha$^{-1}$ yr$^{-1}$, compared with 26.8 Mg ha$^{-1}$ yr$^{-1}$ for 70-month-old stands. Clonal stands also showed higher potential productivity (30.3 Mg ha$^{-1}$ yr$^{-1}$) than seedling-origin stands (24.6 Mg ha$^{-1}$ yr$^{-1}$), but the difference depended solely on the higher overall productivity of clonal stands; the difference between control increment and maximum potential increment was about 10 Mg ha$^{-1}$ yr$^{-1}$ for both clones and seedlings. Oxisols had somewhat higher potential productivity (31.0 Mg ha$^{-1}$ yr$^{-1}$) than Entisols (28.1 Mg ha$^{-1}$ yr$^{-1}$; $P = 0.04$). Interestingly, the potential productivity did not differ among the texture classes for Entisols ($P = 0.64$), unlike both the current increment and the overall treatment response. We speculate that the response to fertilization on coarse-textured Entisols may include a larger increase in efficiency of water use than on the fine-textured Entisols (Binkley et al., 2004).

This illustration of the twin-plot method focused on a single level of fertilization with weed control, with multiple elements to ensure the trees experienced no nutrient limitation. The design can be broadened to include additional treatments, such as single-nutrient treatments, a range of rates, and inclusion of variable weed control. The key would be to include only a single replicate of each treatment at each location, investing the...
replication efforts across locations as a basis for extrapolation to landscapes.

As described by Stape et al. (2004), the response of plots to fertilization can be used to parameterize the soil fertility rating in models such as 3-PG and ProMod (Landsberg, 2003; Battaglia and Sands, 1997). A class of stands that showed little response to fertilization (such as the fine-textured Entisols in this experiment) would have high site fertility, with a near-maximum fertility rating. A class of stands with a strong fertilization response (such as the coarse-textured Entisols) would have a low fertility rating. The same approach might be used to validate estimates of water supply effects on stand growth by gauging productivity in heavily fertilized plots in years of high versus low rainfall (Fig. 7).

From an operational point of view, the twin-plot approach was able to determine, very quickly and at the landscape level, the gap between the real and the potential Eucalyptus productivity. Decision makers can evaluate tradeoffs between increasing wood production through greater investment in purchasing new forest land, or raising the productivity of existing stands from current inventory rates of 19.6 Mg ha\(^{-1}\) yr\(^{-1}\) (41 m\(^3\) ha\(^{-1}\) yr\(^{-1}\)) to the maximum fertilized rates of 24.4 Mg ha\(^{-1}\) yr\(^{-1}\) (51 m\(^3\) ha\(^{-1}\) yr\(^{-1}\)). These sorts of analyses are fostered by experiments designed with across-site replication, rather than within-site replication on one or a few sites.

The twin-plot design was also able to estimate the potential productivity of the sites (29.1 Mg ha\(^{-1}\) yr\(^{-1}\), 62 m\(^3\) ha\(^{-1}\) yr\(^{-1}\)), demonstrating the magnitude of water restriction to growth, and providing a basis for evaluating information at the soil, leaf and canopy level in relation to factors driving forest productivity in the tropics.

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