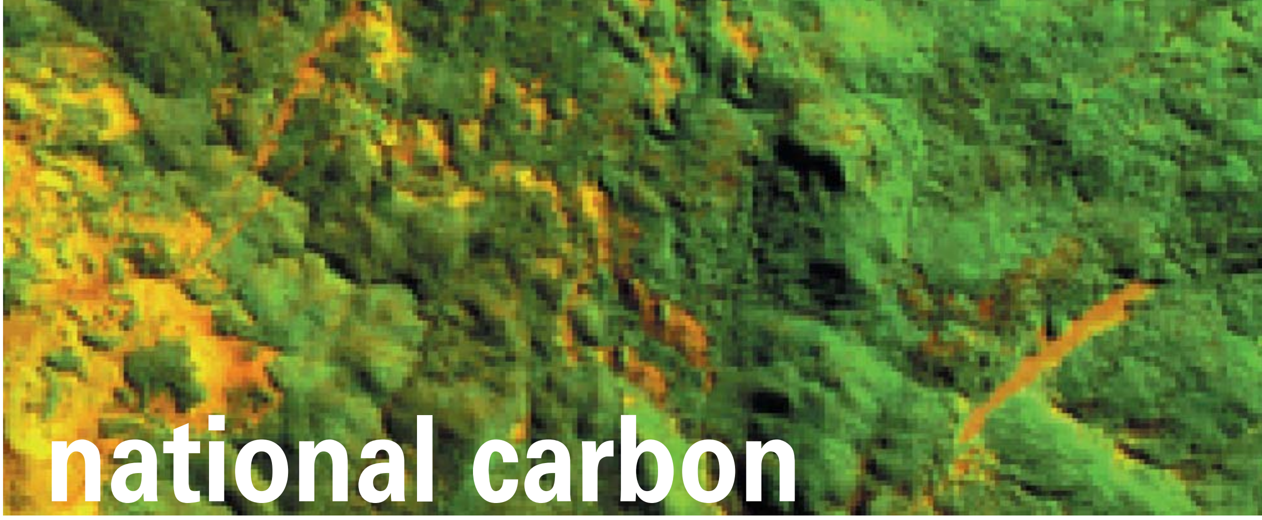

national carbon accounting system

technical report no. 23

Developing a National Forest Productivity Model

Jenny Kesteven,
Joe Landsberg and
URS Australia

Australian Government
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DEVELOPING A NATIONAL FOREST PRODUCTIVITY MODEL

Jenny Kesteven[+], Joe Landsberg[#] and URS Australia[°]

[+]Centre for Resource and Environmental Studies,
Australian National University, Canberra
[#]Landsberg Consulting Pty Ltd
[°]URS Australia

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SUMMARY

Knowledge of the spatial and temporal patterns of forest growth is fundamental to estimating the carbon stocks (and biomass) of mature forests and rates of carbon accumulation in any forest regrowth.

As part of the National Carbon Accounting System developed by the Australian Greenhouse Office, indices of forest growth were developed and used to predict potential biomass at maturity (forest productivity) and rates for biomass increment across the Australian continent over time.

This report documents the application of these forest growth indices in developing a National Forest Productivity Model.

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LIST OF SYMBOLS AND ACRONYMS

AGO	Australian Greenhouse Office
APAR	Absorbed Photosynthetically Active Radiation
BoM	Bureau of Meteorology (Australia)
CRES	Centre for Resource and Environmental Studies
CSIRO	Commonwealth Scientific and Industrial Research Organization
DEM	Digital Elevation Map
$e°(T)$	Saturation vapour pressure at air temperature T (kPa)
E_{eq}	Equilibrium evaporation
$exp(x)$	2.7183 (base of natural logarithm) raised to the power x
F	Frost (days per month)
F_{mod}	Frost modifier
*f*PAR	Fraction of Photosynthetically Active Radiation absorbed
GCV	Generalised Cross Validation
GPP	Gross Primary Productivity
I	Interception intercept
J	Month
LAI	Leaf Area Index (m^2 (leaf area) m^{-2} (soil surface))
M	Moisture ratio
NDVI	Normalised Difference Vegetation Index
λ_I	Near infra-red electromagnetic wavelengths
λ_R	Low micron range electromagnetic wavelengths
NPP	Net Primary Production
P	Rainfall (mm)
R_A	Adjusted direct radiation
R_C	Slope and aspect modified radiation
R_D	Direct radiation
R_F	Diffuse radiation
R_G	Global radiation
R_N	Net radiation (MJ m^{-2} day^{-1})
R_P	Radiation with rainfall
S_N	Soil nutrient status
S_C	Soil water holding capacity
S_W	Soil water
S_{Wmod}	Soil water modifier
T	Temperature (°C)
T_{avg}	Average monthly temperature/mean air temperature (°C)
T_{dew9}, T_{dew3}	Dew point temperature (9 am and 3 pm)
T_{dry9}, T_{dry3}	Dry bulb temperature (9 am and 3 pm)
T_{high}	Monthly average temperature above which plant growth stops
T_{low}	Monthly average temperature below which plant growth stops
T_{max}	Maximum air temperature (°C)
T_{min}	Minimum air temperature (°C)
T_{mod}	Temperature modifier
T_{opt}	Optimum temperature for growth
Trans	Transpiration
VPD	Vapour Pressure Deficit
VPD_{mod}	Vapour Pressure Deficit modifier
W	Water balance

1. INTRODUCTION

Net primary productivity (NPP) is the rate at which chemical or solar energy is converted to biomass. The main primary producers are the green plants, which convert solar energy, carbon dioxide and water to glucose, and eventually to plant tissue.

Estimation of productivity can be obtained through different methods. Direct measurement methods include destructive sampling of the above-ground and below-ground plant biomass, and the recording of carbon dioxide fluxes at the vegetation-atmosphere interface.

Available direct measurements of NPP have some limitations for mapping productivity across the Australian continent. The reliability of available data is variable – the data is limited in number and not evenly distributed among the various types of ecosystems. To overcome these deficiencies in measured data several model types have been developed. These are either physiological models simulating ecosystem fluxes from environmental variables, remote sensing-based models interpreting the light spectrum reflected by the land surface, or inverse models deducing fluxes from time and space variations in atmospheric CO_2 and ^{13}C data. Process models with physiological functions (i.e. those that acknowledge temporal variability due to changing biophysical conditions such as rainfall and temperature) offer the opportunity to simulate past and future changes in NPP according to environmental changes.

A truncated spatial version of the 3-PG (process) model (after Landsberg and Waring, 1997) was developed as part of the National Carbon Accounting System (NCAS) to predict forest productivity across the Australian continent. The resultant 'productivity index' model as documented here retains the essential features of biomass NPP estimation, without the biomass fixation (Gross Primary Productivity (GPP) minus NPP) and carbon partitioning procedures.

A relative index of plant productivity was mapped for Australia using the 'productivity index' model – based on the relationship between the amount of photosynthetically active radiation absorbed by plant canopies (APAR) and the various productivity modifiers that affect plant growth (e.g. temperature, soil water content, frost). The model used a monthly time step to derive both a long-term average monthly productivity index (~250 m resolution) and a monthly productivity index for 1970 to 2002 (1 km resolution).

Factors converting APAR to productivity indices were reduced from presumed optimum values by modifiers dependent on soil fertility, atmospheric vapour pressure deficits, soil water content and temperature. The ANUCLIM and ANUSPLIN programs were used to generate climate surfaces for the continent. Soil fertility and water holding capacity values were obtained from the CSIRO using the digital Soil Atlas of Australia. Leaf Area Index, essential for the calculation of APAR, was estimated from 10-year mean values of Normalised Difference Vegetation Indices (NDVI), for 1 km pixels, for the entire country. Incoming short-wave radiation – and hence APAR – was corrected for slope and aspect using a Digital Elevation Map (DEM) for the long-term average, but with 1 km pixels being used in the monthly productivity maps derived as this made no significant difference to the results. Analyses were, therefore, carried out on estimates based on the assumption of flat terrain.

The resultant maps (as digital grids) of plant productivity index, for each month for Australia, provide relative indices of plant productivity (reflecting the spatial and temporal patterns of plant growth) in any region. The data generated is integral to the estimation of carbon stocks under the NCAS and provides a framework for assessing carbon accumulation by various vegetation types.

2. INPUT DATA

The production of mapped productivity indices for Australia required integration and analysis of a number of spatially represented environmental variables. These included: soil water holding capacity (to estimate water balance), soil nutrient status, Advanced Very High Resolution Radiometer (AVHRR) data (to estimate the Normalised Difference Vegetative Index (NDVI)), and various climate variables (temperature, rainfall and number of frost days).

2.1 SOILS

The Atlas of Australian Soils (Northcote *et. al.* 1960–1968) was integrated with a set of interpreted soil variables from CSIRO (McKenzie and Hook 1992) to produce continental maps of potential available water holding capacity (PAWHC) and nutrient status of soils.

The Atlas of Australian Soils completed in 1968 (Northcote *et. al.* 1960-1968) and made available in digital form in 1990 provides the only consistent source of spatial information for the continent. While large areas have been surveyed in more detail during the last 30 years, those surveys have not been compiled to produce an updated continental map.

McKenzie *et. al.* 2000 provided a set of interpreted soil variables (from McKenzie and Hook 1992) that can be used with the Digital Atlas. The interpretations for each soil type were based, wherever possible, on data held within the CSIRO National Soil Database. Summaries from the database were used with other sources of information to assign an interpreted value for each variable.

Soil fertility and water holding capacity (S_C) were obtained by merging the Atlas of Australian soils (Northcote *et. al.* 1960-1968) and data provided by McKenzie *et. al.* 2000. The data provided included soil fertility and water holding capacity for both the dominant soil type (by area) and the average of the top five dominant soils. McKenzie (pers. comm.) advised using the properties of the dominant soil type (by area) to characterise the region. Caveats on the use of the Digital Atlas of Australian Soils are presented in McKenzie *et. al.* (2000).

The resultant data had limitations, as a large proportion of soil variation within a region occurred over short distances which could not be resolved at the mapping scale of the Atlas. The qualitative nature of the Digital Atlas and restrictions associated with the classification scheme and structure of the soil-landscape model imposed further constraints.

The Atlas of Australian Soils uses 725 soil profile classes, normally at the level of Principle Profile Form (PPF) (e.g. Ug5.15). The legend of the Atlas defines 3,060 map unit types. The map unit types have various combinations of the 725 soil profile classes. The map unit type descriptions identify dominant and subdominant soil profile classes. Many of the map unit types occur more than once and the Digital Atlas has 22,560 mapped polygons.

McKenzie and Hook (1992) prepared interpretations of the 725 soil profile classes. The dominant soil in each map unit type was identified and interpreted values for each soil profile class were ascribed to each map unit type. Lookup tables were created from the accompanying spreadsheets. Some soil polygons had PPFs containing 'Undefined' or 'NS' - their soil attributes were coded so as to represent no data.

2.1.1 Soil Water Holding Capacity (S_C).

Available water capacity is presented on a per unit depth basis, as a total for each horizon, and as a total for the solum. The total solum was recommended (McKenzie pers. comm.) for use. The available water capacities were calculated as the difference in volumetric water content at matric potentials of –0.1 bar and –15 bar for a specified depth increment.

It should be noted that the total available water capacity for the solum is constrained by limitations associated with the estimate of solum thickness of the actual plant available water capacity (see Hillel 1980). Despite these limitations, McKenzie *et. al.* 2000 suggest that it provides a reasonable first approximation of the water storage capacity of a soil.

In the resultant S_C maps derived, PPFs with an S_C equal to 0 were assigned the value of the A Horizon S_C, except for PPF Dy5.91 (comprising 2 spatial units in Kangaroo Island SA) which was assigned the PPF2 S_C as there was no PPF1 A Horizon value.

Mapped values (with a 250 m resolution) ranged from 21 to 270 mm with a mean value of 104 mm (see Figure 1).

Initial soil water content was set to 75% of the potential available water holding capacity. As this is not a true representation of the January soil water content for Australia, the water balance routine was run for two years to derive a reliable estimation of the actual soil water content to inititialise the model for the long-term average. The water balance routine was run for the years 1968 and 1969 to estimate initial soil water holding capacity for the 1970 to 2002 monthly productivity model.

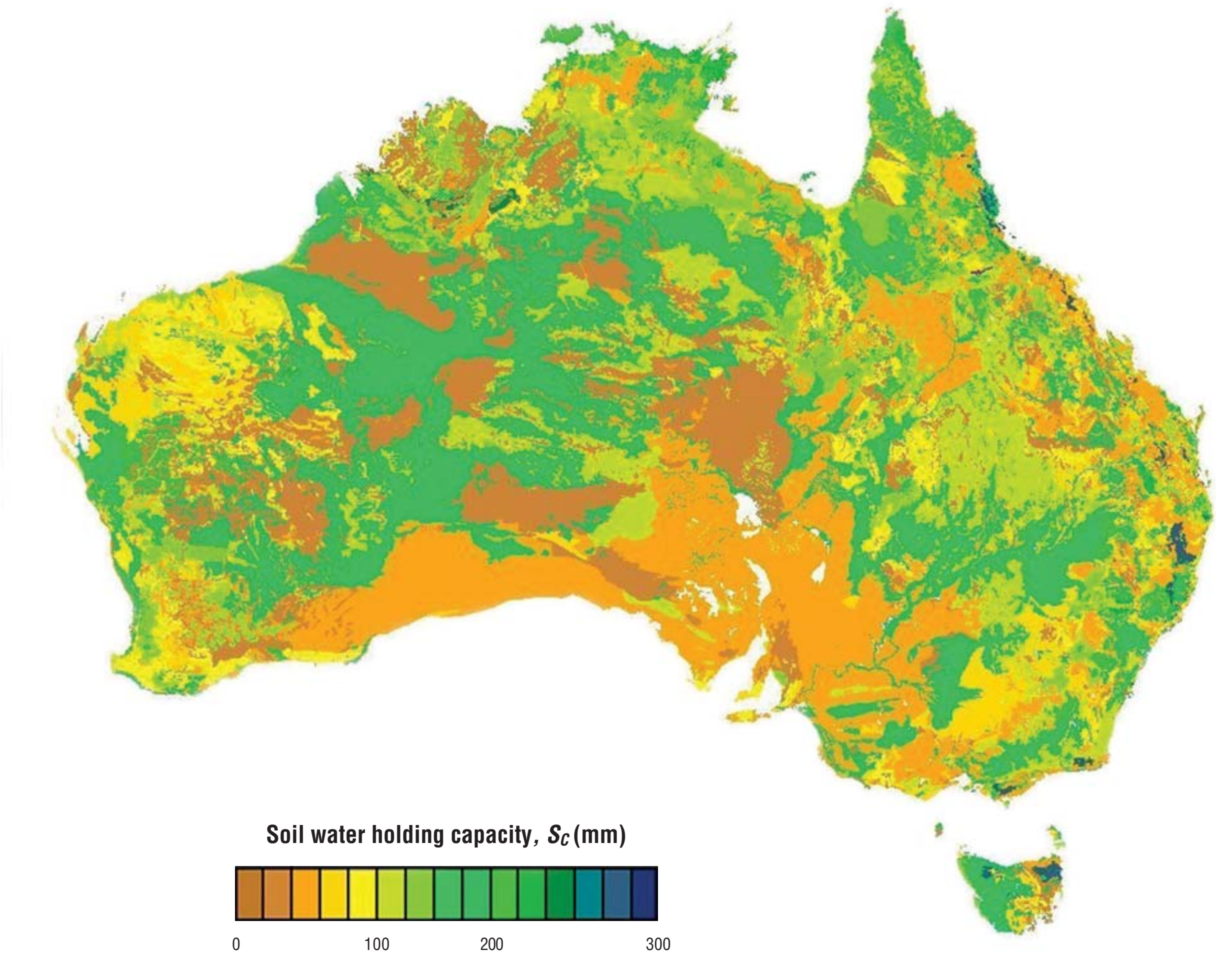


Figure 1. Potential available soil water holding capacity (S_C).

2.1.2 Soil Nutrient Status (S_N)

Because of natural variation and the considerable uncertainty surrounding soil fertility values, only three levels of fertility were used:

- high (effective modifier = 1),
- medium (effective modifier = 0.8) and
- low (effective modifier = 0.6)

giving S_N values of 1.25, 1 and 0.75, respectively. These were applied to each polygon representing a soil type in the Atlas of Australian Soils (Figure 2).

The rating system for gross nutrient status prepared by McKenzie and Hook (1992) relates to the behaviour of profiles under agricultural development. Profiles with a low status (class 1) exhibited major responses to nitrogen, phosphorus and potassium along with most micronutrients. Profiles with a moderate nutrient status (class 2) responded to nitrogen and phosphorus with occasional responses to some micronutrients. It was uncommon for profiles with a high nutrient status (class 3) to respond to nitrogen and phosphorus except after intensive farming. The main sources of information for the assessment of nutrient status were Stace *et. al.* (1968) and Northcote *et. al.* (1975).

In the resultant map derived for application in the productivity model, soil polygons with no nutrient value were assigned the lowest class i.e. S_N = 0.75. The average value for Australia was 0.81 (see Figure 2).

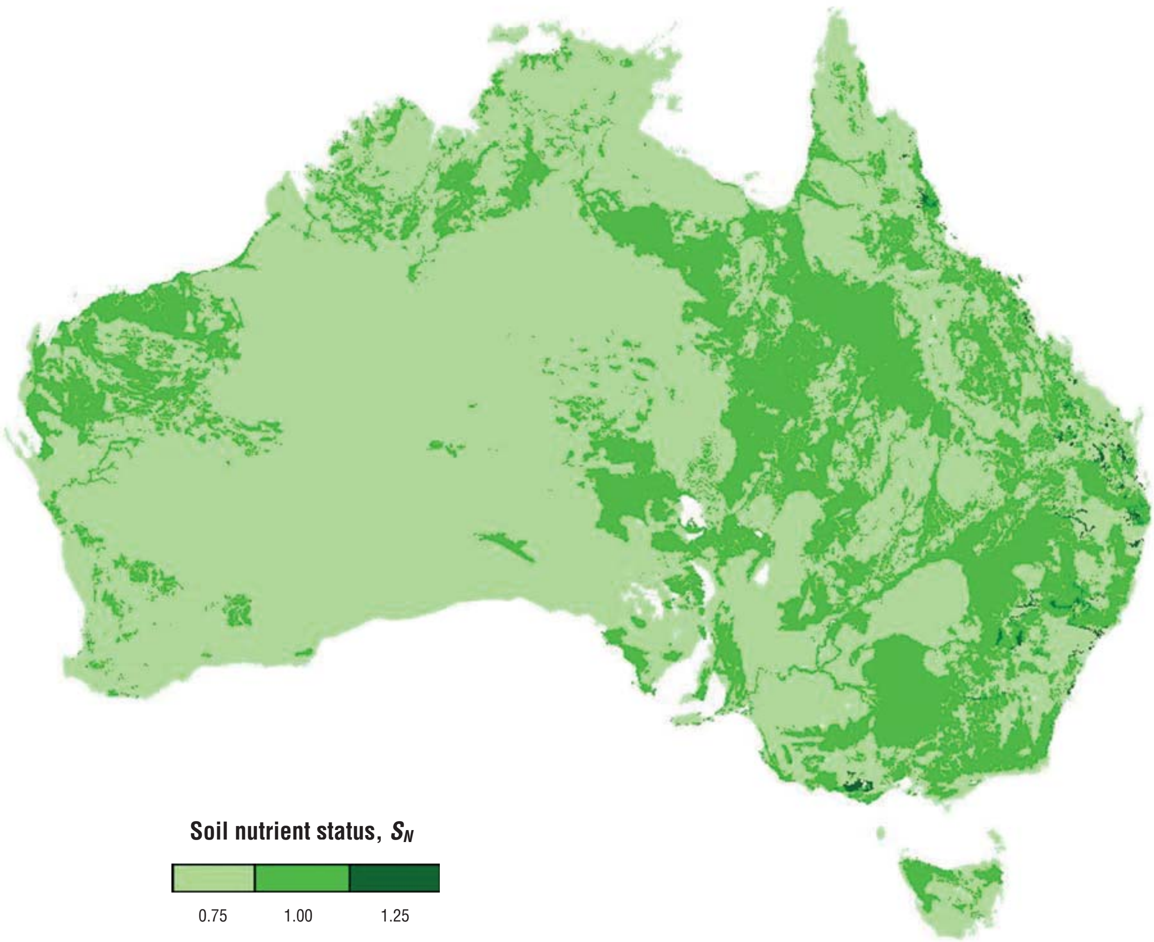


Figure 2. Soil nutrient status (S_N).

2.2 CLIMATE

Climate data was needed to produce the long-term average productivity maps and the 1968 to 2002 monthly productivity maps. Spatial coverage of long-term average climate surfaces for several climate variables were available from the ANUCLIM package. ANUCLIM (incorporating ESOCLIM, BIOCLIM and GROCLIM) is used to store climate surfaces derived by ANUSPLIN and to enable systematic interrogation of these surfaces, in point and grid form, for biophysical applications. Most surfaces need a Digital Elevation Model (DEM) to provide climate values in grid form (see http://cres.anu.edu.au). These climate variables include:

- Long-term average rainfall (*P*)
- Long-term average radiation (*Rad*)
- Long-term average minimum temperature (T_{min})
- Long-term average maximum temperature (T_{max})
- Long-term average 9am and 3pm dry bulb temperature(T_{dry})
- Long-term average 9am and 3pm dew point temperature(T_{dew})

Data layers that were required as inputs for the productivity model but not available in the ANUCLIM package included:

- Long-term average temperature (T_{avg})
- January 1968 to December 2002 monthly minimum temperature (T_{min})
- January 1968 to December 2002 monthly maximum temperature (T_{max})
- January 1968 to December 2002 monthly average temperature (T_{avg})
- January 1968 to December 2002 monthly rainfall (*P*)
- Long-term average number of days with frost (*F*)
- January 1968 to December 2002 monthly number of days with frost (*F*).

2.2.1 Fitting The Climate Surfaces

Climate surfaces for long-term average temperature and frosts and for all the monthly climate variables from 1968 to 2002 were created using the ANUSPLIN software package (see http://cres.anu.edu.au). The ANUSPLIN package provides a facility for transparent analysis and interpolation of noisy multi-variate data using thin plate smoothing splines. The package supports this aim by providing comprehensive statistical analyses, data diagnostics and spatially distributed standard errors. It also supports flexible data input and surface interrogation procedures. The climate surfaces available in the ANUCLIM package were created using the ANUSPLIN package.

A brief description of the surface fitting techniques is given below but for a more comprehensive discussion see Kesteven (1998), Huchinson (1991a, 1991b), Kesteven and Hutchinson (1996) and Wahba (1990).

The original thin plate (formerly Laplacian) surface fitting technique was described by Wahba (1979), with modifications for larger data sets due to Bates and Wahba (1982), Elden (1984) and Hutchinson (1984). Thin plate smoothing spline interpolation is a global method as it uses all the given data for prediction at each point (Laslett *et. al.* 1987). The method is also non-parametric and so is relatively insensitive to the distribution of the parent population.

Thin plate smoothing splines can be viewed as a generalisation of standard multi-variate linear regression, in which the parametric model is replaced by a suitably smooth non-parametric function. The degree of smoothness, or inversely the degree of complexity, of the fitted function is usually determined automatically from the data by minimising a measure of predictive error of the fitted surface given by the generalised cross validation (GCV).

The main idea is to consider a spatial variable as a realisation of a spatially autocorrelated random function that accounts for the complicated behaviour of natural spatial data:

$$z_i = f(x_i) + \varepsilon_i \qquad (i = l,...,n) \tag{1}$$

where f is a function to be estimated from the observations z_i, which include a zero mean, usually spatially discontinuous, error term ε_i. The x_i are commonly assumed to represent coordinates in two- or three-dimensional Euclidean space.

The value of the variable over a region is interpolated by estimating the true underlying function. This function is estimated to be as smooth as possible without significantly distorting the given data values (Hutchinson 1991a). The observational model for a thin plate spline with three independent spline variables is that the observed monthly mean z_i at the position x_i, y_i, z_i of the i^{th} station is given by Equation 1, where f is an unknown smooth function and the ε_i are independent random errors with zero mean and variance ds^2, where d_i is the (local) relative variance and s^2 is the common (normally unknown) variance.

The unknown smooth function is estimated by finding the function f (a thin plate spline) which minimises

$$\sum_{i=l}^{n} [\frac{z_i - f(x_i, y_i, h_i)}{d_i}]^2 + \lambda J_m(f) \tag{2}$$

where is $J_m(f)$ a measure of the roughness of f in terms of the m^{th} order derivatives of f (usually second order), and λ is a positive smoothing parameter.

In meteorological and climatological applications the weights, d_i, are used when the data do not have equal length records. The smoothing parameter λ determines a trade-off between data fidelity and surface roughness. It is usually calculated by minimising the generalised cross validation (GCV). This is a measure of the predictive error of the fitted surface which is calculated by removing each data point in turn and summing, with appropriate weighting, the square of the discrepancy of each omitted data point from a surface fitted to all the other points. The value of λ is chosen to minimise this sum, that is, to minimise the predictive error as ascertained by the performance of the fitted function in predicting omitted data points.

It is possible to calculate the GCV implicitly, and hence efficiently, because the fitted values depend linearly on the data. Intuitively the GCV is a good measure of the predictive power of the fitted surface, as has been verified both theoretically and in applications to real and simulated data (Wahba 1990 and Hutchinson 1991a).

Statistical interpretation proceeds by way of analogy with least squares regression analysis. Thin plate splines can be viewed as a non-parametric generalisation of linear regression analysis. A comprehensive introduction to the technique of thin plate smoothing splines, with various extensions, is given in Wahba (1990). A summary of the basic methodology, with climate interpolation principally in mind, can be found in Hutchinson (1991a). More comprehensive discussion of the algorithms and the associated statistical analyses are given in Hutchinson and Gessler (1994) and Hutchinson (1993, 1995). Comparisons with geostatistical (kriging) methods have been presented by Hutchinson (1993), Hutchinson and Gessler (1994) and Laslett (1994).

The surface fitting procedure was primarily developed for the task of fitting climate data so that there are normally at least two independent spline variables, longitude and latitude in units of decimal degrees. A third independent variable, elevation above sea-level, is often appropriate when fitting surfaces to temperature or precipitation. This is normally included as a third independent spline variable and was scaled to be in units of kilometres. Minor improvements can sometimes be made by slightly altering this scaling of elevation. This scaling was originally determined by Hutchinson and Bischof (1983) and has been verified by Hutchinson (1995, 1996). Extension to real time simulation and surface fitting is discussed by Hutchinson (1995) and Kesteven and Hutchinson (1996).

Over restricted areas, superior performance can sometimes be achieved by including elevation, not as an independent spline variable but as an independent covariate. Thus, in the case of fitting a temperature surface, the coefficient of an elevation covariate would be an empirically determined temperature lapse rate (Kesteven 1998, Hutchinson, 1991a). Other factors which influence the climate variable may be included as additional covariates if appropriate parameterisations can be determined and the relevant data are available. These might include, for example, topographic effects other than elevation above sea-level such as slope and aspect. Other applications to climate interpolation have been described by Hutchinson *et. al.* (1984) and Hutchinson (1989, 1991a, 1991b). Applications of fitted spline climate surfaces to global agroclimatic classifications and to the assessment of biodiversity are described by Hutchinson *et. al.* (1992).

To fit multi-variate climate surfaces, the values of the independent variables need to be known at the data points. Thus meteorological stations should be accurately located in position and elevation. Errors in these locations are often indicated by large values in the output ranked residual list. A number of applications have examined the utility of using elevation and slope and aspect obtained from digital elevation models of various horizontal resolutions (Hutchinson 1995, 1998b).

2.2.1.1 Errors in the Model

In applying data smoothing to climate means, two components of the covariance structure of the ε_i in the model given by Equation 1 should be recognised. The first component allows for deficiencies in the model being fitted. These are essentially due to local effects, including measurement error, which are below the spatial resolution of the observed point data network. The magnitude of these effects depends on the adequacy of the model represented by the function z_i and on the spatial density of the data. These effects can be reasonably assumed to be independent between different locations.

The second component arises when using serially incomplete data to interpolate monthly means for a standard period. This component can be ignored for some variables such as temperature. Monthly means of temperature stabilise after a few years. However, this component is significant for rainfall which normally exhibits large variation from year to year. This variability gives rise to strong correlations between the error components of rainfall means at stations with common periods of record.

Hutchinson (1995) shows how the resulting correlated error structure can be incorporated into the interpolation process. The model permits the rigorous estimation of this smooth function by a thin plate smoothing spline in two ways. The statistical error structure of the data can either be accommodated directly, by using the corresponding non-diagonal error covariance matrix, or observed means can first be standardised to long-term estimates using linear regression. Both methods give similar interpolation accuracy and error estimates of the fitted surfaces were in good agreement with residuals from withheld data (Hutchinson 1995).

There are several useful output statistics in the diagnostics file generated by the SPLINA program, which can be used to check for data homogeneity. The square root of the generalised cross validation (RTGCV) is a good measure of the predictive power of the fitted surface, especially when comparing the values from the same climate variable fitted for different times. In combination with the ranked residuals listing, which allows for each station to be assessed in relation to its deviation from the calculated surface, the RTGCV provides a powerful tool for investigation of station homogeneity. This process of assessing each station in relation to its deviation from the calculated surface and correcting errors may be repeated many times, steadily reducing overall surface error. Once the statistics reach a level where there is very little change with the removal of additional stations and residuals are within expected ranges, the fitted surface coefficients are used to create the monthly surfaces. Coefficients of the surfaces fitted to the monthly values were stored by month. Values for any month at any site or for grids can be calculated using the LAPPNT or LAPGRD programs in the ANUSPLIN package. A visual representation for each month was created using ARCInfo although they could be displayed by any of a number of commonly available computer programs which can display raster images.

2.2.1.2 From Surface Coefficient Files to Maps

The LAPGRD program can be used to calculate regular grids of fitted climate values and their standard errors, for mapping and other purposes, provided a regular grid of values of each independent variable, additional to longitude and latitude, is supplied. This usually means that a regular grid digital elevation model (DEM) is required.

Coefficients of the surfaces fitted to the monthly values are stored by year. They can be used to calculate values of the climate variable for any month at any site using the LAPPNT program in the ANUSPLIN package. Alternatively, regular grids across Australia of monthly climate variables for any month can be calculated using the LAPGRD program in ANUSPLIN and displayed or used by any of a number of commonly available computer programs which can display raster images. The system can be updated to incorporate later years as new data become available.

2.2.2 Digital Elevation Model (DEM)

A Digital Elevation Model (DEM) is a representation of the terrain using point elevation information where each grid point represents the approximate elevation of the centre of the corresponding grid cell. A DEM was required for the production of the climate surfaces and for the estimation of slope and aspect corrected radiation grids.

The GEODATA 9 Second DEM Version 2 is a grid of elevation points covering the whole of Australia with a grid spacing of 9 seconds in longitude and latitude (~250 m resolution) in the GDA94 coordinate system. Version 2 is based on the ANUDEM 5.0 elevation gridding program developed by the Centre for Resource and Environmental Studies (CRES) at the Australian National University.

The ANUDEM program has been designed to produce accurate digital elevation models with sensible drainage properties from point elevations, stream lines, contour lines and cliff lines (Hutchinson 2000). The major data sources for the product were revised national spot height elevation data taken from 1:100,000 scale topographic mapping and revised river information from 1:250,000 scale topographic mapping. These datasets are components of AUSLIG's GEODATA TOPO–250K digital map product (AUSLIG 1994). All revisions to the source data were made by CRES. The data was augmented by national trigonometric data supplied by AUSLIG from the National Geodetic Data Base (NGDB).

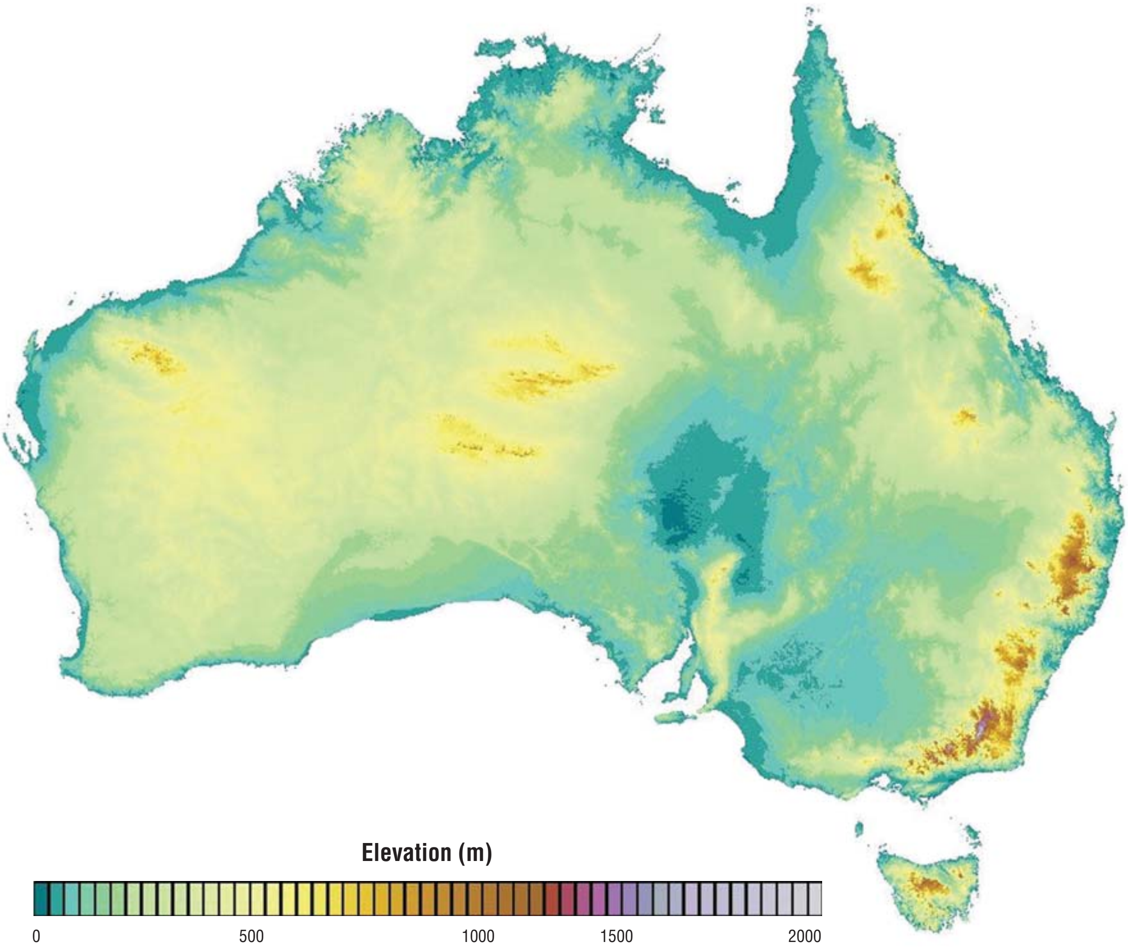


Figure 3. The Australian DEM.

The source elevation data has a standard deviation of around 7.5 m. Errors in the DEM are closely related to terrain complexity. Theoretical estimates and tests of the DEM against trigonometric data distributed evenly across the continent indicate that the standard elevation error of the DEM varies between about 7.5 m and 20 m for most of the continent. Standard errors are larger in highland areas with steep and complex terrain where the largest errors can exceed 200 metres (Hutchinson *et. al.* 2000).

The density of source data points used to create the grid and the horizontal resolution of the grid warrant that the final grid be considered as having a scale of approximately 1:250,000. This makes the DEM useful for national, statewide and regional applications.

A bilinear interpolation technique was used to resample the 250 m elevation grid to produce data at a 1 km resolution to derive subsequent monthly productivity index map grids.

2.2.3 Station Dictionary

The task of spatial interpolation is made difficult by a number of factors. Climate data are often sparse, measured for a limited duration and of varying quality. More significantly, the density of the data may be much less than the resolution of the required interpolated grid. In spite of this, the size of the available data set may be sufficient to cause computational difficulties, particularly when dealing with continental or global data sets.

The iterative process of 'fitting' the statistical surface demonstrates a vitally important characteristic of the spline technique. Verification of climate data poses many challenges and one tool to assist in that verification is placing a climate station in its spatial context. The results of the spline interpolation provided feedback about the meteorological station database by providing summary statistics and the deviation for each station relative to the fitted surface. Examination of data residuals is a powerful aid for detecting and correcting the data errors.

To fit multi-variate climate surfaces, the values of the independent variables need to be known at the data points. Thus meteorological stations should be accurately located in position and elevation. The Bureau of Meteorology (BoM) provided a base station dictionary (23/05/01) with the data. The dictionary provided basic station information including:

- BoM site number – Australian mainland stations range from 001000 to 099999 where the first three digits represent the meteorological region.
- Latitude and longitude – in decimal degrees
- Elevation – in metres (both station and barometer heights may be given – station height is used for all climate variables as barometer heights are only used for pressure data)
- Station name – descriptive
- Start and finish year – gives years of operation of the station.

Climate data from 1968 to 2002 was required to produce the 1970 to 2002 plant productivity map grids for the NCAS, stations with no climate data for this period were removed from the data base. This version of the BoM dictionary was compared with both the CRES (1998) and AGO (2001) dictionary. Any station with a difference greater than 0.1^{o} in position or 50 m in elevation was checked. The BoM base dictionary is updated monthly and comparisons were done in May 2001, September 2001, January 2002 and August 2002.

Stations which showed up as high residuals in the production of the climate surface were checked for correct locations. The final station dictionary which was used consisted of 11,714 stations, 2,511 of which were checked/geo-coded using the digital maps of Australia and the 9 second DEM. The digital maps provided a complete coverage of Australia at the 1:100,000 scale and at 1:250,000. The 1:100,000 scale was used where possible but in areas where only dyelines were available the 1:250,000 maps were also used. The 9 second DEM was used as a general check on elevation. A screen capture of each station checked was also taken (see Figure 4).

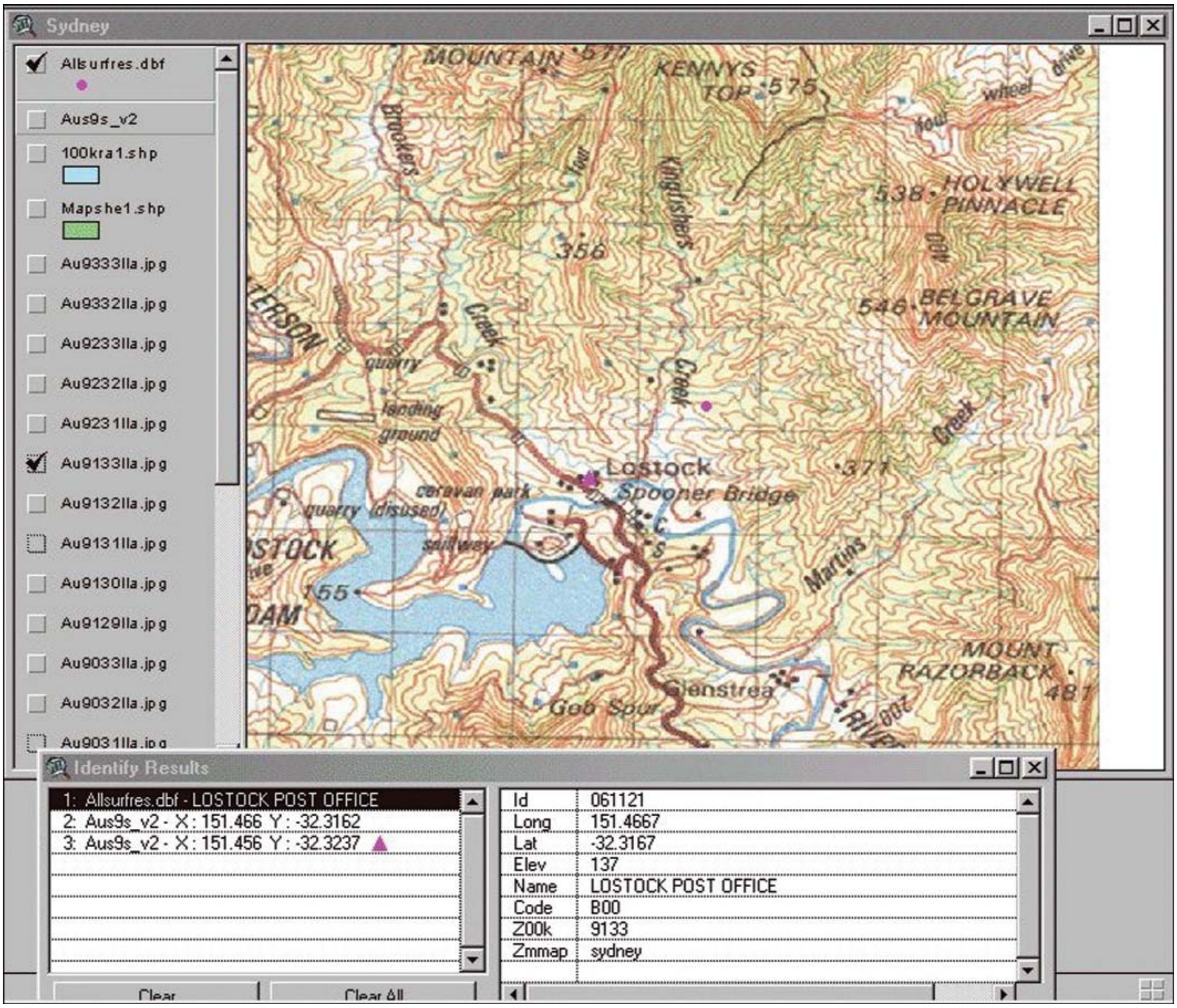


Figure 4. A screen capture for station 061121 – Lostock Post Office.

2.2.4 Long-Term Average Climate Variables

The production of a productivity index map for Australia required a number of climate variables. Long-term average climate surfaces from the ANUCLIM software package were used for the climate variables available (Table 1). The ANUSPLIN software package and methods described in the previous section were used to produce a gridded set of long-term means for average temperature and number of frost days (Table 2).

The concept of a 'long-term average' climate surface has problems associated with the assumption of stationarity of the time series. The earth's climate will probably never settle reliably into an equilibrium with average long-term behaviour. Climatic averages are best given for either the full length of the record or for a standard period (for example a set thirty year period). The long-term averages used to produce productivity index maps used the full length of the record although records prior to 1920 were not used.

Table 1. ANUCLIM variables used in the plant productivity modelling.

ANUCLIM Climate Variable	Data points (knots)	Fitted variables	Order of spline	Transformation
Maximum temperature	1200	3 independent (long,lat,elev)	2	none
Minimum temperature	1200	3 independent (long,lat,elev)	2	none
Rainfall	13000 (3500)	3 independent (long,lat,elev)	2	Square root
9am Dry bulb temperature	185	3 independent (long,lat,elev)	2	none
9am Dew point temperature	176	3 independent (long,lat,elev)	2	none
3pm Dry bulb temperature	190	3 independent (long,lat,elev)	2	none
3pm Dew point temperature	183	3 independent (long,lat,elev)	2	none
Radiation with rainfall	45	3 independent (long,lat,elev) 1 dependent (rainfall)	2	none

Table 2. ANUSPLIN variables created for the long-term plant productivity modelling.

ANUSPLIN Climate Variable	Data points (knots)	Fitted variables	Order of spline	Transformation
Average temperature	1126	3 independent (long,lat,elev)	2	-
Frost days (number)	700	3 independent (long,lat,elev)	2	Square root

2.2.4.1 Average Temperature

ANUSPLIN (SPLINA) was fitted to data created from averaging the BoM monthly minimum and maximum temperature data and then calculating long-term averages. Both a spline and a partial spline function were fitted to these long-term average data (1,126 stations). A second order spline function was fitted to this data using three independent variables (longitude, latitude and elevation). The iterative process meant that five surfaces were produced and the final surface coefficient file was used in the productivity modelling. Errors associated with these surfaces were approximately ± 0.5°C. Figure 5 shows the fitted monthly long-term continental average temperature (T_{avg}).

A second order partial spline function fitted to two independent variables (longitude and latitude) and one independent variable (elevation) was used to check lapse rate values. The lapse rates for average temperature for the Australian continent ranged from 4.9°C in June to 6.0°C in December.

2.2.4.2 Number of Frost Days

SPLINA was used to fit the average of monthly frost days from data provided by the BoM. A second order spline function using three independent variables (longitude, latitude and elevation) was used to create the frost surfaces. Values on the output grids which were greater than the number of days in the month were reduced to the number of days in the month and any values less than 0 were converted to 0. Errors associated with the surfaces ranged from ± 0.2 days in summer to ± 2 days in winter. Figure 5 shows the fitted continental long-term average number of frost days per month (F).

2.2.4.3 Radiation

Long-term radiation surfaces (with rainfall as a covariate, R_P) from the ANUCLIM package were used for both the long-term and monthly productivity indices.

For the slope and aspect corrected solar radiation the ratio of diffuse (R_F) to global radiation (R_G) was derived for each station from the original BoM data. For each of the 32 BoM stations which had monthly measurements of direct and global radiation a long-term average was determined from the monthly

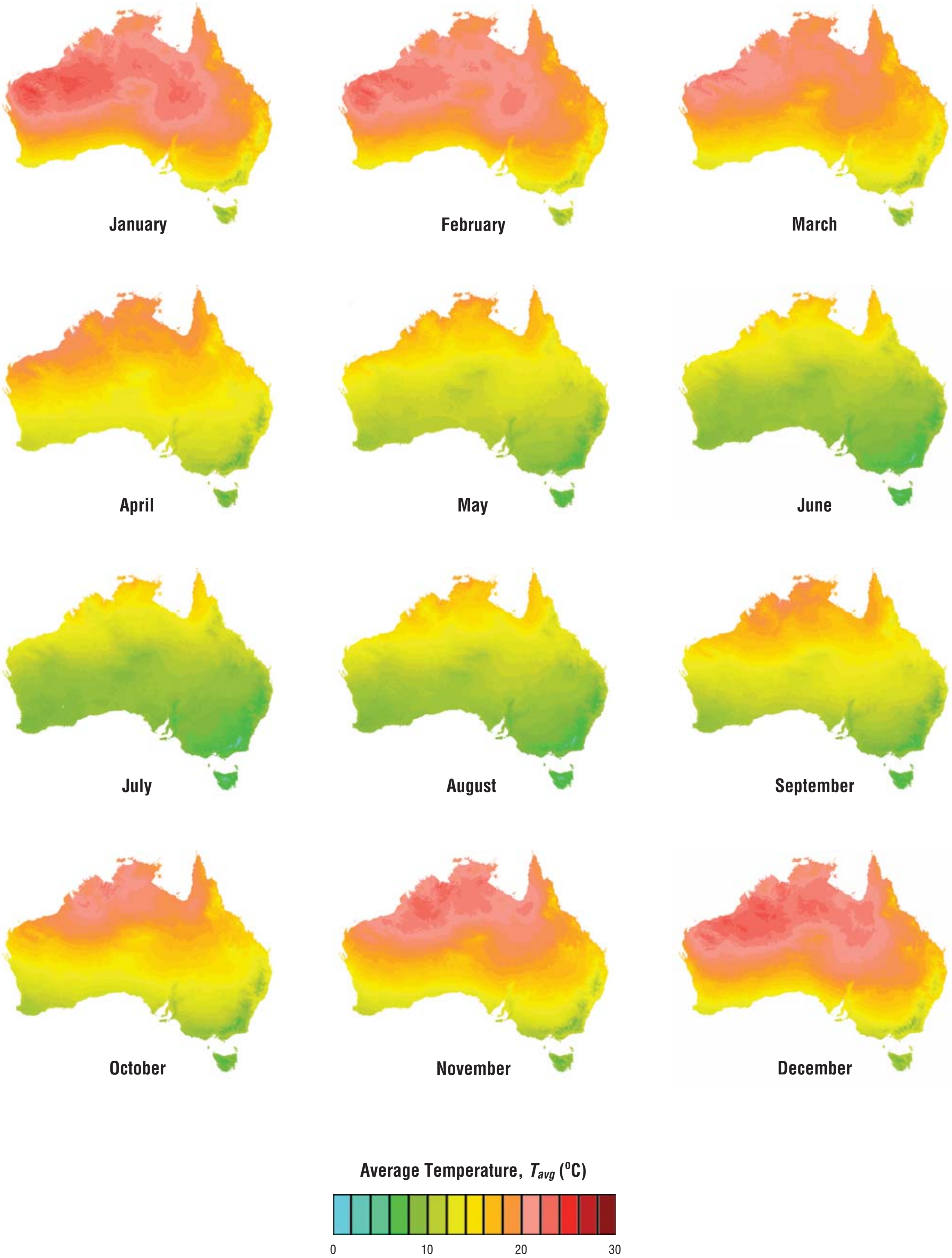


Figure 5. Long-term monthly average temperature.

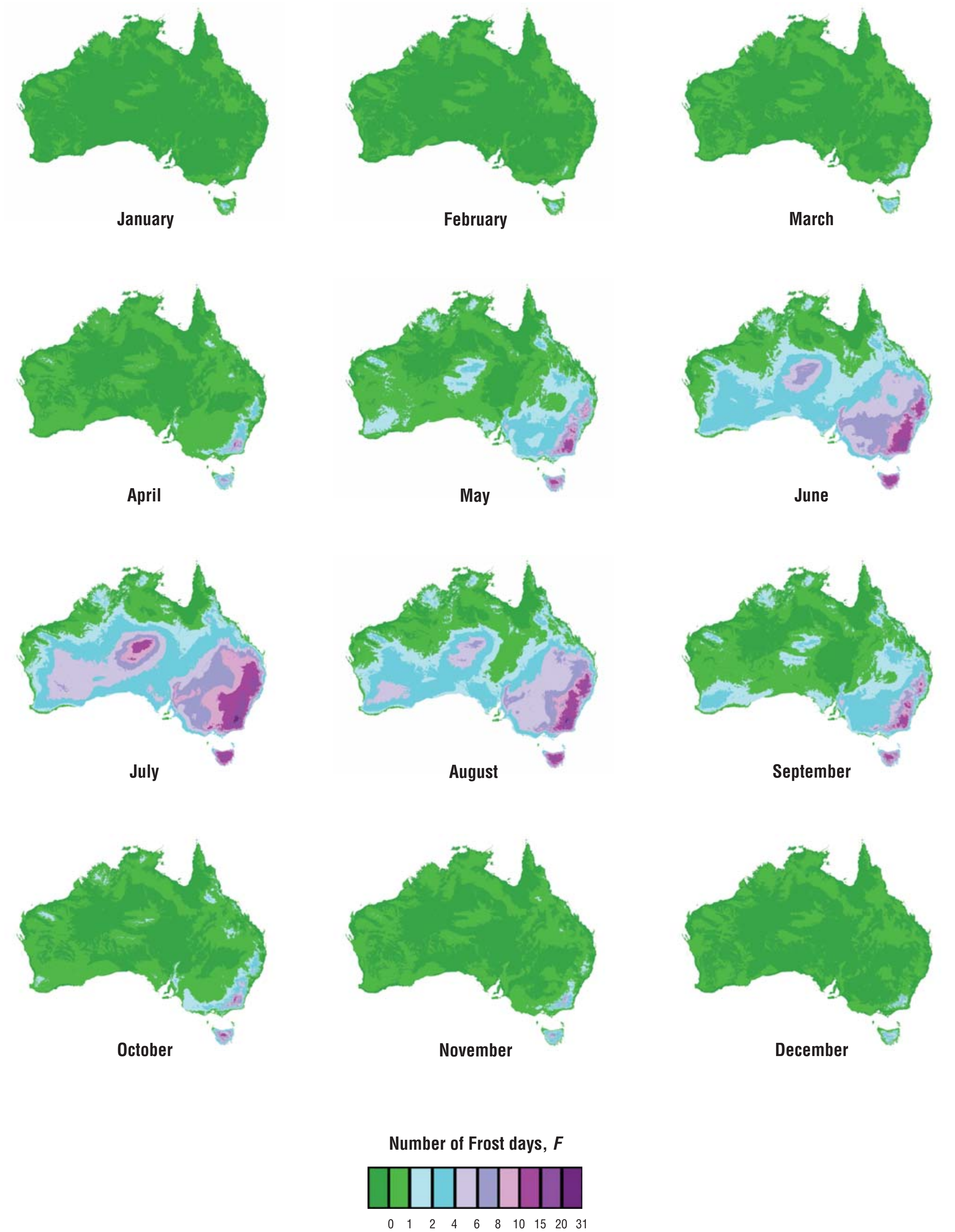


Figure 6. Long-term average number of frost days per month.

data to calculate the ratio of diffuse to global radiation. A 2-dimensional spline (using longitude and latitude) was fitted to the data to give a spatial coverage of the ratio expressed as a percentage for each month. This ratio surface was then applied to the ANUCLIM long-term radiation (R_P) surface to produce coverages of direct and diffuse radiation. By definition the effects of slope and aspect apply to direct solar radiation only.

$$R_D = R_P - (R_P * R_F / R_G) \qquad (3)$$

The radiation calculator is a computer program written by ScienceSpeak in C+ and is based on a spreadsheet by J.B. Moncrieff of Edinburgh University. The radiation calculator estimates the correction to direct radiation from location (latitude) and slope and aspect (calculated from the 9 second DEM). The calculator only uses the zenith-angle correction factor from the Moncrieff spreadsheet as transmissivity effects are assumed to be mainly incorporated in the measured flat-earth measurements. Output is a grid of percentage change to flat earth which is used to adjust the direct radiation grid. This adjusted direct radiation (R_A) grid is then added to the diffuse radiation grid to give the corrected global radiation (R_C) grids.

$$R_C = R_A + R_F \qquad (4)$$

Where R_C is the corrected global radiation, R_A is the slope and aspect adjusted direct radiation and R_F is the diffuse radiation. Grids of net radiation were derived where:

$$R_N = (R_C * 0.8) - 4) \qquad \text{if } R_C > 5$$

$$R_N = 0 \qquad \text{if } R_C <= 5 \qquad (5)$$

2.2.4.4 Vapour Pressure Deficit (*VPD*)

The air absorbs water vapour and as water vapour is a gas it exerts a pressure in addition to that of the air. The higher the air temperature the more water vapour can be absorbed. Saturation vapour pressure ($e°$) specifies the maximum amount of water vapour which air, at a given temperature, can hold. The saturation vapour pressure increases with increasing air temperature. The air inside a green leaf, near the surfaces of the cells where water is evaporating, is very nearly always saturated.

Vapour pressure deficit (*VPD*) is the difference between the actual vapour pressure and the saturation vapour pressure. For water vapour, *VPD* is normally in the range 0.1 kPa (very humid) to 3 kPa (very dry air), or 1 to 30 mbar. A low *VPD* means a high air humidity, and vice-versa. *VPD* indicates the 'drying effect' of the air, the higher the *VPD* the stronger the drying effect, so the stronger the driving force on transpiration.

The ANUCLIM program has long-term average coverages for 9am and 3pm dry bulb temperature (the ambient air temperature) and the 9am and 3pm dew point temperature (the temperature to which air must be cooled if the moisture present is to reach saturation). *VPD* was calculated by averaging the 9am and 3pm difference between the saturation vapour pressure for the dry-bulb temperature and the saturation vapour pressure for the dew point temperature.

$$VPD = ((e°(T_{dry9}) - e°(T_{dew9})) + (e°(T_{dry3}) - e°(T_{dew3})) / 2) \qquad (6)$$

2.2.5 Monthly Average Climate Variables

The production of monthly and annual productivity indices for Australia from 1970 to 2002 required monthly climate surfaces from 1968 to 2002. Climate surfaces for all variables were created using the ANUSPLIN software package and data from the BoM (see Table 3). Long-term radiation data was used as data was not available for monthly radiation for the early part of the time period and data numbers were considered insufficient for the latter part of the time period.

The methods described in the previous section were used to produce a gridded set of maps for monthly and annual means for temperature (minimum, maximum and average), rainfall and number of frost days, from January 1968 to December 2002 (Table 3).

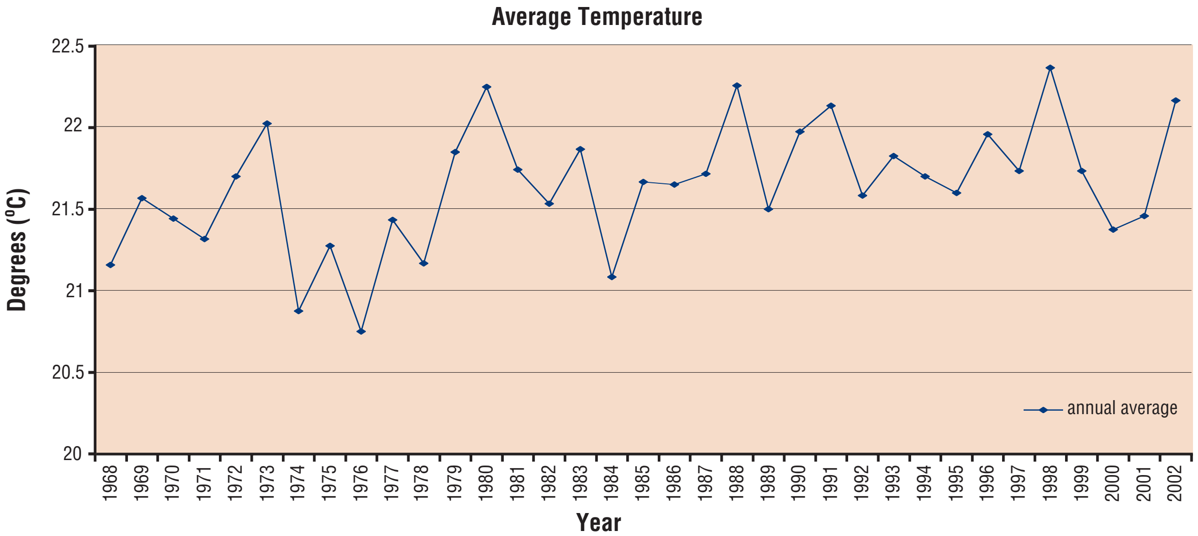
2.2.5.1 Average Temperature

Monthly average temperature (T_{avg}) data was calculated by averaging the BoM monthly minimum and maximum temperature data at each station. Any month which had less than 15 days recorded measurements was removed from the data set and all years which did not have 12 months of data were also removed. The average number of station numbers used for all years was 489.5 ranging from 346 stations in 1986 to 741 stations in 2002.

SPLINA was then fitted to the average temperature data set. Both a spline and a partial spline function was fitted to the data. A second order spline function using three independent variables

Table 3. Monthly climate variables.

ANUSPLIN Climate Variable	Data points (knots)	Fitted variables	Order of spline	Transformation
Average temperature	346-741	3 independent (long,lat,elev)	2	none
Maximum temperature	346-741	3 independent (long,lat,elev)	2	none
Minimum temperature	363-733	3 independent (long,lat,elev)	2	none
Rainfall	4719-7080 (2000)	3 independent (long,lat,elev)	2	Square root
Frost days	350-739	3 independent (long,lat,elev)	2	none



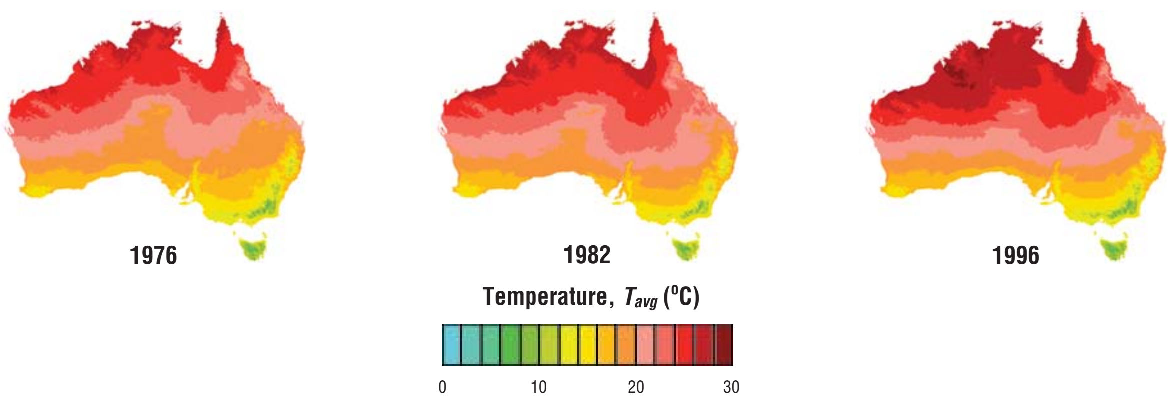


Figure 7. Annual average temperature derived from monthly data grids for 1968-2002 and examples of low (1976), average (1982) and high (1996) temperature years.

(longitude, latitude and elevation) was used to create the average temperature surfaces. The average error associated with the grids was approximately ± 0.5°C.

The continental annual average temperature ranged from 20.75°C in 1976 to 22.37°C in 1998 (see graph, Figure 7). The mean continental average temperature for the period 1968 to 2002 was 21.64°C. The graph in Figure 7 shows a rising trend of 0.45°C but most of the rise in temperature is due to the relatively cooler years of 1974 to 1978 with only a 0.2°C rising trend evident in the last twenty years.

2.2.5.2 Maximum Temperature

Monthly maximum temperature (T_{max}) was fitted from data from the BoM monthly maximum temperature data set. Any month which had less than 15 days recorded measurements was removed from the data set and all years which did not have 12 months of data were also removed. The average number of station numbers used for all years was 489.5, ranging from 346 stations in 1986 to 741 stations in 2002.

SPLINA was then fitted to the average temperature data set. Both a spline and a partial spline function was fitted to the data. A second order spline function using three independent variables (longitude, latitude and elevation) was used to create the average temperature surfaces. The average error associated with the data grids ranged from 0.2 to 0.75°C.

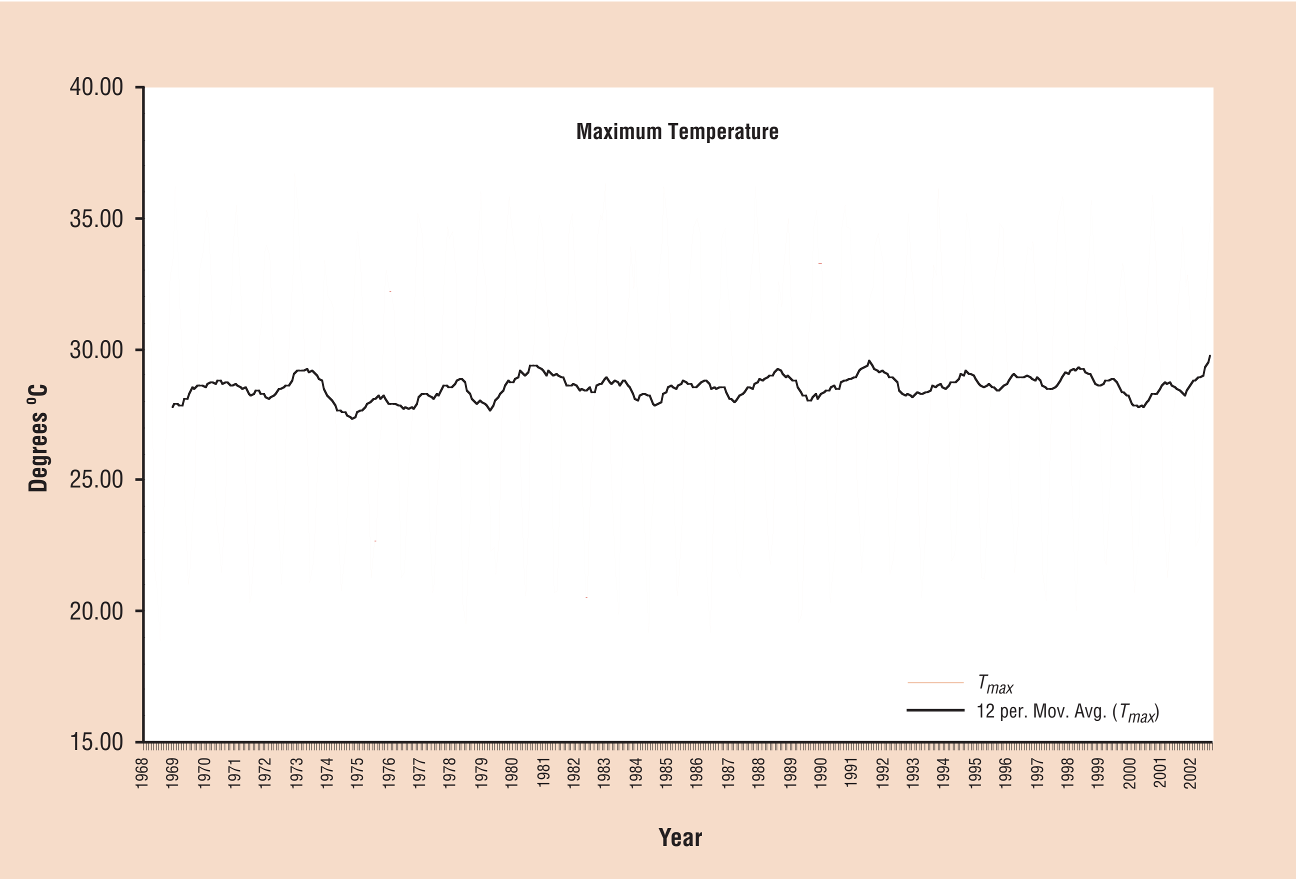


Figure 8. Australian average maximum temperature (T_{max}) and the 12 month running mean.

Figure 8 shows the variation in the Australian average maximum temperature and the 12 month running mean shows an overall increase (~0.4°C) over the period January 1968 to December 2002. Continental monthly maximum temperatures had a mean value of 28.53°C and ranged from a low of 18.9°C in July 1968 to a high of 36.7°C in December 1972. Figure 9 shows example maps for the high (July 2002 and December 1972) and low (July 1968 and December 1975) continental average values.

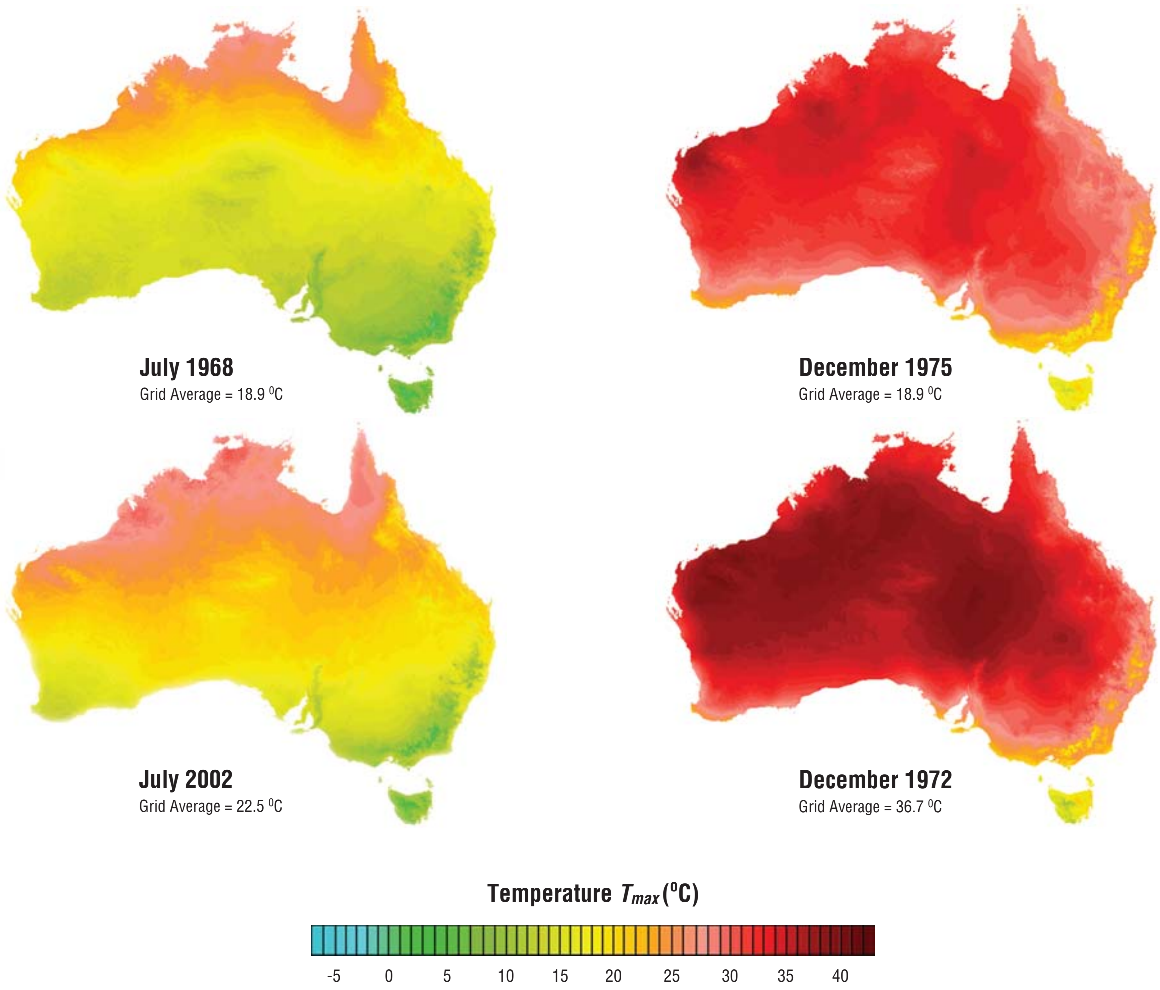


Figure 9. Maximum temperature grids for high and low continental average values for July and December.

2.2.5.3 Minimum Temperature

Monthly maximum temperature (T_{min}) was fitted from data from the BoM monthly minimum temperature data set. Any month which had less than 15 days recorded measurements was removed from the data set and all years which did not have 12 months of data were also removed. The average number of station numbers used for all years was 516, ranging from 363 stations in 1986 to 733 stations in 2002.

Both spline and partial spline functions were fitted to the BoM data. A second order spline function using three independent variables (longitude, latitude and elevation) was used to create the minimum temperature surfaces. The average error associated with the maps ranged from 0.6 to 1.0°C.

Figure 10 shows the variation in the Australian average minimum temperature and the 12 month running mean shows an overall increase (~0.5°C) over the period January 1968 to December 2002. Figure 11 shows the continental monthly minimum temperatures have a mean value of 14.8°C and ranged from a low of 5.5°C in July 1982 to a high of 22.3°C in February 1983. Figure 11 shows example maps for the high (February 1983 and July 1973) and low (February 1972 and July 1982) continental average values.

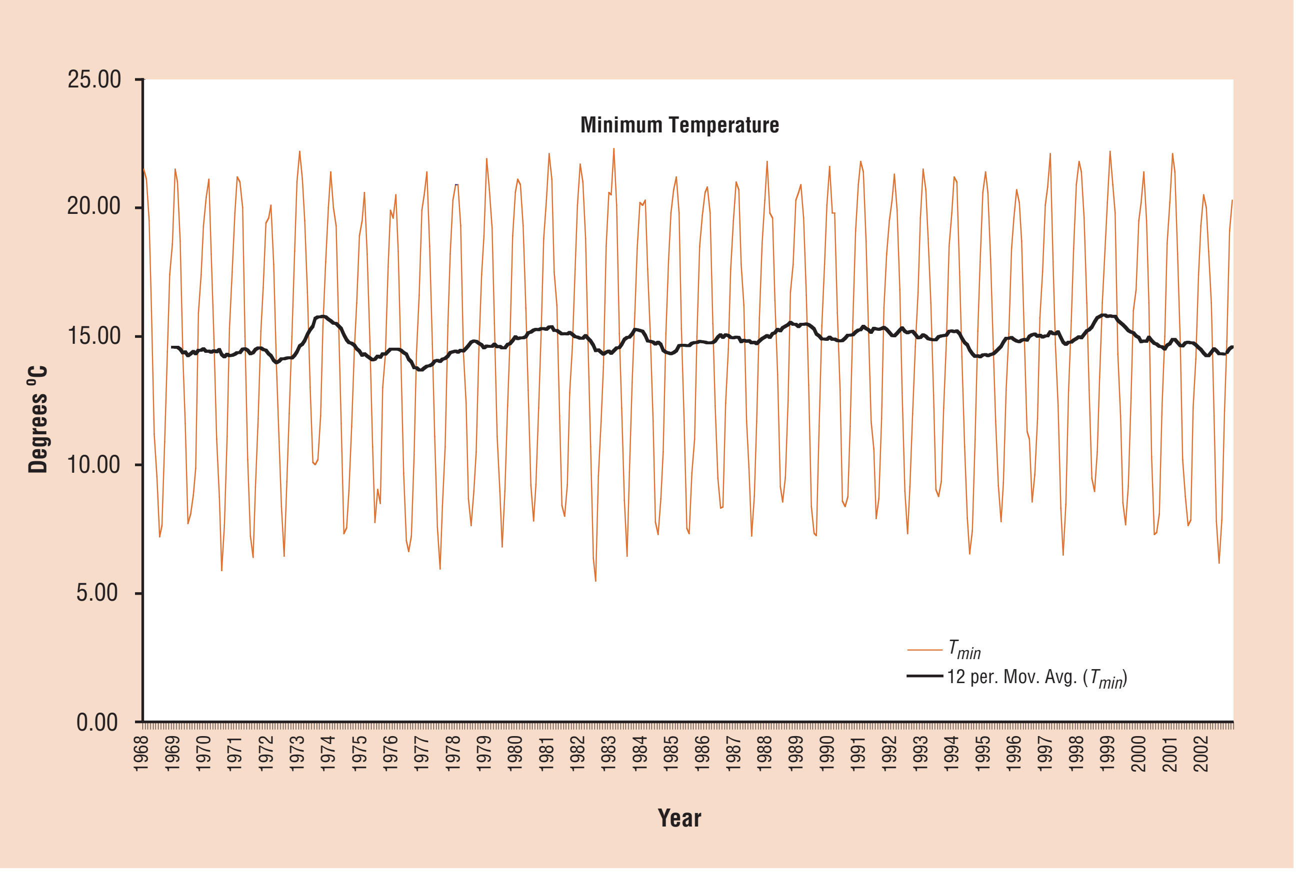


Figure 10. Australian average minimum temperature (T_{min}) and the 12 month running mean.

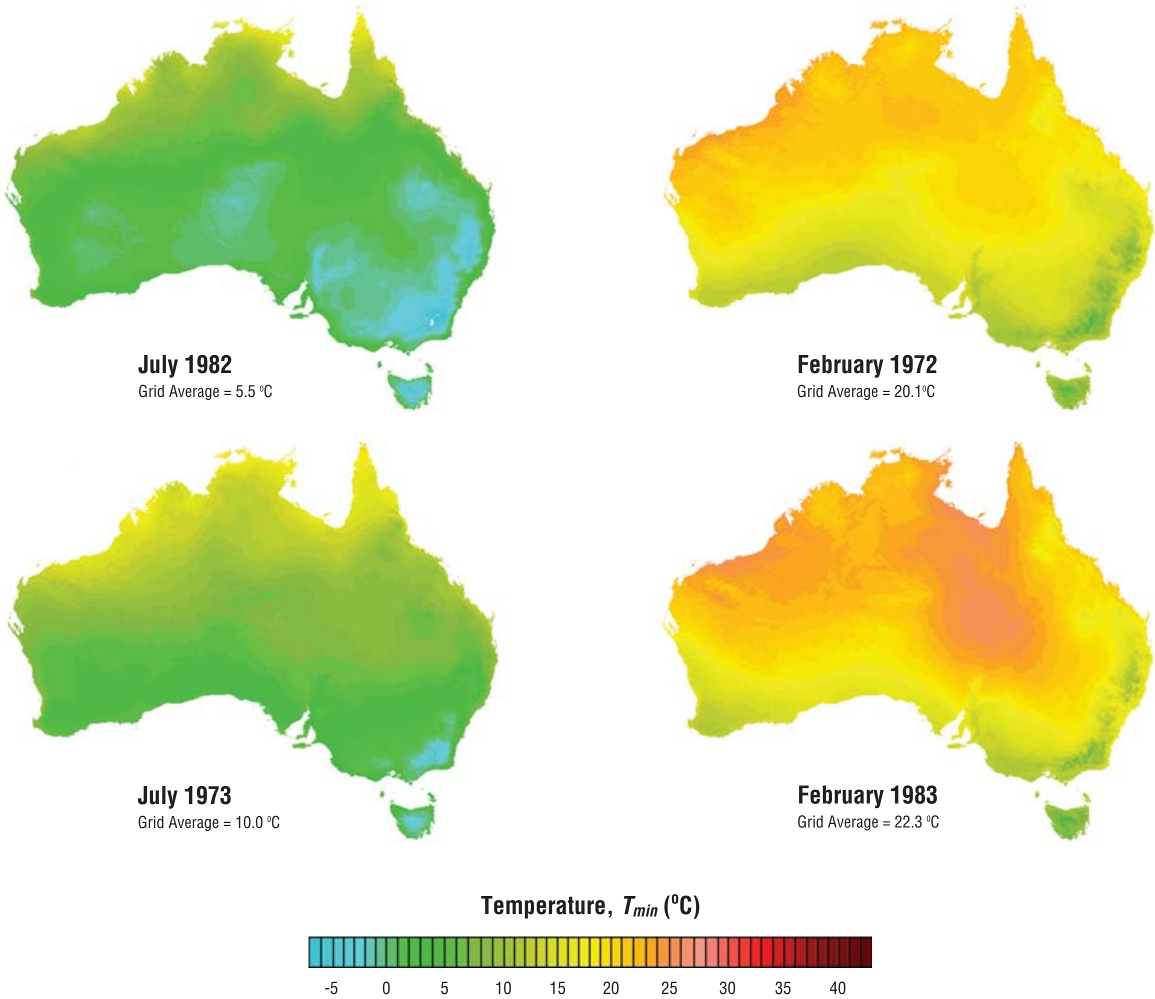


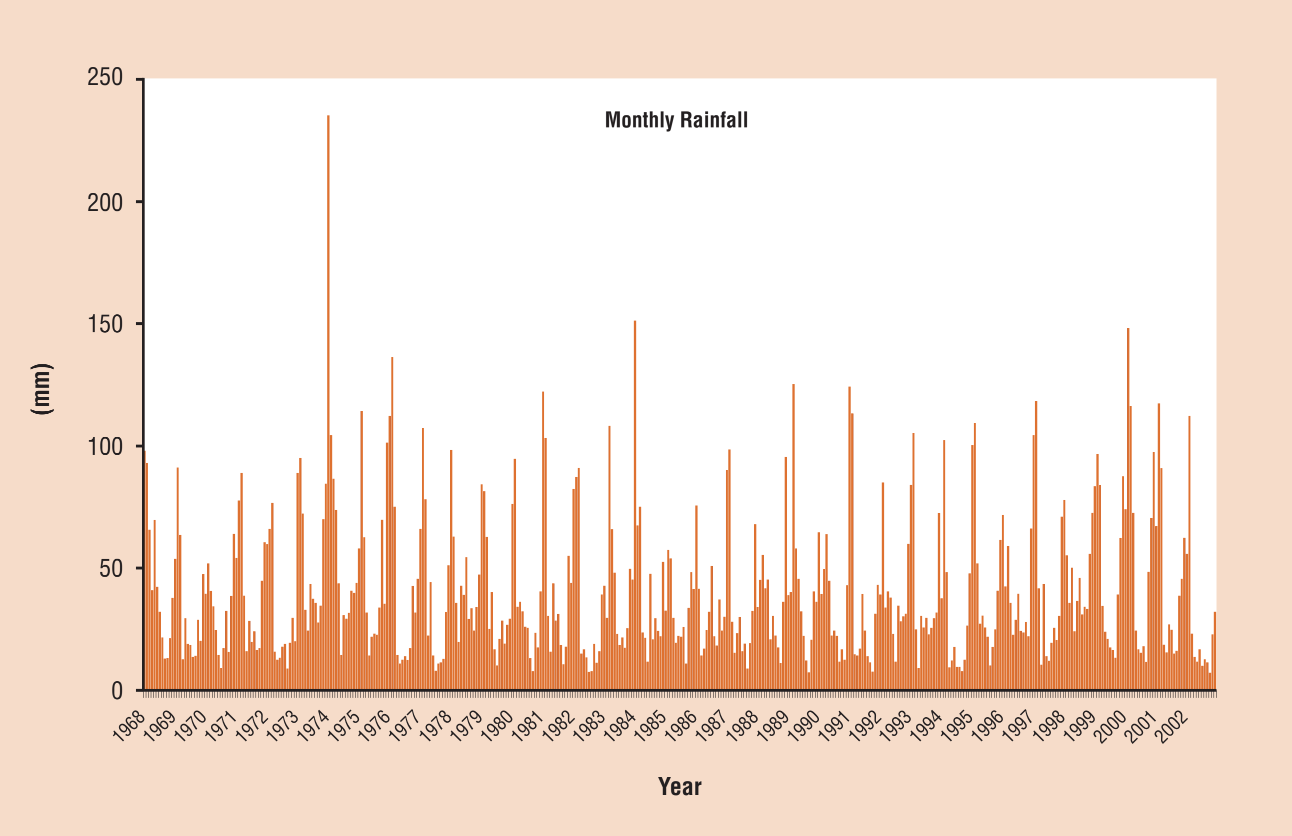
Figure 11. Minimum temperature grids for high and low continental average values for July and February.

2.2.5.4 Rainfall

Rainfall (*P*) was fitted to the data from the BoM monthly rainfall data set. Any month in which had less than 20 days recorded measurements was removed from the data set and all years which did not have 12 months of data were also removed from the data set. The average number of station numbers used for all years was 5,972 ranging from 4,719 stations in 1994 to 7,080 stations in 1970.

A second order spline function using three independent variables (longitude, latitude and elevation) and a square root transformation was used to create the rainfall surfaces. The average grid values ranged from 15.5 mm in November 1982 to 219 mm in January 1974. The error associated with the grids ranged from 14% to 30%, with the higher errors resulting from the lower than average value grids.

Figure 12 shows the Australian continental average monthly and annual rainfall. The mean value for the continental monthly average is 40 mm and ranges from a low of 7 mm in October 2002 to a high of 235 mm in January 1974. The mean annual rainfall was 485 mm and ranged from 327 mm in 2002 to 770 mm in 1974. Figure 13 shows annual rainfall maps for 1970 to 2002.



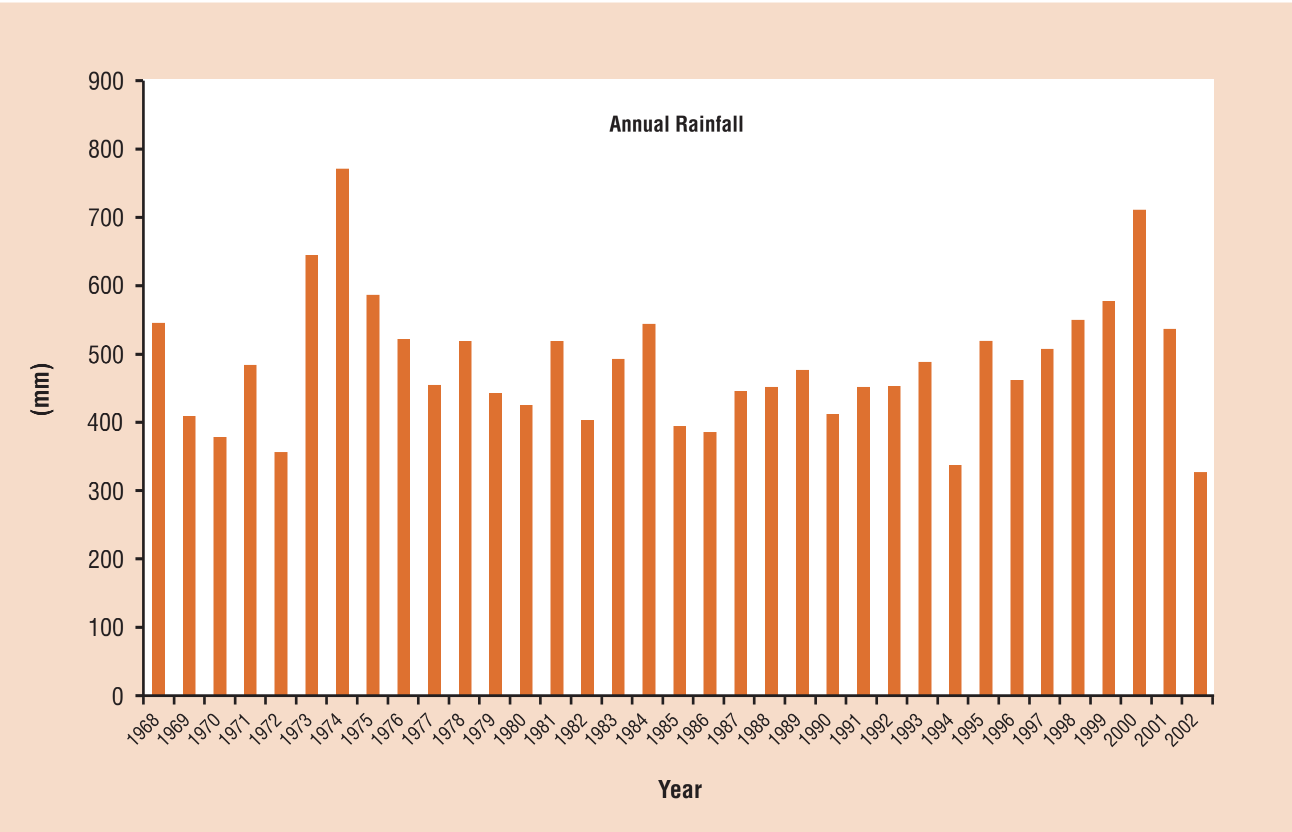


Figure 12. Australian continental average monthly rainfall.

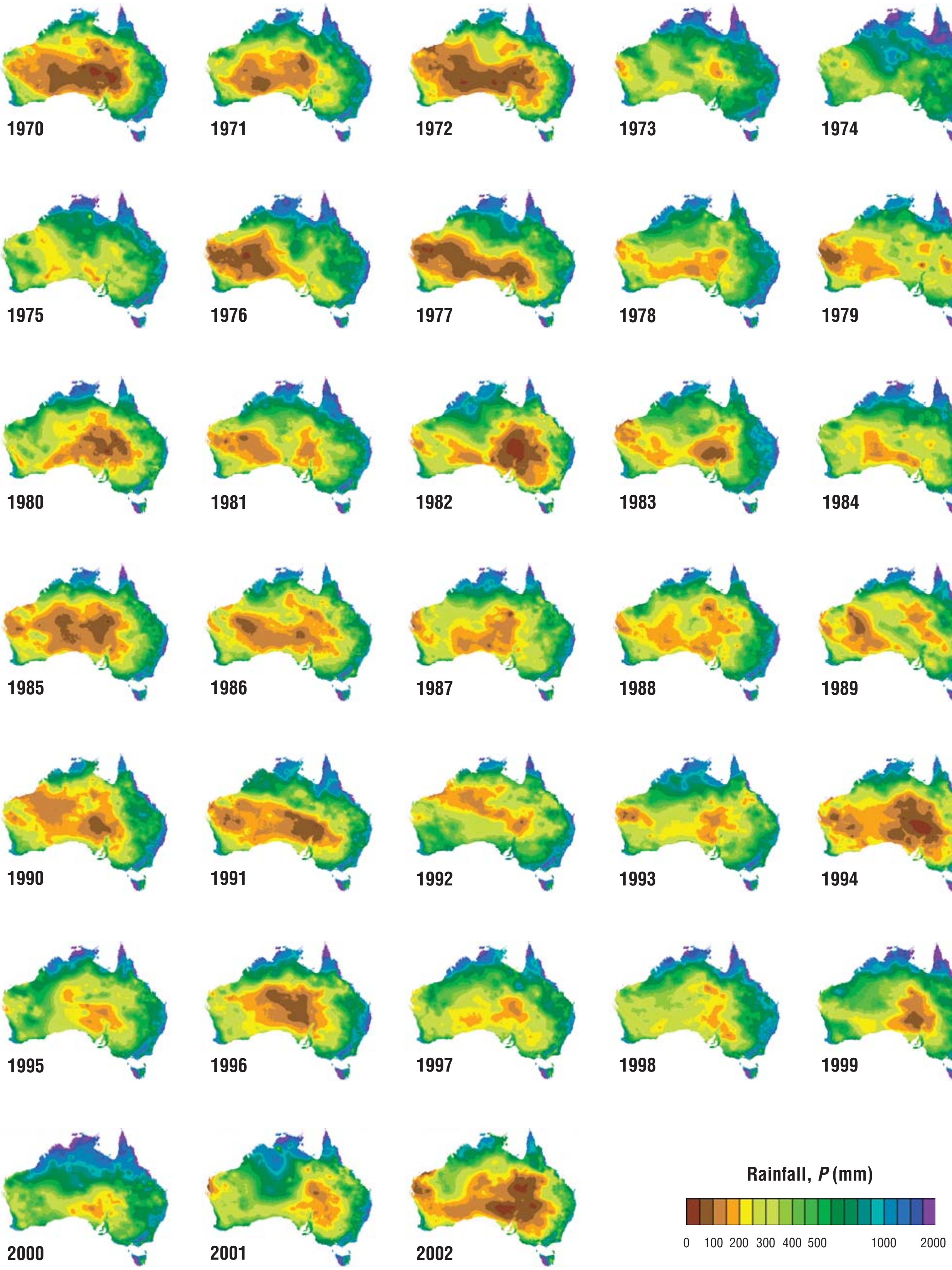


Figure 13. Annual rainfall 1970–2002.

2.2.5.5 Frost Days

The number of frost days per month (*F*) was fitted to the data from the BoM monthly data set. Any month which had less than 20 days recorded measurements was removed from the data set and all years which did not have 12 months of data were also removed. The average number of station numbers used for all years was 548, ranging from 350 stations in 2002 to 739 stations in 1973.

A second order spline function using three independent variables (longitude, latitude and elevation) was used to create the frost surfaces. Values on the output grids which were greater than the number of days in the month were reduced to the number of days in the month and any values less than 0 were converted to 0. The continental average annual number of frost days ranged from 21.1 days in 1982 to 6.1 days in 1991(Figures 14 and 15) with a sharp decline in the latter half of the period. The error associated with the data grids ranged from 0.01 days in the summer months to 3 days in the winter months, with the higher errors resulting from the higher than average value grids.

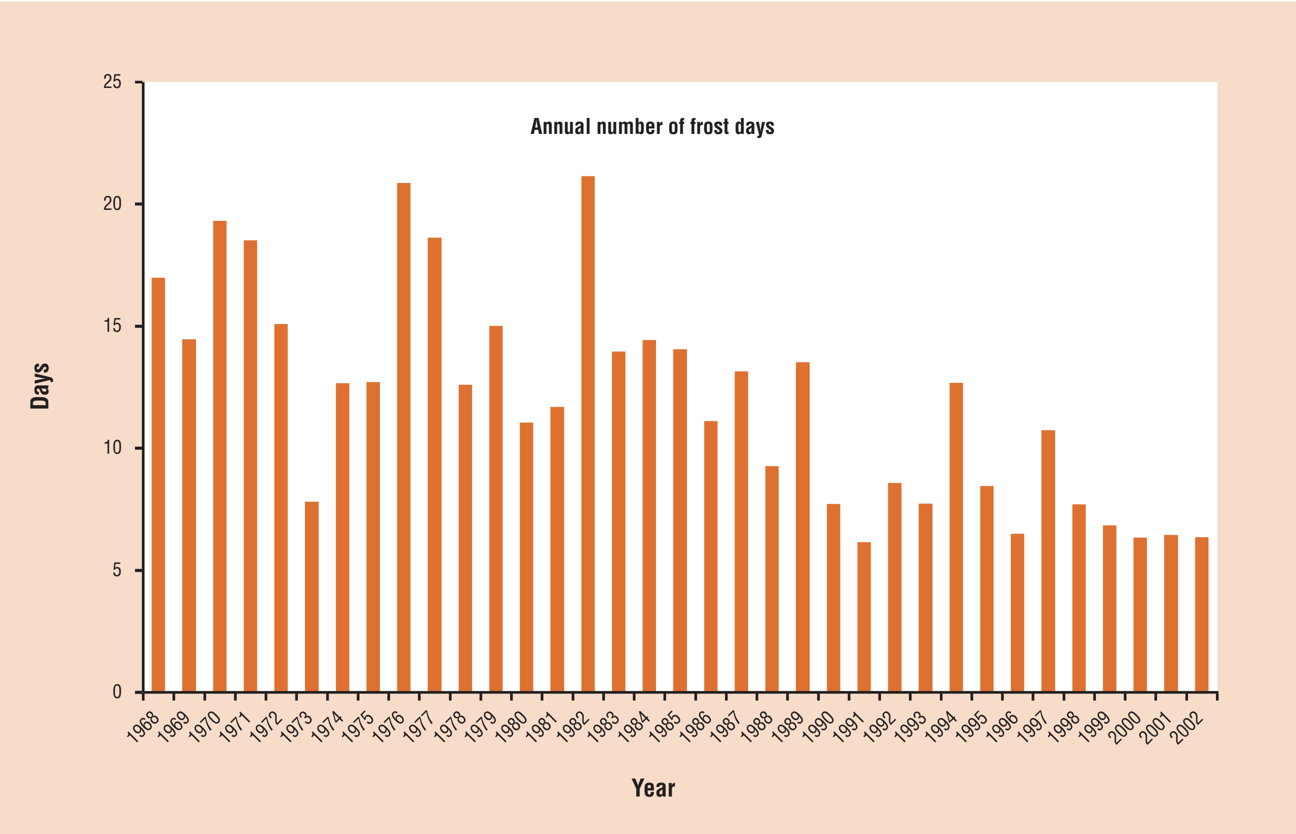


Figure 14. Australian continental average annual number of frost days.

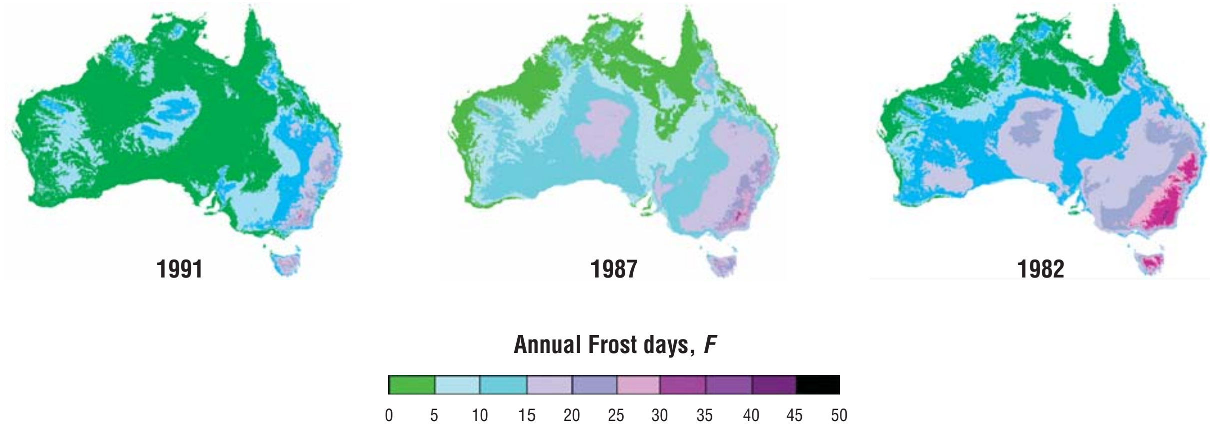


Figure 15. Example grids of low (1991, average = 6.1 days), medium (1987, average =14.0 days) and high (1982, average = 21.1 days) number of days frost.

2.2.5.6 Radiation

As the BoM monthly data would not support the derivation of monthly surfaces, long-term averages were used. For monthly productivity it was decided that 'flat earth' estimates of global radiation would be used as slope and aspect correction at the 1 km scale was thought to be inappropriate. The radiation with rainfall surfaces from ANUCLIM were used. Grids of net radiation were derived where:

$$R_N = (R_P * 0.8) - 4) \qquad \text{if } R_P > 5$$

$$R_N = 0 \qquad \text{if } R_P <= 5 \qquad (7)$$

2.3 NORMALISED DIFFERENCE VEGETATION INDEX (NDVI)

The NDVI provides a crude estimate of vegetation health and a means of monitoring changes in vegetation over time and is one of the most common vegetation indices derived from remotely sensed data. NDVI is related to vegetation as healthy vegetation reflects very well in the near infrared part of the spectrum. Green leaves have a reflectance of 20 percent or less in the 0.5 to 0.7 micron range (green to red, λ_R) and about 60 percent in the 0.7 to 1.3 micron range (near infra-red, λ_I). The value is then normalised to the range –1 <= NDVI <= 1 to partially account for differences in illumination and surface slope but is undefined when λ_R and λ_I are zero. The NDVI is computed by the product of the ratio of the two electromagnetic wavelengths.

$$\text{NDVI} = (\lambda_I - \lambda_R)/(\lambda_I + \lambda_R) \qquad (8)$$

The typical range is between about -0.1 (λ_I less than λ_R for a not very green area) to 0.6 (for a very green area). NDVI values vary with absorption of red light by plant chlorophyll and the reflection of infrared radiation by water-filled leaf cells. Because photosynthesis occurs in the green parts of plant material the NDVI is normally used to estimate green vegetation.

The Advanced Very High Resolution Radiometer (AVHRR) sensor collects imagery at a 1 km resolution that is then used to generate a NDVI product for Australia. The Environmental Resources Information Network (ERIN) of the Australian Government Department of Environment and Heritage .01 degree NDVI archive contains data from the National Oceanic and Atmospheric Administration (NOAA) Satellite 9, 11, 14 and 16. The NOAA 14 data is calibrated using the equations in 'Revised post-launch calibration of channels 1 and 2 of the AVHRR on board the NOAA-14 spacecraft' by Rao and Chen on the NOAA web site at http://orbit-net.nesdis.noaa.gov/. Data from NOAAs 9, 11 and 16 are cross-calculated to NOAA 14 by assuming that the reflectance of the 10,000 pixels with the lowest standard deviation in the NOAA 14 dataset from each of 5 of Australian Deserts are stable.

The data for April to September 1994 obtained from NOAA 11 was very poor due to very low sun angles, thus large angular corrections. For this period, NOAA 9 NDVI images were calibrated and then composited into the NOAA 11 image data.

The images were cloud screened by masking out pixels that did not appear to be biologically consistent with the pixels in the images taken immediately before and after. The first stage of this process was performed by a filter that masks out pixels that show a large decrease followed by a large increase. This procedure was also designed to remove 'dropout' values and abnormally high values probably associated with low sun angles. This was followed by a manual (subjective) stage where suspect areas were compared on screen with adjacent images. The cloud masks were then adjusted as required. It should be noted that the screening procedure contained a degree of subjectivity and was not exhaustive and the cloud masks were expected to change slightly with further work (N. Fitzgerald pers. comm.).

NDVI values were available for the ten year period, 1991 to 2000. Long-term averages were derived from the data and used in both the long-term and monthly productivity indices to provide a comprehensive cloud free data set. Monthly and annual data were not usable because of the extent of cloud cover obscuring data signals over the shorter time spans.

The 28 day average NDVI (in BIL file format) ($NDVI_b$) files supplied by ERIN had values which ranged from 1 to 256. NDVI values less than 50 were considered to be cloud and given a no data value of -99. For each month NDVI was then rescaled:

$$NDVI = (NDVI_b - 50)/200 \quad \text{if } NDVI_b > 50$$

$$NDVI = -99 \quad \text{if } NDVI_b <= 50 \qquad (9)$$

The satellite-derived NDVI data represents the photosynthetic capacity of all vegetation within a 1 km pixel for a given month, correlated with the fraction of photosynthetically active radiation (PAR) absorbed (*f*PAR). Sellers (1985, 1987) derived an important relationship between leaf area index (LAI), absorbed photosynthetically active radiation (APAR) and NDVI. This research found that under specified canopy properties APAR was linearly related to NDVI and curvilinear related to LAI. LAI is usually positively corelated to an increase in the difference between λ_I and λ_R radiation. This relationship has been shown to hold generally over a number of different biomes. LAI can be calculated from:

$$LAI = \ln (1 - (NDVI * 1.0611) + 0.3431) / - 0.5 \qquad (10)$$

3. CALCULATION OF PLANT PRODUCTIVITY

Monthly values of environmental constraints on productivity indices were expressed by modifiers calculated from the temperature, vapour pressure deficit (*VPD*) of the atmosphere, soil water deficit and number of frost days.

3.1 TEMPERATURE MODIFIER

The growth of any plant species is limited by temperatures outside the optimum range for that species. A general assumption is made that, in any particular region, the plants are well-adapted to the existing temperature range. T_{low} was set to ½ the minimum temperature of the coldest month if the minimum temperature of the coldest month was greater than or equal to 0. If the minimum temperature of the coldest month was less than 0, T_{low} was set to ½ the minimum temperature of the coldest month plus the minimum temperature of the coldest month. T_{high} was set to 5°C above the maximum temperature of the hottest month of the year and T_{opt} as equal to the average of T_{low} and T_{high}. T_{avg} was the average temperature described in Sections 2.2.4.1 and 2.2.5.1. The equation describing the effects of temperature is:

$$T_{mod} = \frac{T_{avg} - T_{low}}{T_{opt} - T_{low}} \left(\frac{T_{high} - T_{avg}}{T_{high} - T_{opt}} \right) \tag{11}$$

T_{low} represents the monthly average temperature below which plant growth stops; T_{high} is the monthly average temperature above which plant growth stops and T_{opt} is the optimum temperature for growth. Minimum and maximum temperature data were derived from the ESOCLIM and ANUSPLIN packages and T_{avg} T_{high}, T_{low} and T_{opt} were derived from these values. The temperature modifier (T_{mod}) was 1 when $T_{avg} = T_{opt}$. Equation 10 gives a hyperbolic response curve, with $T_{mod} = 0$ when $T_{avg} = T_{low}$ or T_{high}. Consequently T_{mod} generally had relatively small effects on the calculation of plant productivity. Figure 16 shows the spatial temperature modifier equations for January and July long-term averages.

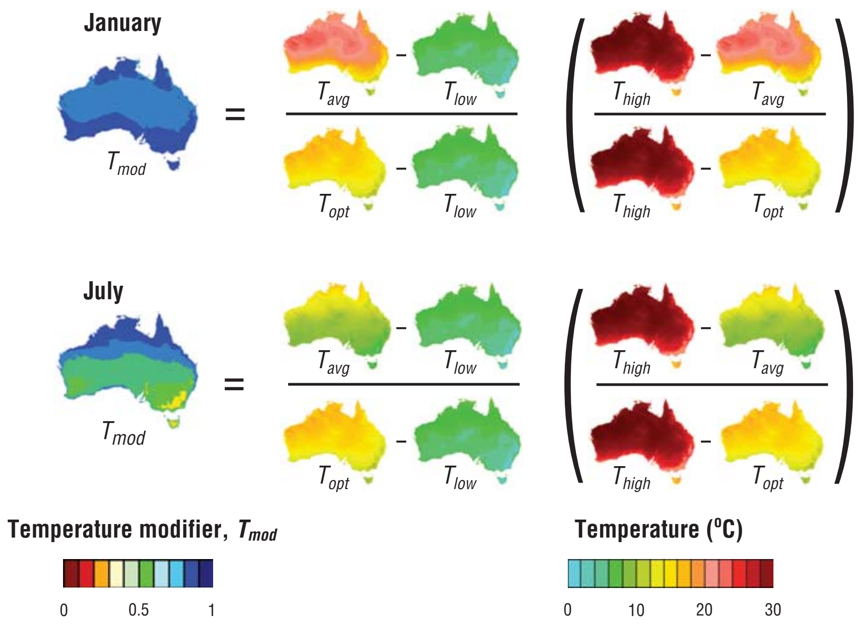


Figure 16. Temperature modifier spatial equations (from Equation 11) for January and July long-term averages.

3.2 FROST MODIFIER

A frost modifier (F_{mod}) was applied, using the simple assumption that frost temporarily inactivates the photosynthetic mechanism in foliage, so there is no growth on a frost day. The modifier is simply one minus of number of frost days per month (F) divided by the number of days in the month (Figure 17).

$$F_{mod} = (1 - F \;/\; \text{Days in month}) \qquad (12)$$

3.3 VAPOUR PRESSURE DEFICIT (*VPD*) MODIFIER

The *VPD* modifier is important because plants respond to the *VPD* rather than relative humidity and the *VPD* provides the driving force for evaporation of water from the leaves. There is a gradient of water vapour from the leaves to the air because the air in the leaf is saturated whereas the air outside is drier. The larger the *VPD* the steeper the gradient. The *VPD* acting on stomatal, and hence canopy, conductance. The equation used is:

$$VPD_{mod} = \text{Exp}(-0.05 * VPD) \qquad (13)$$

Figure 18 shows the *VPD* modifier spatial equations for the January and July long-term averages. This modifier essentially acts as a control on the rate of water loss; it is conditional upon soil water balance (see over page).

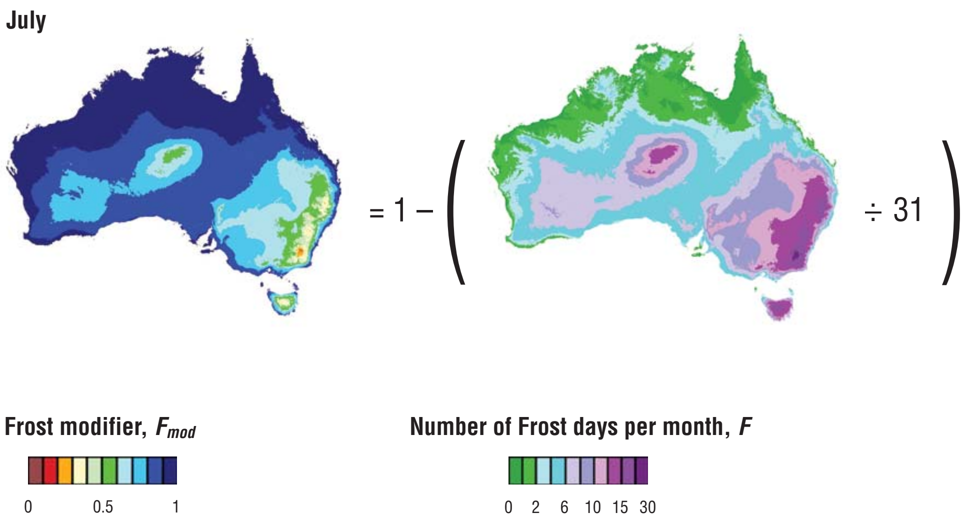


Figure 17. The frost modifier equation for the July long-term average.

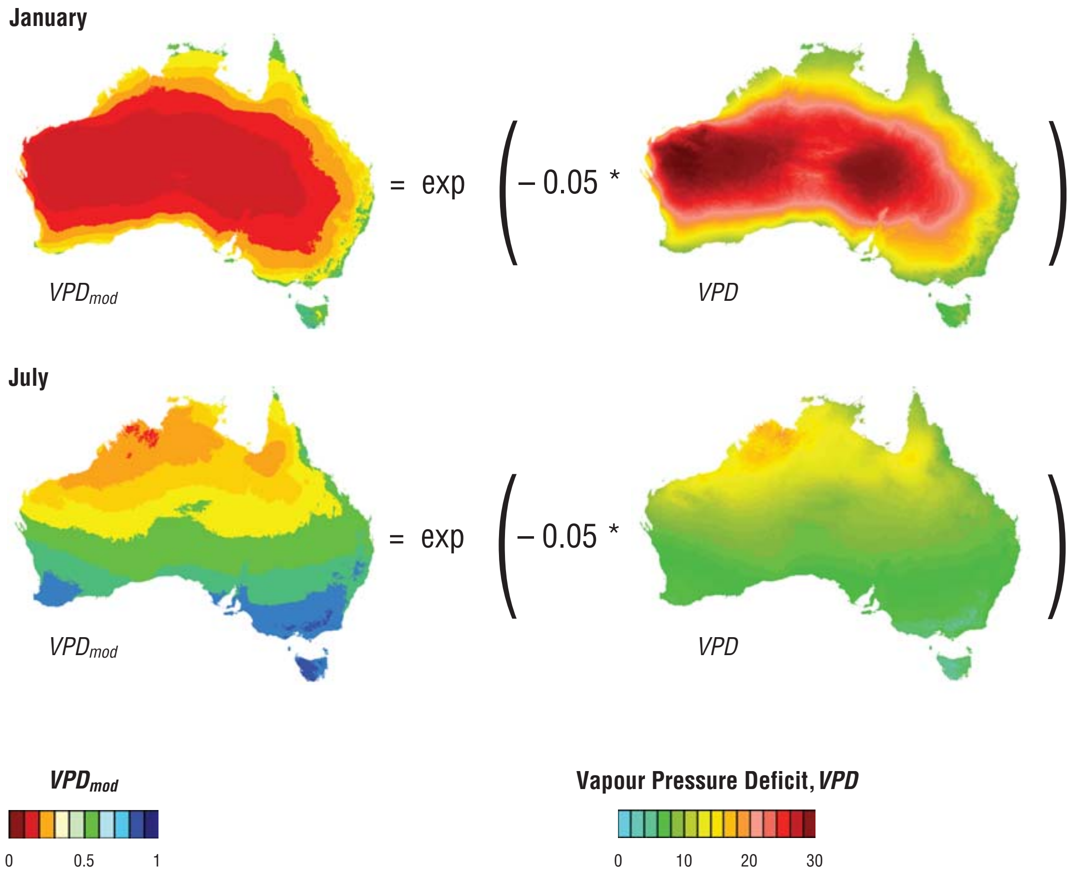


Figure 18. *VPD* modifier spatial equations for January and July long-term averages.

3.4 SOIL WATER CONTENT (S_W)

Soil water content (S_W) is derived from water balance calculations, which take into account the maximum soil water holding capacity (S_C) in the root zone of plants. Plant water use, transpiration (*Trans*), is calculated from the equation for equilibrium evaporation (E_{eq}, see Landsberg and Gower 1997; p 79), modified by feed-back from current soil water content, and a conventional water balance equation:

$$E_{eq} = ((0.67 * R_N * (1 - 0.05)) / 2.47) * \text{days in month} \quad (14)$$

Where E_{eq} is the equilibrium evaporation and R_N is the net radiation (see Equation 7)

Monthly transpiration (*Trans*) was calculated as:

$$Trans(j) = E_{eq}(j) * S_{Wmod}(j\text{-}1) \quad (15)$$

Where *Trans*(*j*) is the transpiration for the month (*j*), $E_{eq}(j)$ is the equilibrium evaporation for the month and $S_{Wmod}(j\text{-}1)$ is the soil water modifier (see Equation 20) for the previous month (Figure 20).

Rainfall interception (I) is derived from the leaf area index (LAI) and is defined as:

$$I = 0.05 + (0.02 * LAI) \quad (16)$$

Australian continental rainfall interception (I) values were derived for long-term averages only as monthly data was not available for the period 1970 to 2002. Figure 21 shows the long-term average I for January.

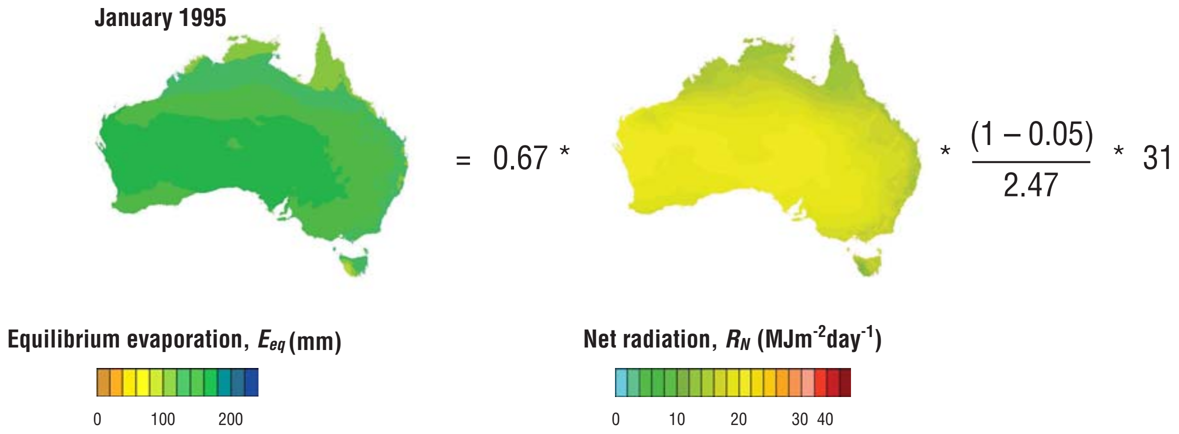


Figure 19. Spatial equation for equilibrium evaporation, January 1995.

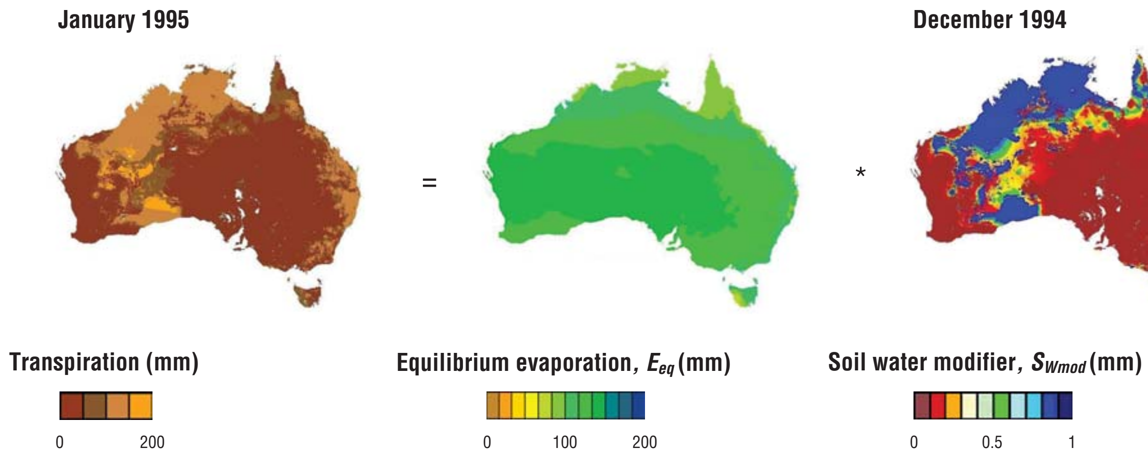


Figure 20. Spatial equation for transpiration, January 1995.

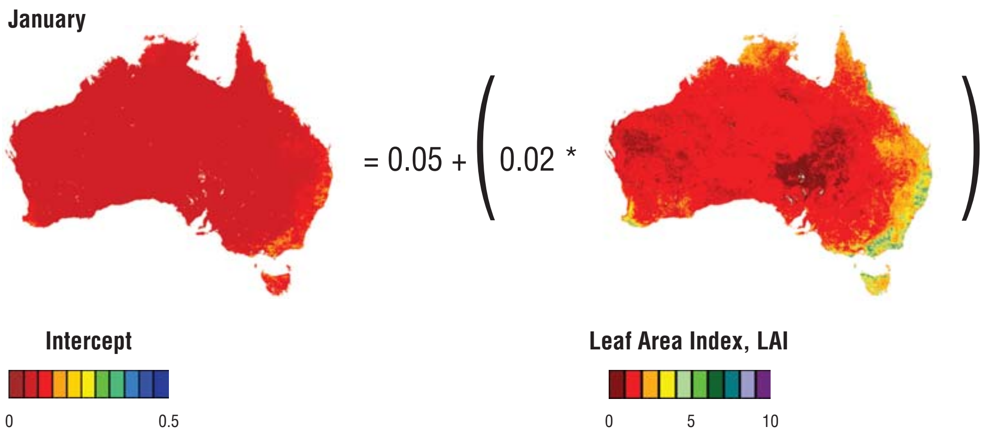


Figure 21. Spatial equation for interception, January long term average.

The conventional water balance (W) equation is derived from the rainfall (P), the rainfall interception (I) and transpiration (*Trans*) and is given by:

$$W = (P * (1 - I)) - Trans \qquad (17)$$

The soil water content (S_W) is derived by adding the water balance (change in soil water content over the month) (W) to the previous months soil water content (Equation 18, Figure 23). The soil water content is reduced to the soil water holding capacity if it is greater than soil holding water capacity. Negative soil water content values are set to zero.

$$S_W(j) = S_W(j-1) + W \qquad (18)$$

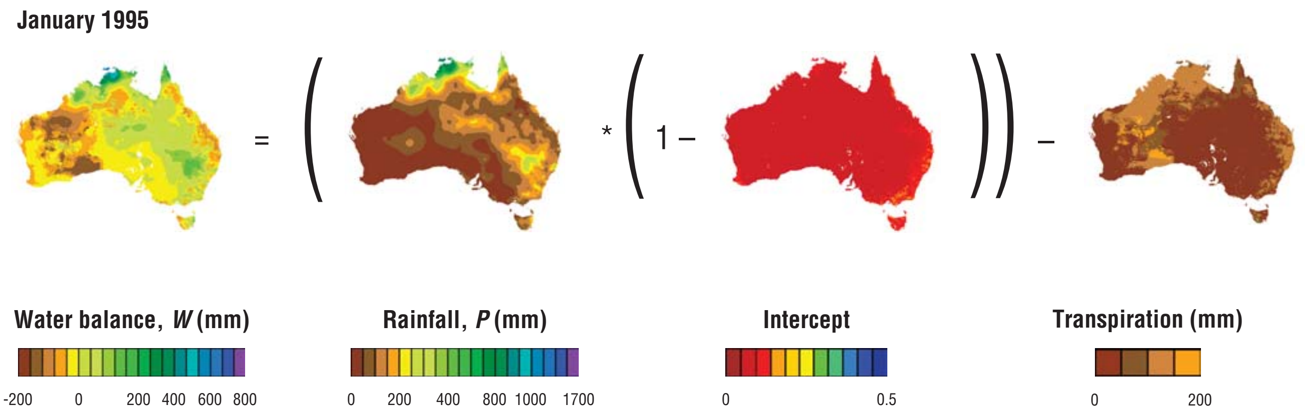


Figure 22. Spatial equation for water balance, January 1995.

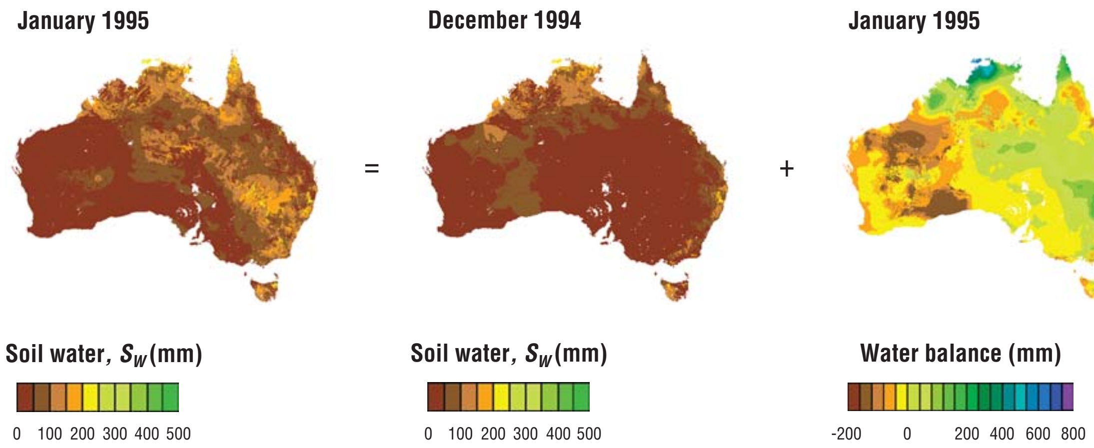


Figure 23. Spatial equation for soil water content, January 1995.

Initial (first month) S_W was taken as 0.75 of the soil water holding capacity (S_C) and carries over from one time step to the next. The soil moisture calculation was sequenced so that initial S_W was set by running the water balance model for two years prior to initiating the productivity model. For the January 1970 to December 2002 monthly analysis, the S_W calculation sequence was initialised using the 1968 and 1969 climate data.

The soil water modifier (S_{Wmod}) (Equation 20) was calculated from the moisture ratio (M), which is the S_W divided by S_C. The equation describes the variable effect of M across the range from wet soil (M ≈ 1) to dry soil (M ≈ 0).

$$M = S_W / S_C \tag{19}$$

The soil water and *VPD* modifiers are not multiplicative; the lowest one applies. The argument is that if plant growth (conversion of radiant energy into biomass) is limited more by *VPD* than soil water (i.e. if $VPD_{mod} < S_{Wmod}$) then soil water is not a limiting factor, even if soil water content is relatively low. The converse applies; i.e. if $S_{Wmod} < VPD_{mod}$, soil water is the limiting factor.

$$S_{Wmod} = 1 / (1 + ((1 - M) / 0.6)^7) \text{ if } 1 / (1 + ((1 - M) / 0.6)7) < VPD_{mod}$$

$$S_{Wmod} = VPD_{mod} \text{ if } 1 / (1 + ((1 - M) / 0.6)^7) > VPD_{mod} \tag{20}$$

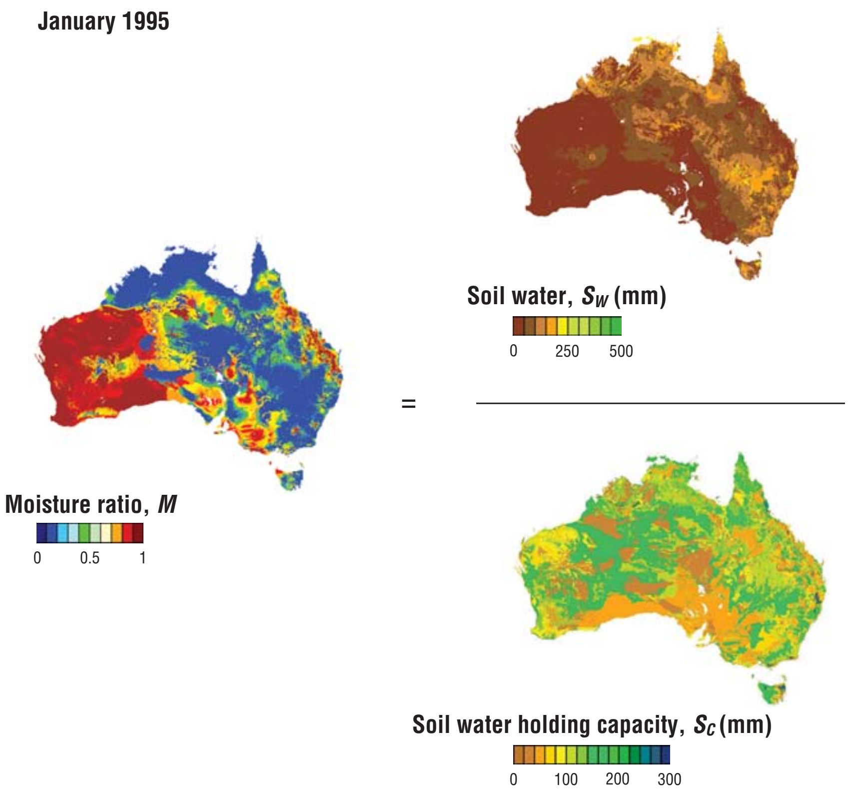


Figure 24. Spatial equation for moisture ratio, January 1995.

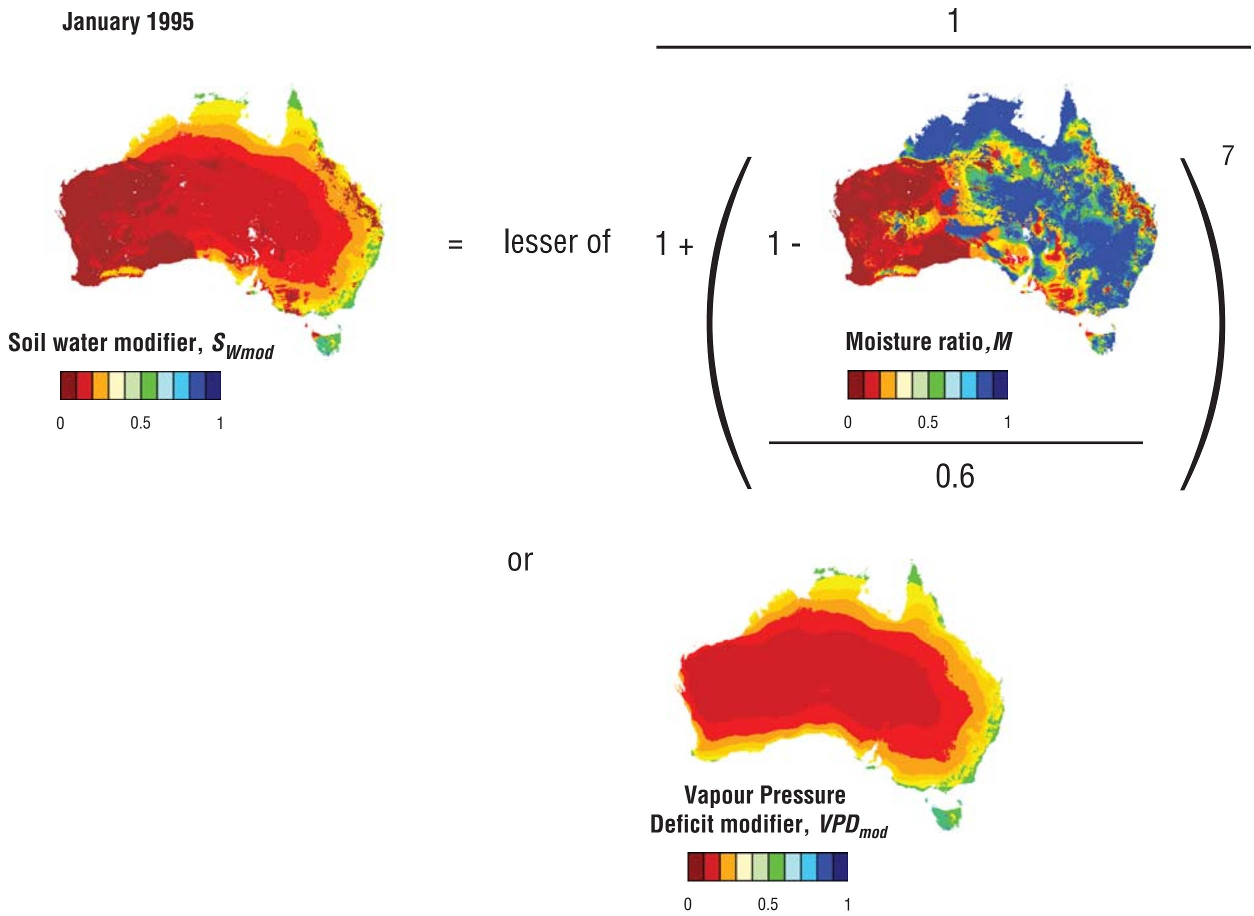


Figure 25. Spatial equation for soil water modifier, January 1995.

3.5 ABSORBED PHOTOSYNTHETICALLY ACTIVE RADIATION (APAR)

In the original version of the 3-PG model (following Landsberg and Waring 1997), APAR is multiplied by a factor that converts it to a biomass accumulation equivalent. This, in effect, amalgamates two physiological processes: the conversion of absorbed CO_2 into initial carbon products (gross primary production) and the loss of a proportion of those products by respiration to give net primary productivity. The value of the conversion factor (ε, gm C MJ^{-1} APAR) used was obtained from the literature (Potter *et. al.* 1993, Ruimey *et. al.* 1994, Landsberg *et. al.* 1997). There is significant variation in ε values, but no clear pattern in relation to plant type, so a 'best estimate' value of 1.25 gm C MJ^{-1} APAR was used. In the productivity model the net primary productivity equivalent was taken as an index of 'plant productivity' and was not used to infer an absolute mass increase. Used in this way the conversion factor was not critical as it had only a linear (direct multiplicative) effect on the index.

Absorbed photosynthetically active radiation (APAR) was estimated from global solar radiation, interpolated from station data provided by the BoM, and from a linear relation with the satellite-derived NDVI which represents the photosynthetic capacity of all vegetation within each 1 km pixel and is correlated with the fraction of PAR absorbed (*f*PAR).

APAR is calculated as half the amount of short-wave (global) incoming radiation (R_P) absorbed by plant canopies:

$$APAR = R_P * 0.5 * (1 - Exp(-0.5 * LAI)) \times \text{days in month} \quad (21)$$

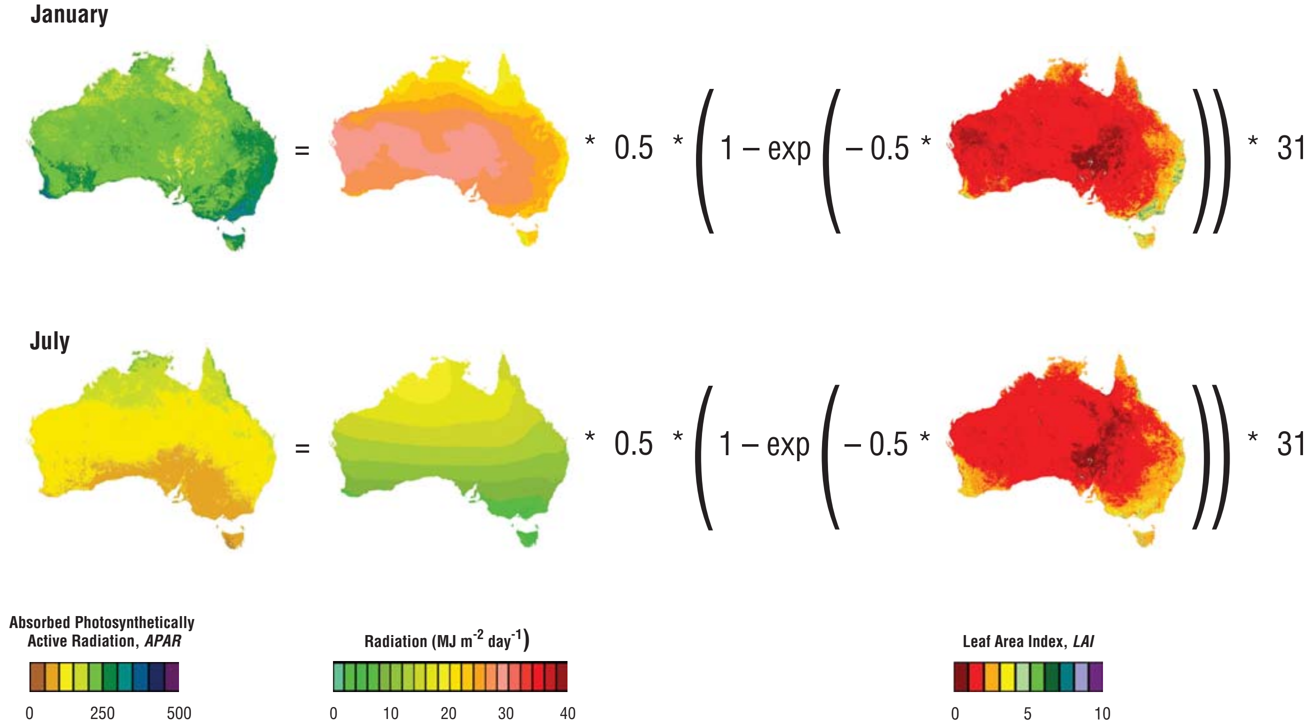


Figure 26. Long-term average APAR for January and July.

Where LAI is the Leaf Area Index and the coefficient 0.5 is a general value for the extinction coefficient. In a slope and aspect corrected form of the productivity model radiation with rainfall (R_P) is replaced by slope and aspect corrected radiation (R_C). APAR was calculated for long-term means as the available radiation and LAI data were long-term averages.

3.6 PLANT PRODUCTIVITY INDEX

Productivity is reduced by modifiers reflecting non-optimal nutrition, soil water status, temperature and atmospheric vapour pressure deficits. Modifiers are dimensionless factors with values between 0 (complete restriction of growth) and 1 (no limitation). Modifiers used in this way are discussed by Landsberg (1986), McMurtrie *et. al.* (1994) and Landsberg and Waring (1997).

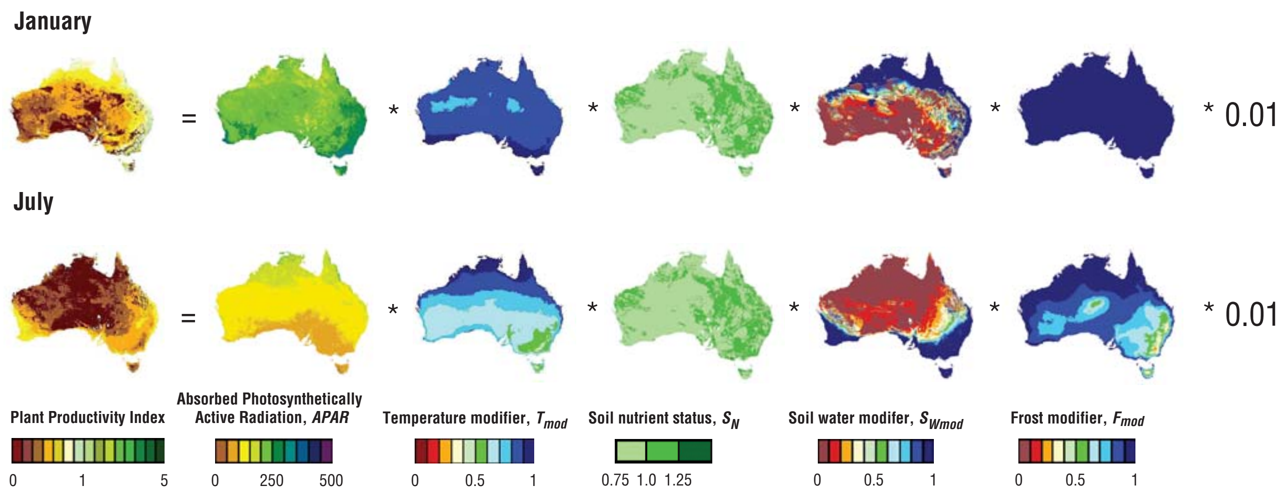


Figure 27. Spatial equations for productivity indices, January and July long-term averages.

Monthly values of plant productivity index (Figure 27) are expressed by APAR multiplied by the modifiers calculated from soil water balance, temperature, number of frost days and soil nutrient values.

$$\text{Productivity Index} = \text{APAR} * T_{mod} * S_N * S_{Wmod} * 0.01 * F_{mod} \quad (22)$$

Australia's annual plant productivity is the sum of the 12 monthly values for the year of interest

$$\text{Productivity Index}_{ann} = \sum_{j=1}^{j=12} \text{Productivity Index}_j \quad (23)$$

where j is the month. Figure 28 shows the long-term annual average productivity index for Australia and Figure 29 shows the annual productivity indices for 1970 to 2002.

A comparison of the annual productivity index maps in Figure 29 and the annual rainfall maps (Figure 13) shows the dominance of rainfall in the estimation of plant productivity.

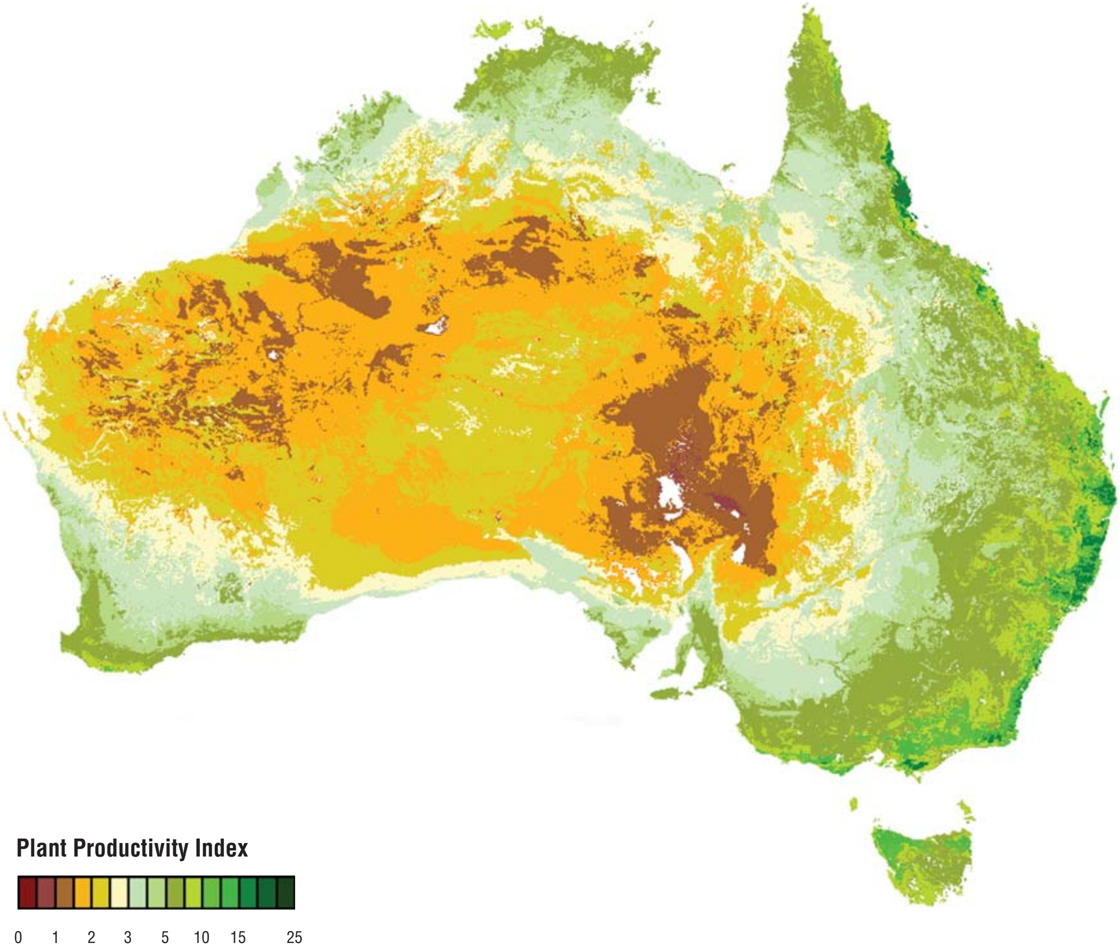


Figure 28. Derived long-term average plant productivity index for Australia.

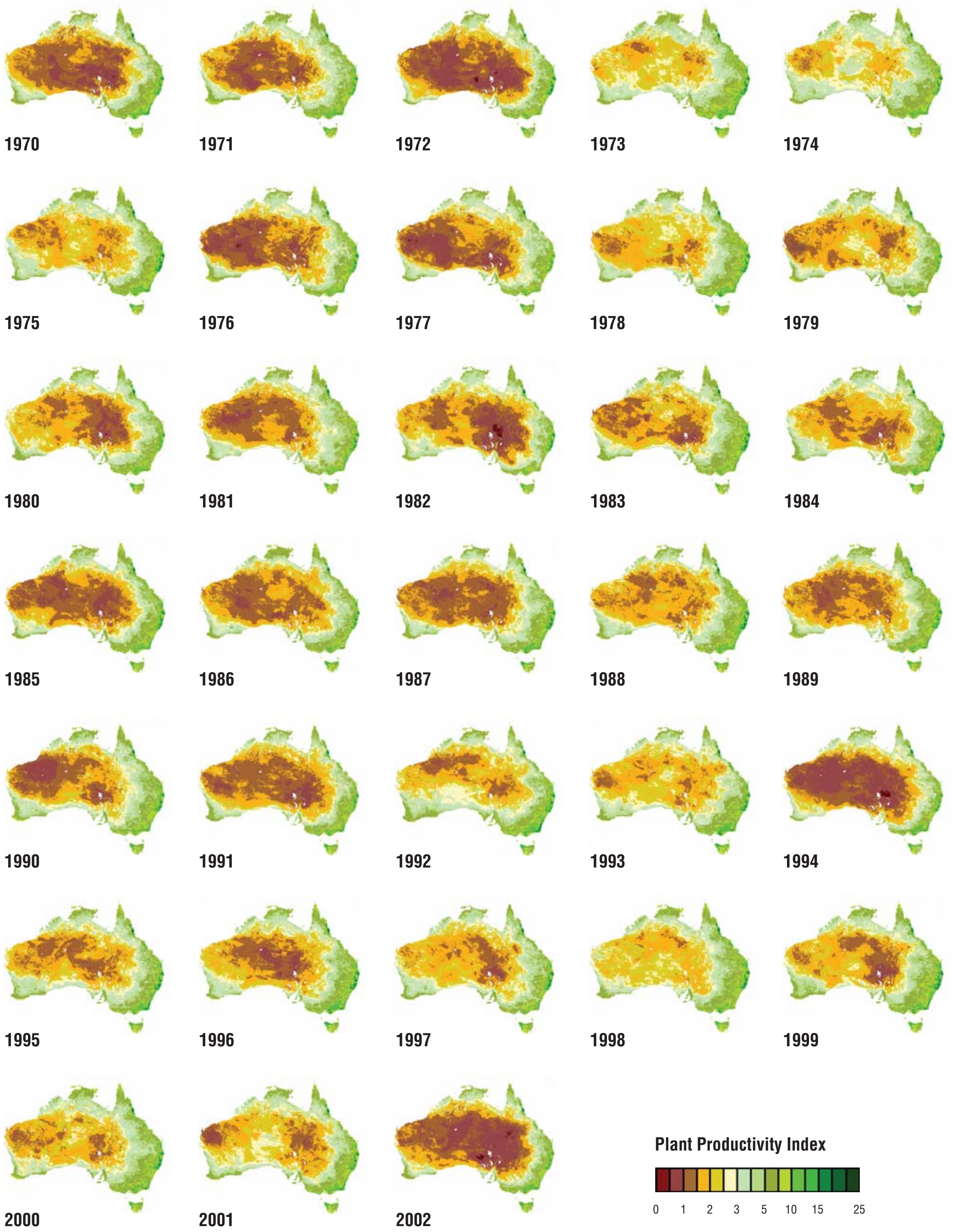


Figure 29. Derived annual continental productivity indices 1970-2002.

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APPENDIX 1

Preliminary Investigations: Spatial Estimation of Plant Productivity and Classification of Non-Commercial Vegetation Types

URS Australia

Joe Landsberg

Jenny Kesteven

July 2001

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A1. OVERVIEW

The work reported here represents preliminary investigations toward developing the capability of the National Carbon Accounting System (NCAS) to estimate carbon sequestration in 'non-commercial' vegetation types, largely environmental plantings and native regrowth. This preliminary work provided guidance on the preferred framework and evolution of methods presented in the main body of this report.

Most of the collection of forest growth data and modelling activity has historically been focussed on commercial plantings which have higher productivity. Non-commercial plantings are important because of their associated benefits e.g. windbreaks, salinity control, erosion control, habitat and biodiversity, visual amenity. With the drive to more sustainable land management, there is a need for more of such plantings integrated with whole farm and whole region planning. Likewise, native regrowth following disturbance, e.g. fire and land clearing, is a common feature of the Australian landscape, and is a desirable form of revegetation. Carbon sequestration can likewise facilitate sound land management.

A relatively small, yet important, part of Australia's National Greenhouse Gas Inventory is the carbon stored in environmental plantings and native regrowth; however there are few data available on which to develop Growth Tables, whereby empirical estimates may be made for specific projects or for regions. The NCAS is working to fill this gap, and this project is a means to that end. The NCAS has chosen the second of two broad options to do so:

1. Sample stands of environmental plantings and native regrowth systematically across Australia, along with associated environmental data, and develop the relationships needed to develop Growth Tables; or
2. Stratify the Australian landmass on the basis of plant productivity and use this to undertake a more-efficient stratified sampling and modelling of the growth potential within these strata.

This project comprises two steps:

1. Collate and analyse available data for the main types of environmental plantings and regrowth vegetation relevant to forming Growth Tables (as reported in Section A2 and A4); and, concurrently
2. Develop the possible methodologies for productivity stratification and vegetation classification; and apply the stratification methodology to produce the documented GIS layer over Australia (as reported in Section A3).

The original intent of this work was to develop a classification method for non-commercial plantings around potential carbon accumulation and to develop Growth Tables for regions of varying productivity throughout Australia. The aim was to classify vegetation into a manageable number of types of similar carbon accumulation patterns. This would provide default estimates of the carbon accumulation for a particular vegetation class in a particular region/location.

This was planned as a desktop study with 3 steps:

1. Draft classification of environmental plantings and native regrowth.
    a) Define classes (classification)
    b) Define productivity regions (stratification);
2. Consult with experts to refine the classification; and
3. Refine the classification.

The initial intention was to produce a series of 'look-up' Growth Tables for each of the types of non-commercial plantings, so that they could be applied in the relevant regions as defined in the first step of this project.

However, it was soon recognised that there were few data available concerning carbon accumulation patterns i.e. 'plant growth rates' of these vegetation types. Thus the classification would be extremely coarse and, on its own, would add little value. This conclusion led to the development of methods explored in Richards (2002) and described in detail in Richards (2001).

In light of this, an alternative approach of developing Growth Tables for typical vegetation types was pursued and is reported in the following Section A2 and data is tabulated in Section A4.

To guide data collection a list of about 40 vegetation types was compiled, but feedback was that this needed to be greatly expanded by incorporating height classes as well. Height class is generally used as a site index, that is, as a measure of site productivity. There are few experts in this field, and those who provided information or advice confirmed the paucity of this data and that it would be difficult to provide the necessary Growth Tables for each vegetation type.

Feedback received confirmed that the best way to proceed was to collate as much of the available growth information for native regrowth and environmental plantings that would allow potential development of growth models and likely carbon accumulation for particular regions. This sparse data could then be used as a basis for interpolation, guided by relative site productivity assessments, to fill gaps. The paucity of purely 'non-commercial' data led to the inclusion of data from some commercial plantings data.

A2. COLLATION AND ANALYSIS OF GROWTH DATA

URS Australia

A2.1 ASSEMBLY OF DATASETS

Datasets were sourced widely and because the data were sparse, all possibilities were considered: Fortech (now URS Forestry) files, CSIRO, Greening Australia, State agencies, Bureau of Rural Sciences (BRS), and relevant Universities.

Data sources included:

- The Australian Government Bushcare/Natural Heritage Trust (NHT) funded work undertaken by Hassalls 'Measurements of Plantations of Trees in [*region*] to Improve the Estimates of Carbon Sequestration in Low Rainfall Areas', for the following regions: South Australia, Victoria and WA;
- The publication commissioned by the AGO (NCAS Technical Report No. 25) by Grierson, Williams and Adams (2000) which listed sources of unpublished data; and
- The ABARE Trees on Farms survey, for leads as to what might be available. (Wilson *et al.* 1995)

A number of other published and unpublished reports and databases were reviewed. In most cases, these resources did not incorporate measured volumetric growth data and/or were not made available to URS Australia.

The surprising finding was just how little *relevant* data were available, even from native forestry agencies. This was after extensive consultations. The paucity of data led to the inclusion of some commercial plantings data. Because of this, careful consideration of the comparability and compatibility of data was undertaken before calculating Growth Tables.

It was clear that a large volume of related data exists, but there would be a need to establish its utility for this particular purpose. It is likely that further data will be identified and its utility should also be examined. Synthesis of such data has considerable cost benefit advantages over field sampling.

A2.2 CODING

Information was gathered under data fields that would be useful for developing Growth Tables and interpreting the variation, including:

- Site information (ID #, name/location/coordinates, year established, area planted, species list);
- Biomass estimate (value, age of trees at time of measurement, type of estimate);
- Mean Annual Increment (MAI);
- Planting density (trees per hectare);
- Wood density (kg/m^3);
- Site factors, e.g. rainfall, soil type/quality, topography, access to water, salinity;
- Husbandry, e.g. tubestock/direct seed, weed and pest control, fire, irrigation; and
- Source of information.

A2.3 SELECTION OF VEGETATION TYPES

The selection of vegetation types for analysis of growth parameters was based on two considerations:

- The datasets that were made available – the best represented types can support the most robust Growth Tables and model calibrations; and
- Having a wide range of vegetation types, to give most scope for estimating the performance of other vegetation types by 'interpolation'.

A2.4 PREPARATION OF GROWTH TABLES

The revised plan was that the data for each species would be summarised statistically to understand the causes of variation. These have been presented in Section A4, Tables 1 and 2.

Having compiled the growth tables and examined the data, it became apparent that the paucity of data and the different methodologies used to arrive at this data, meant that comparisons of growth and the estimation of growth tables was inappropriate. Adjustments and assumptions could be made to lessen the impacts of these incompatibilities. Undertaking these adjustments was outside the scope of this project.

A2.5 FINDINGS

A2.5.1 Review of Publications

Grierson *et. al.* (2000) *Review of Unpublished Biomass-Related Information: Western Australia, South Australia, New South Wales and Queensland*

This presents data for mature vegetation or at least snap shots in time, e.g. Table 2. There are references to publications and datasets that may be able to supply growth rate data. The publication represents the first stage (identification of potentially usable datasets) of a two stage process. The second stage will provide comprehensive assembling and synthesis of this data.

Particular issues that were noted within Grierson *et. al.* (2000) include:

- Mallee-type species will likely need different estimates for single and multi-stemmed species;
- p. 7-8: Forestry SA, see Kiddle *et. al.* (1987), Boardman *et. al.* (1992) for growth curves of native species growth in plantations;
- p. 9: see reviews by Eamus *et. al.* (2000), Snowden *et. al.* (2000), Keith *et. al.* (2000), Burrows *et. al.* (2001) for mulga and other species;

- Root:shoot ratios - most decline with age, a few increase and a few have no clear trend (Table 4, p. 12). There is a wide range of mean values, even within the same genus. There is clear evidence of an environmental gradient and further work on the dominant factors of change, e.g. soil depth texture etc., nutrient and water availability that may permit modelled estimates;
- p. 21: see Todd (2000) for jarrah regeneration;
- p. 23: WA oil mallee growth data. Not really relevant as these are dense plantings. Might illuminate the shape of the growth curve;
- p. 24: see chenopod growth (Koonamore data, see Noble (1977) for recovery after over-grazing), also Sinclair (Botany Department, Adelaide University);
- p. 26: cypress pine growth rates quoted;
- MAI quoted for tropical dry forest and woodland;
- p. 29: wide variation in (fine) root biomass, similar to variation in leaf biomass; and
- p. 30: mountain ash data – summary values, see Grierson *et. al.* (1992).

Hassall & Associates (1998, 1999a 1999b) *Measurements of Plantations of Trees in [region] to Improve the Estimates of Carbon Sequestration in Low Rainfall Areas*

This set of three reports funded by Bushcare and the NHT aims to improve the knowledge on carbon sequestration estimates from tree planting in three States, Victoria, South Australia and Western Australia. Approximately a dozen sites were sampled in each state, incorporating a large range of climatic and physical variation and species mix.

Very diverse growth rates were observed throughout the regions studied. The diversity of the species mix, site characteristics and differing husbandry made comparisons between different sites and regions difficult and few conclusions could be reached regarding the effect of different environmental conditions on biomass accumulation.

The approach used a constant wood density value for all tree ages in their estimation of volume, plus their use of total stem volume including bark as the base for estimating volume, make comparisons difficult with other major sources of data. Also, the surveying of multiple species plots necessitates the use of mean estimates for many of the numerical results, leading to further incompatabilities with other datasets.

Summaries of growth data for each site in the three States are provided in Section A4, Tables 1a-1c.

Eamus *et. al.* (2000) *Review of Allometric Relationships for Estimating Woody Biomass: Queensland, the Northern Territory and Western Australia*

This report entailed the collection of primary volumetric data from a number of sites in Queensland and the Northern Territory. The report itself concentrates on constructing allometric equations linking this data with growth parameters such as height (DBH) and growth rate. The fundamental datasets from this work were not available for this study.

Wong *et. al.* (2000) *Forecasting Growth of Key Agroforestry Species in South Eastern Australia*

This report, prepared for the Agroforestry Joint Venture Program, aimed to improve the reliability of forecasting tree growth and yield of key agroforestry, i.e. commercial species on cleared land across South Australia and Victoria. As part of this, primary data including volumetric information, was collected from long-established trials for six major *Eucalypt* species.

Despite focussing on commercial plantings, the Wong report was included in this study given the paucity of purely non-commercial data.

Summaries of growth data for each site in each State are provided in Section A4, Tables 2a-2b.

Miscellaneous hardcopy and online databases and reports

A number of other published and unpublished reports and databases were reviewed. In most cases, these resources did not incorporate measured volumetric growth data and/or were not made available for this study. These included:

- *TREEDAT* – Stores the results of field trials of species, provenances and other sub-species taxa so they can be selectively retrieved to assist people to choose plants for nominated end uses and sites.
- *MPTDAT* – Provides information on the growth of Australian trees in various locations and assists staff of the Australian Tree Seed Centre.
- *Subtropical Tree Site Management (STSM)* – Provides a recording, analysis and delivery structure for data on tree growth, management techniques, and species selection in the subtropical region of Australia.
- *Optimising the Growth of Trees Planted on Farms* – This report summarises farm tree and shrub plantings on the Northwest slopes and Plains and Northern Tablelands of New South Wales.

The records available for *E. camaldulensis* in Hassall & Associates (1998, 1999a and 1999b) were one-off snap-shots only, hence no growth estimates for the one plot were able to be estimated. Further records for *E. camaldulensis* and other species are thought to be available in other inaccessible (and/or costly to obtain) databases and in the records of individuals and other operators in the industry.

A2.5.2 Comparability Issues and Adjustment Factors

For the data that was collected, there were several comparability and compatibility issues which prevented the generation and comparison of biomass growth curves. These are discussed below.

Wood Density. Biomass growth data can be estimated in Wong *et. al.* (2000) by applying estimates of wood density at various ages to the supplied volumetric growth data. This differs from Hassall & Associates (1998, 1999a and 1999b) where constant wood density values are assumed in its biomass projections. URS Australia initially attempted to estimate biomass values for Wong using wood density estimates provided from URS Forestry consultant staff, but subsequently abandoned this given the constant density assumptions used in Hassall & Associates and other biasing factors described below.

Basis for Estimating Volume. Hassall & Associates (1998, 1999a and 1999b) used total stem volume overbark as the basis for estimating volume. Wong's South Australian data was for total stem volume under bark, and the Victorian data was stem volume to 2 cm under bark. Even with similar wood density assumptions, the difference in base volume estimates prevents direct comparability of any resultant biomass estimates.

Unclear Volume Parameters. The height at which diameter measurements are made for estimating volume directly influences all subsequent calculations. The same applies for the shape of the tree bole. Hassall & Associates (1998, 1999a and 1999b) assumes a conical shape, while the Wong reporting is unclear about this assumption. Wong points out that the methodologies are not consistent by saying *"The growth data has been collected by numerous forestry organisations over the past 10 to 15 years. Tree measurements followed the standard measurational procedures for each State organisation…"*

The inconsistency in the current data collections highlights the merit of the NCAS in developing standard protocols for new data collection, making the protocols widely available, and requiring them to be used for all new data collection.

A2.5.3 Forest Growth Data

All data compiled in this study is summarised in the Growth Tables presented in Section A4.

A2.6 DISCUSSION

The above is a modest harvest for a reasonable search effort. It is however a fair reflection of how sparse forest growth data are, and how difficult they are to access. There is doubtless more data around, effectively 'lost' in old files, and it would take more resources than were available (including financial purchase) to access them.

Adding to the problem of accessing data, is the current lack of suitable data. There is little data that includes biomass estimates. The focus on height parameters for the majority of vegetation and revegetation databases, rather than biomass, is one of the factors that limited the development of the Growth Tables. The incompatabilities of the data that do exist and are available is another major factor, as discussed above.

It would be possible to estimate biomass accumulation using allometric equations of height growth data, but this was outside the scope of the study and is in itself potentially subject to considerable error – see Eamus *et. al.* (2000).

In summary, the growth data contained in Section A4, Tables 1 and 2 provides a good representation of biomass accumulation levels for some major native species in differing husbandry, environmental and climatic conditions across southern Australia. It could be argued that with appropriate adjustments and suitably broad assumptions, growth tables could be estimated and compared over different datasets, as has been discussed in Section 3.2, albeit with certain caveats for compatibility and comparability.

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A3. SPATIAL ESTIMATION OF PLANT PRODUCTIVITY

Joe Landsberg & Jenny Kesteven

A3.1 INTRODUCTION

Preliminary plant productivity indices were calculated for the 80 IBRA regions of Australia (following Thackway and Cresswell, 1995) using a variant of the 3-PG (spatial) model based on the relationship between the photosynthetically active radiation absorbed by plant canopies (APAR) and the biomass productivity of those canopies. The model used a monthly time step. The factor converting APAR to biomass was reduced from the selected optimum value by modifiers dependent on soil fertility, atmospheric vapour pressure deficits, soil water content and temperature. The ESOCLIM package was used to generate climate surfaces for the country. Soil fertility and water holding capacity values were obtained from the Digital Soil Atlas of Australia. Leaf Area Index, essential for the calculation of APAR, was estimated from 10-year mean values of Normalised Difference Vegetation Indices, for 1 km pixels, for the whole country. Incoming short-wave radiation – and hence APAR – was corrected for slope and aspect using a Digital Elevation Map (DEM), but with 1 km pixels (which made no significant difference to the results). All analyses were carried out on estimates based on the assumption of flat terrain.

One hundred point plant productivity values, evenly spaced, were calculated for every IBRA region. Statistical analysis indicated that, as expected, there were significant differences in productivity between regions and, more importantly, that there was significant within-region variation. IBRA regions were not homogenous for biomass production. Part of the reason for this lay in the fact that most of them crossed climatic zones, and contained a variety of soils.

The result of this preliminary exercise was a map (and digital values) of plant productivity index, by months, for Australia. This provided general estimates of plant productivity in any region, and hence a basis for estimates of carbon sequestration and a framework for the analysis of carbon accumulation by various vegetation types. The products of the project could be tested empirically by statistical methods applied to all the measured biomass data available, or by modelling productivity in detail, for selected locations for which the appropriate soil and climatic data were provided as inputs.

A3.2 BACKGROUND

URS Australia were contracted by the Australian Greenhouse Office (AGO) to produce a map of Australia showing the regional distribution of estimated plant productivity potential, in terms of carbon sequestration.

The task was to develop an information system which could be used to obtain reasonable estimates of probable carbon accumulation rates in any region of the country. These regional estimates would also provide the framework for more detailed research and analysis of carbon flows and carbon storage capacities.

It was recognised that a simple modelling approach would have to be adopted and Dr. Joe Landsberg was sub-contracted to do the work.

A3.3 PLANNING AND PROCEDURE

Several meetings were held to determine the scope of the project, and the best approach to take. It was agreed that the project would be based around a simplified version of the 3-PG model (Landsberg and Waring, 1997), which has been extensively tested as a tool for the spatial estimation of plant productivity (see Coops *et. al.*, 2001). This is described in the following section.

It was agreed that the project would be based around an analysis of plant productivity potential by IBRA regions[1]. These provided defined areas, classified in terms of clearly stated characteristics, that are well recognised and quite widely used. It was assumed that the IBRA regions were based on data likely to correlate with plant productivity.

The work was to be GIS-based, using a raster system, with sampling on the basis of pixels, or sample points, rather than polygons whose definitions involved assumptions that may not be justified. Initial discussions proposed the use of ~250 m pixels, since this was the scale of the Digital Elevation Map (DEM) available and it was proposed that the short-wave radiation incident on land surfaces should be corrected for slope and aspect. However, this involved an enormous amount of computing time so the calculations were initially done using 1 km pixels, compatible with the scale at which estimates of Leaf Area Index (LAI), derived from satellite data, were available for the country as a whole. Estimates of plant productivity using radiation not corrected for slope and aspect were referred to as the 'flat earth' estimates. Water bodies were screened out of the Normalised Difference Vegetation Index (NDVI) data.

The basic procedure was to sample 100 pixels per IBRA region, for each of which plant productivity would be calculated. This allowed statistical evaluation of the variation in plant productivity across a region – information that cannot be obtained from analysis of polygons. To determine whether 100 samples was enough, 300 samples from each of 4 regions were to be analysed to determine the number needed to reduce the standard error of the mean to the lowest possible (stable) level. Note that taking 100 samples per region, across regions that vary in size from 2,400 to 42,400 km^2, means that the sampling density will vary enormously. This was considered reasonable on the grounds that the larger regions were, virtually by definition, more homogeneous[2].

It was agreed that the AGO would make available all the data bases it had, or had access to, and that it would be actively involved in the project through its Scientific Adviser, Dr Jenny Kesteven. That is, the project would be, in effect, collaborative with the AGO. In fact the AGO did most of the computing work involving data bases and GIS analysis, Joe Landsberg produced the productivity model and they worked together on de-bugging and analyses. The data bases required, and their sources, are described below.

The project took a great deal longer to complete than was initially planned. This was largely a result of delays in obtaining data; Australia-wide digital soil maps, including values for fertility and water holding capacity in each pixel, had to be obtained from ERIN (Environmental Resources Information Network, The Australian Government Department of Environment and Heritage) and interpretation provide by Dr Neil McKenzie (CSIRO Division of Land and Water; see McKenzie *et. al.* 2000). Climatic data for each month were produced using the ANUCLIM package; the number of frost days had to be calculated for each month for the whole country. The greatest delays were caused by the requirement for estimates of Leaf Area Index (LAI) for the whole country. These were initially provided by Dr Nicholas Coops (CSIRO Division of Forestry and Forest Products), using NDVI[3] data for 1995. However, the data had gaps and it was eventually decided that using data from a single year, even one

1 The IBRA (Interim Biogeographic Regionalisation for Australia) regions were developed to provide a framework for establishing priorities for delivering the National Reserves System Cooperative Program (NRSCP) (Thackway and Creswell, 1995). They were derived by compiling the best available data and information about each State and Territory including specialist field knowledge, published resource and environmental reports and are based on climate, lithology/geology, landform, vegetation, flora and fauna and land use. There are 80 IBRA regions within Australia.

2 In fact there was no reason to assume that plant productivity would be homogenous across IBRA regions (Richard Thackway; pers. comm.)

3 Normalised Digital Vegetation Index, obtained from satellite data. This is a ratio of the reflectances in the infra-red and near infrared wavebands. It actually provides a good measure of the amount of chlorophyll in the vegetation, but this generally correlates well with LAI. Empirical equations are used to calculate LAI from NDVI.

that conformed, in many respects, to average climatic conditions, was a dangerous procedure. There is always significant seasonal variation in weather conditions across Australia, and a year that is ‘average’ in one region may be far from average in others. LAI was therefore estimated from 10-year means of NDVI (from Landsat) for the whole country, provided by ERIN. Joe Landsberg produced the code (in Visual Basic) for a simplified, spatial version of the 3-PG model. This was implemented in the ARCINFO system by the AGO.

A3.4 THE PLANT PRODUCTIVITY MODEL

The long-term average plant productivity maps used in this preliminary study (Figure 1) were generated using the methods described in the main body of this report (Section 3.6, see page 33).

A3.5 ANALYSIS OF PLANT PRODUCTIVITY BY IBRA REGIONS

There were no significant differences between the ‘flat earth’ and slope and azimuth-corrected estimates of APAR when the analysis was based on 1 km pixels. All the analyses presented in this section are based on the ‘flat earth’ analysis.

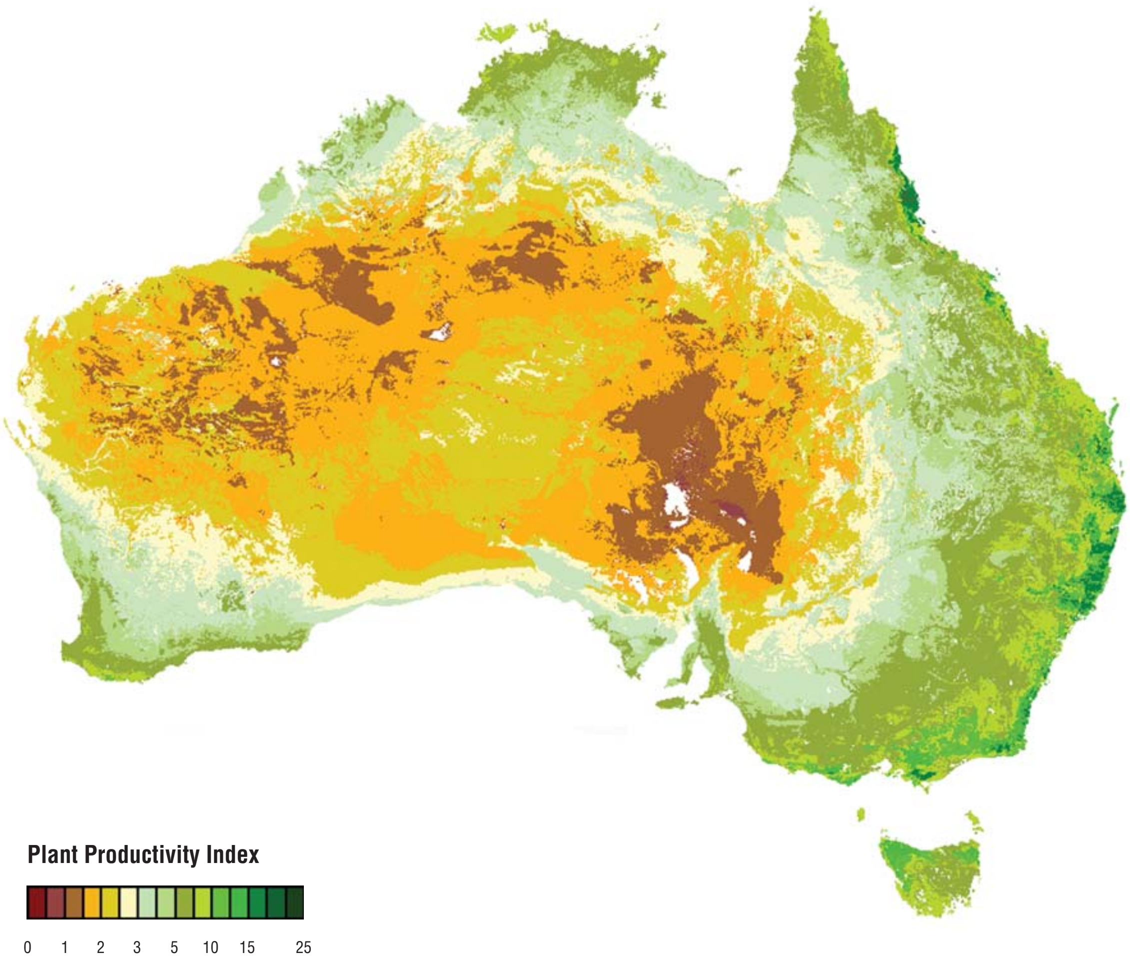


Figure 1. Derived long-term average plant productivity index for Australia.

Two approaches were used to characterise plant productivity in the IBRA regions. As noted in Section A3.1, 100 points uniformly spaced, were sampled in each region. This provided the basis for statistical analysis of the variation in primary productivity across these areas, allowing assessment of whether they were homogeneous for this property. The characteristics used to calculate these point estimates of plant productivity were those of the pixels on which each sampling point fell. Subsequently the model was applied to the whole surface of Australia to give a complete map of plant productivity (Figure 1).

A3.6 PLANT PRODUCTIVITY VALUES BY IBRA REGIONS

Average annual plant productivity values for each of the 80 IBRA regions are given in Figure 2. As we would expect, the highest productivity is in the Wet Tropics (13.4), followed by the New South Wales North Coast (11.1), while the lowest productivity areas are the dry desert areas (Little Sandy and Simpson-Strezlecki deserts, each with 1.1).

Standard analysis of variance shows that, between IBRA regions, many of the productivity values were significantly different, an unsurprising result of little interest in itself. For comparisons between particular values the critical value for F-tests with 95% confidence (that differences are real) was 1.28.

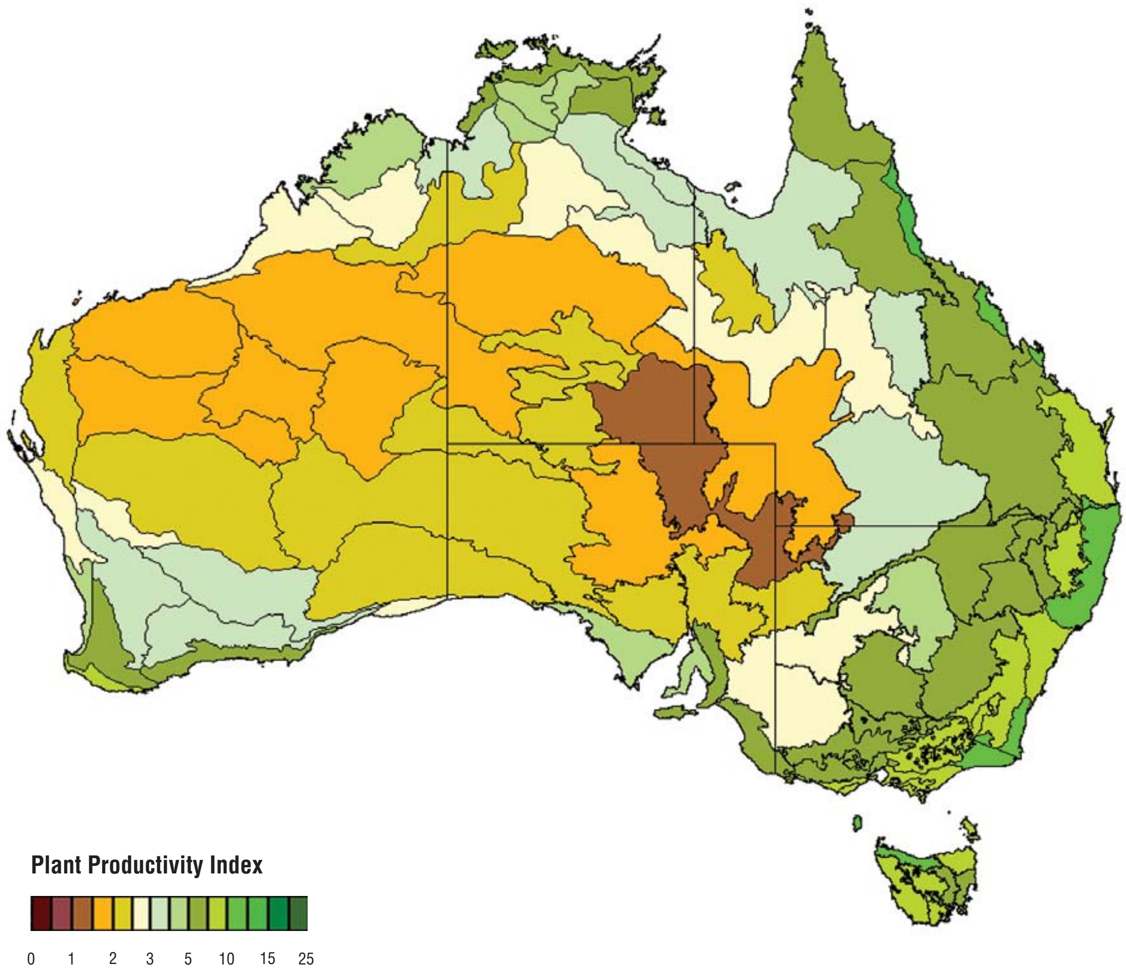


Figure 2. Annual average Plant Productivity by IBRA regions.

The widest range of calculated productivity values was in the Wet Tropics (between 5.8 and 22.5; Standard Deviation 4.22), followed by the Central Mackay Coast (between 6.2 and 18.2; Standard Deviation 2.98). However, taking Standard Deviation as a ratio of the mean regional value, the largest variation was in the Victorian Volcanic Plain (mean productivity index = 5.9, ratio = 56 %), followed by the Tanami Desert (mean productivity index = 2.3, ratio = 47 %) and the Little Sandy Desert (mean productivity index = 1.1, ratio = 44 %).

Figure 3 shows the variation in average monthly plant productivity across four IBRA regions with markedly different characteristics and more than three-fold difference in mean annual productivity[4]. The regions were (mean productivity index in parenthesis): Jarrah Forest (4.7); South East Highlands (7.5), Darling River Plains (5.3); and Central Kimberly (2.1). Figure 4 shows the monthly water balance for the same regions. Clearly, water balance, while it explains some of the monthly variation, does not account for all of it, particularly in the case of the South East Highlands, where maximum productivity was in the spring even though the water balance for plant growth in that period was decreasing. Productivity in early summer was reduced by the lack of water in the soil. Similarly, in the Jarrah Forest region, maximum productivity was in the late winter/spring period, based on water stored from the winter rainfall. Here too, productivity declines in the summer.

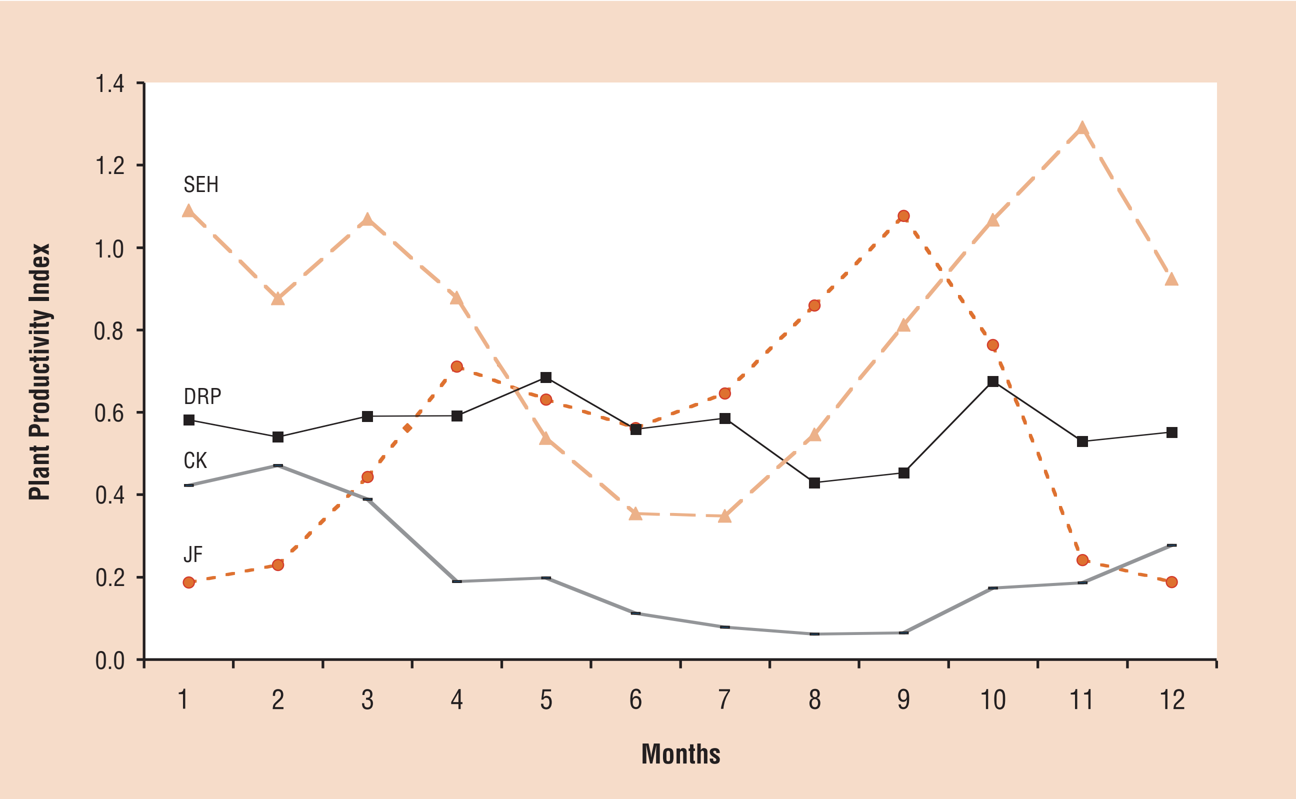


Figure 3. Monthly plant productivity index in four IBRA regions: South East Highlands (SEH); Jarrah Forest (JF); Darling River Plains (DRP); and Central Kimberly (CK).

4 Maps of monthly plant productivity, water balance and the effects of temperature (temperature modifier) can be produced.

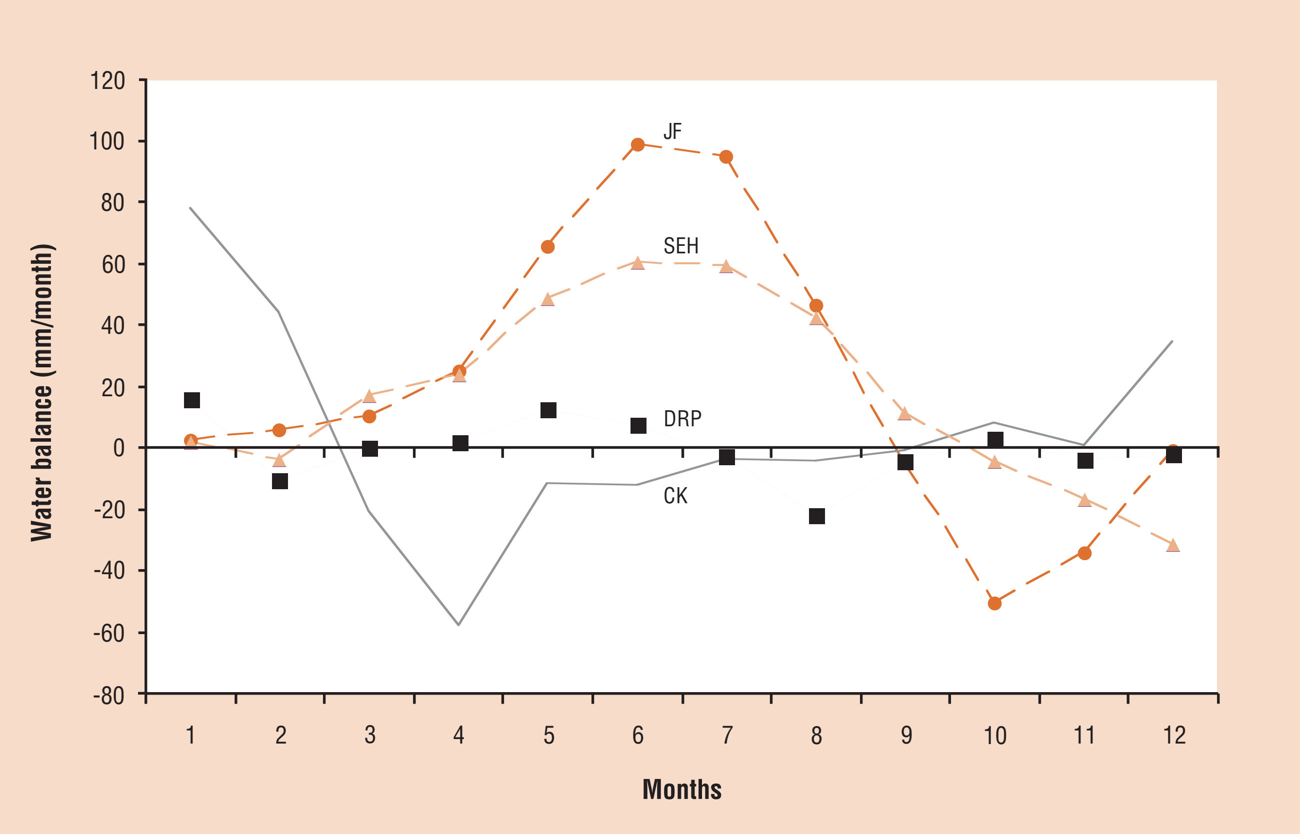
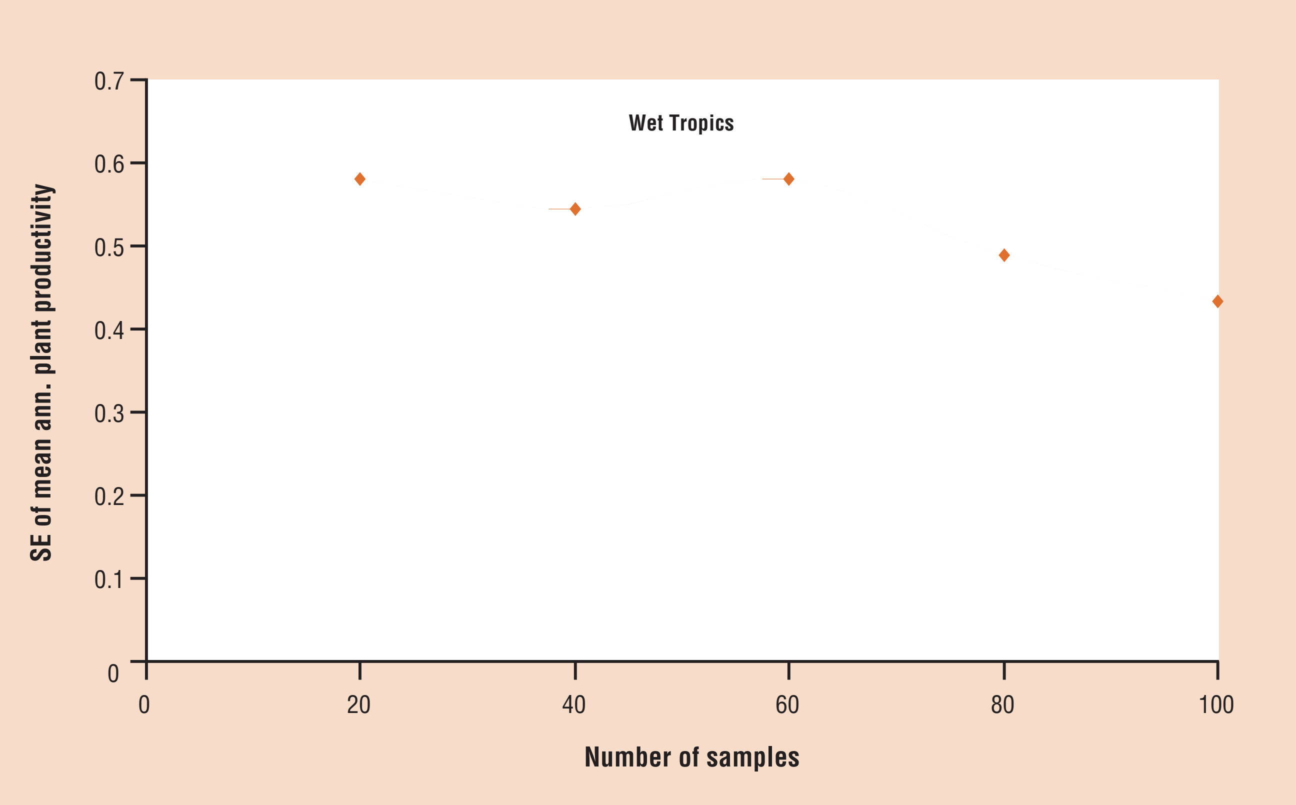


Figure 4. Monthly water balance in the four IBRA regions for which plant productivity data are shown in Figure 3. Negative values indicate the dryness of the area but note that in the calculation of water balances for the model soil water content cannot go below zero.

A3.7 SPATIAL VARIATION IN PLANT PRODUCTIVITY WITHIN REGIONS

To assess the spatial variation of plant productivity across IBRA regions, we plotted the standard errors (SEs) of the mean values obtained with varying numbers of samples for the two regions (Wet Tropics and the Tanami) with the widest range in point values. In both cases (Figs. 5a, 6a) the SE decreased with increasing numbers of sample points, but showed little sign of reaching a steady value. The spatial distribution of plant productivity values in the two regions was quite different. In the Wet Tropics (Figure 5b) there was a fairly uniform distribution of values, with a peak towards the higher productivity end of the spectrum, while in the Tanami (Figure 6b) the distribution was skewed strongly left (towards the low productivity end of the spectrum). There was little apparent relationship between the spatial distribution of plant productivity and the SE of the sample mean.

To evaluate the number of samples needed to minimise the SE of the mean, we took 300 sample points from each of the four regions (Jarrah Forest, South East Highlands, Darling River Plains, Central Kimberly) analysed earlier. The results are shown in Figures 7a, 8a, 9a and 10a, where the SEs are plotted against number of samples. The spatial distributions of plant productivity are presented in Figures 7b, 8b, 9b and 10b. The data indicate that, in most cases, at least 200 sample points would need to be analysed to minimise the SE of the mean value. Again, the spatial distribution of plant productivity values provides little guidance to the number of samples needed.



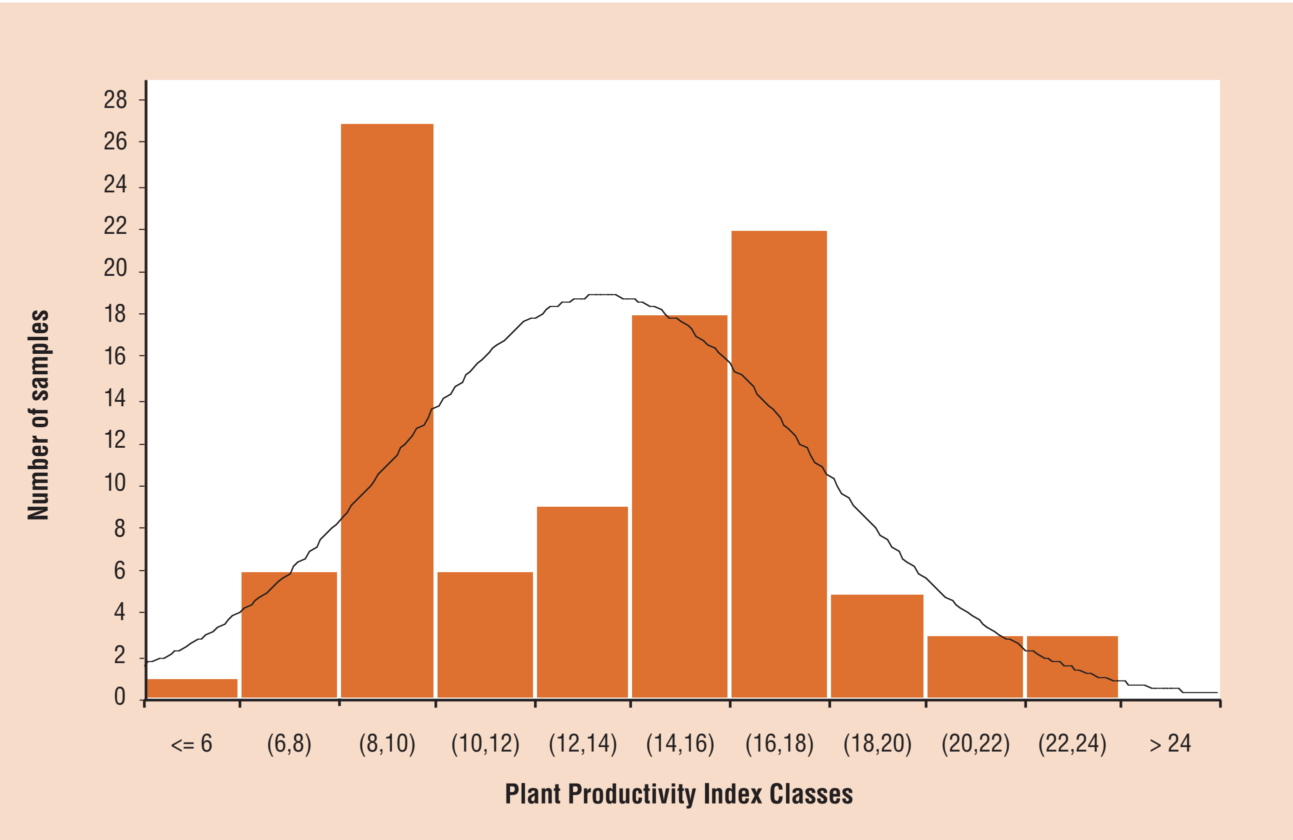
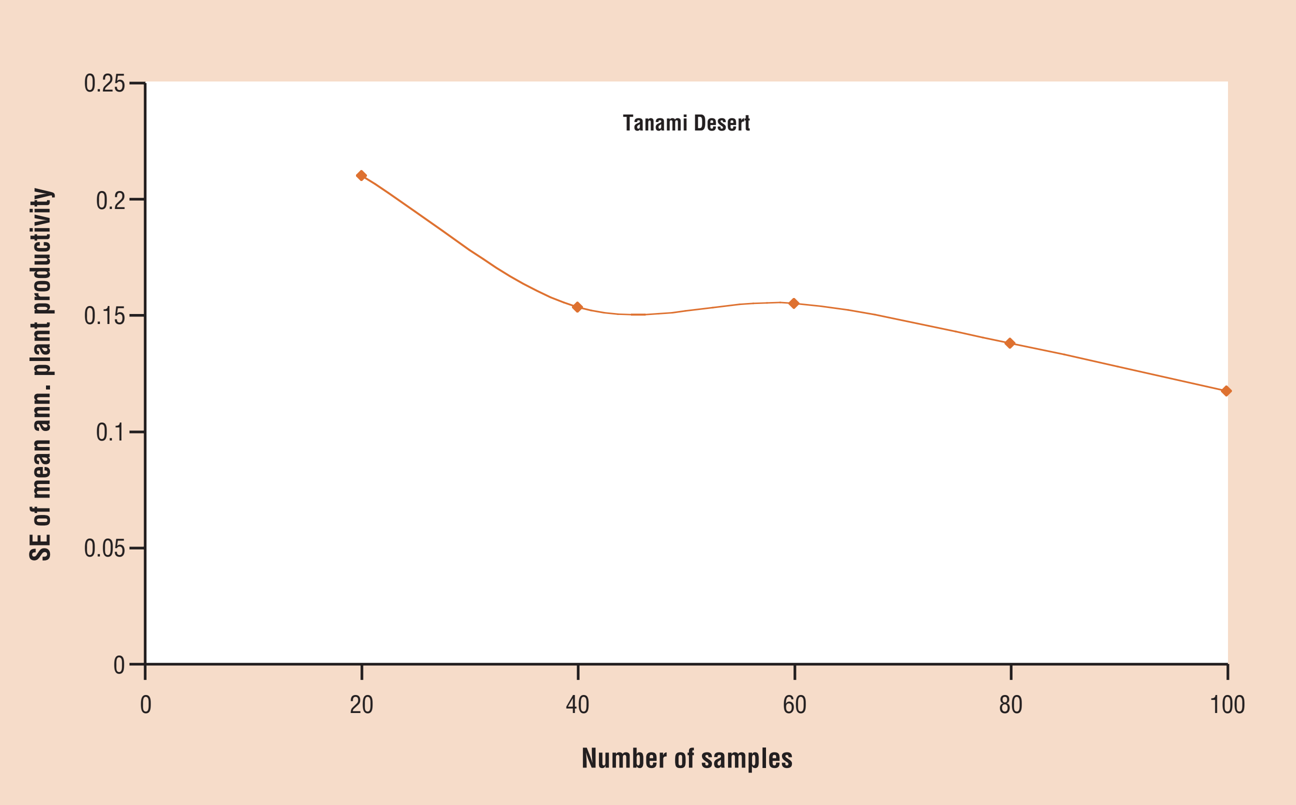


Figure 5a. (top) Change in the standard error of the mean productivity value with various numbers of sample points, up to 100, in the Wet Topics region. There was no indication that a minimum value had been reached. b. (bottom) Spatial distribution of plant productivity across the Wet Tropics region. The data exhibit significant variation.



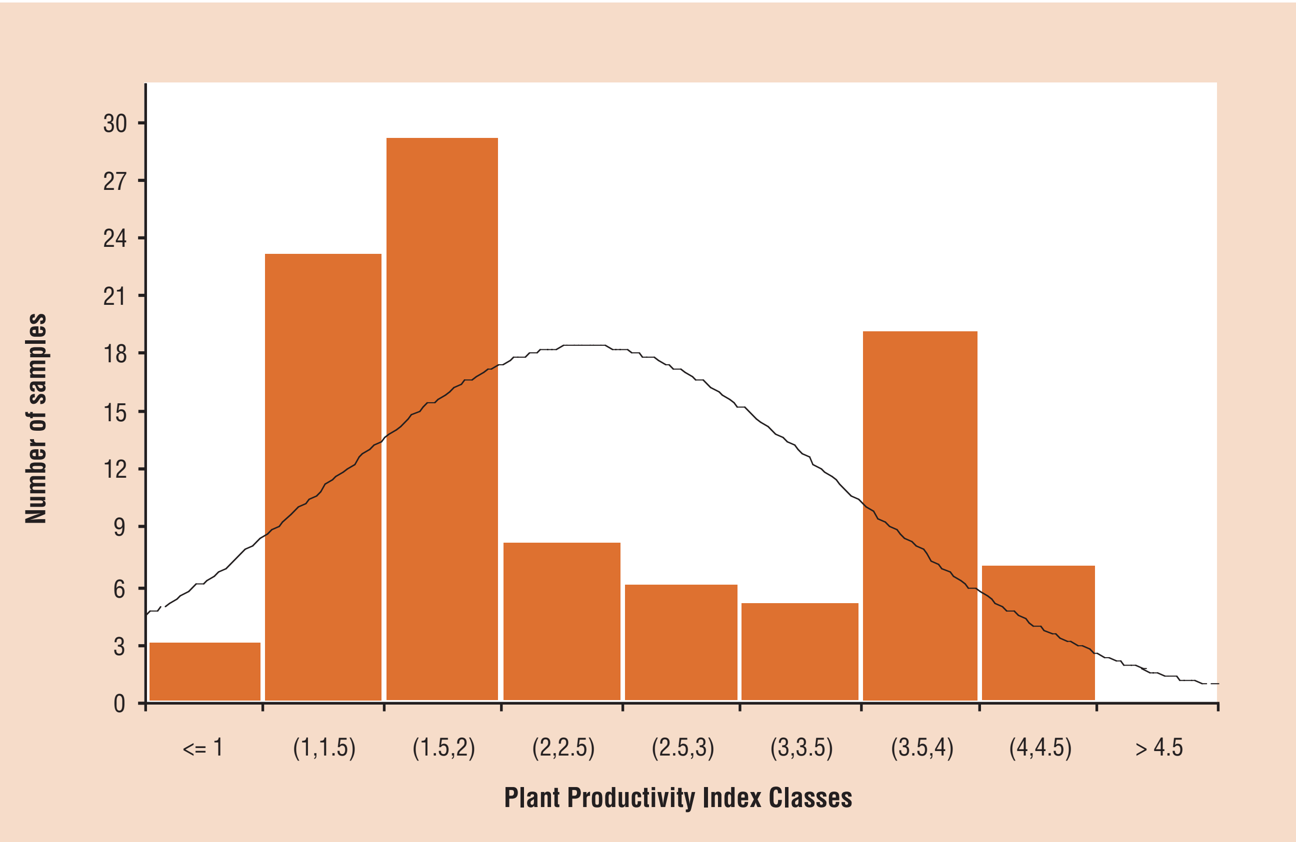
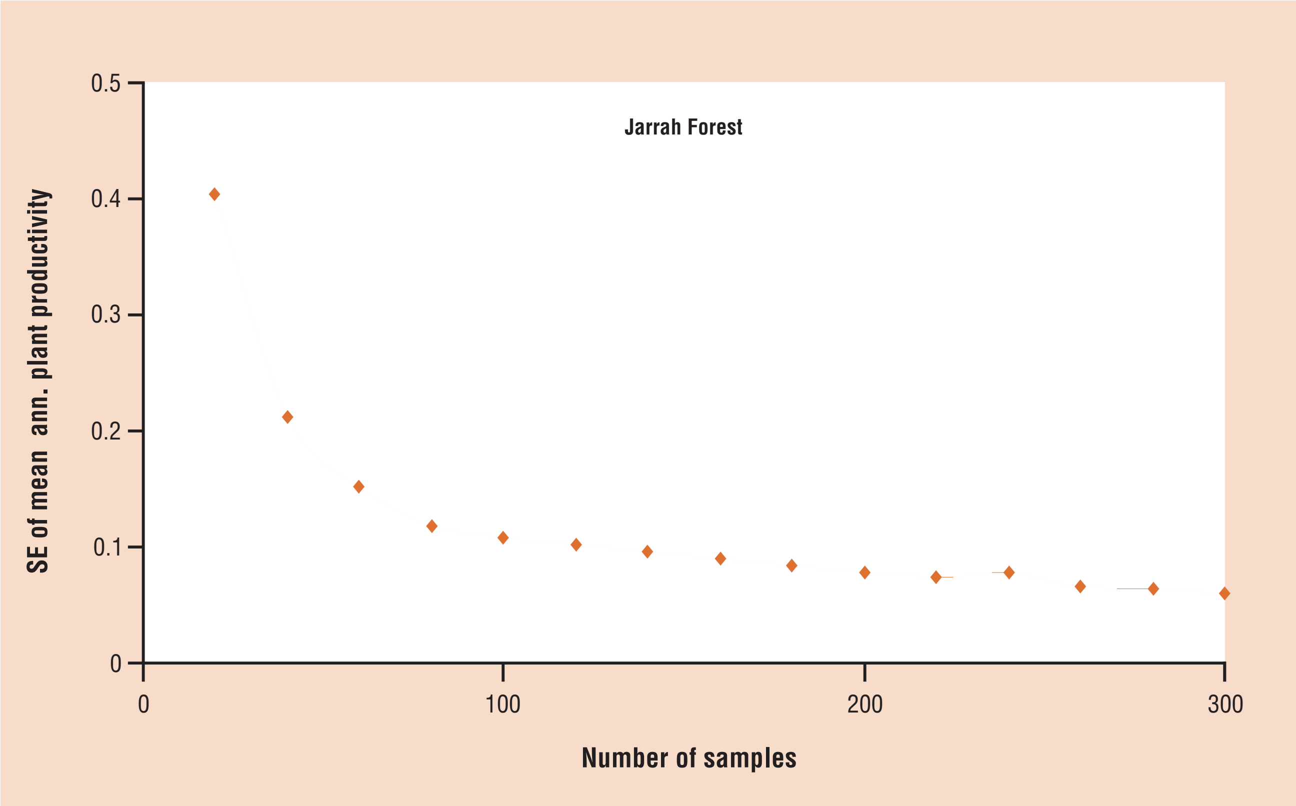


Figure 6a. (top) Change in the standard error of the mean productivity value with various numbers of sample points, up to 100, in the Tanami Desert region. There was no indication that a minimum value had been reached. b. (bottom) Spatial distribution of mean annual plant productivity across the Tanami Desert. The data exhibit significant variation, with a marked peak in the low productivity range.



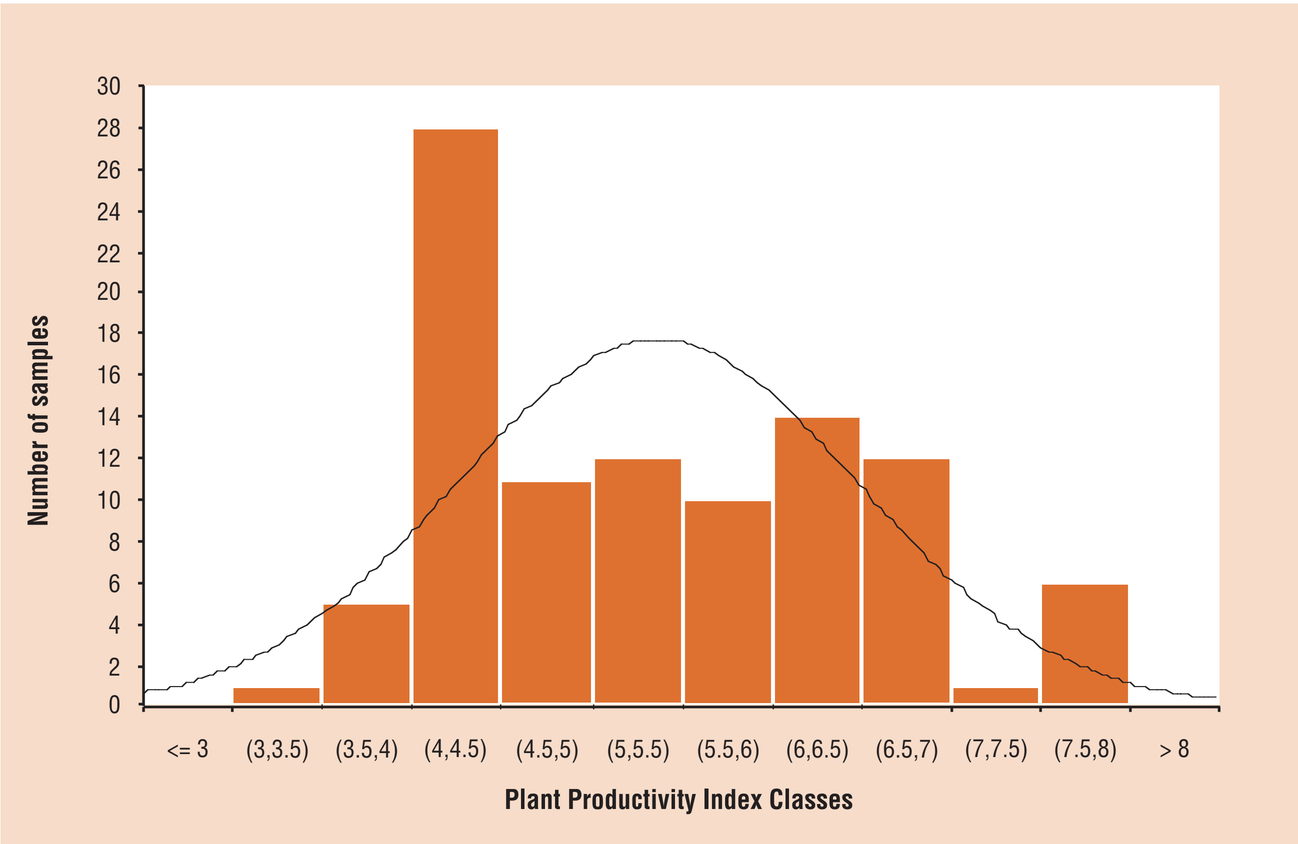
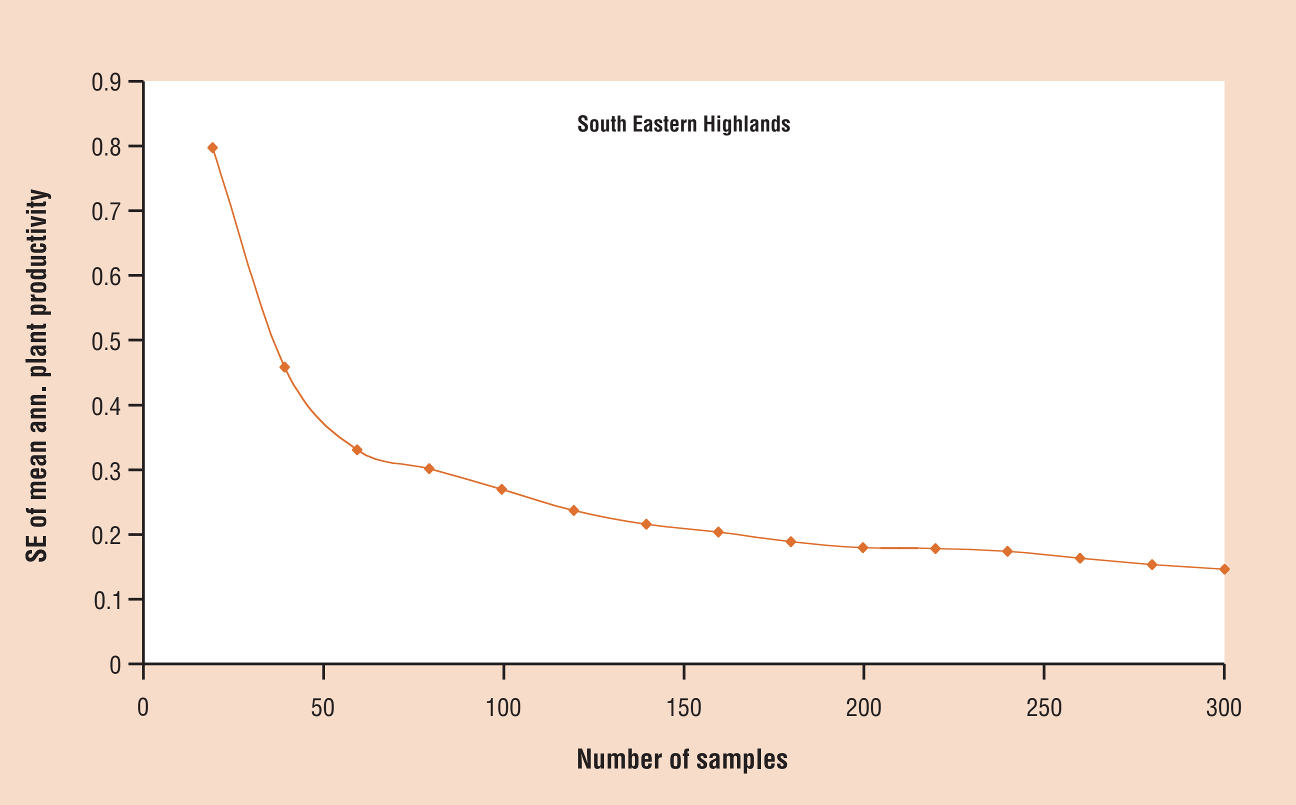


Figure 7a. (top) Change in the standard error of the mean productivity value with various numbers of sample points, up to 300, in the Jarrah Forest region. The curve indicates that 2-300 sample points would be required to give an accurate value of the mean. b. (bottom) Spatial distribution of mean annual plant productivity across the Jarrah Forest region. The curve is skewed towards lower values.



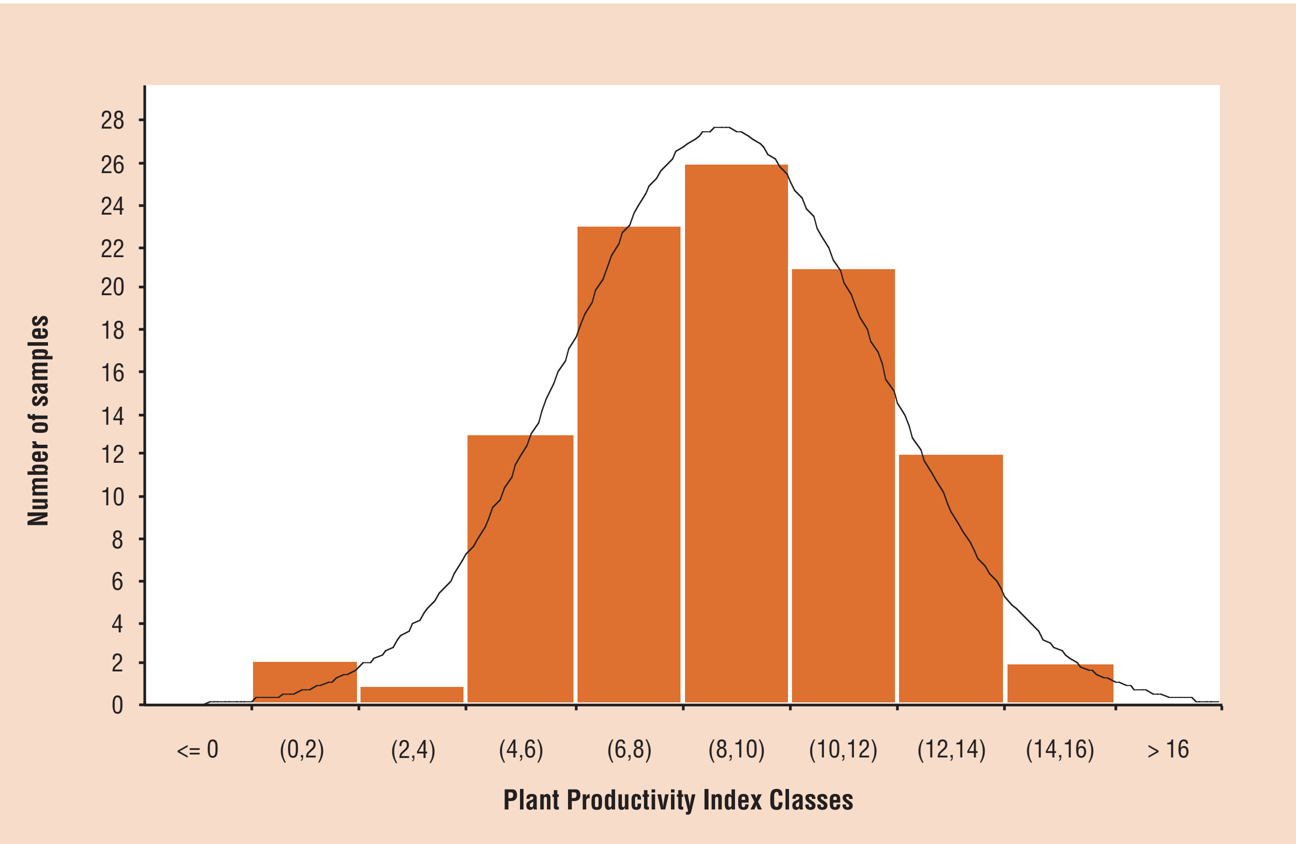
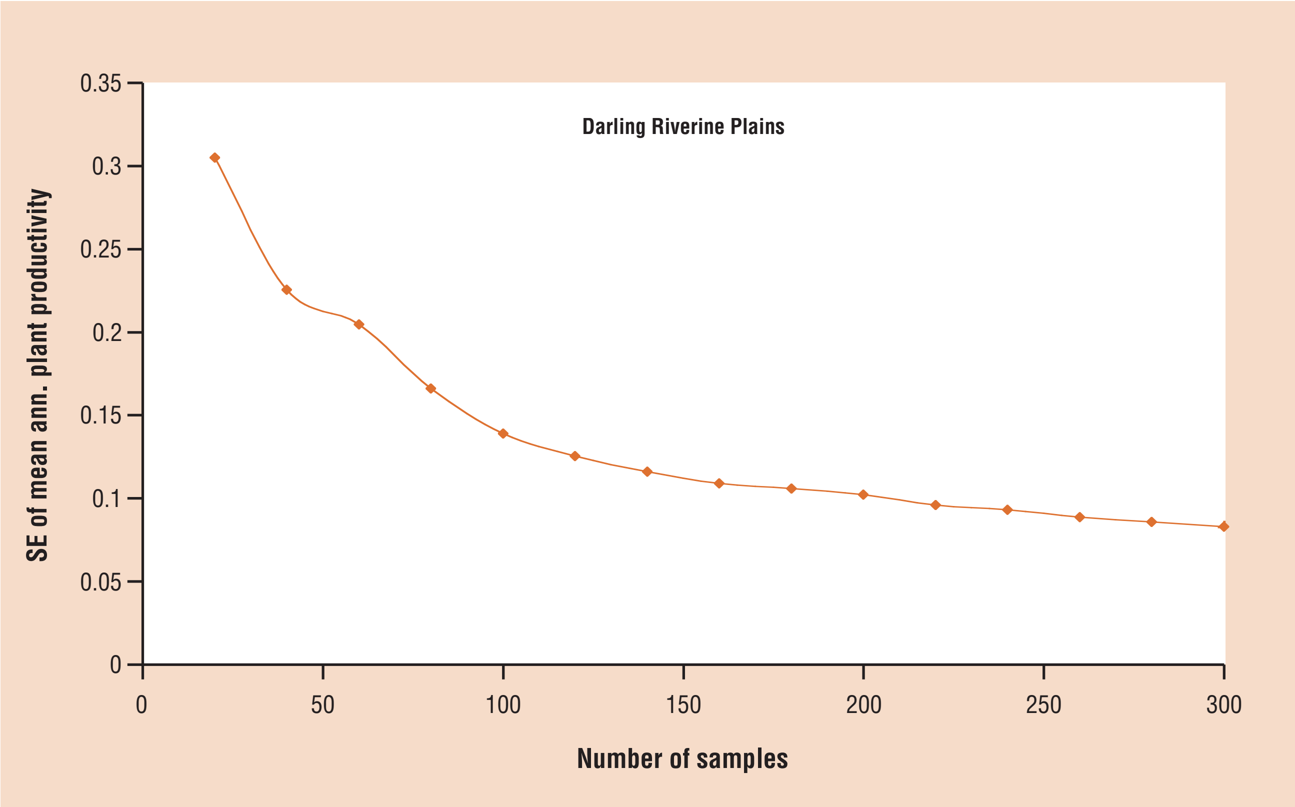


Figure 8a. (top) Change in the standard error of the mean productivity value with various numbers of sample points, up to 300, in the South Eastern Highlands. The curve indicates that 2-300 sample points would be required to give an accurate value of the mean. b. (bottom) Spatial distribution of mean annual plant productivity across the South Eastern Highlands region. The distribution is more uniform than in most other regions.



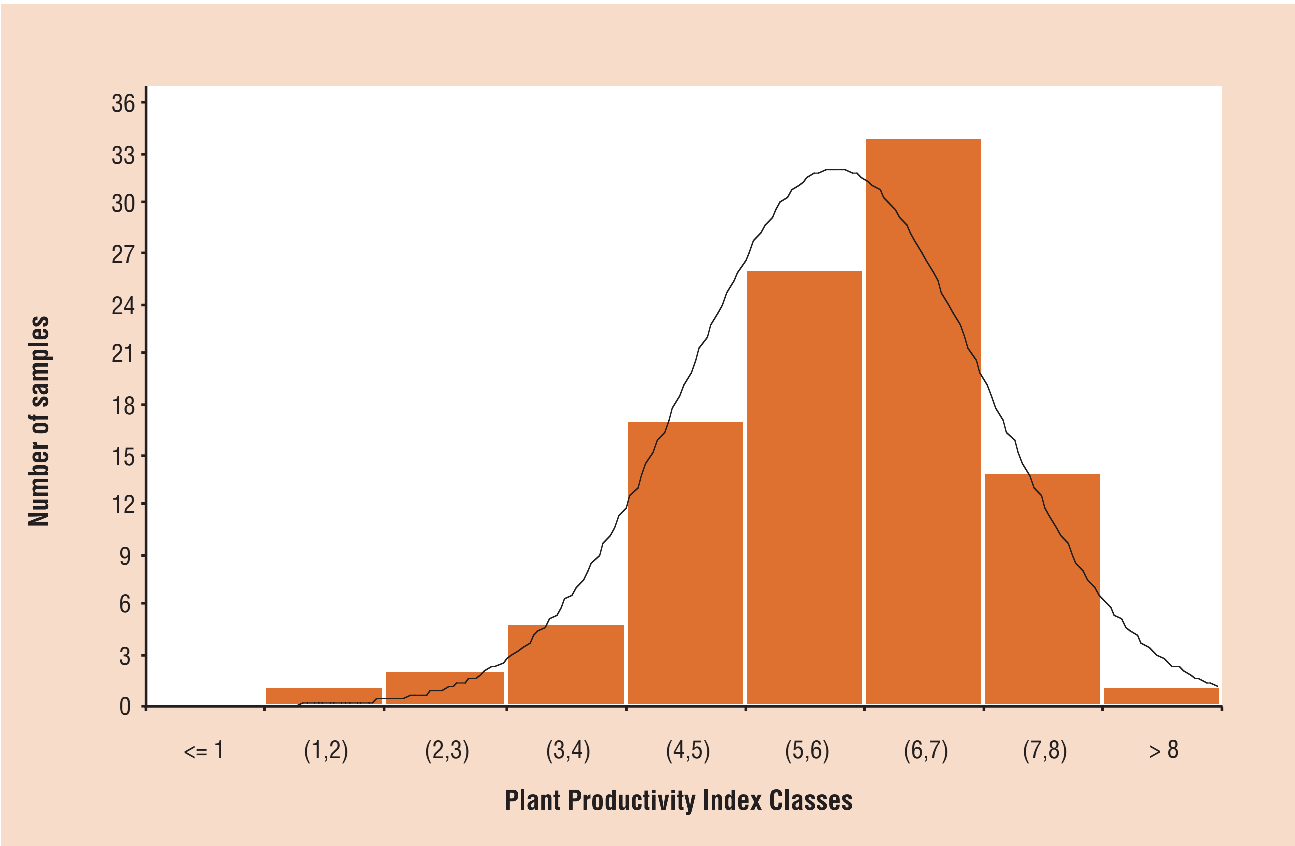
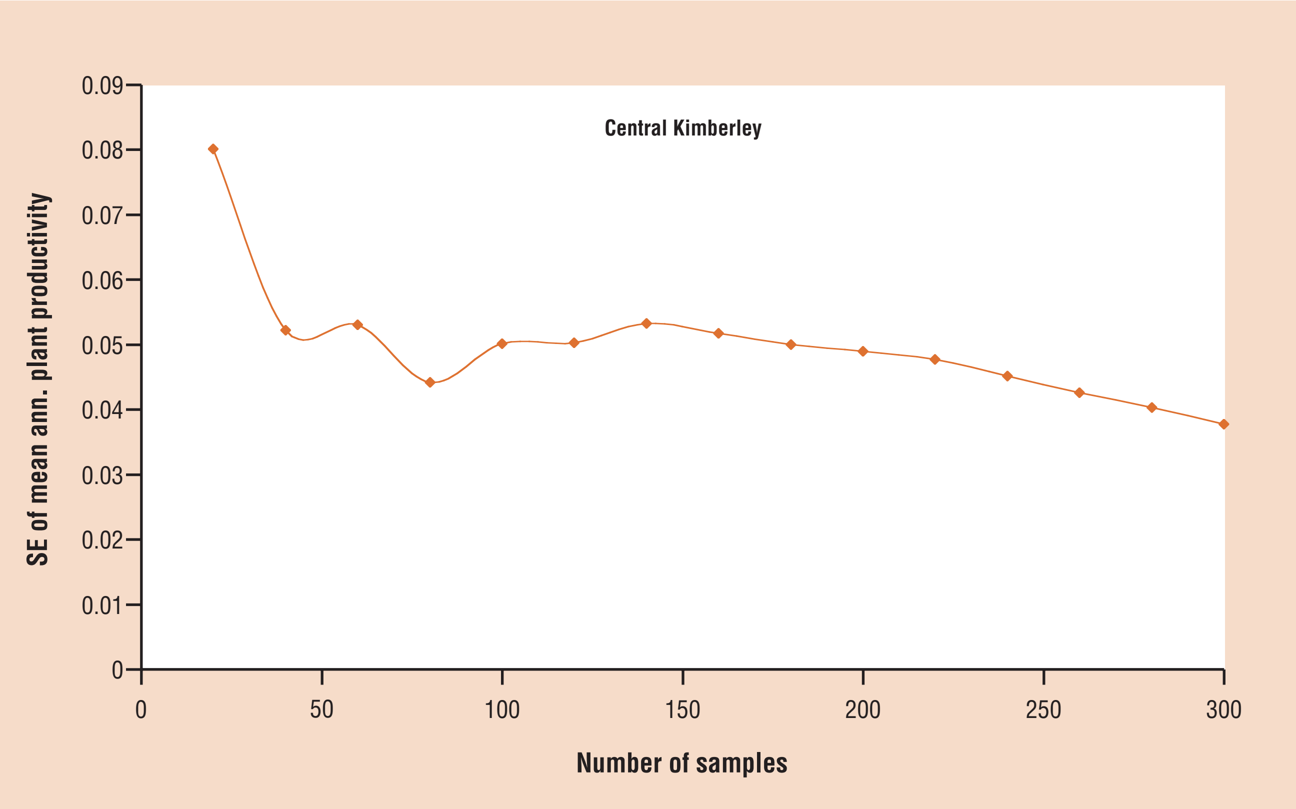


Figure 9a. (top) Change in the standard error of the mean productivity value with various numbers of sample points, up to 300, in the Darling River Plains. The curve indicates that at least 300 sample points would be required to give an accurate value of the mean. b. (bottom) Spatial distribution of mean annual plant productivity across the Darling River Plains. The distribution is reasonably uniform, slightly skewed to the higher values.



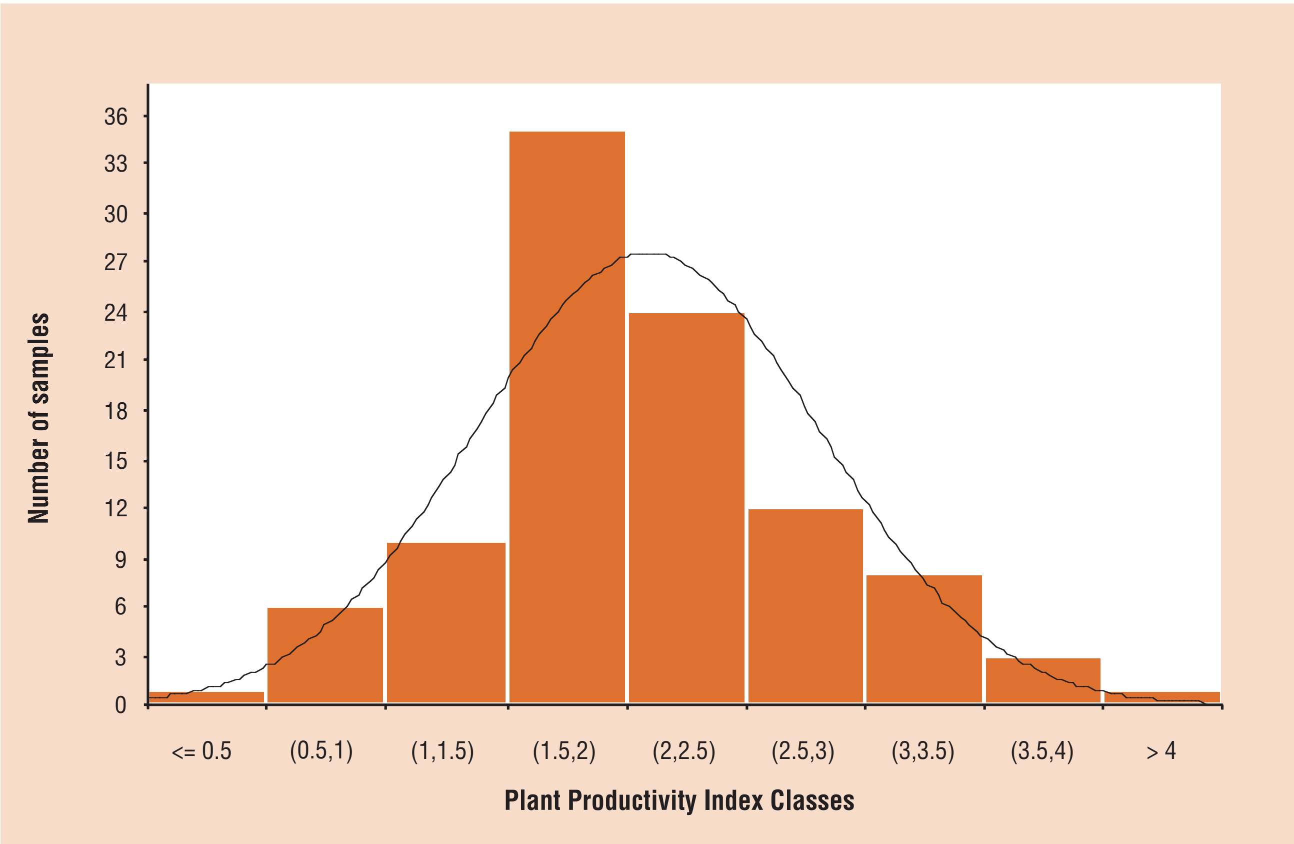


Figure 10a. (top) Change in the standard error of the mean productivity value with varying numbers of sample points, up to 300, in the Central Kimberley region. The curve has not reached stable values; at least 300 sample points would be required to give an accurate value of the mean. b. (bottom) Spatial distribution of mean annual plant productivity across the Central Kimberley region. The distribution is approximately normal.

A3.8 ANALYSIS OF PLANT PRODUCTIVITY BY CARNAHAN VEGETATION CLASSES

An analysis of productivity by Carnahan vegetation (present) classes was done by overlaying the Carnahan vegetation on the productivity surface. While the distribution of productivity values for most of the Carnahan vegetation classes shows that there was a preferred value or niche, the range for each vegetation class could be large. Figure 11 shows the distribution of open woodland as shaded by the plant productivity index value. Due to the wide distribution of the open woodland vegetation class it is not surprising that the productivity index values have a range from 1 to 25.

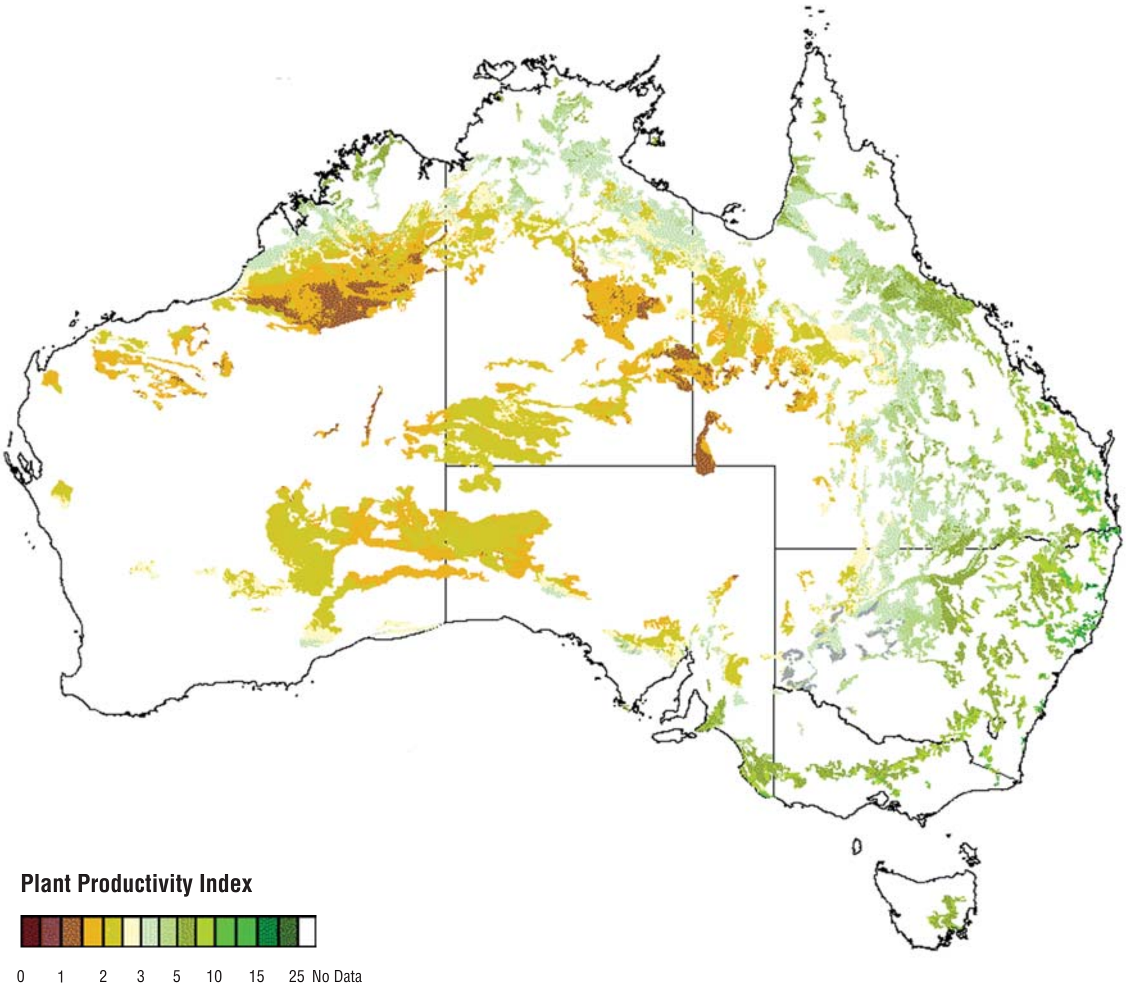


Figure 11. The distribution of open woodland shaded by the plant productivity index value.

Figure 12 clearly shows the wide range of plant productivity values for each vegetation class (e.g. open woodland ranges from a productivity index of 1 to 20, open forest ranges from 2 to 20). It also clearly shows that the overlap between the vegetation classes is large and would not allow for discrimination of classes by plant productivity. This will have implications for any stratification based on vegetation classes.

A3.9 CONCLUSIONS

The mean productivity values obtained for IBRA regions appear to be 'reasonable', insofar as they correspond well to vegetation and climatic regions. The method of calculation used here is based on the premise that there is a linear relationship between the PAR absorbed by vegetation and production. This is not linear over short periods (e.g. hours-days), and the use of the simple Beer's Law equation to calculate energy absorption by plant canopies could lead to significant errors over such periods. However when we consider time periods as long as a month, the assumption that biomass production is linearly related to biomass production is justified (Landsberg *et. al.*, 1997) and Beer's Law provides good estimates of the energy absorbed.

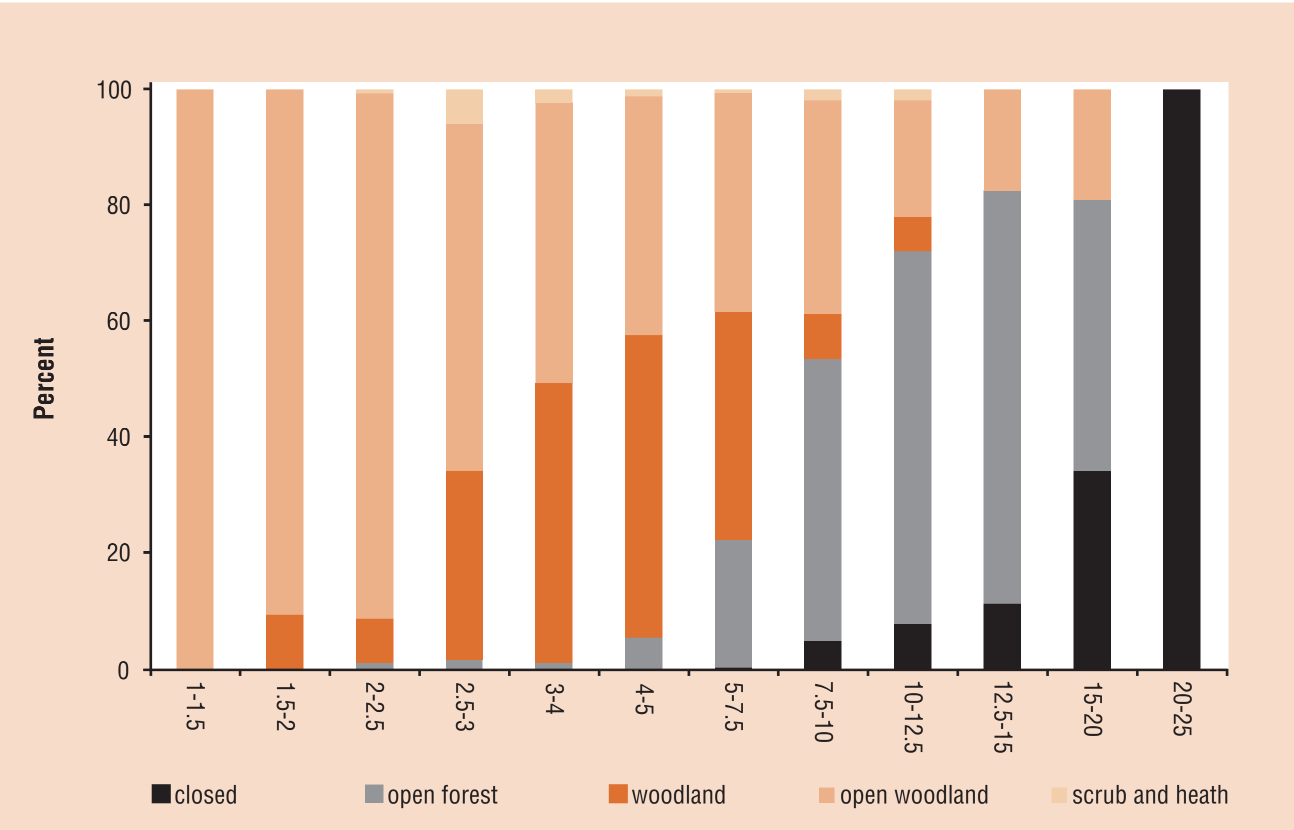


Figure 12. Range of plant productivity values for the forest classes of present Carnahan vegetation classes.

The full version of 3-PG (spatial) model has been shown to provide good estimates of the productivity of forest types ranging from large, long-lived conifers (Coops *et. al.* 2001) to native forests in New South Wales (Tickle *et. al.* 2001) and fast-growing eucalypt plantations in Brazil (A.C. de Almeida and J.J.Landsberg; unpublished data). The model has also been tested against biomass measurements made in New Zealand re-growth scrub (White *et. al.*, 2000; Neal Scott, Landcare NZ; pers. comm.) and was found to perform well. These examples show that, given appropriate inputs, the basic model provides good estimates of productivity for specific locations, allowing confidence in the model as an estimator of wide-scale productivity values.

The spatial variation in plant productivity across the IBRA regions indicates that, whatever their value in terms of ecological regions and guides for the establishment of reserves, these regions are not homogeneous in terms of productivity. It is clear that the IBRA regions not only contain a variety of soil types – which would have been impossible to avoid – but, in most cases, they lay across the boundaries of several quite different climatic regions. This would explain some of the variance that needs to be able to be taken into account when making calculations for specific locations.

A3.10 FOLLOW UP RESEARCH

Ultimately, a variant of the 3-PG model (as used here in these preliminary investigations, following Landsberg *et. al.* 1997) was used as the productivity model, in addition to the long-term average plant production index and top soil moisture deficits for the NCAS (as fully described in the main body of this report). Annual plant productivity indices were also subsequently used in development of the full carbon accounting model for the NCAS (see Richards 2001).

A3.11 RELEVANT CITATIONS

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A4. FOREST GROWTH DATA

URS Australia

Compiled forest growth data tables are presented overleaf.

A4 - Table 1a. Growth Data for Sites in South Australia, Hassall & Associates (1999a)

Site Information (South Australia, Hassall & Associates, 1999a)					Biomass		MAI	Planting	Volume	Site Factors	Establishment & Stand Management
ID	Name, Location, Coordinates	Est.	Area Planted	Species List & Purpose	t/ha	Age	t/ha/yr	Density (trees/ha)	m^3/ha	e.g. rainfall, soil type/quality, topography, access to water, salinity	e.g. site preparation and prior landuse, tubestock/ direct seed, weeds/disease/pests, fire, irrigation
1	Hynam Park, Lower South East Lat/long: 365713, 1405244	1990	-	*E. camaldulensis, E. leucoxylon, E. occidentallis* Shelterbelt	88.03[1] 66.02[2]	8	11.00	-	N/A	Rainfall: Av 581 mm Soil: Sandy loam over clay, pH 5.5 at surface to 7.0 at 50 cm Topography: Flat plain Water: Rainfed, adjacent to dairy farm which may or may not be irrigated (unspecified). Depth to groundwater unknown.	Site preparation unknown. Previously used for dairy grazing. Direct seeding. Selective thinnings for firewood. Some stunted growth due to crowding out. No other problems associated with weeds/disease/pests, drought or fire. No history of irrigation on the trees or in the adjacent dairy pasture is specified.
2	Struan Fairlamb, Lower South East Lat/long: 360622,1404534	1993	0.7 ha	*E. ovata, E. occidentalis, Allocasuarina verticillate* Purpose not specified	4.76[1] 3.57[2]	5	0.95	1,089	N/A	Rainfall: Av 558 mm Soil: Black rendzina soils with an impervious limestone layer at 30 cm, pH 7.0 at surface to 8.5 at 30 cm Topography: Flat plain Water: Rainfed, depth to groundwater unknown.	Site preparation unknown. Previously used for sheep grazing. Tubestock. No thinnings. Some incidence of pests (spitfire catepillars) and weeds. No treatment. No other problems. Rainfed only.
3	Struan Roadside, Lower South East Lat/long: 370620, 1404729	1990	0.9 ha	*E. viminalis E. leucoxylon, Acacia pycnantha* Purpose not specified	96.19[1] 72.14[2]	8	12.02	-	N/A	Rainfall: Av 558 mm Soil: Sandy clay loam over clay Terra Rossa, pH 6.0 at surface to 7.0 at 30 cm Topography: Not specified Water: Rainfed, depth to groundwater unknown.	Site preparation unknown. Previous use unknown. Direct seeding. Thinnings history not specified. Some incidence of insect attack and weeds, but no damage. Some stunted growth due to crowding out. No other problems. Rainfed only.
4	Mark Morris, Kangaroo Island Lat/long: 354911, 1374211	1993	2.5 ha	*E. cneorifolia, E. diversifolia, E. cosmophylla* Groundwater recharge/salinity control	18.29[1] 13.7[2]	5	3.66	-	N/A	Rainfall: Av 532 mm Soil: Clay loam over clay, pH 6.0 at surface to 7.0 at 50 cm Topography: Not specified Water: Rainfed, depth to groundwater unknown.	Site preparation unknown. Previous use mixed farming. Direct seeding. Thinnings history not specified. No problems associated with weeds/disease/pests, drought or fire. Rainfed only.

Site Information (South Australia, Hassall & Associates, 1999a)					Biomass		MAI	Planting	Volume	Site Factors	Establishment & Stand Management
ID	Name, Location, Coordinates	Est.	Area Planted	Species List & Purpose	t/ha	Age	t/ha/yr	Density (trees/ha)	m^3/ha	e.g. rainfall, soil type/quality, topography, access to water, salinity	e.g. site preparation and prior landuse, tubestock/ direct seed, weeds/disease/pests, fire, irrigation
5	Snellings Beach (tubestock) Kangaroo Island Lat/long: 354016, 1370360	1992	0.3 ha	*E. cneorifolia, E. diversifolia, Melaleuca lanceolata* Soil stabilisation, shelterbelt, amenity	7.90[1] 5.93[2]	6	1.32	-	N/A	Rainfall: Av 655 mm Soil: Clay loam over clay, pH 6.0 at surface to 6.5 at 50 cm Topography: Not specified Water: Rainfed only (following irrigation for first 12 months), depth to groundwater unknown.	Site preparation unknown. Previously used for sheep grazing. Tubestock. Thinnings history not specified. No problems associated with weeds/disease/pests, drought or fire. Rainfed, plus drip fed for initial 12 months.
6	Snellings Beach (direct seed) Kangaroo Island Lat/long: 354015, 1370354	1992	0.3 ha	*Allocasuarina verticillata* Shelterbelt, amenity	5.81[1] 4.36[2]	6	0.97	-	N/A	Rainfall: Av 655 mm Soil: Clay loam over clay, pH 6.0 at surface to 6.5 at 50 cm Topography: Rolling coastal hills Water: Rainfed, depth to groundwater unknown Aspect: S.	Site preparation unknown. Previous use unknown. Direct seeding. Thinnings history not specified. No problems associated with weeds/disease/pests, drought or fire. Rainfed only.
7	Magpie Creek, Mid North Lat/Long: 334340, 1382353	1992	1.5 ha	*E. camaldulensis, E. leucoxylon, E. odorata* Soil stabilisation	10.06[1] 7.55[2]	6	2.01	2,333	N/A	Rainfall: Av 408 mm Soil: Clay loam over deep limestone, pH 9.0 at surface to 50 cm Topography: Gently sloping hills Water: Rainfed, depth to groundwater approx. 7m Aspect: Unknown.	Site preparation unknown. Previous use unknown. Tubestock. Thinnings history not specified. Replanting in 1996 to fill originally missed areas. No problems associated with weeds/disease/pests, drought or fire. Rainfed only.
8	Blyth-Brinkworth Corridor, Mid North Lat/long: 334352, 1382514	1996	1.2 ha	*E. odorata, E. porosa, E. calamifolia* Visual amenity	0.14[1] 0.11[2]	2	0.07	916	N/A	Rainfall: Av 408 mm Soil: Clay loam, pH 8.5 at surface to 50 cm Topography: Flat plain Water: Rainfed, depth to groundwater approx. 15m.	Site preparation unknown. Previously used for mixed farming. Direct seeding. Thinnings history not specified. Some problems with weeds. Potential impact on growth rates of trees. No treatment. No other problems. Rainfed only.

A4 - Table 1a. Growth Data for Sites in South Australia, Hassall & Associates (1999a) continued.

Site Information (South Australia, Hassall & Associates, 1999a)					Biomass		MAI	Planting	Volume	Site Factors	Establishment & Stand Management
ID	Name, Location, Coordinates	Est.	Area Planted	Species List & Purpose	t/ha	Age	t/ha/yr	Density (trees/ha)	m^3/ha	e.g. rainfall, soil type/quality, topography, access to water, salinity	e.g. site preparation and prior landuse, tubestock/ direct seed, weeds/disease/pests, fire, irrigation
9	Blyth, Mid North Lat/long: 334957, 1382859	1996	2.5 ha	*E. odorata,* *Allocasuarina verticillata,* *Acacia pycnantha* Visual amenity	0.18[1] 0.14[2]	2	0.09	833	N/A	Rainfall: Av 427 mm Soil: Clay loam, pH approx. 8.0 Topography: Flat plain Water: Rainfed, depth to groundwater 10-15m.	Site preparation unknown. Previously used as a railway corridor. Direct seeding. No Thinnings. Significant weed infestation requiring treatment. No other problems. Rainfed only.
10	Mourilya (direct seed) Eyre Peninsula Lat/long: 343612, 1354336	1992	1 ha	*E. cladocalyx,* *Acacia pycnantha* *Allocasuarina verticillata,* Purpose not specified	6.34[1] 4.75[2]	6	1.06	-	N/A	Rainfall: Av 495 mm Soil: Sandy loam, pH approx. 6.5 Topography: Gently sloping low hills Water: Rainfed, depth to groundwater 10-15m Aspect: S.	Site preparation unknown. Previous use unknown. Direct seeding. Thinnings history unknown. No problems associated with weeds/disease/pests, drought or fire. Rainfed only.
11	Mourilya (tubestock) Eyre Peninsula Lat/long: 343453, 1354336	1994	2 ha	*E. cladocalyx,* *E. lansdowneana var. albopurpurea* *E. leucoxylon* Shelterbelt	7.53[1] 5.64[2]	4	1.88	-	N/A	Rainfall: Av 424 mm Soil: Sandy loam over clay, pH unknown Topography: Gently sloping low hills Water: Rainfed, depth to groundwater 5m Aspect: S.	Site preparation unknown. Previously used for mixed farming. Tubestock. Thinnings history unknown. No problems associated with weeds/disease/pests, drought or fire. Rainfed only.
12	Warrow, Eyre Peninsula Lat/long: 341855, 1352840	1992	2.5 ha	*E. incrassata,* *E. porosa,* *Allocasuarina verticllata* Habitat	5.35[1] 4.01[2]	6	0.89	-	N/A	Rainfall: Av 420 mm Soil: Sand over limestone, pH 7.5 at surface to 8.5-9.0 at 30-40 cm Topography: Flat plain - gentle slope Water: Rainfed, depth to groundwater 3m Aspect: SW.	Site preparation unknown. Previously used for grazing. Direct seeding. Thinnings history unknown. No problems associated with weeds/disease/pests, drought or fire. Rainfed only.

Site Information (South Australia, Hassall & Associates, 1999a)					Biomass		MAI	Planting	Volume	Site Factors	Establishment & Stand Management
ID	Name, Location, Coordinates	Est.	Area Planted	Species List & Purpose	t/ha	Age	t/ha/yr	Density (trees/ha)	m^3/ha	e.g. rainfall, soil type/quality, topography, access to water, salinity	e.g. site preparation and prior landuse, tubestock/ direct seed, weeds/disease/pests, fire, irrigation
13	Jackson (direct seed) Upper South East Lat/long: 362251, 1401934	1990	-	*E. gracilis,* *E. leucoxylon,* *E. leptophylla* Purpose not specified	133.37[1] 100.03[2]	8	16.67	-	N/A	Rainfall: Av 560 mm Soil: Sand over shallow clay, pH 6.0 at surface to 7.0 at 50 cm Topography: Rolling plains Water: Rainfed, depth to groundwater unknown.	Site preparation unknown. Previous use unknown. Direct seeding. Thinnings history unknown. No problems associated with weeds/disease/pests, drought or fire. Rainfed only.
14	Jackson (tubestock) Upper South East Lat/long: 362248, 1401934	1988	0.6 ha	*E. gracilis,* *E. fasciculosa,* *E. camaldulensis* Purpose not specified	15.21[1] 11.40[2]	10	1.52	-	N/A	Rainfall: Av 560 mm Soil: Sand, low salinity, pH 6.0-6.5 at surface to 7.0-8.5 at 50 cm Topography: Rolling plains Water: Rainfed, depth to groundwater unknown.	Site preparation unknown. Previous use unknown. Tubestock. Thinnings history unknown. No problems associated with weeds/disease/pests, drought or fire. Rainfed only.
15	Meningie-Coonalpyn Road, Upper South East Lat/long: 354132, 1392646	1993	-	*E. leucoxylon,* *Allocasuarina verticillata,* *Allocasuarina muelleriana* Roadside shelterbelt, revegetation trial	10.77[1] 8.08[2]	5	2.15	-	N/A	Rainfall: Av 468 mm Soil: Non-wetting sand, low salinity, pH 8.0 at surface to 9.0 at 50 cm Topography: Flat plain Water: Rainfed, depth to groundwater unknown.	Site preparation unknown. Previous use unknown. Direct seeding. Thinnings history unknown. No problems associated with weeds/disease/pests, drought or fire. Rainfed only.
16	Del Fabbro, Upper South East Lat/long: 363921, 1401708	194	10 ha	*Melaleuca brevifolia* *Melaleuca halmaturorum* *E. leucoxylon* Groundwater recharge/ salinity control	6.89[1] 5.16[2]	4	1.72	-	N/A	Rainfall: Av 521 mm Soil: Poor sands over clay, evidence of salinity, pH 6.0 Topography: Rolling plain Water: Rainfed, plus shallow depth to watertable, particularly in winter months.	Site fenced off and sprayed for weeds prior to sowing. Previously used as sheep grazing. Direct seeding. No thinnings. No problems associated with weeds/disease/pests, drought or fire. Rainfed, plus access to shallow groundwater.

A4 - Table 1a. Growth Data for Sites in South Australia, Hassall & Associates (1999a) continued.

Site Information (South Australia, Hassall & Associates, 1999a)					Biomass		MAI	Planting	Volume	Site Factors	Establishment & Stand Management
ID	Name, Location, Coordinates	Est.	Area Planted	Species List & Purpose	t/ha	Age	t/ha/yr	Density (trees/ha)	m^3/ha	e.g. rainfall, soil type/quality, topography, access to water, salinity	e.g. site preparation and prior landuse, tubestock/ direct seed, weeds/disease/pests, fire, irrigation
17	Langhorne Creek Cemetery, Murraylands Lat/long: 351749, 1390312	1992	-	*E. leucoxylon, Acacia pycnantha, Acacia brachybotrya* Seed collection	10.36[1] 7.77[2]	6	1.73	-	N/A	Rainfall: Av 392 mm Soil: Clay with increasing levels of limestone at 50 cm, pH 6.0-6.5 at surface to 7.5-8.5 at 50 cm Topography: Low gently sloping hillside Water: Rainfed, depth to watertable approx. 3m.	Site preparation unknown. Previously used for dairy farming and cropping. Direct seeding. Thinnings of lower limbs and inferior saplings. No problems associated with weeds/disease/pests, drought or fire. Rainfed, plus possible access to groundwater.
18	Hartley Dump, Murraylands Lat/long: 351111, 1390205	1992	-	*E. leucoxylon, E. porosa, Acacia calamifolia* Site rehabilitation	5.26[1] 3.94[2]	6	0.88	-	N/A	Rainfall: Av 392 mm Soil: Clay with varying levels of limestone, pH 8.0 at surface to 9.0 at 30 cm Topography: Gently rolling hills Water: Rainfed, depth to watertable unknown.	Site preparation unknown. Adjoining rubbish dump/quarry. Direct seeding. Thinnings history unknown. No problems associated with weeds/disease/pests, drought or fire. Rainfed only.
19	Swanport, Murraylands Lat/long: 350855, 1391842	1991	-	*E. leucoxylon spp. leucoxylon, E. leucoxylon spp. stephenae, E. porosa* Purpose not specified	24.17[1] 18.13[2]	7	3.45	-	N/A	Rainfall: Av 346 mm Soil: Sand, low salinity, pH 7.0 at surface to 8.0-8.5 at 50 cm Topography: Gently undulating Water: Rainfed, depth to watertable 7-10m Aspect: W.	Site preparation unknown. Previously used for agricultural purposes. Tubestock. Thinnings history unknown. Some problems associated with weeds and rabbits which may be affecting growth. No other problems. Rainfed only.
20	Hugh Longbottom, Yorke Peninsula Lat/long: 342137, 1373235	1992	0.9 ha	*E. porosa, Acacia pycnantha, Acacia notabilis* Shelterbelt	11.51[1] 8.63[2]	6	1.92	-	N/A	Rainfall: Av 504 mm Soil: Clay-loam, pH unknown Topography: Gently rolling plain Water: Rainfed, depth to watertable unknown.	Site preparation unknown. Previously used for cropping. Direct seeding. Thinnings history unknown. No problems associated with weeds/disease/pests, drought or fire. Rainfed only.

Site Information (South Australia, Hassall & Associates, 1999a)					Biomass		MAI	Planting	Volume	Site Factors	Establishment & Stand Management
ID	Name, Location, Coordinates	Est.	Area Planted	Species List & Purpose	t/ha	Age	t/ha/yr	Density (trees/ha)	m^3/ha	e.g. rainfall, soil type/quality, topography, access to water, salinity	e.g. site preparation and prior landuse, tubestock/ direct seed, weeds/disease/pests, fire, irrigation
21	Maitland-Minlaton Road, Yorke Peninsula Lat/long: 342637, 1373920	1994	0.6 ha	*E. porosa, Acacia spinescens, Dodenaea viscosa* Roadside revegetation trial	2.10[1] 1.57[2]	4	0.52	-	N/A	Rainfall: Av 504 mm Soil: Clay-loam, pH unknown Topography: Gently rolling plain Water: Rainfed, depth to watertable unknown.	Site preparation unknown. Previous use not specified. Direct seeding. Thinnings history unknown. No problems associated with weeds/disease/pests, drought or fire. Rainfed only.
22	Klopp, Yorke Peninsula Lat/long: 342855, 1374520	1990	0.27 ha	*E. porosa, E. socialis, E. calycogona* Roadside planting	22.56[1] 16.92[2]	8	2.82	-	N/A	Rainfall: Av 414 mm Soil: Sandy loam, pH 8.5 at surface to 9.0 at 50 cm Topography: Rolling plains Water: Rainfed, depth to watertable unknown but believed to seasonally be within root zone Aspect: N.	Site preparation unknown. Previous use not specified. Tubestock. Thinnings history unknown. Some weeds present but not affecting growth. No other problems associated with disease, pests, drought or fire. Rainfed but with potential access to groundwater.
23	Mount Barker Tannery, Mount Lofty Ranges Lat/long: 350332, 1385151	1992	12 ha	*E. viminalis, E. leucoxylon, E. fasciculosa* Site rehabilitation, amenity	30.30[1] 22.72[2]	6	5.05	-	N/A	Rainfall: Av 769 mm Soil: Sandy loam over clay, pH 8.5 to 9.0 Topography: Undulating hills Water: Rainfed, depth to watertable unknown.	Fresh soils spread over contaminated site. Previously used as a tannery and later on as pasture for grazing. Direct seeding. Thinnings history unknown. No problems associated with weeds/disease/pests, drought or fire. Rainfed only.
24	Flaxley Holistic Trading, Mount Lofty Ranges Lat/long: 350820, 1384950	1991	5 ha	*E. fasciculosa, E. obliqua, Acacia melanoxylon* Revegetation	97.55[1] 73.17[2]	7	13.94	-	N/A	Rainfall: Av 740 mm Soil: Sandy loam, pH 6.0 to 5.5 Topography: Unknown Water: Rainfed, depth to watertable unknown.	Site preparation unknown. Previous use unknown. Direct seeding. Thinnings history unknown. No problems associated with weeds/disease/pests, drought or fire. Rainfed only.

A4 - Table 1a. Growth Data for Sites in South Australia, Hassall & Associates (1999a) continued.

Site Information (South Australia, Hassall & Associates, 1999a)					Biomass		MAI	Planting	Volume	Site Factors	Establishment & Stand Management
ID	Name, Location, Coordinates	Est.	Area Planted	Species List & Purpose	t/ha	Age	t/ha/yr	Density (trees/ha)	m^3/ha	e.g. rainfall, soil type/quality, topography, access to water, salinity	e.g. site preparation and prior landuse, tubestock/ direct seed, weeds/disease/pests, fire, irrigation
25	Flaxley Lodge (tubestock) Mount Lofty Ranges Lat/long: 350812, 1384950	1990	0.3 ha	*E. globulus* Shelterbelt, farm forestry	46.37[1] 34.78[2]	8	5.80	-	N/A	Rainfall: Av 740 mm Soil: Sandy loam, pH 5.5 to 6.0 Topography: Flat Water: Rainfed, depth to watertable unknown.	Site preparation unknown. Previously used for sheep grazing Tubestock. Thinnings history unknown. No problems associated with weeds/disease/pests, drought or fire. Rainfed only.
26	Dingo Plains (direct seed) Mallee Lat/long: 352042, 1402337	1991	0.9 ha	*Acacia argyrophylla Acacia calamifolia, Acacia microcarpa* Purpose not specified	3.49[1] 2.61[2]	7	0.50	-	N/A	Rainfall: Av 368 mm Soil: Clay loam with significant calcium carbonate deposits, pH 7.5 at surface to 8.0 at 30 cm Topography: Rolling plain Water: Rainfed, depth to watertable unknown.	Site preparation unknown. Previous use unknown. Direct seeding. Thinnings history unknown. No problems associated with weeds/disease/pests, drought or fire. Rainfed only.
27	Lameroo (tubestock) Mallee Lat/long: 352012, 1402539	1990	1.1 ha	*E. leucoxylon E. occidentalis* Farm forestry trial	14.35[1] 10.76[2]	8	1.78	-	N/A	Rainfall: Av 368 mm Soil: Sand over clay loam, pH 7.0 at surface to 8.0 at 30 cm Topography: Rolling plain Water: Rainfed, depth to watertable unknown.	Site preparation unknown. Previous use unknown. Tubestock. Thinnings history unknown. No problems associated with weeds/disease/pests, drought or fire. Rainfed only.
28	Wilkawatt (direct seed) Mallee Lat/long: 352541, 1402451	1992	0.6 ha	*Dodonaea viscosa, E. porosa, Melaleuca acuminata* Roadside shelterbelt	24.99[1] 18.74[2]	6	4.16	-	N/A	Rainfall: Av 368 mm Soil: Red brown loam over brown clay, pH 7.0 at surface to 8.5 at 40 cm Topography: Flat plain Water: Rainfed, depth to watertable unknown.	Site preparation unknown. Previously used for mixed cropping. Direct seeding. Thinnings history unknown. No problems associated with weeds/disease/pests, drought or fire. Rainfed only.

Site Information (South Australia, Hassall & Associates, 1999a)					Biomass		MAI	Planting	Volume	Site Factors	Establishment & Stand Management
ID	Name, Location, Coordinates	Est.	Area Planted	Species List & Purpose	t/ha	Age	t/ha/yr	Density (trees/ha)	m^3/ha	e.g. rainfall, soil type/quality, topography, access to water, salinity	e.g. site preparation and prior landuse, tubestock/direct seed, weeds/disease/pests, fire, irrigation
29	Kalisch, Riverland Lat/long: 341245, 1400423	1995	4 ha	*Acacia oswaldii, Acacia ligulata, Acacia cyanophylla* Purpose not specified	0.00[1] 0.00[2]	3	0.00	-	N/A	Rainfall: Av 266 mm Soil: Sand, pH 6.5 at surface to 7.5 at 50 cm Topography: Flat plain Water: Rainfed, depth to watertable unknown.	Site preparation unknown. Previously used for grazing. Direct seeding. No thinnings. No problems associated with weeds/disease/pests, drought or fire. Rainfed only.
30	Karelia, Riverland Lat/long: 1401751, 341156	1994	0.7 ha	*Acacia ligulata, Acacia oswaldii, Acacia sp. (juvenile)* Dryland revegetation demonstration	0.07[1] 0.05[2]	4	0.02	-	N/A	Rainfall: Av 241 mm Soil: Sandy loam over limestone with significant calcium carbonate throughout, pH 9.0 Topography: Rolling plain Water: Rainfed, depth to watertable unknown.	Site preparation unknown. Previous use unknown. Direct seeding. No thinnings. No problems associated with weeds/disease/pests, drought or fire. Rainfed only.
31	Orlando-Wyndham, Riverland Lat/long: 340849, 1395434	1994	0.9 ha	*Casuarina obesa, E. camaldulensis, E. largiflorens* Groundwater recharge control	31.97[1] 23.98[2]	4	7.99	-	N/A	Rainfall: Av 235 mm Soil: Sandy loam, pH 7.0-7.5 Topography: River floodplain Water: Rainfed plus access irrigation from neighboring vineyards, depth to watertable unknown but expected to be within root zone.	Site preparation unknown. Previous use unknown. Tubestock. Thinnings history unknown. Some weeds present but no threat. No other problems associated with disease, pests, drought or fire. Rainfed plus irrigated.
32	Little Desert Lodge, Victoria Lat/long: 362725, 1413937			*Allocasuarina verticillata E. fasciculosa, E. leucoxylon* Soil stabilisation, habitat	3.00[1] 2.25[2]	6	0.5	-	N/A	Rainfall: Av 418 mm Soil: Sand, pH 7.0 at surface to 7.5 at 50 cm Topography: Low undulating plain Water: Rainfed, depth to watertable unknown.	Site preparation unknown. Previously used for cattle grazing. Direct seeding. Thinnings history unknown. No problems associated with weeds, disease, pests, drought or fire. Rainfed only.

[1] measured using bole and branches
[2] measured using bole only

A4 - Table 1b. Growth Data for Sites in Victoria, Hassall & Associates (1998)

Site Information (Victoria, Hassall & Associates, 1998)					Biomass		MAI	Planting	Volume	Site Factors	Husbandry
ID	Name, Location, Coordinates	Est.	Area Planted	Species List & Purpose	t/ha	Age	t/ha/yr	Density (trees/ha)	m^3/ha	e.g. rainfall, soil type/quality, topography, access to water, salinity	e.g. tubestock/direct seed, weed & pest control, fire, irrigation
1	Wail, near Horsham, Vic Vic Roads map ref: 26 C10	1973	Approx 130 ha	Sugar Gum *(E. cladocalyx)* Wood products	81^1 61^2	23	3.5	N/A	N/A	Rainfall: Av 420 mm Soil: Clay loam overlying impeding layer of clay, pH 6.5-7.5 Topography: Flat Water: No runon/runoff, depth to groundwater unknown.	Seedlings planted in block formation, thinnings history unknown. Land previously was native bush, cleared, cultivated and ripped before planting. Weeds/disease/pests have not been a problem. Unburnt. Rainfed only, some periods of drought.
2	Wail, near Horsham, Vic. Vic Roads map ref: 26 C10	1975	Approx 130 ha	See above	121^1 90^2	21	5.8	N/A	N/A	See above	See above
3	Barrett Reserve, near Horsham, Vic. Vic Roads map ref: 26 F8	1978	Approx 32 ha	Shining Gum *(E. sieberi)* Sugar Gum *(E. cladocalyx)* Wood Products	77^1 58^2	17	4.5	N/A	N/A	Rainfall: Av 454 mm Soil: Black with high clay content, pH 7.0-7.5 Topography: Flat Water: No runon/runoff, depth to groundwater unknown.	Seedlings planted in block formation, selective thinnings in parts of the plantation. Land preparation unknown, previously used for grazing. Weeds/disease/pests have not been a problem. Unburnt. Rainfed only, some periods of drought which may have affected growth.
4	Barrett Reserve, near Horsham, Vic. Vic Roads map ref: 26 F8	1986	Approx 32 ha	See above	16^1 12^2	9	1.8	N/A	N/A	See above	See above
5	Barrett Reserve, near Horsham, Vic. Vic Roads map ref: 26 F8	1973	Approx 32 ha	See above	72^1 54^2	22	3.3	N/A	N/A	See above	See above
6	Barrett Reserve, near Horsham, Vic. Vic Roads map ref: 26 F8	1971	Approx 32 ha	See above	78^1 59^2	24	3.3	N/A	N/A	See above	See above

Site Information (Victoria, Hassall & Associates, 1998)					Biomass		MAI	Planting	Volume	Site Factors	Husbandry
ID	**Name, Location, Coordinates**	**Est.**	**Area Planted**	**Species List & Purpose**	**t/ha**	**Age**	**t/ha/yr**	**Density (trees/ha)**	**m^3/ha**	**e.g. rainfall, soil type/quality, topography, access to water, salinity**	**e.g. tubestock/direct seed, weed & pest control, fire, irrigation**
7	Barrett Reserve, near Horsham, Vic. Vic Roads map ref: 26 F8	1975	Approx 32 ha	Sugar Gum *(E. cladocalyx)* Shining Gum *(E. sieberi)* Wood Products	64[1] 48[2]	20	3.2	N/A	N/A	See above	See above
8	You Yangs, near Geelong, Vic. Vic Roads map ref: 77 H9	1966	Approx 450 ha	Sugar Gum *(E. cladocalyx)* Wood Products	145[1] 108[2]	30	4.8	N/A	N/A	Rainfall: Av 491 mm Soil: Granitic Topography: Flat Water: No runon/runoff, depth to groundwater unknown.	Trees probably planted as seedlings, block formations. No thinnings. Land preparation unknown. No significant problems with weeds, disease or pests. Fire has occurred but does not appear to have affected the trees significantly. Rainfed only, some periods of drought which may have affected the trees.
9	You Yangs, near Geelong, Vic. Vic Roads map ref: 77 H9	1965	Approx 450 ha	See above	175[1] 131[2]	31	5.6	N/A	N/A	See above	See above
10	You Yangs, near Geelong, Vic. Vic Roads map ref: 77 H9	1958	Approx 450 ha	Brown Mallett *(E. astringens)* Wood Products	175[1] 131[2]	39	4.5	N/A	N/A	See above	See above
11	You Yangs, near Geelong, Vic. Vic Roads map ref: 77 H9		Approx 450 ha	Brown Mallett *(E. astringens)* Wood Products	115[1] 86[2]	38	3.0	N/A	N/A	See above	See above
12	'Titanga', near Lismore, Vic.	1994	Approx 8 ha	Southern Blue Gum *(E. globulus ssp. globulus)* Wood Products	7.1[1] 5.3[2]	2	3.6	N/A	N/A	Rainfall: Av 630 mm Soil: Granitic sand and red lateritic gravel, pH unknown Topography: Gentle slope from elevation 30m to 200m, NW aspect Water: Surface runoff downslope, depth to groundwater unknown.	Seedlings used in rows. No thinnings. Land ripped, formed and sprayed along rows before planting, previously used for grazing. Weeds a problem during establishment, more recently attacks from insects. No treatment undertaken. No other problems. Rainfed only, some periods of drought that do not appear to have affected growth.

A4 - Table 1b. Growth Data for Sites in Victoria, Hassall & Associates (1998) continued.

Site Information (Victoria, Hassall & Associates, 1998)					Biomass		MAI	Planting	Volume	Site Factors	Husbandry
ID	Name, Location, Coordinates	Est.	Area Planted	Species List & Purpose	t/ha	Age	t/ha/yr	Density (trees/ha)	m^3/ha	e.g. rainfall, soil type/quality, topography, access to water, salinity	e.g. tubestock/direct seed, weed & pest control, fire, irrigation
13	'Lingalonga', Mitiamo, NW of Bendigo, Vic Vic Roads map ref: 30 B4	1984	Approx 40 ha	River Red Gum *(E. camaldulensis)* Amenity	66[1] 50[2]	12	5.5	N/A	N/A	Rainfall: Av 399 mm Soil: Grey cracking clay, pH neutral Topography: Flat Water: Some surface runon during wet months; depth to groundwater 1m.	Grown from seed collected on property in to 2 rows along roads and property boundaries. No thinnings, but some trees blown over or dead. Limited preparation prior to planting, deep ripped but no weed control, previously used for irrigated dairy pastures. Initial weed problems, recently rabbits/hares in plague numbers. No treatments undertaken. Unburnt. Rainfed mainly, but close to irrigated pastures.
14	Cohuna, N of Bendigo, Vic Vic Roads map ref: 21 E6	1979	Approx 2.5 ha	River Red Gum *(E. camaldulensis)* Shelterbelts, pest control, amenity	286[1] 214[2]	17	16.8	N/A	N/A	Rainfall: Av 450 mm Soil: Clay loams, pH 6.0-6.5, saline in areas Topography: Flat Water: Some surface runon from irrigation; depth to groundwater >1m.	Seedlings planted in block formations. No thinnings since. Land deep ripped and formed prior to planting, previously used for irrigated annual and perennial pastures. Some disease and pests present during establishment, but no treatments used. Unburnt. Rainfed, plus some areas flooded occasionally from adjacent irrigated pastures.
15	Stanhope, W of Shepparton, Vic Vic Roads map ref: 31 H9	1955	N/A	River Red Gum *(E. camaldulensis)* Shelterbelts	902[1] 677[2]	37	24.4	N/A	N/A	Rainfall: Av 500 mm Soil: Lemnos loam, pH 4.5, no salinity, high fertility from a long history of dairy farming Topography: Flat Water: Regularly irrigated plus rainfed, depth to groundwater 1-2m.	Seedlings planted mainly as single rows along fence lines. No thinnings since. Land not prepared before planting. Hares a problem during establishment. A once-off outbreak of Sawflies affected young trees and growth, treated with 'Curacine'. Unburnt. Regularly irrigated (approx once per fortnight) via adjacent irrigated dairy pastures.

Site Information (Victoria, Hassall & Associates, 1998)					Biomass		MAI	Planting	Volume	Site Factors	Husbandry
ID	Name, Location, Coordinates	Est.	Area Planted	Species List & Purpose	t/ha	Age	t/ha/yr	Density (trees/ha)	m^3/ha	e.g. rainfall, soil type/quality, topography, access to water, salinity	e.g. tubestock/direct seed, weed & pest control, fire, irrigation
16	Stanhope, W of Shepparton, Vic Vic Roads map ref: 31 H9	1958	N/A	River Red Gum *(E. camaldulensis)* Shelterbelts	2,889[1] 2,167[2]	42	16.8	N/A	N/A	See above	See above
17	Stanhope, W of Shepparton, Vic Vic Roads map ref: 31 H9	1960	N/A	River Red Gum (E. camaldulensis) Shelterbelts	4131 3102	39	10.6	N/A	N/A	See above	See above
18	Stanhope, W of Shepparton, Vic Vic Roads map ref: 31 H9	1965	N/A	River Red Gum *(E. camaldulensis)* Shelterbelts	1,620[1] 1,215[2]	32	50.6	N/A	N/A	See above	See above
19	Katamatite, NE of Shepparton, Vic Vic Roads map ref: 33 C3	1965	N/A	River Red Gum *(E. camaldulensis)* Shelterbelts, amenity	1,271[1] 953[2]	21	60.5	N/A	N/A	Rainfall: Av 500 mm Soil: Moira loam, pH 5.5, no salinity, high fertility from a history of dairy farming Topography: Flat Water: Regularly irrigated plus rainfed, depth to groundwater varies between 3m and 9m depending on season.	Seedlings planted as a single row along property boundary. No thinnings since. Land ripped and formed before planting. Hares a problem during establishment. No other problems since. Regularly irrigated (approx once per fortnight) via adjacent water channel for dairy pasture.
20	Leichardt, near Bendigo, Vic. Vic Roads map ref: 44 B5	1987	10 ha	River Red Gum *(E. camaldulensis)* Drooping Sheoak *(Allocasuarina verticillata)* Various Mallee species Erosion control, watertable/ dryland salinity control	5.1[1] 3.8[2]	9	0.6	N/A	N/A	Rainfall: Av 373 mm Soil: Red loam, slightly acidic, rocky in parts Topography: Gentle undulating Water: Rainfed only, depth to groundwater varies between 1m and 2m.	Seedlings planted in widely spaced shelterbelt formations. No thinnings. Land previously used for grazing, ripped prior to planting. Rabbits initially a problem but less so now due to ongoing control. No other problems. Rainfed only.

A4 - Table 1b. Growth Data for Sites in Victoria, Hassall & Associates (1998) continued.

Site Information (Victoria, Hassall & Associates, 1998)					Biomass		MAI	Planting	Volume	Site Factors	Husbandry
ID	Name, Location, Coordinates	Est.	Area Planted	Species List & Purpose	t/ha	Age	t/ha/yr	Density (trees/ha)	m^3/ha	e.g. rainfall, soil type/quality, topography, access to water, salinity	e.g. tubestock/direct seed, weed & pest control, fire, irrigation
21	Bear's Lagoon, NE of Bendigo, Vic. Vic Roads map ref: 29 H7	1972	N/A	River Red Gum *(E. camaldulensis)* Black Box *(E. largiflorens)* Manna Gum *(E. viminalis)* Shelterbelts	190[1] 143[2]	24	7.9	N/A	N/A	Rainfall: Av 450 mm Soil: Heavy clay loam, pH 5.5 Topography: Flat Water: Rainfed with occasional flooding, depth to groundwater 7m.	Seedlings planted in a single row along fence lines. No thinnings since. Land preparation unknown. Previously used for mixed farming. No known problems from insects, disease, pests, drought or fire. Rainfed, with occasional flooding.
22	Burke's Flat, W of Bendigo, Vic. Vic Roads map ref: 43 A4	1983	5-10 ha	Red Ironbark *(Eucalyptus sideroxylon)* Yellow Gum *(Eucalyptus leucoxylon)* Erosion control, watertable/ dryland salinity control	72[1] 54[2]	13	5.6	600-300	N/A	Rainfall: Av 458 mm Soil: Heavily leached, gradational, pH 4.0-4.5 Topography: Gently undulating Water: Rainfed only, depth to groundwater <10m.	Trees planted as tubestock. No thinnings but some natural deaths and regeneration. Land ripped prior to planting. Previously used for grazing. Some insect damage from 1989-2001 during the winter months. No other problems from insects, disease, pests, drought or fire. Rainfed only.
23	Colbinabbin Range (Toolleen), W of Shepparton, Vic. Vic Roads map ref: 45 D5	1982	5-10 ha	Grey Box *(Eucalyptus microcarpa)* Drooping Sheoak *(Allocasuarina verticillata)* Watertable/ dryland salinity control, amenity	25[1] 19[2]	14	1.8	N/A	N/A	Rainfall: Av 491 mm Soil: Gradational red brown, mild acidity, not saline Topography: 10% slope on hilltop Water: Rainfed only, depth to groundwater <10m.	Seedlings planted in rows on hilltop. No thinnings, but significant natural attrition. Land ripped prior to planting. Previously used for grazing. No known problems from insects, disease, pests or fire. Severe drought in 1982/83 killed approx 55% of plot. Rainfed only.

Site Information (Victoria, Hassall & Associates, 1998)					Biomass		MAI	Planting	Volume	Site Factors	Husbandry
ID	Name, Location, Coordinates	Est.	Area Planted	Species List & Purpose	t/ha	Age	t/ha/yr	Density (trees/ha)	m^3/ha	e.g. rainfall, soil type/quality, topography, access to water, salinity	e.g. tubestock/direct seed, weed & pest control, fire, irrigation
24	Pyalong, SW of Shepparton, Vic. Vic Roads map ref: 60 F3	1991	0.25 ha	Red Stringybark *(E. macrorhyncha)* Black Wattle *(Acacia mearnsii)* Watertable/ dryland salinity control, experimental	6[1] 4.5[2]	5	1.2	N/A	N/A	Rainfall: Av 631 mm Soil: Ironstone of sedimentary origin, pH approx 4.8 Topography: 20% hillside Water: Rainfed only, depth to groundwater unknown.	Trees planted via direct seeding. Some removal of unwanted species since planting, but otherwise no thinnings. Some ripping to prepare the land prior to seeding, but not over the entire plot. Previously used for grazing. No problems from insects, disease, pests, drought or fire. Rainfed only.
25	Puckapunyal Range, SW of Shepparton, Vic Vic Roads map ref: 61 B1	1980	40 ha	Red Ironbark *(Eucalyptus sideroxylon)* Yellow Gum *(E.leucoxylon)* Grey Box *(E. microcarpa)* Watertable/dryland salinity control, ecology & biodiversity	659[1] 494[2]	15	43.9	N/A	N/A	Rainfall: Av 598 mm Soil: Heavy clay (buckshot gravel), pH 5.5-6.0 Topography: Gentle slope or flat Water: Rainfed plus groundwater discharge in parts.	Trees planted as seedlings on contour lines around hilltop. No thinnings. Before planting, the site was contour ripped and sprayed. Previously used for grazing and army training. Attacks by insects have been assumed although not recorded as the cause of foliage decline over the years. No treatment undertaken. No other problems with disease, fire or drought. Rainfed, although proximity to groundwater discharge is having an impact on growth rates.
26	Toolleen, E of Bendigo, Vic. Vic Roads map ref: 45 D5	1987	N/A	River Red Gum *(Eucalyptus camaldulensis)* Yate *(E. accidentalis)* Watertable/ dryland salinity control, shelterbelts	104[1] 78[2]	9	11.6	N/A	N/A	Rainfall: Av 450 mm Soil: Red volcanic loam, with heavy clay lower horizon, pH approx 5.9 Topography: Unknown Water: Rainfed only, depth to groundwater varies around 1m depending on season.	Seedlings planted as a double row windbreak along fence lines. No thinnings. Site was deep ripped (up to 40 cm) and sprayed. Previously used for mixed farming. Outbreak of spitfires treated with Malathion. Some trees have died and been replanted because of drought in 1982/83. No other problems from insects, disease, pests or fire. Rainfed, with occasional flooding. Flooding frequency unknown.

A4 - Table 1b. Growth Data for Sites in Victoria, Hassall & Associates (1998) continued.

Site Information (Victoria, Hassall & Associates, 1998)					Biomass		MAI	Planting	Volume	Site Factors	Husbandry
ID	Name, Location, Coordinates	Est.	Area Planted	Species List & Purpose	t/ha	Age	t/ha/yr	Density (trees/ha)	m^3/ha	e.g. rainfall, soil type/quality, topography, access to water, salinity	e.g. tubestock/direct seed, weed & pest control, fire, irrigation
27	Ardmona, near Shepparton, Vic. Vic Roads map ref: 32 E8	1978	N/A	Victoria Eurabbie *(E. globulus ssp. pseudoglobulus)* Southern Mahogany *(E. botryoides)* Sydney Blue Gum *(E. saligna)* Yellow Gum *(E. leucoxylon)* Spotted Gum *(Corymbia maculata)* Shelterbelts	930[1] 697[2]	18	11.6	N/A	N/A	Rainfall: Av 550 mm Soil: Fine sandy loam, pH approx 7.2 Topography: Flat Water: Rainfed, with occasional flooding from adjacent dairy farm. Depth to groundwater >1m.	Seedlings planted in a single row along residential/dairy farm boundary. No thinnings. Site was ripped before planting. Previously used as a track and then as a fruit orchard. Some problems associated with weeds, hares, frost and strong wind. Trees replanted as required. No other problems from insects, disease, pests or fire. Rainfed, with occasional flooding from adjacent dairy farm. Flooding frequency unknown.

[3] measured using bole and branches
[4] measured using bole only

A4 - Table 1c. Growth Data for Sites in Western Australia, Hassall & Associates (1999b)

Site Information (Western Australia, Hassall & Associates, 1999b)					Biomass		MAI	Planting	Volume	Site Factors	Husbandry
ID	Name, Location, Coordinates	Est.	Area Planted	Species List & Purpose	t/ha	Age	t/ha/yr	Density (trees/ha)	m^3/ha	e.g. rainfall, soil type/quality, topography, access to water, salinity	e.g. tubestock/direct seed, weed & pest control, fire, irrigation
1	Wongon Hills	1965	3.5 ha	Dwarf Sugar Gum *(E.cladocalyx var. nana)* Amenity	76[1] 57[2]	32.5	2.4	150	N/A	Rainfall: Av 392 mm Soil: Yellow/brown sand over deep loamy sand, pH approx 4.8-5.2 (CaCl2) Topography: Gently undulating Water: Rainfed only, depth to groundwater >1m Aspect: NE.	Site preparation unknown. Previously cropping/grazing. Tubestock planted in rows No thinnings and no replanting. Some species have suffered from competition from more vigorous species. No other problems associated with weeds/disease/pests, drought or fire. Rainfed only.
2	Wongon Hills	1965	3.5 ha	Sugar Gum *(E. cladocalyx)* Amenity	160[1] 120[2]	32.5	4.9	110	N/A	See above	See above
3	Wongon Hills	1951	8 ha	Salt River Gum *(E. sargentii)* Erosion control, watertable/dryland salinity control	73[1] 55[2]	46.5	1.6	200	N/A	Rainfall: Av 392 mm Soil: Black clayey sand over brown sandy loam, pH approx 5.0 (CaCl2) Topography: Flat Water: Rainfed plus possible access to groundwater, depth to groundwater approx 20 cm Aspect: N/A.	Site preparation unknown. Prior land use unknown. Tubestock planted in rows along contours. No thinnings, but site replanted to replace deaths and increase density. Incidence of weeds/disease/pests, drought or fire unknown. Rainfed plus access to shallow groundwater.
4	Ejanding West	1984	20 ha	Dwarf Sugar Gum *(E. cladocalyx var. nana)* Coastal Mort *(E. platypus var. heterophylla)* Erosion control, watertable/dryland salinity control, windbreak	68[1] 51[2]	13.5		285	N/A	Rainfall: Av 311 mm Soil: Sand over yellow brown clayey sand, non-saline, pH approx 4.5 Topography: Gentle slope Water: Rainfed only, depth to groundwater approx 10-12m Aspect: W.	Site ripped prior to planting. Previously used for cropping/grazing. Tubestock planted in rows across contours. No thinnings. Some initial loss of trees due to drought and wind damage, but none since. Incidence of weeds/disease/pests, drought or fire unknown. Rainfed only.

A4 - Table 1c. Growth Data for Sites in Western Australia, Hassall & Associates (1999b) continued.

Site Information (Western Australia, Hassall & Associates, 1999b)					Biomass		MAI	Planting	Volume	Site Factors	Husbandry
ID	Name, Location, Coordinates	Est.	Area Planted	Species List & Purpose	t/ha	Age	t/ha/yr	Density (trees/ha)	m^3/ha	e.g. rainfall, soil type/quality, topography, access to water, salinity	e.g. tubestock/direct seed, weed & pest control, fire, irrigation
5	Ejanding	1985	2 ha	Salt River Gum *(E. sargentii)* Erosion control, watertable/dryland salinity control	10^1 7^2	12.5		500	N/A	Rainfall: Av 311 mm Soil: yellow brown sand over light grey sandy clay loam, moderate salinity, pH approx 5.0 Topography: unknown Water: Rainfed plus possible access to groundwater, depth to groundwater approx 20 cm Aspect: N/A.	Site ripped and sprayed prior to planting. Previously used for cropping/grazing. Seedlings planted in rows parallel to a bulldozed drain line using a tree planter. No thinnings. Some recent deaths due to drought. No replanting. No damage from weeds/disease/pests or fire. Rainfed only, plus access to shallow groundwater.
6	Trayning	1987	1 ha	River Red Gum *(E. camaldulensis)* Erosion control, watertable/dryland salinity control	45^1 34^2	10.5		450-500	N/A	Rainfall: Av 323 mm Soil: Yellow brown sand over bright yellow brown sandy loam, pH 6.1 Topography: Midslope, very gentle slope Water: Rainfed only, depth to groundwater approx 30 cm Aspect: NNE.	Site ripped and sprayed prior to planting. Previously used for cropping. Seedlings planted in contoured rows using a tree planter. No thinnings. Some recent deaths due to drought. No replanting. No damage from weeds/disease/pests or fire. Rainfed only.
7	Trayning	1987	1 ha	See above	7.3^1 5.4^2	10.5		450-500	N/A	See above except: Water: Rainfed only, depth to groundwater >1.5m.	See above
8	Trayning	1987	1 ha	Salt River Gum *(E. sargentii)* Erosion control, watertable/dryland salinity control	28^1 21^2	10.5		450-500	N/A	See above except: pH 5.1 Aspect: SSW.	See above except: Some deaths due to borers in the drier areas.
9	Trayning	1987	1 ha	See above	3.9^1 3.0^2	10.5		450-500	N/A	See above	See above

Site Information (Western Australia, Hassall & Associates, 1999b)					Biomass		MAI	Planting	Volume	Site Factors	Husbandry
ID	Name, Location, Coordinates	Est.	Area Planted	Species List & Purpose	t/ha	Age	t/ha/yr	Density (trees/ha)	m^3/ha	e.g. rainfall, soil type/quality, topography, access to water, salinity	e.g. tubestock/direct seed, weed & pest control, fire, irrigation
10	Bencubbin	1982	N/A	River Red Gum *(E. camaldulensis)* Windbreak	16[1] 12[2]	15.5		500	N/A	Rainfall: Av 322 mm Soil: Deep yellow wodjil sands, pH 4.5 (H_20) Topography: High up on a gently sloping hillside Water: Rainfed only, depth to groundwater unknown but deep Aspect: W.	Site ripped and sprayed prior to planting. Previously used for cropping/grazing. Seedlings planted in rows. Thinnings history unknown. Initial deaths due to rabbits. Treated by baiting and protective netting. Seedlings replanted. Some recent deaths due to drought and associated borer activity. No treatment. Rainfed only.
11	Beacon	1986	0.25 ha	River Red Gum *(E. camaldulensis)* Shade and shelter	11[1] 8[2]	11.5		200	N/A	Rainfall: Av 314 mm Soil: Reddish brown sandy loam, low salinity, pH 7.6-7.8 (H_20) Topography: Flat Water: Rainfed plus access to groundwater. Depth to groundwater approx 1.5m, salinity 6000 mS/m Aspect: N/A.	Site preparation history unknown. Previously used for cropping/grazing. Seedlings planted in rows by hand. Thinnings history unknown. The only site difficulty appears to be reasonably shallow and saline groundwater. Rainfed plus access to groundwater.
12	Murkinbudin	1986	1.5 ha	York Gum (I) Strickland's Gum *(E. stricklandii)* Sheath's Gum *(E. sheathiana)* Erosion control, watertable/dryland salinity control	18[1] 13[2]	11.5		250	N/A	Rainfall: Av 285 mm Soil: Brown sandy loam, over bedrock, salt scalds in parts, moderately acid. Topography: Very gentle midslope Water: Rainfed plus potential access to groundwater seep. Depth to groundwater unknown. Aspect: S.	Site ripped but not sprayed. Previously used for cropping/grazing. Seedlings planted in 5 contoured rows adjacent salt scald using a tree planter. Thinnings history unknown. No reported problems with pests/weeds/disease, fire or drought. Rainfed, plus potential access to groundwater

A4 - Table 1c. Growth Data for Sites in Western Australia, Hassall & Associates (1999b) continued.

Site Information (Western Australia, Hassall & Associates, 1999b)					Biomass		MAI	Planting	Volume	Site Factors	Husbandry
ID	Name, Location, Coordinates	Est.	Area Planted	Species List & Purpose	t/ha	Age	t/ha/yr	Density (trees/ha)	m^3/ha	e.g. rainfall, soil type/quality, topography, access to water, salinity	e.g. tubestock/direct seed, weed & pest control, fire, irrigation
13	Belka East	1988	2 ha	River Red Gum *(E. camaldulensis)* Red Ironbark *(E. sideroxylon)* Erosion control, watertable/dryland salinity control, amenity	56[1] 42[2]	9.5		N/A	N/A	Rainfall: Av 332 mm Soil: Sand over bright yellowish brown sandy loam, pH 4.2 Topography: Midslope Water: Rainfed plus potential access to groundwater seep, depth to groundwater >5m Aspect: NE.	Site ripped and sprayed the year before. Previously used for cropping/grazing. Seedlings planted in contoured rows perpendicular from seep using a tree planter. No thinnings. No reported problems with pests/weeds/disease, fire or drought. Rainfed, plus potential access to groundwater.
14	Belka East	1988	2 ha	See above, except only Red Ironbark *(E. sideroxylon)*	30[1] 22[2]	9.5		N/A	N/A	See above except: No access to groundwater seep, greater depth.	See above except: Lower growth rates associated with droughting.
15	Bakers Hill	1978	N/A (larger than those below)	River Red Gum *(E. camaldulensis)* Erosion control, watertable/dryland salinity control, experiment	38[1] 282	19.5		Originally 550, now much lower	N/A	Rainfall: Av 593 mm Soil: Brownish black gravelly sand over gravelly yellow orange sand, pH unknown. Topography: Very gently sloping low hillside. Water: Rainfed, depth to groundwater >2m Aspect: Unknown.	Site preparation unknown. Previously used for grazing. Trees planted in rows. Thinnings occurred several years ago. History of problems with pests/weeds/disease, fire or drought unknown. Rainfed only.
16	Bakers Hill	1977	1 ha	See above	46[1] 35[2]	20.5		650	N/A	See above except: Soil: Dark brown gravelly loamy sand over a gravelly clayey sand.	See above, except: No thinnings.
17	Bakers Hill	1984	1.5 ha	See above	30[1] 22[2]	13.5		260	N/A	See above except: Soil: Dark brown loamy sand over yellowish brown light clay with mottles. Adjacent saline areas. Water: Rainfed, depth to groundwater <2m.	See above

Site Information (Western Australia, Hassall & Associates, 1999b)					Biomass		MAI	Planting	Volume	Site Factors	Husbandry
ID	Name, Location, Coordinates	Est.	Area Planted	Species List & Purpose	t/ha	Age	t/ha/yr	Density (trees/ha)	m^3/ha	e.g. rainfall, soil type/quality, topography, access to water, salinity	e.g. tubestock/direct seed, weed & pest control, fire, irrigation
18	North Bannister	1976	0.75 ha	River Red Gum *(E. camaldulensis)* Erosion control, watertable/dryland salinity control, experiment	197^1 148^2	21.5		815	N/A	Rainfall: Av 760 mm Soil: Duplex with sandy gravel over sandy clay, inpenetrable layers in parts. pH unknown. Topography: Gentle midslope. Water: Rainfed. Depth to groundwater >2.8m Aspect: W.	Site preparation unknown. Previously used for grazing. Trees planted in randomised blocks. No thinnings. No reported problems with pests/weeds/disease, fire or drought. Rainfed, plus potential access to groundwater.
19	North Bannister	1976	0.75 ha	Blue Gum *(E. globulus)* Erosion control, watertable/dryland salinity control	531^1 398^2	21.5		815	N/A	See above	See above
20	North Bannister	1976	1.5 ha	River Red Gum *(E. camaldulensis)* Erosion control, watertable/dryland salinity control	146^1 110^2	21.5		815	N/A	See above	See above except: Survival rate poor (66%), apparently due to impenetrable layer in soil horizon and droughting.
21	Dryandra	1976	1.5 ha	River Red Gum *(E. camaldulensis)* Erosion control, watertable/dryland salinity control, experiment	43^1 32^2	21.5		815	N/A	Rainfall: Av 530 mm Soil: Sandy loam with gravel over light to dense brown clay, pH unknown. Topography: Gentle slope. Water: Rainfed. Depth to groundwater >1.6m. Aspect: N.	Site preparation unknown. Previously used for grazing. Trees planted in randomised blocks. No thinnings. No reported problems with pests/weeds/disease, fire or drought. Rainfed, plus potential access to groundwater.
22	Dryandra	1976	1.5 ha	See above	80^1 60^2	21.5		815	N/A	See above	See above

A4 - Table 1c. Growth Data for Sites in Western Australia, Hassall & Associates (1999b) continued.

Site Information (Western Australia, Hassall & Associates, 1999b)					Biomass		MAI	Planting	Volume	Site Factors	Husbandry
ID	Name, Location, Coordinates	Est.	Area Planted	Species List & Purpose	t/ha	Age	t/ha/yr	Density (trees/ha)	m^3/ha	e.g. rainfall, soil type/quality, topography, access to water, salinity	e.g. tubestock/direct seed, weed & pest control, fire, irrigation
23	Bingham River	1976	N/A	Blue Gum *(E. globulus)* Erosion control, watertable/dryland salinity control	83[1] 62[2]	20		N/A	N/A	Rainfall: Av 713 mm Soil: Sand over sandy clay, pH unknown. Topography: Gentle slope. Water: Rainfed. Depth to groundwater unknown.	Site preparation unknown. Previously used for mixed farming. Establishment and management regime unknown.
24	Bingham River	1978	N/A	See above	69[1] 52[2]	18		N/A	N/A	See above	See above
25	Bowelling	1981	N/A	River Red Gum *(E. camaldulensis)* Erosion control, watertable/dryland salinity control, wood products	113[1] 85[2]	14		600	N/A	Rainfall: Av 692 mm Soil: Heavy clay, moderately saline (EC 140m S/m), pH unknown. Topography: Flat. Water: Rainfed, plus possible access to groundwater. Depth to groundwater <1.5m. Water table salinity 2000 mS/m.	Site preparation unknown. Previously used for grazing. Trees planted in mounded rows. Thinnings history unknown. No reported problems with pests/weeds/disease, fire or drought. Rainfed, plus potential access to groundwater.
26	Cordering	1984	N/A	Blue Gum *(E. globulus)* Erosion control, watertable/dryland salinity control, wood products	121[1] 91[2]	12		375	N/A	Rainfall: Av 621 mm Soil: N/A Topography: Very gentle slope to flat. Water: Rainfed. Depth to groundwater unknown.	Site preparation unknown. Previously used for grazing. Trees planted in rows. Thinnings history unknown. No reported problems with pests/weeds/disease, fire or drought. Rainfed.
27	Cordering	1984	N/A	River Red Gum *(E. camaldulensis)*	36[1] 27[2]	12		325	N/A	See above	See above except: Trees planted on a salt scald and barley grass site.

Site Information (Western Australia, Hassall & Associates, 1999b)					Biomass		MAI	Planting	Volume	Site Factors	Husbandry
ID	Name, Location, Coordinates	Est.	Area Planted	Species List & Purpose	t/ha	Age	t/ha/yr	Density (trees/ha)	m^3/ha	e.g. rainfall, soil type/quality, topography, access to water, salinity	e.g. tubestock/direct seed, weed & pest control, fire, irrigation
28	Dinninup	1983	< 1 ha	Blue Gum *(E. globulus)* Erosion control, watertable/dryland salinity control, wind break	83[1] 62[2]	14.5		1,100	N/A	Rainfall: Av 601 mm Soil: Black loam over sandy clay loam, pH unknown. Topography: Gentle midslope. Water: Rainfed. Depth to groundwater >2m although it is wet in winter. Aspect: E.	Site ripped and sprayed but not mounded prior to planting. Previously used for grazing. Seedlings hand planted in irregluarly spaced rows. Thinnings history unknown. No reported problems with weeds/disease or fire. Some initial deaths from kangaroos and some recent extensive deaths due to droughting. Rainfed.
29	Dinninup	1984	< 1 ha	River Red Gum *(E. camaldulensis)*	77[1] 58[2]	13.5		1,100	N/A	See above	See above except: No deaths associated with droughting.
30	Dinninup	1983	< 1 ha	Blue Gum *(E. globulus)*	146[1] 109[2]	14.5		900	N/A	See above except: Soil: Grey sand over yellow brown loamy sand.	See above
31	Mayanup	1987	5 ha	River Red Gum *(E. camaldulensis)* Erosion control, watertable/dryland salinity control, amenity	76[1] 57[2]	8.5		500	N/A	Rainfall: Av 668 mm Soil: Shallow sand over clay, moderately saline (EC 50-140 mS/m), pH unknown. Topography: Gentle slope to flat. Water: Rainfed. Shallow, depth unknown, saline (2,200 mS/m) Aspect: N.	Site ripped and mounded prior to planting. Previously use unknown. Thinnings history unknown. No reported problems with pests/weeds/disease, drought or fire. Rainfed, plus access to groudwater.

[5] measured using bole and branches
[6] measured using bole only

A4 - Table 2a. Growth Data for Sites in South Australia, Wong *et al.* (2000)

Site information (South Australia, Wong *et. al.*, 2000)					Biomass		MAI	Planting	Volume	Site Factors	Husbandry
ID	**Name, Location, Coordinates**	**Est.**	**Area Planted**	**Species List & Purpose**	**t/ha**	**Age**	**t/ha/yr**	**Density (trees/ha)**	**m^3/ha**	**e.g. rainfall, soil type/quality, topography, access to water, salinity**	**e.g. tubestock/direct seed, weed & pest control, fire, irrigation**
1	RT123C, Mt. Lofty Ranges Lat/long: 3453, 13849	1988	N/A	*E. globulus* Southern Blue Gum		3	N/A	N/A	4	Rainfall: Av 926 mm Soil: Loam over medium clay, depth to clay 30 cm Topography: 20% slope.	Previously planted with *Pinus radiata*.
	See above					5			42		
	See above					7			108		
	See above					9			200		
	See above					11			32		
	See above		N/A	*E. nitens* Shining Gum		3	N/A	N/A	5		
	See above					5			65		
	See above					7			151		
	See above					9			268		
	See above					11			390		
	See above		N/A	*E. viminalis* Manna Gum		3	N/A	N/A	1		
	See above					5			32		
	See above					7			89		
	See above					9			173		
	See above					11			288		
	See above		N/A	*E. botryoides* Southern Mahogany		3	N/A	N/A	4		
	See above					5			37		
	See above					7			91		

Site information (South Australia, Wong *et. al.*, 2000)					Biomass		MAI	Planting	Volume	Site Factors	Husbandry
ID	Name, Location, Coordinates	Est.	Area Planted	Species List & Purpose	t/ha	Age	t/ha/yr	Density (trees/ha)	m^3/ha	e.g. rainfall, soil type/quality, topography, access to water, salinity	e.g. tubestock/direct seed, weed & pest control, fire, irrigation
	RT123C, Mt. Lofty Ranges					9			164		
	See above		N/A	*E. grandis* Flooded Gum		3	N/A	N/A	2		
	See above					5			37		
	See above					7			88		
	See above					9			150		
	See above					11			232		
	See above		N/A	*E. saligna* Sydney Blue Gum		3	N/A	N/A	2		
	See above					5			35		
	See above					7			85		
	See above					9			162		
	See above					11			240		
2	EP205, NW of Mt. Gambier Lat/long: 3743, 14037	1988	N/A	*E. globulus* Southern Blue Gum		2	N/A	N/A	11	Rainfall: Av 766 mm Soil: Sand over medium clay, depth to clay 70 cm Topography: Flat.	Previously used as pasture for grazing.
	See above					3			37		
	See above					4			60		
	See above					6			130		
	See above					9			196		
	See above					11			279		
	See above		N/A	*E. nitens* Shining Gum		2	N/A	N/A	5		
	See above					3			20		
	See above					4			39		

A4 - Table 2a. Growth Data for Sites in South Australia, Wong *et al.* (2000) continued.

Site information (South Australia, Wong *et. al.*, 2000)					Biomass		MAI	Planting	Volume	Site Factors	Husbandry
ID	Name, Location, Coordinates	Est.	Area Planted	Species List & Purpose	t/ha	Age	t/ha/yr	Density (trees/ha)	m^3/ha	e.g. rainfall, soil type/quality, topography, access to water, salinity	e.g. tubestock/direct seed, weed & pest control, fire, irrigation
	See above					6			93		
	See above					9			147		
	See above		N/A	*E. viminalis* Manna Gum		2	N/A	N/A	4		
	See above					3			20		
	See above					4			37		
	See above					6			80		
	See above					9			123		
	See above		N/A	*E. botryoides* Southern Mahogany		2	N/A	N/A	5		
	See above					3			20		
	See above					4			35		
	See above					6			92		
	See above					9			147		
3	EM133, N of Mt. Gambier Lat/long: 3745, 14047	1991	N/A	*E. globulus* Southern Blue Gum		2	N/A	N/A	3	Rainfall: Av 745 mm Soil: Uniform sandy profile, depth to clay 200 cm+ Topography: Flat.	Previously used as pasture for grazing.
	See above					3			21		
	See above					4			48		
	See above					5			69		
	See above		N/A	*E. saligna* Sydney Blue Gum		3	N/A	N/A	4		
	See above					4			15		
	See above					5			24		

Site information (South Australia, Wong *et. al.*, 2000)					Biomass		MAI	Planting	Volume	Site Factors	Husbandry
ID	Name, Location, Coordinates	Est.	Area Planted	Species List & Purpose	t/ha	Age	t/ha/yr	Density (trees/ha)	m^3/ha	e.g. rainfall, soil type/quality, topography, access to water, salinity	e.g. tubestock/direct seed, weed & pest control, fire, irrigation
	See above		N/A	*E. grandis* Flooded Gum		2	N/A	N/A	1		
	EM133, N of Mt. Gambier					3			13		
	See above					4			37		
	See above					5			51		

A4 - Table 2b. Growth Data for Sites in Victoria, Wong *et al.* (2000)

Site information (Victoria, Wong *et. al.*, 2000)					Biomass		MAI	Planting	Volume	Site Factors	Husbandry
ID	Name, Location, Coordinates	Est.	Area Planted	Species List & Purpose	t/ha	Age	t/ha/yr	Density (trees/ha)	m^3/ha	e.g. rainfall, soil type/quality, topography, access to water, salinity	e.g. tubestock/direct seed, weed & pest control, fire, irrigation
1	Tostaree, near Lakes Entrance, Vic. Lat/long: 3747S, 14811E	1988	N/A	*E. globulus* Southern Blue Gum		2	N/A	951	13	Rainfall: Av 819 mm Soil: Loamy sand over light medium clay Topography: 3-6% slope.	Small scale plot (<1 ha). Previously used for grazing on improved pasture with a history of relatively high rates of fertiliser application. Direct seeding.
	See above					4		942	74		
	See above					6		924	157		
	See above					8		884	262		
	See above					10		840	334		
2	Tostaree			*E. nitens* Shining Gum		2	N/A	920	13		
	See above					4		916	76		
	See above					6		900	147		
	See above					8		860	237		
	See above					10		832	287		
3	Tostaree			*E. viminalis* Manna Gum		2	N/A	980	12		
	See above					4		904	81		
	See above					6		892	166		
	See above					8		876	262		
	See above					10		872	319		
4	Tostaree			*E. botryoides* Southern Mahogany		2	N/A	964	8		
	See above					4		960	49		
	See above					6		952	103		
	See above					8		936	171		
	See above					10		888	216		

Site information (Victoria, Wong *et. al.*, 2000)					Biomass		MAI	Planting	Volume	Site Factors	Husbandry
ID	Name, Location, Coordinates	Est.	Area Planted	Species List & Purpose	t/ha	Age	t/ha/yr	Density (trees/ha)	m^3/ha	e.g. rainfall, soil type/quality, topography, access to water, salinity	e.g. tubestock/direct seed, weed & pest control, fire, irrigation
5	Tostaree			*E. grandis* Flooded Gum		2	N/A	980	8		
	See above					4		972	45		
	See above					6		972	93		
	See above					8		960	161		
	See above					10		940	215		
6	Tostaree			*E. saligna* Sydney Blue Gum		2	N/A	960	8		
	See above					4		948	46		
	See above					6		948	95		
	See above					8		928	154		
	See above					10	N/A	908	195		
7	Waygara, near Orbost, Vic. Lat/long: 3741S, 14819E	1989	N/A	*E. globulus* Southern Blue Gum		2	N/A	938	10	Rainfall: Av 870 mm Soil: Loam over light medium clay Topography: Flat.	Small scale plot (<1 ha). Previous land use degraded native forest severely affected by fungal pathogen *Phytophthora cinnamomi*. Cleared before direct seeding.
	See above					4		938	65		
	See above					6		917	115		
	See above					8		892	159		
	See above					10		858	181		
8	Waygara			*E. nitens* Shining Gum		2		695	5		
	See above					4		685	41		
	See above					6		662	70		
	See above					8		643	87		
	See above					10		656	114		

A4 - Table 2b. Growth Data for Sites in Victoria, Wong *et al.* (2000) continued.

Site information (Victoria, Wong *et. al.*, 2000)					Biomass		MAI	Planting	Volume	Site Factors	Husbandry
ID	Name, Location, Coordinates	Est.	Area Planted	Species List & Purpose	t/ha	Age	t/ha/yr	Density (trees/ha)	m^3/ha	e.g. rainfall, soil type/quality, topography, access to water, salinity	e.g. tubestock/direct seed, weed & pest control, fire, irrigation
9	Waygara			*E. viminalis* Manna Gum		2		713	5		
	See above					4		696	38		
	See above					6		688	74		
	See above					8		683	103		
	See above					10		679	109		
10	Waygara			*E. botryoides* Southern Mahogany		2		963	5		
	See above					4		963	24		
	See above					6		958	64		
	See above					8		938	86		
	See above					10		938	102		
11	Waygara			*E. grandis* Flooded Gum		2		911	5		
	See above					4		911	30		
	See above					6		911	68		
	See above					8		894	92		
	See above					10		886	95		
12	Waygara			*E. saligna* Sydney Blue Gum		2		954	6		
	See above					4		946	30		
	See above					6		921	69		
	See above					8		904	92		
	See above					10		896	105		

Site information (Victoria, Wong *et. al.*, 2000)					Biomass		MAI	Planting	Volume	Site Factors	Husbandry
ID	Name, Location, Coordinates	Est.	Area Planted	Species List & Purpose	t/ha	Age	t/ha/yr	Density (trees/ha)	m^3/ha	e.g. rainfall, soil type/quality, topography, access to water, salinity	e.g. tubestock/direct seed, weed & pest control, fire, irrigation
13	Mt Worth West, near Warragul, Vic. Lat/long: 3818S, 14559E	1986	N/A	*E. globulus* Southern Blue Gum		3.5	N/A	800	31	Rainfall: Av 1212 mm Soil: Clay loam over light medium clay Topography: 24-28% slope.	Small scale plot (<1 ha). Previously used for grazing on improved pasture with a history of relatively high rates of fertiliser application. Cleared before direct seeding.
	See above					6		831	135		
	Mt Worth West					8.5		800	227		
	See above					12		631	401		
	See above			*E. nitens* Shining Gum		3.5		970	48		
	See above					6		954	206		
	See above					8.5		970	356		
	See above					12		818	558		
14	Narracan East, near Morwell, Vic. Lat/long: 3817S, 14616E	1986	N/A	*E. globulus* Southern Blue Gum		3.5	N/A	927	33	Rainfall: Av 963 mm Soil: Loam over medium clay Topography: 2-3% slope.	Small scale plot (<1 ha). Previous landuse *Pinus radiata*. Cleared before direct seeding.
	See above					6		889	94		
	See above					12		800	365		
	See above			*E. nitens* Shining Gum		3.5		912	29		
	See above					6		902	85		
	See above					12		776	305		
15	Yinnar, near Morwell, Vic. Lat/long: 3818S, 14618E	1986	N/A	*E. globulus* Southern Blue Gum		3.5	N/A	970	8	Rainfall: Av 930 mm Soil: Shallow sandy loam over medium heavy clay Topography: 0-5% slope.	Small scale plot (<1 ha). Previous landuse *Pinus radiata*. Low growth rates experienced at this site due to shallow surface soils. Cleared before direct seeding.
	See above					6		929	38		
	See above					12		866	152		

A4 - Table 2b. Growth Data for Sites in Victoria, Wong *et al.* (2000) continued.

Site information (Victoria, Wong *et. al.*, 2000)					Biomass		MAI	Planting	Volume	Site Factors	Husbandry
ID	Name, Location, Coordinates	Est.	Area Planted	Species List & Purpose	t/ha	Age	t/ha/yr	Density (trees/ha)	m^3/ha	e.g. rainfall, soil type/quality, topography, access to water, salinity	e.g. tubestock/direct seed, weed & pest control, fire, irrigation
	See above			*E. nitens* Shining Gum		3.5		800	6		
	See above					6		803	28		
	See above					12		707	81		
16	Maryvale, N of Morwell, Vic. Lat/long: 3812S, 14628E	1986	N/A	*E. globulus* Southern Blue Gum		3.5	N/A	932	20	Rainfall: Av 768 mm Soil: Sandy loam over medium clay Topography: Flat.	Small scale plot (<1 ha). Previous landuse *Pinus radiata*. Cleared before direct seeding.
	See above					6		888	65		
	See above					12		883	214		
	See above			*E. nitens* Shining Gum		3.5		966	13		
	See above					6		966	41		
	See above					12		638	87		
17	Gormondale, between Sale and Traralgon, Vic. Lat/long: 3816S, 14642E	1986	N/A	*E. globulus* Southern Blue Gum		3.5	N/A	992	31	Rainfall: Av 830 mm Soil: Sand over loamy sand Topography: 0-5% slope.	Small scale plot (<1 ha). Previous landuse *Pinus radiata*. Cleared before direct seeding.
	See above					6		992	86		
	See above					12		868	216		
	See above			*E. nitens* Shining Gum		3.5		979	20		
	See above					6		966	58		
	See above					12		916	135		

Site information (Victoria, Wong *et. al.*, 2000)					Biomass		MAI	Planting	Volume	Site Factors	Husbandry
ID	Name, Location, Coordinates	Est.	Area Planted	Species List & Purpose	t/ha	Age	t/ha/yr	Density (trees/ha)	m^3/ha	e.g. rainfall, soil type/quality, topography, access to water, salinity	e.g. tubestock/direct seed, weed & pest control, fire, irrigation
18	Mt Worth East, near Warragul, Vic. Lat/long: 3819S, 14559E	1987	N/A	*E. globulus* Southern Blue Gum		3.5	N/A	884	27	Rainfall: Av 1224 mm Soil: Clay loam over light to medium clay Topography: 5-28% slope.	Small scale plot (<1 ha). Previously used for grazing on improved pasture with a history of relatively high rates of fertiliser application. Unrealistically high productivity experienced at this site. Not considered representative of broad-scale plantations. Cleared before direct seeding.
	Mt Worth East					6		876	114		
	See above					11		828	340		
	See above			*E. viminalis* Manna Gum		3.5		960	32		
	See above					6		961	138		
	See above					11		938	435		
	See above			*E. botryoides* Southern Mahogany		3.5		884	15		
	See above					6		857	77		
	See above					11		764	212		
	See above			*E. grandis* Flooded Gum		3.5		846	11		
	See above					6		856	44		
	See above					11		720	120		
	See above			*E. saligna* Sydney Blue Gum		3.5		918	23		
	See above					6		901	101		
	See above					11		838	281		

A4 - Table 2b. Growth Data for Sites in Victoria, Wong *et al.* (2000) continued.

Site information (Victoria, Wong *et. al.*, 2000)					Biomass		MAI	Planting	Volume	Site Factors	Husbandry
ID	Name, Location, Coordinates	Est.	Area Planted	Species List & Purpose	t/ha	Age	t/ha/yr	Density (trees/ha)	m^3/ha	e.g. rainfall, soil type/quality, topography, access to water, salinity	e.g. tubestock/direct seed, weed & pest control, fire, irrigation
19	Delburn, near Leongatha, Vic. Lat/long: 3821S, 14614E	1987	N/A	*E. globulus* Southern Blue Gum		3.5	N/A	935	15	Rainfall: Av 1002 mm Soil: Loam over medium clay Topography: 0-8% slope.	Small scale plot (<1 ha). Previous landuse *Pinus radiata*. Cleared before direct seeding.
	See above					6		935	84		
	See above					11		917	316		
	See above			*E. nitens* Shining Gum		3.5		817	11		
	See above					6		817	70		
	See above					11		817	259		
	See above			*E. viminalis* Manna Gum		3.5		876	11		
	See above					6		850	63		
	See above					11		850	224		
	See above			*E. botryoides* Southern Mahogany		3.5		972	8		
	See above					6		943	57		
	See above					11		926	211		
	See above			*E. grandis* Flooded Gum		3.5		951	9		
	See above					6		935	54		
	See above					11		892	183		
	See above			*E. saligna* Sydney Blue Gum		3.5		978	10		
	See above					6		962	59		
	See above					11		935	215		

Site information (Victoria, Wong *et. al.*, 2000)					Biomass		MAI	Planting	Volume	Site Factors	Husbandry
ID	Name, Location, Coordinates	Est.	Area Planted	Species List & Purpose	t/ha	Age	t/ha/yr	Density (trees/ha)	m^3/ha	e.g. rainfall, soil type/quality, topography, access to water, salinity	e.g. tubestock/direct seed, weed & pest control, fire, irrigation
20	Flynns Creek, between Sale and Traralgon, Vic. Lat/long: 3816S, 14636E	1987	N/A	*E. globulus* Southern Blue Gum		3.5	N/A	919	13	Rainfall: Av 1173 mm Soil: Loamy sand over light to medium clay Topography: Flat.	Small scale plot (<1 ha). Previous landuse *Pinus radiata*. Cleared before direct seeding.
	See above					6		910	52		
	See above					11		884	179		
	See above			*E. nitens* Shining Gum		3.5		744	10		
	See above					6		695	44		
	See above					11		678	139		
	See above			*E. viminalis* Manna Gum		3.5		860	9		
	Flynns Creek					6		860	37		
	See above					11		835	105		
	See above			*E. botryoides* Southern Mahogany		3.5		910	9		
	See above					6		902	40		
	See above					11		885	136		
	See above			*E. grandis* Flooded Gum		3.5		886	8		
	See above					6		877	34		
	See above					11		860	98		
	See above			*E. saligna* Sydney Blue Gum		3.5		851	9		
	See above					6		842	38		
	See above					11		786	113		

A4 - Table 2b. Growth Data for Sites in Victoria, Wong *et al.* (2000) continued.

Site information (Victoria, Wong *et. al.*, 2000)					Biomass		MAI	Planting	Volume	Site Factors	Husbandry
ID	Name, Location, Coordinates	Est.	Area Planted	Species List & Purpose	t/ha	Age	t/ha/yr	Density (trees/ha)	m^3/ha	e.g. rainfall, soil type/quality, topography, access to water, salinity	e.g. tubestock/direct seed, weed & pest control, fire, irrigation
21	Stradbroke, near Sale, Vic. Lat/long: 3816S, 14703E	1987	N/A	*E. globulus* Southern Blue Gum		3.5	N/A	943	18	Rainfall: Av 598 mm Soil: Sand Topography: 2-7% slope.	Small scale plot (<1 ha). Previous landuse *Pinus radiata.* Cleared before direct seeding.
	See above					6		919	54		
	See above					11		888	106		
	See above			*E. nitens* Shining Gum		3.5		934	16		
	See above					6		927	49		
	See above					11		876	86		
	See above			*E. viminalis* Manna Gum		3.5		951	20		
	See above					6		943	59		
	See above					11		898	107		
	See above			*E. botryoides* Southern Mahogany		3.5		959	30		
	See above					6		959	97		
	See above					11		947	257		
	See above			*E. grandis* Flooded Gum		3.5		934	23		
	See above					6		927	74		
	See above					11		921	172		
	See above			*E. saligna* Sydney Blue Gum		3.5		935	28		
	See above					6		927	78		
	See above					11		924	183		

Site information (Victoria, Wong *et. al.*, 2000)					Biomass		MAI	Planting	Volume	Site Factors	Husbandry
ID	Name, Location, Coordinates	Est.	Area Planted	Species List & Purpose	t/ha	Age	t/ha/yr	Density (trees/ha)	m^3/ha	e.g. rainfall, soil type/quality, topography, access to water, salinity	e.g. tubestock/direct seed, weed & pest control, fire, irrigation
22	Stockdale, N of Sale, Vic. Lat/long: 3751S, 14711E	1987	N/A	*E. globulus* Southern Blue Gum		3.5	N/A	919	19	Rainfall: Av 1182 mm Soil: Loamy sand over medium heavy clay Topography: Flat	Small scale plot (<1 ha). Previous landuse *Pinus radiata*. Cleared before direct seeding.
	See above					6		902	61		
	See above					11		877	141		
	See above			*E. nitens* Shining Gum		3.5		910	17		
	See above					6		893	52		
	See above					11		679	84		
	See above			*E. viminalis* Manna Gum		3.5		959	18		
	See above					6		934	59		
	See above					11		883	117		
	See above			*E. botryoides* Southern Mahogany		3.5		919	15		
	See above					6		919	49		
	Stockdale					11		900	102		
	See above			*E. grandis* Flooded Gum		3.5		901	12		
	See above					6		901	43		
	See above					11		876	89		
	See above			*E. saligna* Sydney Blue Gum		3.5		911	15		
	See above					6		893	48		
	See above					11		829	98		

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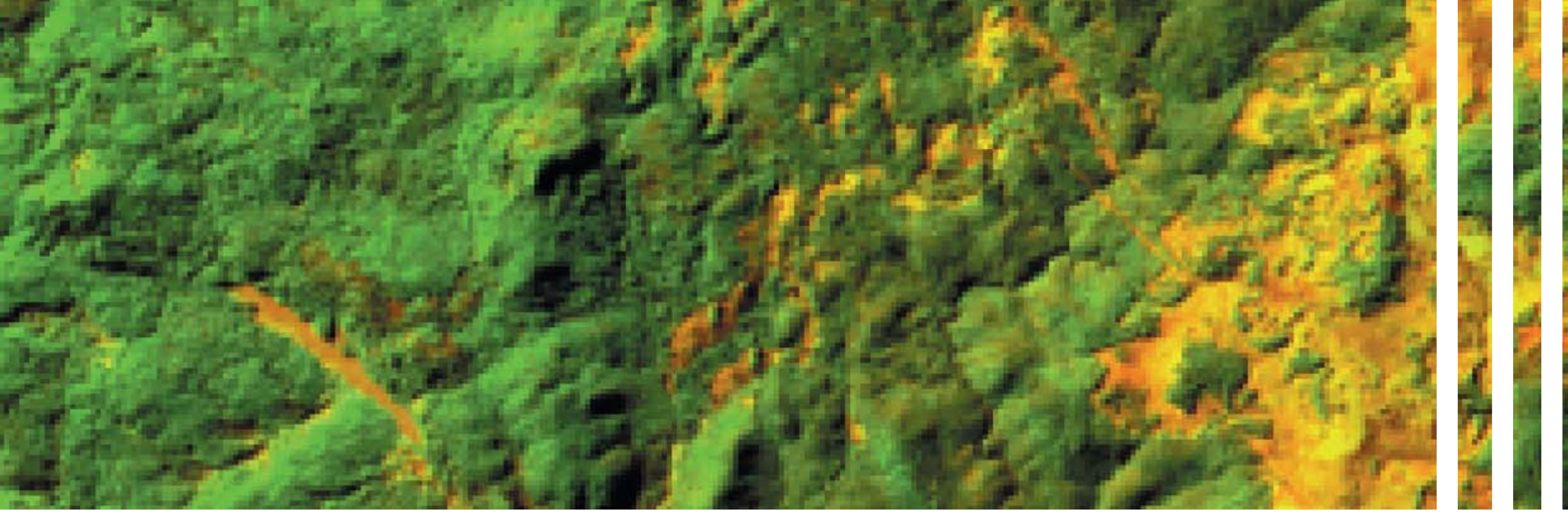

The National Carbon Accounting System provides a complete accounting and forecasting capability for human-induced sources and sinks of greenhouse gas emissions from Australian land based systems. It will provide a basis for assessing Australia's progress towards meeting its international emissions commitments.

technical report no. 23 Developing a National Forest Productivity Model