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Mobilizing expert knowledge of tree growth with the PLANTGRO and INFER systems

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Abstract

PLANTGRO can provide estimates of plant and tree growth under a wide range of conditions by evaluating responses to some 20 environmental variables ranging from day length to soil pH and determining the limiting factor. Although intended only to indicate the suitability of a given site-species combination, empirical trials suggest that the suitability index provides a reasonable indication of growth potential, offering correlations with height growth as high as 80%. PLANTGRO can be calibrated for new situations by providing appropriate soil, climate and species files. These can be compiled from plot-based data, casual observations, or expert knowledge. INFER is an expert system which complements PLANTGRO by providing an objective framework to elucidate plant growth details from casual observations. Together, INFER and PLANTGRO offer an effective way to provide initial growth estimates for species-site combinations not covered by plot data or other models. PLANTGRO is available from the first author, and INFER and many PLANTGRO files for forest trees may be accessed on the internet at `http://www.cgiar.org/cifor/research/tropis/plantgro.html`

Keywords: forest growth modelling; expert system; plantation; species-site matching; model evaluation

Introduction

Land use planning is often handicapped by a lack of suitable information on the performance of candidate species (or variety, provenance, etc.). Frequently, the problem is not the absence of information *per se*, but rather that decision support systems rely on empirical models calibrated to plot-based data, and are unable to utilize alternative sources such as informal data and expert knowledge. However, expert systems and other approaches enable such data to be incorporated into models compatible with prevailing planning systems. PLANTGRO is one such system.

PLANTGRO is a package designed to help assess the suitability of a species for a site, by ranking species performance on a qualitative scale, 0 (death almost certain) to 9 (ideal conditions). It uses information on 20 environmental variables reflecting factors as diverse as day length and soil pH (Table 1). The plant's response to each of these factors is expressed as a simple relationship (Fig. 1), which is used with site-specific soil and climate data to estimate growth limitations. PLANTGRO is somewhat unusual among plant-growth prediction systems in that it can use informal data and personal knowledge to supplement more formal experimental data. Thus PLANTGRO may be particularly helpful in providing preliminary growth estimates for species and sites for which no formal data or empirical models are available.

The original version of PLANTGRO, designed for land evaluation and field crops, was well received, with some 650 sales of DOS-based versions (Hackett, 1991; Harris and Hackett, 1996). Continuing demand has stimulated the development of a new Windows-based version (White, 1997). Despite its origin in field crops, PLANTGRO has received considerable attention from other disciplines, including forestry, entomology and plant pathology. The present synthesis contributes to an investigation into the ability of PLANTGRO to provide tree growth information within the TROPIS system (Vanclay, 1998).

Basis for predictions: PLANTGRO overview

The main inputs to PLANTGRO are site-based soil (Box 1) and climate data (Box 2), and species-based files indicating plant responses to these environmental factors (Table 1, Box 3). The site-based files are simple tabulations of conditions recorded for a site (Boxes 1 & 2), but the plant-files are more complex as they embody many growth responses. Most of the relationships are expressed as piecewise-continuous linear functions comprising up to 5 straight-line segments (Fig. 1), but as many as 9 segments can be accommodated. Because these curves have a characteristic plateau-shape (or part of it), they can often be defined with only 4 parameters, namely the X-values of the 4 nodes (since X_1 and X_4 represent lethal extremes with suitability 0, and X_2 and X_3 are optimal, with suitability 9; Fig. 1). However, more complex relationships can be accommodated.

Plant-files currently exist for some 2000 taxa, including some 400 forest tree species, but not all are freely available and at present, only about 30 tree files are in the public domain (Table 2). All PLANTGRO files are plain text (ASCII) files, which can be read and modified with any text editor. PLANTGRO files are being archived progressively on the internet and may be accessed from the CIFOR home page at `http://www.cgiar.com/cifor/research/tropis/plantgro.html`. Users are welcome to download these files, are encouraged to improve the embedded relationships with their own experience and data, and are urged to provide updates and additions to improve the archive. It is anticipated that with use, and with collaboration between scientists, the underlying relationships may be improved.

In making a prediction, PLANTGRO compares a plant's specific requirements (as specified in its plant-file) with site conditions described in the soil and climate files. For some factors, site data are compared directly with relationships in the plant-file, and offer a direct indication of the suitability of the site for the plant in question. For other more complex factors, conditions experienced by the plant are estimated with a sub-model, such as the soil water balance predicted from rainfall, evaporation, soil depth and soil texture. Other sub-models are used to estimate plant responses to day length and temperature. Plant-files can be made for each phase of development, in which case, outputs from all phases are used to produce the overall suitability.

Plant responses are recorded internally in PLANTGRO as suitability ($0 \leq S_i \leq 9$) or limitation ratings ($L_i = 9 - S_i$), and are based on Liebig's Law of the Minimum (see Boyd *et al.*, 1976; Browne, 1942; Hackett, 1988), so the suitability index, and the limiting factor (L_{max}), is indicated by the largest L_i for each period (Fig. 2). If all the L_{max} are less than 9, the overall limitation rating is estimated as the arithmetic average of the L_{max} recorded across all the time intervals. If any L_{max} is 9, death is assumed and suitability is set to zero. Conventional yield estimates can be prepared by scaling the anticipated maximum yield (if known, or given in the plant-file), or from an established correlation with the suitability index (see below, Fig. 5). This generic approach towards definition of maximum yield is flexible, and facilitates adjustments for weeds, insects and plant pathogens, all of which can be estimated within PLANTGRO.

Since PLANTGRO relies on the limiting factor to estimate growth from the various environmental variables, prediction errors depend largely on the most limiting factor. Thus, the overall accuracy of a PLANTGRO prediction tends to be determined by the ability of scientists to elucidate the environmental relationships of a plant. Since these relationships are subjective, and may be preserved in plant-files used by others, some indicators of confidence are given in the form of reliability indicators, ranging from 1 to 9. The first indicator refers to the world knowledge about the plant, using rice and wheat as a benchmark. The second indicates how the specific entry relates to the total knowledge available. For example, for *Pinus radiata* (Box 3), the first index was set at 7 (overall knowledge of the species is good), and the second at 5 (e.g., the author had difficulty reviewing all the material available), giving an overall reliability rating of 3.5 (i.e., 7×5/10). This should indicate to any subsequent user that caution is required, and that checks and improvements are desirable.

Quantifying environmental responses: INFER

Since comprehensive experimental data are scarce for many tree species, one challenge in using PLANTGRO is to quantify how a species responds to environmental factors. One option is to consult experts, sketch impressions, and iteratively check and improve these descriptions by discussing the PLANTGRO predictions with the experts. This approach seems effective, at least for agronomists who may observe their crops in detail over many generations and in many places. However, this method seems less effective for forestry (Hackett, 1996a), in part because few forest scientists have the opportunity to observe tree growth in such detail over a wide range of conditions.

This difficulty was foreseen, however, and a formal procedure was developed (Hackett, 1991) to estimate species-environment relationships from observations on conditions tolerated by plant species. Trials with data from the INSPIRE database (Webb *et al*., 1984) showed that such an approach could produce preliminary relationships for PLANTGRO plant-files. However, the approach was unavoidably subjective, and the only way to know if relationships were adequate was to ask specialists to check them against any field evidence available.

Fresh interest in this approach was stimulated in 1995 by a request from PROSEA (Plant Resources of South East Asia) to develop PLANTGRO files for selected plants within the region. An expert system was devised to deal with the great volume of data anticipated. The system, INFER, had two main components (Hackett, 1996a): (a) a set of three check-sheets to indicate the soil and climate conditions that the species was known to tolerate (e.g., Fig. 3), and (b) a set of rules to estimate relationships from the check-sheet data (e.g., Box 4, Fig. 4).

Check-sheets were distributed to PROSEA's collaborators, and some two hundred sets of data were returned. Unfortunately, only 90 of these have been examined (because of resource constraints), and only 45 have been processed with INFER into plant-files. Of the 90 data sets, 20 provided ready-to-use plant-files after routine processing and checking, 25 needed a few clarifications only, 25 required further interaction with authors, and 20 were incomplete or otherwise unsuitable for further processing. Their utility depended on the degree of consistency in the data, the nature of supporting notes provided, and evaluations of the preliminary PLANTGRO plant-files produced. This outcome was better than anticipated and suggested that the proformas were reasonable and the rules adequate. The latest version of INFER (Hackett, 1996b) remains paper-based, but has been well received and has been used with acacia and eucalypt species in Australia and elsewhere (e.g., by the Brazilian Enterprise for Agricultural Research, EMBRAPA, Brazil).

One innovative feature of INFER is its ability to add value to simple observational data. Entries (ticks and blanks) in a table suggest how a species experiences a particular soil or climate (Fig. 3), and can be converted into functional relationships with simple rules (Box 4, Fig. 4). Rarely will these preliminary relationships be adequate at first, but that does not matter, as INFER will have precipitated the important initial step of turning raw data into a series of explicit and testable relationships which can be improved and re-tested until they are considered adequate.

Another strength of INFER for eliciting environmental responses of little-known species is the wide range of data sources that can be used, e.g.:

- databases such as ECOCROP1 (FAO, 1996) and SEPASAL (Cook, 1995);
- details from the TROPIS meta-database (Vanclay, 1996);
- herbarium records with adequate locational details (e.g., latitude and longitude, which can be used to obtain climate data, and sometimes soil data);
- records held by IPGRI (the International Plant Genetic Resources Institute) and other institutions on the location, soil and climate of collections;
- entries in field notebooks compiled during vegetation surveys; and
- records held by institutions concerned with endangered plants.

Testing growth predictions

Users should always consider the suitability of a model for their particular site, species and purpose. Tests conducted by the model's author may build user confidence, but do not necessarily constitute an adequate test for every situation. PLANTGRO is no exception and warrants special attention since much of the model logic is not embedded in the PLANTGRO package, but is contained in the soil, climate and plant-files that may be provided or modified by users. However, taken as a whole, PLANTGRO, INFER, and their associated files may be evaluated using standard procedures such as those advocated by Vanclay and Skovsgaard (1997). To facilitate such testing, the PLANTGRO package includes a number of standard files for species and sites, including some extreme situations (e.g., climate and soil files for Dacca, Moscow, and Ushuaia). The most rigorous testing requires data from a range of sources, and this may involve goodwill, collaboration, and mutual agreement on any intellectual property which may be contributed or created.

Notwithstanding the above caveat to users, model authors should also conduct extensive evaluation of a model to ascertain its properties. PLANTGRO has been tested formally and informally for a wide range of scenarios, including a series of tests conducted by 4th year agronomy students at the Wageningen Agricultural University in 1993, but none of these tests has been formally published. Here we present a preliminary evaluation as a precursor to a more comprehensive evaluation currently under way.

Data

Our evaluation used measurements taken from nine *Pinus radiata* trial plots established during 1969-70 in the south-eastern Australian mainland (Australian Capital Territory, New South Wales, South Australia and Victoria; we disregard 2 plots in Queensland and Western Australia because of missing data and storm damage respectively). The ages of the plantings at time of measurement ranged from 8 to 11 years. Unfortunately, no detailed climate records were kept, so climate data used for our analyses were based on monthly averages obtained from the climate surface for Australia. Similarly, soil descriptions were not formally documented for all sites, but were kindly provided by one of scientists involved (D. Spencer, CSIRO, pers. comm.). These data enabled PLANTGRO climate and soil files to be compiled for the 9 sites used. The specific PLANTGRO file for *Pinus radiata* was originally created in 1990, based on data in Webb *et al*. (1984).

Results

Initial predictions made for the 9 sites with the 1990 *P. radiata* file helped to identify and rectify some deficiencies in these *a priori* relationships. Some adjustments led to improved correlations between the predicted index and the observed growth (expressed as mean annual height increment at age 8-11, m/yr), but a bias observed for the warmer sites suggested that the temperature relationship remained inadequate. When the optimal temperature was set to 19°C (Fig. 1) instead of 16°C as had previously been assumed, the correlation improved to 0.81 (Fig. 5). When data from the storm damaged plot in Western Australia was taken into account (legitimate since PLANTGRO accommodates wind), the R^2 rose to 0.95. While this outcome is reassuring, it does not constitute the independent testing needed to corroborate the model. Thus further formal testing is warranted, and is presently underway.

Implications

Although the high correlation between observations and predictions is satisfying, it does little to reveal the strengths and weaknesses of the PLANTGRO system, so a more detailed comparison was made. Results were tabulated according to the 9 sites and 12 time periods (Table 3) to reveal the limiting factor and nature of growth limitations. In this case, it is clear that the average monthly temperatures were limiting at all sites on some occasions, and that solar radiation was frequently limiting. Deficits in water availability were apparent, and soil conditions also were limiting at times.

While this is interesting, our real concern was to test the *Pinus radiata* plant-file thoroughly, including an evaluation of those factors that do not appear in Table 3. Further analysis showed that of the 20 factors considered (Table 1), 10 did not limit growth in the cases examined, and thus effectively remained untested in the present analysis. The soil factors concerned (from Qld through SA) included soil aeration, pH, salinity, slope, and texture, while the climatic factors were brief cold, extended cold, heat damage, day length, and flooding. Clearly, thorough evaluation of the PLANTGRO system requires extreme situations to be represented in the benchmarking database (as with all models; Vanclay and Skovsgaard, 1997). The present data, although geographically diverse, do not provide a comprehensive test, in part because the trials in question were presumably placed where survival and growth were expected to be good.

Practical application

To date, the most ambitious application of PLANTGRO in forestry has been Indonesia's National Masterplan for Forest Plantations (NMFP, 1995; Pawitan, 1996). A central component of the masterplan is a multi-disciplinary decision-support system (DSS), linked to a geographic information system based on the land system concept of Christian and Stewart (1968). PLANTGRO was an integral part of the DSS, plant-files being compiled for about 45 species (Davidson, 1996) and soil and climate files made for all land units involved. To support land use planning for forested area, yield curves corresponding to PLANTGRO suitabilities 0-9 were developed for each species. These allowed specific recommendations to be made for any nominated land unit, including species choice and end-use of products. The DSS also considered other aspects such as transport, processing facilities, etc. Unfortunately, specific details of the DSS and the PLANTGRO files have not been formally published.

Discussion

One advantage of the PLANTGRO approach is the ease with which models may be formulated and tested, and the variety of methods which can be used to elicit and test the environmental relationships of plants as a precursor to field trials or more sophisticated models. Given the shortage of suitable alternatives, and the fact that many forestry operations currently rely on crude empirical models, systems such as PLANTGRO may make a useful contribution in providing preliminary estimates of tree growth for sites of interest. However, goodwill and collaboration will be needed for the full potential of these possibilities to be exploited.

Conclusions

PLANTGRO and INFER offer a robust way to predict tree growth when no alternatives are available. INFER provides an objective way to convert casual observations on species occurrence into functional relationships amenable to testing and further improvement. PLANTGRO provides a framework to make growth predictions from a series of plant-environment relationships, and to investigate limiting factors. Like INFER, PLANTGRO draws on subjective and informal information to provide concise, explicit and testable relationships that have practical applications. Preliminary tests with *P. radiata* reveal a high correlation between predicted suitability indices and observed height growth, supporting previous unpublished tests of the utility and reliability of the system.

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```
*** SOIL FILE*** - soils\LO-SA200.SL-
Soil data file written on Friday September 2, 1994 at 12:23:15 p.m.

 1. SOIL site:  Loam + sand (sandy loam - 200 cm)
 2. Local soil name:  Generic file
 3. A soil taxonomy name:
 4. Brief description:  Loam with a high proportion of sand.
 5. Name of file author:  Anne Bennett
10. Remarks:  This file is an example only

*** DATA
 1. Aeration (class 1-6, nil to good):           6
 2. Base saturation (% CEC):                    40
 3. CEC (meq/100 g):                            20
 4. Depth overall (root access)(cm):           200
 5. Nitrogen (%):                                0.4
 6. pH:                                          5.5
 7. Phosphorus (avail. ppm Olsen):               8
 8. Potassium (meq/100g):                        0.1
 9. Salinity (dS/m):                             0
10. Slope (°):                                   7
31. Depth - layer A (cm):                       50
32. Depth - layer B (cm):                      150
33. Depth - infiltration zone I (cm):           75
34. Texture - layer A (class 1-8):               4
35. Texture - layer B (class 1-8):               4
36. Texture - infil'n zone I (class 1-8):        6
37. AWCA% (pl. avail. water - cm/m):            13
38. AWCB%:                                      13
39. DRWCA% (drainable ....):                    18
40. DRWCB%:                                     18
41. DRWCI%:                                     40
```

Box 1. Example of a PLANTGRO soil file (reformatted slightly for display purposes).

***** CLIMATE FILE ***** - climates\months\average\CANBERRA.cmv
Climate data file written on Monday October 24, 1994 at 1:12:14 p.m.

1. CLIMATE site: Canberra
2. Country: Australia
3. Latitude (° N/S): 35 S
4. Longitude (° E/W): 149 E
5. Station no: 070014
6. Elevation (m): 571

10. Provider's name: Bureau of Meteorology Climatic Averages
11.

***** DATA**

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Comment
1.	61	59	55	50	49	38	37	46	52	71	61	52	Rainfall (mm)
2.	260	207	171	108	68	48	53	78	108	155	192	83	Evaporation (mm)
3.	0	0	0	0	0	0	0	0	0	0	0	0	Irrigation (mm)
4.	0	0	0	0	0	0	0	0	0	0	0	0	Flooding (0 or 1)
5.	152	142	131	120	112	108	109	116	126	137	148	155	Av day len. (10^{-1} hr)
6.	27	24	19	14	10	9	9	11	16	22	26	27	Solar radn (MJ/m^2/day)
7.	27	27	24	20	15	12	11	13	16	19	23	26	Mean daily max (°C)
8.	13	13	11	6	3	0	0	1	3	6	9	11	Mean daily min (°C)
9.	9	9	7	2	-2	-4	-5	-3	-1	2	4	7	Temp, lowest (°C)
10.	8	7	6	6	5	6	5	7	7	7	8	8	Wind, average (km/hr)
11.	0	0	0	0	0	0	0	0	0	0	0	0	Wind, extreme (km/hr)
12.	0	0	0	0	0	0	0	0	0	0	0	0	Humidity (%)

Box 2. Example of PLANTGRO Climate file (reformatted slightly for display purposes).

```
***PLANT FILE*** - plants\general\PINU19MS.pgn
 1. Plant name: Pinus radiata D. Don
 5. File author: C. Hackett
 6. Date created: 0295/0896
 7. Quantity of world information on species (0-9): 7
 8. Coverage of world information on data-set (0-9): 5
 9. Main reference(s) used: Webb et al.(1984), Matheson & Raymond (1984)
13. Remarks: T. Booth & D. Spencer (CSIRO) helped with 1996 enhancements

***DATA SECTION***
 1.Y 0    9    .    .    .    .    .    .    0    0    Aeration
   X 1    6    .    .    .    .    .    .    0    0    (stagnant-well)
   Z 0    0    .    .    .    .    3    .    .    6
 2.Y 4    9    .    .    .    .    .    .    0    0    Base saturation
   X 0    20   .    .    .    .    .    .    0    0    (% CEC)
 3.Y 4    9    .    .    .    .    .    .    0    0    CEC
   X 0    10   .    .    .    .    .    .    0    0    (meq/100g)
 4.Y 0    4    9    .    .    .    .    .    0    0    Soil Depth
   X 0    20   100  .    .    .    .    .    0    0    (% non-limiting)
   Z 80   400  0    .    .    .    .    .    .    2
 5.Y 2    9    .    .    .    .    .    .    0    0    Nitrogen
   X 0    0.15 .    .    .    .    .    .    0    0    (%)
 6.Y 1    9    9    1    .    .    .    .    0    0    pH
   X 3.5  5    6    7.5  .    .    .    .    0    0
 7.Y 2    9    .    .    .    .    .    .    0    0    Phosphorus
   X 0    5    .    .    .    .    .    .    0    0    (avail. P, Olsen, ppm)
 8.Y 2    9    .    .    .    .    .    .    0    0    Potassium
   X 0    0.15 .    .    .    .    .    .    0    0    (meq/100g)
 9.Y 9    9    0    .    .    .    .    .    0    0    Salinity
   X 0    2    10   .    .    .    .    .    0    0    (dS/m)
10.Y 9    9    0    .    .    .    .    .    0    0    Slope
   X 0    15   60   .    .    .    .    .    0    0    (deg.)
11.Y 4    6    9    9    9    6    2    9    0    0    Texture
   X 1    2    3    4    5    6    7    8    0    0    (v.fine - v.coarse)
12.Y 9    .    .    .    .    .    .    .    0    0    Daylength
   X 5    .    .    .    .    .    .    .    0    0    (hr, plant clock)
   Z 0    .    .    .    .    .    .    .    1    1
13.Y 9    .    .    .    .    .    .    .    0    0    Daylength
   X 5    .    .    .    .    .    .    .    0    0    (hr, management view)
   Z 0    .    .    .    .    .    .    .    1    1
14.Y 1    9    .    .    .    .    .    .    0    0    Solar radiation
   X 0    21   .    .    .    .    .    .    0    0    (MJ/m2/day)
15.Y 0    9    .    .    .    .    .    .    0    0    Brief cold
   X .18  .15  .    .    .    .    .    .    0    0    (deg. C)
   Z 3    7    .    .    .    .    .    .    0    1
16.Y 0    9    .    .    .    .    .    .    0    0    Extended cold
   X .15  .12  .    .    .    .    .    .    0    0    (deg. C)
   Z 3    7    .    .    .    .    .    .    0    1
17.Y 9    0    .    .    .    .    .    .    0    0    Heat damage
   X 39   42   .    .    .    .    .    .    0    0    (deg. C)
   Z 3    1    .    .    .    .    .    .    0    1
18.Y 1    9    9    1    .    .    .    .    0    0    Thermal units
   X 5    19   19   29   .    .    .    .    0    0    (cardinal temps, deg. C)
   Z 52   .9   .9   0    .    .    .    .    0    1
19.Y 1    7    9    .    .    .    .    .    0    0    Water availability
   X 0    40   100  .    .    .    .    .    0    0    (AET/PET %)
   Z 0.70 0    0    .    .    .    .    .    0    5
20.Y 9    0    .    .    .    .    .    .    0    0    Seas. waterlogging
   X 0    20   .    .    .    .    .    .    0    0    (days)
   Z 100  0    .    .    .    .    .    .    0    2
21.Y 9    0    .    .    .    .    .    .    0    0    Flooding
   X 0    10   .    .    .    .    .    .    0    0    (days)
22.Y 9    0    .    .    .    .    .    .    0    0    Wind damage
   X 50   130  .    .    .    .    .    .    0    0    (km/hr)
23.Y 9    .    .    .    .    .    .    .    0    0    Quality
   X 5    .    .    .    .    .    .    .    0    0
```

Box 3. PLANTGRO plant-file for *Pinus radiata* (edited for display purposes). Each of the 23 relationships is characterised by 3 vectors, but the Z-vector has been omitted where redundant. See Hackett (1996b) for full details of relationships.

To estimate the pH relationship:

1. *Assume that the suitability rating*

a) increases as pH changes from acid to neutral (pH_a to pH_b)

b) reaches 9 for the optimum pH range (plateau from pH_b to pH_c)

c) decreases as pH changes from neutral to alkaline (pH_c to pH_d)

2. *Acidity*

- If the lowest box marked is "<4.5"
- Then set pH_a to 3 and pH_b to 5
- Else set pH_b to the mid-point of the lowest class indicated, and pH_a to pH_b-1.5

3. *Alkalinity*

- If the highest box marked is ">8.4"
- Then set pHc to 8 and pHd to 10
- Else set pHc to the mid-point of the highest class indicated, and pH_d to pH_c+1.5

4. *Cross check*

- against "Habitats - harsh soils - natural" and against any other indicators available.

Box 4. Example of rules used by INFER to derive relationships from check-sheets (Fig. 3), illustrated here for the soil acidity relationship.

Table 1. Environmental factors incorporated, directly or indirectly, in PLANTGRO assessment of the suitability of a species for a particular site.

Factor	Scale	Comments
Soil		
aeration	1-6	six levels, poor - good
texture	1-8	by layers; to calculate root growth and water balance
depth	cm	non-limiting rooting depth, critical drained depth
slope	degrees	indicates risk of plant falling over
nitrogen	%	
phosphorus	ppm	Olsen available P
potassium	meq/100g	
acidity	pH	
salinity	dS/m	
Climate		(*all average daily data per month*)
day length	hr	average daylight hours, sunrise-sunset
solar radiation	$MJ/m^2/day$	actual, adjusted for cloud
wind speeds	km/hr	wind damage calculation
av. monthly temp	°C	(see Figure 1)
brief cold	°C	threshold for leaf damage
extended cold	°C	threshold
heat damage	°C	threshold for leaf damage
water availability	mm	calculated from water balance
waterlogging	days	
flooding	0,1	
Other		
user-defined, e.g.		as required,
growth rate,	user-defined	e.g. convert suitability to height growth estimate
characteristics		e.g. predict wood density from site factors, etc.

Table 2. Tree species for which PLANTGRO files are presently available from `http://www.cgiar.com/cifor/research/tropis.htm`. Additional files will be made available from time to time.

Acacia alba	*A. saligna*	*E. deglupta*
A. auriculiformis	*A. senegal*	*E. globulus*
A. cyclops	*A. tortilis* ssp. *raddiana*	*E. nitens*
A. decurrens	*Acrocarpus fraxinifolius*	*Grevillea robusta*
A. farnesiana	*Agathis damara*	*Leucaena leucocephala*
A. mangium	*Albizia lebbek*	*Octomeles sumatrana*
A. mearnsii	*Alnus acuminata*	*Paraserianthes falcataria*
A. melanoxylon	*Azadirachta indica*	*Pinus radiata*
A. nilotica	*Casuarina equisetifolia*	*Prosopis juliflora*
A. pendula	*Cordia allidora*	*Swietenia macrophylla*
A. salicina	*Eucalyptus camaldulensis*	*Terminalia brassii*

Table 3. Example of limitations to *P. radiata* growth predicted by PLANTGRO for a range of sites in southern Australia.

Site	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Boboyan (ACT)	S 2	S 2	S/T 2	T 5	T 7	T 8	T 8	T 8	T 7	T 5	T 4	S/T 2
Gibraltar Ck (ACT)	S 2	S 2	S/T 2	T 4	T 6	T 7	T 8	T 7	T 6	T 4	T 3	S 2
Myora (SA)	W 5	W 4	S/R 2	R 4	R 5	R 6	R/T 5	R 5	T 4	S/R 2	S 2	S 2
Narbethon (Vic)	T 1	T 1	R/T 2	T 4	T 6	T 7	T 8	T 7	T 6	T 4	T 3	T 2
Nundle (NSW)	nil	nil	T 1	T 3	T 6	T 7	T 7	T 7	T 6	T 3	T 2	T 1
Rennick (Vic)	W 5	W 5	R/W 2	R 4	R 5	R 5	R/T 5	R/T 4	R/T 3	T 2	T 1	W 1
Tantanoola (SA)	W 5	W 5	W 3	R 4	R 4	R/T 5	R/T 5	R/T 4	T 4	T 2	T 1	T/W 1
Traralgon (Vic)	S/W 2	S/W 2	S/R 2	R 3	R 5	R 6	R/T 5	R/T 5	T 4	S/T 2	S 2	S 2
Warrenbayne (Vic)	T 1	T/W 1	R/T 1	R 3	R 5	T 6	T 7	T 6	T 4	T 2	T 1	T 1

Notes:

The table indicates predicted limitations to growth experienced by *Pinus radiata* at the 9 planting sites. Limitations range from 0 (negligible) to 9 (serious). Limiting factors include soil (S), solar radiation (R), temperatures (T), and water availability (W). Sites vary considerably in limitations observed: solar radiation and temperature prevailing during winter and water deficits in summer.

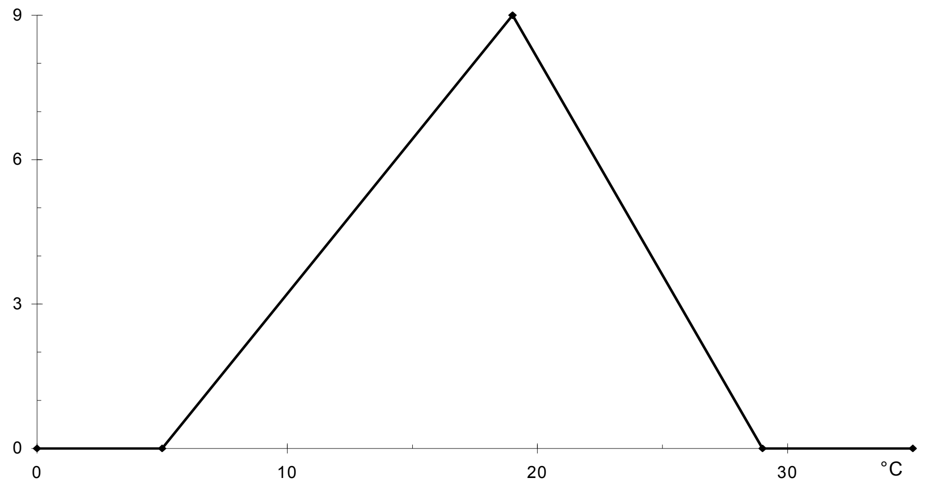

Fig. 1. The relationship used to estimate suitability rating for *Pinus radiata* from temperature. Notice that it is represented as a series of 5 straight-line segments. The 3rd segment is a horizontal at the maximum, and in this case, has zero length.

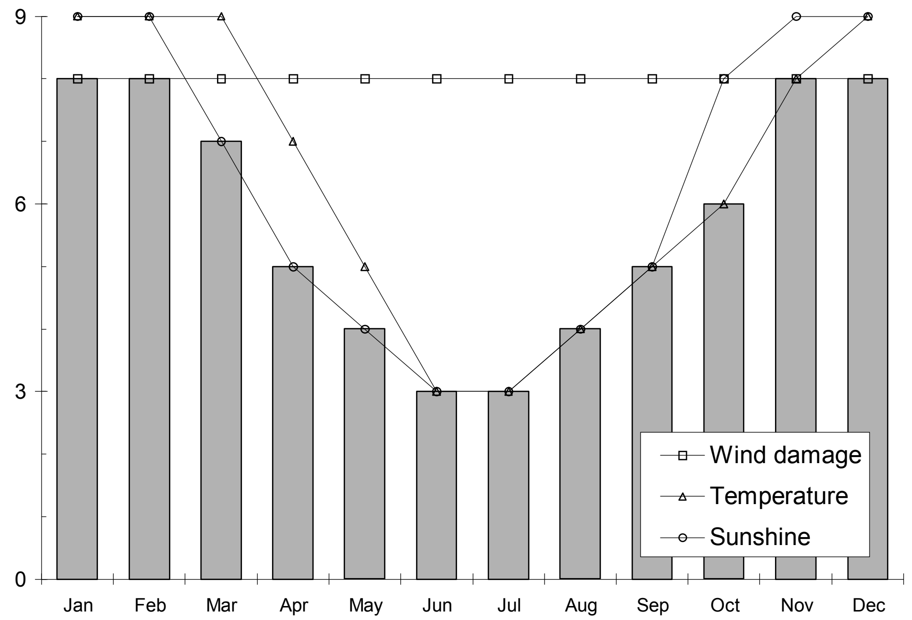

Fig. 2. Summary of selected PLANTGRO output to illustrate factors limiting growth of *P. radiata* at Nelson (NZ). Note that the species never attains its full potential at this site, because at least one factor is always limiting (e.g., wind).

Please indicate soil requirements of a species by marking conditions tolerated by the species in question. You may also indicate any special conditions and offer additional notes or comments.

Depth (cm)	< 10		10-20		20-50		50-100		100-200		>200	
Nutrients	almost nil		v. low		low		moderate		high		v. high	
Total N (%)	almost nil		v. low (0.05-0.1)		low (0.1-0.2)		mod. (0.2-0.3)		high (0.4-0.6)		v. high (>0.6)	
Available K (meq/100 mg)	almost nil		v. low (0.05-0.1)		low (0.1-0.2)		mod. (0.2-0.3)		high (0.4-0.6)		v. high (>0.6)	
Available P (ppm Olsen)	almost nil		v. low (1-4)		low (5-9)		mod. (10-15)		high (18-25)		v. high (>25)	
pH	< 4.5	**x**	4.5-5.4	**x**	5.5-6.4	**x**	6.5-7.4		7.5-8.4		>8.4	
Salinity (dS/m)	0		Traces (1-4)		low (5-10)		mod. (11-20)		high (21-30)		v. high (>30)	
Slope (°)	0 (incl. lakes, sea)		1-15 tractor limit		16-30 can walk		31-50 hard to walk		51-70 clamber		>70	
Texture	heavy (eg. clay)		Medium (eg. loam)		light (eg. sand)		stony/rocky		leaf mould peat		well drained clays	

Fig. 3. Check-sheet forming part of the paper-based INFER expert system. The full set of check-sheets can be accessed from `http://www.cgiar.com/cifor/research/tropis.htm`

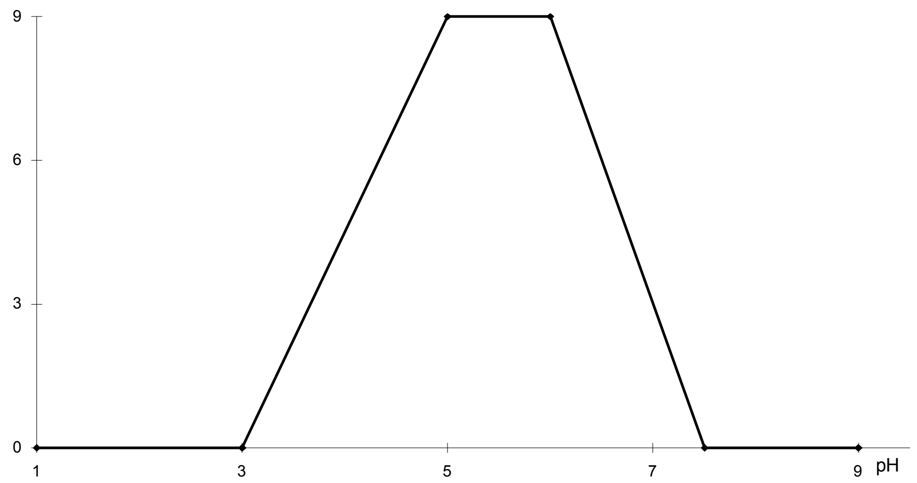

Fig. 4. Soil acidity relationship for a hypothetical species, calibrated using the data given in Fig. 3, using the INFER estimation system (Box 4). Notice that extremely acid (pH<3) and alkaline soils (pH>7.5) are assumed to be toxic, and that soil conditions are non-limiting only for slightly acid soils (5<pH<6).

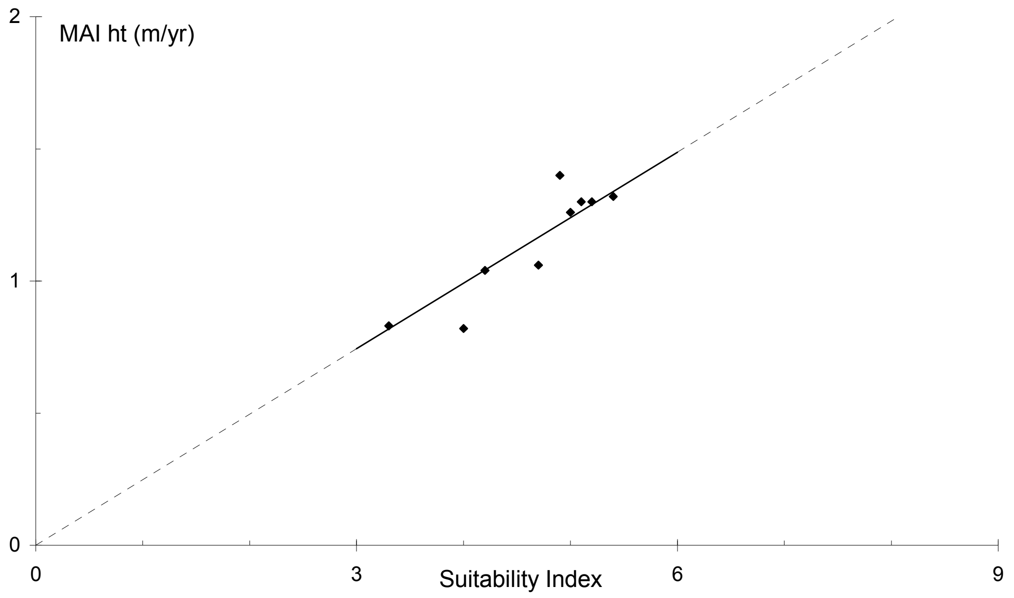

Fig. 5. Correlation between predicted suitability and observed MAI in height. The line illustrates the least-square regression MAI = 0.25 SI (R^2=0.80, se=0.007).