Minimum data for forest plantation management*

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Introduction

Forest plantations, exotic species, and monocultures are a source of controversy in relation to their environmental impact and their role in sustainable development. They are accused of using up water, damaging the soil, causing pollution with their industrial products, displacing indigenous peoples and generating other social conflicts, altering the landscape, accelerating the destruction of natural forests, diminishing wildlife and biodiversity. It is not my intention to analyze here these issues over which much has been written. It is sufficient to say that each and every one of these objections is valid, somewhere. It does not seem useful to discuss these problems as generalized abstractions, in a vacuum, without examining specific situations and considering the alternatives. Water consumption may not be that important in a location that receives 2500 mm of rain. Forestry may be bad, but not much worse than goat or sugar cane farming. Capturing solar energy through photosynthesis may be quieter and have a lower impact on the landscape than windmill farms or solar panel arrays. It may be preferable to obtain firewood from plantations instead of from the natural vegetation. Etc. There are instances where intensive plantation forestry is clearly beneficial (at least to humans), making an important contribution to the sustainability of life on earth.

Rational forest management requires data and information about the resource that may be scarce, unreliable or nonexistent. This is often the case with forest plantations, which frequently are new developments that evolve rapidly without much previous local experience. We discuss the typical

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information requirements, and some approaches to acquiring the necessary data used in a research program in Chile.

Forestry information and modelling systems

A forestry organization dealing with intensively managed wood production plantations should have a system similar to that depicted in Fig. 1 (see also Shirley, 1984). Arrows indicate outputs used by other components. The focus here is on decision support for forest management planning. Obviously, there is much more necessary information that has not been included in this view, such as the technical details of establishment techniques, nutrition, tree improvement, etc.

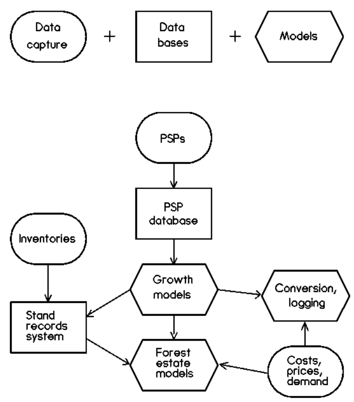

Figure 1: Forestry information and modelling system.

The functions of this information and modelling system are prediction, control, and monitoring. That is, figuring out what will happen, what is happening, and what has happened. A stand database keeps track of the current state of the forest. This data is collected through periodic forest inventories, and it may be kept up-to-date with the help of growth models. In most instances the evaluation of stand management alternatives on a per-hectare basis is inadequate, and planning must take care of forest-wide considerations (or region-wide, or nation-wide, depending of the agency doing the planning). This is the purpose of the forest planning or forest estate models (García, 1990b). They use the stand data, and require also growth predictions, and financial and other resource information. Conversion and logging models may help to estimate yields and costs as a function of projected stand conditions. Growth models are developed and validated with data from remeasured, or permanent, sample plots (PSPs).

A case study: eucalypt plantations in Chile

Chile stretches over 4300 km in a narrow strip between the southwest coast of South America and the Andes Mountains. The climate varies between desertic in the north, through mediterranean in the center, to cold and wet in the extreme south. Of a total of 76 million hectares (Mha), 34 Mha are classified as potentially productive forest lands. There are some 7 Mha of native forests left, and 1.7 Mha of forest plantations. However, forestry is dominated by radiata pine plantations, which with 1.4 Mha account for 15 of the 20 million m^3 of industrial roundwood production. To this must be added an estimated fuelwood consumption of 9 million m^3, 61% from native forests, 22% eucalypts, and 15% radiata pine (Instituto Forestal, 1993).

Plantation forestry has a relatively long history in Chile, with radiata pine and Eucalyptus globulus being introduced last century, and large scale planting starting in the 1930's. In the last three decades planting rates have been high, fuelled by a 75% government subsidy of the establishment and part of the administration and silviculture costs. Planting has generally been on abandoned or marginal farming and grazing lands, although currently eucalypts are sometimes competing with agricultural crops for good quality soils. In the past there have been isolated instances of clearing native forest for exotic tree planting, something now not allowed under new laws.

A new development has been a spectacular surge of interest in eucalypts. Recent planting rates are shown in figure 2. The area of eucalypt plantations has increased from 46,000 ha in 1985 to around 250,000 ha today. Among the reasons for this diversification are changes in pulp and paper technology and economics (the price of a cubic meter of eucalypt pulplogs is now about twice the price for pine), the appearance in 1984 in the South of the shoot moth *Rhyacionia buoliana*, spreading north and threatening the pine plantations, and research and promotion by Instituto Forestal (INFOR), notably of the more frost-resistant Eucalyptus nitens.

Together with the increased eucalypt planting, there has been much research and experimentation on nursery and establishment techniques, and on tree improvement (Barros A. et al., 1994). Knowledge about growth past the establishment stages is very limited, however, hampering financial evaluation and management decisions.

To address this situation, a project entitled "Biometric information and decision support systems for the management of eucalypt plantations" was

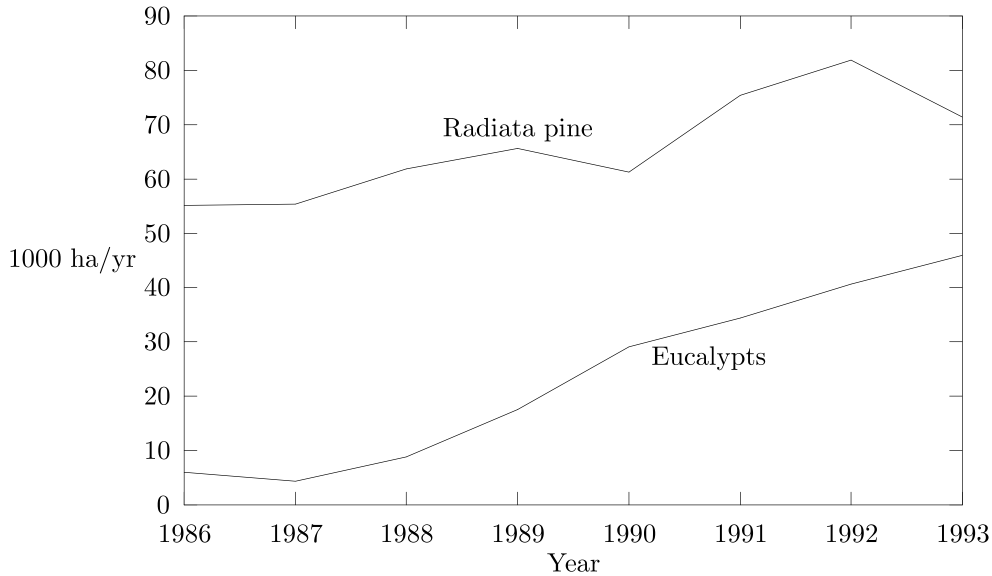

Figure 2: Planting rates (includes replanting)

prepared by Instituto Forestal (INFOR) and submitted to CONICYT, the Government Committee for Scientific and Technological Research. The three-year program was approved in January 1994, funded largely by CONICYT through FONDEF (Scientific and Technological Development Promotion Fund), with substantial contributions from 15 collaborating forestry companies and from INFOR.

The project contemplates work in four areas: *a)* Establishment. A review of techniques used and being investigated by INFOR and the forestry companies has been completed, and an attempt at quantifying the effects of various alternatives on early development is being carried out. *b)* "Static" relationships, evaluating available, and developing new volume and taper equations. *c)* Growth modelling, including preliminary models using available information, and improved versions incorporating new data to be collected. *d)* Trials and permanent sample plots.

The aim is to cover Regions V to X (approximately from latitude 33°S to 41°S), and the species *Eucalyptus globulus, E. nitens, E. regnans, E. delegatensis*, and *E. camaldulensis*. This is very much an instance of trying to develop useful management tools with minimum data. A discussion of some work on *c)* and *d)* follows.

Analysis of existing data

Currently, the main source of eucalypt growth data is a program of species introduction trials initiated by INFOR in 1962. By 1974, 7665 plots had been established in 61 locations around the country, with over 160 different tree species (Instituto Forestal, 1986). 81 species of eucalypts have been tested.

There are also some other experimental trials established by INFOR and by forestry companies, largely for testing establishment techniques, weed control, fertilizing, thinning, and other treatments. Most of the trees in these are still very young. The INFOR species introduction data is being analyzed first. The preliminary results will later be confronted with other data, to the degree that these are made available by the various companies.

Unfortunately, the species trials are far from ideal for growth modelling, having been designed with a different purpose. Plots were established with 49 plants at 3 by 3 meters spacing from Region V to the north, and with 100 plants at 2 by 2 to the south, in both instances measuring at the 25 central tree locations. Most of the measurements correspond then to 100 m^2 plots, with some of 225 m^2, which is very small. Having height measurements for all trees and not just for a subsample partially compensates for this. Planting was at 2500 or at 1111 stems per hectare, but a range of densities developed through plant failures, allowing some modelling of the effect of this variable. However, stands with less than about 600 stems per hectare (6 trees per plot) cannot be represented reliably. Most of the initial controls without a full set of DBH are not useful for modelling, and many others were eliminated for various reasons through several stages of data screening. Another difficulty is that many plots were measured in the middle of the growing season, introducing uncertainty into the effective measurement age. Lacking information on the seasonal growth of eucalypts, monthly age adjustments obtained for radiata pine in New Zealand were used.

A special problem is how to define and estimate a measure of stand top height. It is known that the usual definitions and procedures are sensitive to plot size (Fries, 1974; Matérn, 1976; Rennolls, 1978). In addition, simple approaches such as taking just the largest tree in a 100 m^2 plot would produce very large variances. After trying a few alternatives, it was decided to use a method that can be described roughly as follows. We define top height as that corresponding to the quantile of order $45/N$ in the DBH distribution, where N is the number of stems per hectare. Under some reasonable distributional assumptions, this is close to what would be obtained in 500 or 1000 m^2 plots with the usual "100 largest per hectare" methods. Given the definition, an estimation procedure is needed. This consisted in fitting a Weibull diameter distribution, a height–diameter regression, and taking the regression height for the appropriate quantile. The method produced satisfactory results, given the smallness of the samples.

After the data screening and pre-processing, the first step is to develop height growth or site index models. The height growth data was studied graphically, and models fitted for various species and geographical groupings. Not finding any large differences in growing patterns, and considering the sparsity and variability of the data, all the data for the eucalypts from the "Southern blue gum" group (*E. globulus ssp. globulus, ssp. bicostata, ssp. maidenii*, and *E. nitens*) was pooled together. The available data for the "ash" group (*E. regnans* and *E. delegatensis*), although not showing obviously different trends, appears much more variable, both within and between plots. The modelling of these species was postponed.

The method of García (1983) was used to obtain site index curves. Despite of the data consisting largely of only two measurements per plot, and of the high noise component, the curves seem reasonable (Fig. 3). A model with a common asymptote (estimated as 75.3 m) fitted the data somewhat better than an anamorphic model. The use of such a complex methodology on this kind of data might be seen as overkill. But perhaps it is with scarce, variable, and incomplete data where sophisticated methods are most needed.

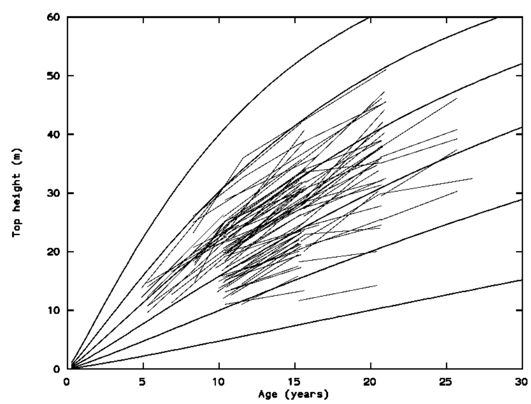

Figure 3: Site index curves and data for E. globulus and E. nitens.

Site index enters in this height growth model through a time scale parameter, that is, the site curves are anamorphic or proportional along the time axis. This fact can be used to standardize the age multiplying by a site-related factor, in order to reduce differences due to site when displaying data. Figures 4 and 5 show volume per hectare over age, without and with the site scaling. The volume was computed with an individual-tree volume equation for cubic volume above the stump, up to a 10 cm limit diameter in 3.1 m logs (Lisboa, 1960).

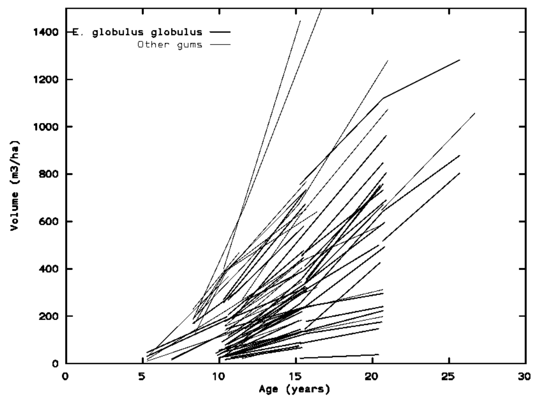

Figure 4: Volume per hectare.

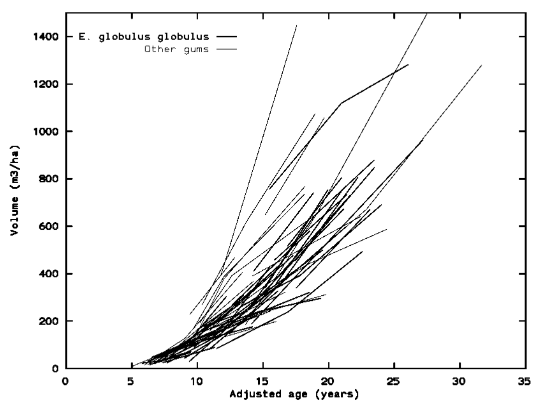

Figure 5: Volume per hectare. Age standardized to site index 35.

Although noisy, the data is not inconsistent with the observations of García (1990a) for radiata pine in New Zealand: After canopy closure gross volume increment is more or less constant, and the sigmoid of the textbooks is not evident at all, at least not within normal rotation lengths. With a much wider range of stand densities, in the radiata study it was found that the increment decreased slightly with increasing spacing. As a first approximation it could be taken here as constant, roughly 70 m^3/ha-yr for the standardized data (close to the average site). It can be seen also that, ignoring likely outliers, current annual increments can easily reach 77 m^3/ha-yr. Mean annual increment depends much of the age, site, and stand density, but some representative values could be read from the graphs. It is interesting that most of the apparent outliers correspond to *E. nitens* and to the subspecies other than *globulus*. More detailed analysis, including growth before crown closure and likely responses to thinning, is in progress.

It is probable that the improved establishment techniques used today will accelerate early growth, causing a shift of the curves toward the left. The appropriate shifts or time gains need to be assessed, using existing establishment trials, and in the longer term with the new data being collected. Plotting the initial measurements from the PSPs that have been installed this year should provide some clues.

New data

Growth modelling data requirements

With appropriate modelling techniques, long-term growth data in the form of long time series is no longer necessary. In principle, it would be sufficient to have pairs of consecutive measurements in different plots, separated by arbitrary time intervals and covering a range of ages, densities, and site qualities (García, 1994). Three or more successive measurements would be desirable, however, to check for consistency and errors, and weather variations require data over several years to ensure representative results. Although not strictly necessary, plots with long series of measurements may be useful for model evaluation and confidence building.

We can expect that, with a good coverage of growing conditions, the data obtained at the end of the first measurement year would contribute substantially to improve projections based on the older data. It may be possible to develop adjustments for the variability of weather conditions by remeasuring existing plots. After two or three years there would be a very adequate data base for model development.

In addition to remeasured sample plots, tree-ring analysis can be another source of growth data. It has been found that growth ring measurements in just a few carefully selected trees can give good estimates of previous stand conditions (García, 1992). Unfortunately, in our eucalypt plantations the formation of growth rings is highly irregular, and their structure is not a reliable indicator of annual growth. Although success seems unlikely, because of the potential benefits the possibility of finding chemical indicators might be worth exploring.

Growth measurements can be taken in plots grouped into statistically designed experiments, or in individual permanent sample plots dispersed through the forests. Both approaches present advantages and disadvantages.

Some of the advantages of experiments or trials are: The effects of certain variables can be assessed in a controlled way, maintaining other variables fixed, usually producing more conclusive comparative results. They can be installed in convenient places, with easy access and maintenance. Results of various treatments can be visually compared on site. Can be based on a "valid statistical design", keeping referees happy and allowing the use of certain traditional analysis procedures (although the usefulness of the ANOVA ritual and of concluding that treatments result in "significant differences" is debatable). They are highly visible, can be signposted and shown to managers and visitors.

On the other hand, trials are relatively expensive, requiring careful installation and maintenance, large areas of land, and plot surrounding guard strips. They are fragile, accidents can easily destroy the design and compromise the validity of the conclusions. It is possible to study only a few variables at a time. Growth conditions may be somewhat artificial, not representative of operational situations.

The virtues and defects of sets of isolated plots are complementary to those for trials: They are subject to many variables acting independently, needing more sophisticated models and analysis methods. Comparisons for the effects of specific variables are less clear and conclusive. When measuring, the effort spent in locating the plots and in moving between them can be significant. Their presence is not obvious to outsiders. On the other hand, costs are lower, being possible to treat them as part of the surrounding stand, without guard strips. The loss of a plot does not compromise the rest of the data. They tend to be more representative, sampling more widely the various stand conditions. An important consideration is that often a network of permanent sample plots is needed anyway as part of the forest enterprise information system for planning and monitoring purposes, sometimes as part of a continuous forest inventory (CFI).

In general, individual permanent sample plots distributed across existing stands are more efficient as a source of growth modelling data. Properly designed replicated trials are more effective for testing hypothesis and for comparing specific alternatives. For the eucalypt modelling project it was decided to have both a network of permanent sample plots, and a set of spacing trials. In addition, installations to determine the distribution of growth within a year were set up.

Plots in existing stands

Distributed over the range of ages, sites, stand densities and other characteristics, these permanent sample plots will immediately start producing data useful for modelling. They are intended to be used both internally for planning and monitoring purposes by each participating company, and to develop models by analyzing them together at a regional or national level.

Much thought was given initially to the questions of how many plots and where to locate them to achieve a good coverage of the various regions and sites. A number of available soil-climate classifications were considered as a basis for allocating the sample. Finally, we decided that the most practical approach was simply to set a target of about 12 plots per company for the first year. The companies were asked to provide a list of some 15 candidate stands, following certain guidelines to spread them out over the species, ages, and sites in their properties. Later, the project team selected 12 from these, taking into account the proposals from companies with neighboring or overlapping territories. The coverage thus obtained will be evaluated to guide next year's exercise, and INFOR will fill obvious gaps outside the company forests with additional plots.

A minimum standard for sample plots was developed, and an installation and measuring manual was prepared. The emphasis was on reliability, simplicity, and low cost. At this stage it seems preferable to have more, cheaper plots, than fewer plots with more detailed measurements. We tried to prevent sources of error, and to resist the temptation of measuring every variable we can think of.

Some characteristics of the sample plots: Square, of either 500 or 1000 m^2 to contain at least 50 trees. They are layed out with distance tape and right-angle prisms. There is no central peg, and the exact location of the starting point is strictly randomized, avoiding possible biases associated with the tendency to placing pegs away from trees. Plot sides oriented at 30° from plantation rows to reduce variability in the number of trees included in the plot. The trees are mapped with a method similar to that described by Reed et al. (1989). Although time-consuming and not strictly necessary, it was decided to determine tree coordinates partly because of possible future use in individual-tree modelling or spatial variation studies, and partly as an insurance against the loss of tree identification markings (a likely occurrence with the shedding of bark in eucalypts). Measurements must be done in winter, to reduce variability due to weather during the growing season and problems with the different patterns of seasonal growth in diameter and height. This is important with fast-growing trees. We measure DBH on all trees, and heights in a subsample of 16 trees, selected as the four closest to each corner. Only direct readings are recorded in the forms, avoiding slope corrections and hypsometer calculations in the field.

Spacing trials

Besides the plots that sample the range of conditions present in existing stands, it is desirable to obtain information on extremes, and in stands established with the most recent techniques. For this it was decided to set up trials with various initial spacings. In addition to producing data for growth modelling, a good design would allow a more precise and reliable determination of the best spacings. These trials, however, will only provide useful data in the long-term, and measurements should be continued up to rotation age.

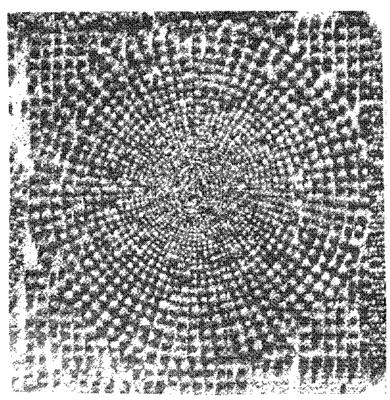

Figure 6: Aerial photograph of radiata pine Nelder plot, New Zealand.

After studying alternative designs, the choices were narrowed down to two options. One is the Nelder design (Nelder, 1962; Bleasdale, 1967), where trees are planted on the intersection between radii and concentric circles (Fig. 6). It is a systematic design, where the spacing increases gradually from the center toward the edge of the plot. The other option was based on the proposal of Lin and Morse (Lin & Morse, 1975; Amateis et al., 1988), where a number of spacing levels are assigned at random to groups of rows and columns, separated by guard rows (Fig. 7).

The Lin-Morse design is perhaps easier to set up, analysis is simpler, and it can test for rectangularity effects. In addition, it leaves open the

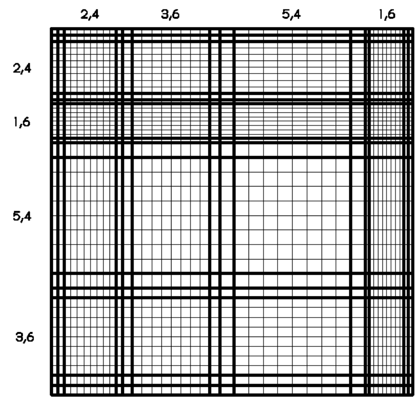

Figure 7: Lin-Morse block. Thick lines are guard rows, numbers are spacings in meters.

possibility of eventually adding a thinning on top of the trial. The Nelder plot has the advantages of not wasting plants in guard rows (except in the center and in the periphery), of being able to visualize the effects of spacing simply by walking along a radius, and of being more spectacular, with nice aerial photos for papers and annual reports.

The decision was to establish at least one Lin-Morse block per company. For cost reasons we did not ask for full trials with the three or four replications usually recommended (risking the ire of the variance analysts). Ideally there will be, however, a replication in the second or third year, and often it will be appropriate to combine blocks from several locations into a joint analysis.

Considering cost, compactness, precision, and desired results, the specific design in Fig. 7 was devised, similar to that of Amateis et al. (1988), with four spacing levels, 7×7 rows per plot, and 3 guard rows. The spacing level permutations are chosen at random in each instance. The levels differ from those of Amateis et al. (1988) in that here they follow a geometric progression. This is advantageous in generating within each block plots with the same number of plants per hectare but different rectangularity, and plots with the same rectangularity but different number of plants. The following set of four spacing levels (in meters) are in a geometric progression, are round numbers, and cover the range of interest including reasonable extremes: 1.6 2.4 3.6 5.4 . Other possibilities are 1.20 1.80 2.70 4.05, and 1.25 2.00 3.20 5.12 . In each block there are two plots with the same density and rectangularity, and in the future one of them could be thinned if so desired.

Intra-annual growth

Especially with fast-growing plantations, it is important to know how growth is distributed within the year. This information can be used for measurement date adjustments when fitting or using models, and to decide on the best dates for PSP measurement.

With this purpose, in one PSP from each company, 10 trees were selected for periodic DBH growth measurement, and 5 for height measurement. For DBH, vernier band dendrometers have been installed (Liming, 1957; Auchmoody, 1976). Heights are determined with telescopic rods, or with a hypsometer supported on top of fixed 1.5m-high poles. The sample trees were selected with the OSP[3] procedure described in García (1992), a systematic/variable-probability sampling method that provides good estimates of plot means and totals. Measurements are made every two or four weeks.

Summary and conclusions

There are some fundamental data sets and models that interact in the decision support system needed for a rational management of plantation forests. Some possible approaches are typified by a project currently underway to use available information and collect additional data for the management of eucalypt plantations in Chile.

What seem like efficient strategies to obtain useful results in the short and the longer term have been devised. These include the analysis of existing data for the immediate generation of preliminary estimates and models, and the installation of appropriate sample plots and experimental trials to produce reliable growth models in the near future.

In its first season the project has installed 9 spacing trials, 15 intra-annual growth measurement experiments, and some 140 permanent sample plots. With advanced modelling techniques the PSPs should make possible a substantial improvement in growth projections in one or two years.

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