Site Selection for Farm Forestry in Australia

by RJ Harper, TH Booth, PJ Ryan, RJ Gilkes, NJ McKenzie and MF Lewis

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Foreword

This report deals with assessing sites for their potential and limitations for growing trees, whether the trees are for timber production, carbon sequestration, recharge reduction, erosion control, wildlife habitat, biofuel or any other purpose. It was developed to suit the needs of farm forestry advisers or consultants and landholders anywhere in Australia, although the emphasis is on southern agricultural regions (another JVAP report — Growing rainforest timber trees: A farm forestry manual for north Queensland — focuses on north-eastern Australia).

For the potential benefits of farm forestry to be realised, trees have to grow well. Tree performance (survival and growth) is related to the site’s climate and soil—if trees are planted on inappropriate sites they will grow poorly or die. Similarly, various management decisions (e.g. whether or not to rip the soil, apply fertilisers, which species to select and how closely to plant them) should be based on site conditions. This report is founded on the view that tailoring species choice and management inputs to a site’s requirements will increase the success of the planting and the sustainability of the land use.

The report discusses how various site properties influence tree growth, and then describes how to obtain information on them, either from existing sources or by carrying out field surveys. It also illustrates how site information is used in models designed to predict tree growth.

This project was funded by the Joint Venture Agroforestry Program (JVAP), which is supported by three R&D Corporations - Rural Industries Research and Development Corporation (RIRDC), Land & Water Australia (L&WA), and Forest and Wood Products Research and Development Corporation (FWPRDC). The Murray-Darling Basin Commission (MDBC) also contributed to this project. The R&D Corporations are funded principally by the Australian Government. State and Australian Governments contribute funds to the MDBC.

This report is an addition to RIRDC’s diverse range of over 1800 research publications. It forms part of our Agroforestry and Farm Forestry R&D program, which aims to integrate sustainable and productive agroforestry within Australian farming systems. The JVAP, under this program, is managed by RIRDC. Most of our publications are available for viewing, downloading or purchasing online through our website:

- purchases at www.rirdc.gov.au/eshop

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Executive Summary

What the report is about
The site evaluation procedures outlined in this report are intended to be applicable across the range of stages of development of farm forestry enterprises. The procedures described can be applied to areas where there is no specific information on the requirements of tree species—in these cases, site evaluations focus on identifying conditions likely to limit tree growth. But the procedures are also applicable in areas where there is a large body of knowledge on tree performance—in these cases, the data collected during the site evaluation can be interpreted with a high degree of confidence and can be used to estimate tree growth rates. The scientific underpinnings of site evaluation for Australian forestry are reviewed by Ryan et al. (2002), as another output of this project.

This report was prepared in 2002. While it has been updated in parts, it is important to note that research of relevance to site selection (e.g., site effects on tree performance, climate change and variability, species selection, growth modelling and regional assessments of land suitability) has been conducted since.

Who is the report targeted at?
This report is written for anyone who has the task of evaluating land for farm forestry, whatever the purpose of the planting. We assume that farm forestry is practised by three groups:

- Farmers planting trees for commercial purposes: this group consists of farmers who regard trees as another crop.
- Farmers and groups planting trees for environmental purposes: this group will plant trees on farms primarily for land and nature conservation with commercial benefits seen as secondary.
- Investment-driven forestry companies: this group, which includes private companies and government agencies, establish large areas of trees on many different properties, sometimes across several regions of Australia.

Background
The area of land being committed to farm forestry is increasing rapidly. These trees are not only being planted for profit, but also to produce more sustainable farming systems, by controlling erosion and salinity, enhancing biodiversity and providing shade and shelter to livestock. Although trees have been traditionally planted for timber and pulpwood, in the future new products, such as sequestered carbon or bioenergy, may attract investment.

The nature of the sites being chosen for trees on farms are markedly different from those traditionally used for commercial forestry, and this means that management and silvicultural techniques are being adapted to suit the changed conditions.

Most benefits will flow from reforestation projects that have high tree survival rates and adequate tree growth. Although management practices play a role, tree survival and growth are strongly related to site conditions. Simply put, if trees are planted on inappropriate sites, they will grow poorly or die.

Aims/Objectives
The aim of this report is to provide a set of procedures for gathering, interpreting and applying site evaluation information in ways that are repeatable and transparent.
Methods used

Procedures are given for regional as well as paddock-scale evaluations. The report assumes that well-founded site evaluation will lead to appropriate choices of tree species and management practices, such as planting density, cultivation techniques and fertiliser rates. The report is based on the principle that site evaluation methods should be explicit and consistent.

Results

The main site conditions influencing the success of a farm forestry project are climate, soil water regime, soil nutrient regime and site hazards. Some broad understanding of these is available in many areas, but there is a lack of relevant data at the paddock scale. Thus, in most situations a field survey will be needed to collect the information required to adequately evaluate a site’s potential. The collected information will then be interpreted and used to construct maps showing the suitability of land for particular species, to plan management operations and to estimate tree growth rates.

Implications for stakeholders

The level of investment in site evaluation can be matched to both the level of knowledge of the site requirements of tree species and the expected return from the investment. For some species in some areas of Australia, the survival and growth rates of trees can be predicted with reasonable accuracy. In areas where there have not been systematic studies it may only be possible to make broad estimates of tree survival and growth rates.
1. Purpose and Structure of this Report

R.J. Harper, P.J. Ryan, N.J. McKenzie, T H. Booth, R.J. Gilkes and M.F. Lewis

**Farm forestry** is the term used to describe forestry that is planned, managed and conducted at the farm level; it aims to fit into existing farming culture rather than replace it (Reid and Stephen, 2001).

### 1.1 Introduction

Farm forestry is emerging as a major new land use in Australia and is starting to provide a range of benefits including income diversification, restoration of hydrology, shelter for stock, land degradation control and increased rural employment.

Farm forestry has traditionally been undertaken to produce sawn timber, pulpwood or firewood; however, markets for new products have started to emerge, including for sequestered carbon and bioenergy. The extent that these markets develop will depend in a large part on government policies, such as emissions and renewable energy targets. Future products from farm forestry could include extractives, feedstocks for liquid biofuels and payments for environmental services, such as the restoration of catchment water quality or enhancement of biodiversity.

The nature of the sites being chosen for farm forestry are markedly different from those traditionally used for commercial forestry in Australia, and consequently management and silvicultural techniques are being adapted to suit the changed conditions. Significant expansion of farm forestry is expected in drier areas, and a major feature of these plantings is that they are likely to be integrated with farming activities, unlike much of the recent high rainfall area plantings.

### 1.2 The need for site evaluation

Irrespective of purpose—wood, increased water use, habitat restoration or carbon sequestration—the benefits of reforestation depend on tree survival and adequate growth. Although management practices play a role, tree survival and growth are strongly related to site conditions. Simply put, if trees are planted on inappropriate sites, they will grow poorly or die.

The assumption behind this report is that well-founded site evaluation and selection for trees will lead to sustainable and profitable farm forestry. It will do this by influencing choices of tree species and management practices (e.g. planting density, cultivation techniques and fertiliser rates) with the aims of optimising tree performance and generating environmental benefits. Some potential uses of the information collected during site evaluation are described in Table 1.1. One additional use of the data collected is as input for tree growth prediction models, and this is particularly important for investment-focused projects.
Table 1.1: Potential uses of site evaluation information for farm forestry

<table>
<thead>
<tr>
<th>Theme</th>
<th>Outcomes</th>
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<tbody>
<tr>
<td>Site selection</td>
<td>Prediction of tree performance (survival, growth, wood quality)</td>
</tr>
<tr>
<td></td>
<td>Identification of hazards to tree growth (flooding, salinity, wind-throw)</td>
</tr>
<tr>
<td></td>
<td>Matching genetic material (tree species, provenances) to site conditions</td>
</tr>
<tr>
<td>Site management</td>
<td>Predicting responses to ripping, mounding, fertilisation and drainage</td>
</tr>
<tr>
<td></td>
<td>Thinning trees with respect to site capacity</td>
</tr>
<tr>
<td></td>
<td>Predicting trafficability at harvest</td>
</tr>
<tr>
<td></td>
<td>Predicting erosion (water and wind) hazards at establishment</td>
</tr>
<tr>
<td></td>
<td>Reducing environmental impact of farm forestry (nutrient and herbicide leaching, predicting fate of run-off waters)</td>
</tr>
<tr>
<td></td>
<td>Providing a stratification framework for timber and carbon inventory</td>
</tr>
<tr>
<td>Integration</td>
<td>Farm planning and integration of trees with farming systems</td>
</tr>
<tr>
<td>Technology transfer</td>
<td>Extension of research results</td>
</tr>
</tbody>
</table>

Farm forestry is being extended in districts where plantation forestry has not been practised in the past and information on tree performance is lacking. Although detailed information on the optimum conditions for individual species is not available in most areas, generalisations can be made about site conditions that are likely to limit the survival and growth of trees. For instance, it may be assumed that extreme site conditions (such as extremely saline soils or very shallow rock) are unsuitable for trees.

1.3 Evaluating sites

Broad principles for land evaluation have been developed for a range of crops (FAO, 1976) and forests (FAO, 1984) In broad terms, land evaluation involves a comparison of the requirements of a particular land use with the resources offered by the land (Dent, 1981). The term ‘land suitability’ is defined as the fitness of a given type of land for a specified kind of land use. The nature of the proposed land use should be clearly stated before undertaking any evaluation. This ensures that the appropriate land properties are measured and mapped.

Maps are often seen as the most important product of site evaluations, but we encourage investigators to document all of procedures they use, the results that they obtain, and the interpretations that they make. Other people (land managers, for example) can then follow the reasoning behind the choices of mapping units and their boundaries.

1.4 Using native vegetation to predict site capacity

Native plants in Australia are adapted to specific site conditions; undisturbed vegetation communities therefore reflect the combined influences of many site factors. The strong relationship that commonly exists between soils and native vegetation has been used by farmers in the past to select land. In many parts of Australia soils are still referred to in terms of their original native vegetation. ‘Indicator’
species that are known to have occurred in the forest vegetation prior to clearing or that exist in remnants on or close to farmland have been used to infer the nature of sites.

This approach has some limitations because:

- the relationships between specific site factors and the vigour or occurrence of native plants is often only poorly understood;
- remnants of native vegetation on farmland may not contain the complete range of species that were originally present, but it is sometimes the full range of species that is required to indicate site suitability (Havel, 1968);
- remnant vegetation may indicate the conditions of the land that it occupies, but the conditions may differ from those of nearby agricultural land—the reason for not clearing the remnant vegetation may have been that it was different to the surrounding vegetation;
- clearing native vegetation and farming change the nature of sites—for instance, watertables may rise and nutrients are invariably added; and
- the condition of the remnant native vegetation may have changed following clearing, due to access to more water and nutrients.

It is therefore considered that better results are likely if site and soil properties are measured directly.

1.5 The intended audience and aims of this report

This report was prepared in 2002. While it has been updated in parts, it is important to note that research of relevance to site selection (e.g., site effects on tree performance, climate change and variability, species selection, growth modelling and regional assessments of land suitability) has been conducted since.

We assume that farm forestry is practised by three groups:

- **Farmers planting trees for commercial purposes**: this group consists of farmers who regard trees as another crop.
- **Farmers and groups planting trees for environmental purposes**: this group will plant trees on farms primarily for land and nature conservation with commercial benefits seen as secondary.
- **Investment-driven forestry companies**: this group, which includes private companies and government agencies, establish large areas of trees on many different properties, sometimes across several regions of Australia.

These three groups plant trees over areas ranging from small woodlots to large block plantings and use a variety of different planting and management practices. The expect returns on investment and their budgets for site evaluation also differ greatly. Depending on the purpose of the farm forestry project, the questions to be answered by the site evaluation will differ. One person may have the task of finding land suited to one particular commercial species, while another may have particular sites in mind and wish to identify species that will grow well there.

The level of investment in site survey should depend on how well the information can be interpreted and in proportion to the expected return from the investment (Figure 1.1). In areas with much past experience and experimentation it may be possible to make reasonably accurate predictions of growth. Similarly, in these areas the relationships between silvicultural practices and growth responses may have been well defined. In other areas where farm forestry has just commenced, or there have not been systematic studies, it may only be possible to make broad estimates based on site properties. In these cases, it can be assumed, for example, that extreme values (e.g. pH, soil depth) are unsuitable for tree growth. In either case, systematic site evaluation is the preferred procedure rather than guesswork or using routine prescriptions developed for other regions.
This report is written for anyone who has the task of evaluating land for farm forestry, whatever the purpose of the planting. It aims to provide a set of procedures for gathering, interpreting and applying site evaluation information in ways that are repeatable and transparent. Procedures are given for regional as well as paddock-scale evaluations.

Figure 1.1: Expenditure on land evaluation for farm forestry may be directly related to the expected return on investment and the potential risk. Source: Stone (1975).

### 1.6 The site concept

The concept of ‘site’ in forestry has been used to integrate the array of environmental factors influencing tree performance (Table 1.2). For the purposes of this report, ‘site’ is defined as the integrated effect of environmental attributes (climate, soil and landforms) that influence the potential growth of a particular tree genotype, and affect the management of that stand of trees to produce a particular product. This concept of site is independent of the presence of trees, and covers a range of scales. The combination of these factors, from climate to soil nutrient regime, constitutes ‘site’.

**Table 1.2: Tree stand growth definitions (Wood, 2001)**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Definition</th>
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<tbody>
<tr>
<td>Stocking (Density)</td>
<td>Number of tree stems per hectare (stems/ha).</td>
</tr>
<tr>
<td>Mean Total Height</td>
<td>Mean height of every stem in the stand (m).</td>
</tr>
<tr>
<td>Predominant Height (Top Height)</td>
<td>In Australia, predominant height (incorrectly called top height in some areas) is defined as the arithmetic mean height of the tallest trees in the stand generally at the rate of 40-75 trees/ha.</td>
</tr>
<tr>
<td>Mean Diameter</td>
<td>The mean diameter of a group or stand of trees can be expressed by either the arithmetic or quadratic mean. The latter is the more useful and more widely applied measure because it is directly related to volume. It is the diameter of the tree, of mean basal area (m), measured at a height of 1.3 m above ground.</td>
</tr>
</tbody>
</table>
Basal Area

The basal area of a stand is the sum of the basal areas of the individual trees converted to a per hectare basis (m²/ha). Tree basal area is measured over-bark at a height of 1.3 m on the stems.

Volume

It is not practical to measure stand volume (m³/ha) directly. Rather, it is estimated in a variety of ways. The method chosen depends on the purpose of measurement, the location, size and value of the stand, stand characteristics, and the time, funds and labour available. Invariably, the estimation procedure involves measurement of some or all of the characteristics of either individual sample trees (e.g. diameter, height, volume, bark thickness, taper) or stands (e.g. number of trees, mean diameter, basal area, mean total or predominant height).

Terms such as ‘site quality’ and ‘site index’ have various qualitative and quantitative definitions. Most rely on measurements of tree growth, at an arbitrary reference age, and such indices are not often associated with any particular environmental factor. Site index, for example, may describe tree height at a particular age – this provides a relative measure of the potential productivity of different sites.

1.7 The structure of this report

This report provides methods for characterising and quantifying the site factors that influence tree performance. It elaborates on the underpinning principles for farm forestry site evaluation described by Ryan et al. (2002). The main factors considered relate to:

- climate;
- soil water regime;
- nutrient regime; and
- site hazards.

This report is based on the concept that site selection methods should be explicit, consistent and repeatable. Although the science of site selection and interpretation is imperfect – with the quality of knowledge varying markedly across the country – we contend that the approach of systematic observations across a site and weighing the resultant evidence is preferable to guess work or ‘gut feeling’. We also recognise that logistical constraints determine the time and money that can be spent on site selection; however, we encourage investment in site selection to ensure successful tree performance. Learning about a site’s capabilities through a failed tree planting is much more costly than systematically examining a site prior to tree planting. Stone (1982) summarised this approach for plantation forestry by stating:

‘If an organisation cannot afford the insurance provided by soil mapping and interpretation it cannot afford the risks of investing in plantation establishment.’

The structure of the report is outlined below, which takes into account the differences in farm forestry development across Australia. Where farm forestry is well developed and suitable species have been identified, potential farm foresters are well-positioned to assess development prospects. In areas where there is little or no farm forestry, a regional evaluation of farm forestry potential is required. Existing survey information varies markedly across the country – soils have been mapped in limited areas at scales (1:10,000-20,000) that mean further investigation may not be required, whereas in most cases existing soil survey information is inadequate for making decisions about a site’s capabilities. This is because the information is at an inappropriate scale, based on observations of attributes not relevant to trees or based on inadequate soil examination (Harper et al., 2000b; Ryan et al., 2002).
The report specifies methods for site selection for farm forestry at three general levels. Users can select their own entry level and proceed:

- **Predominantly desk-top methods for regional assessment.** In this stage, assessment is made of a region’s broad-scale attributes, such as climate (chapter 2), broad landform, drainage patterns, geology and the availability and quality of existing soil-landscape mapping (chapter 3), the species likely to be suitable (chapter 6) and non-site factors such as land use zoning, distance to processing or exporting facilities and existing infrastructure. From this information a decision can be made whether the district is suitable for an industry, or the proposed tree species, and whether either to proceed with further investigations or decide that no further investigation is required.

  The emphasis at this scale is to eliminate obviously unsuitable land (i.e. exclusion rules). Similarly, estimates can be made of total areas of land that are likely to be suitable and their location in relation to necessary infrastructure (i.e. mills, export facilities).

- **Field and office methods for property level assessment.** If the local district is considered suitable for farm forestry the farm property itself can be considered and a range of attributes assessed (chapter 4). These include physical attributes such as topography and drainage, the location of any obvious hazards to tree growing, the layout of paddocks and farm buildings and the distribution of remnant bushland. This process will identify broad areas where tree growing appears promising, where there are environmental problems that may need fixing or where farm forestry may enhance existing agricultural enterprises.

- **Site survey.** This involves a three-stage process.
  
  (a) **Observation:** A detailed assessment of the soils of those areas of the farm identified as promising (chapter 4). This step can include examination of soil pits, sampling for laboratory analysis and the collation of data from other sources. An enlarged aerial photograph forms an ideal base for this activity.

  (b) **Mapping:** From these point observations, maps can be drawn that depict a series of land management units (LMU). These maps are made from various observations and measurements extrapolated across the landscape. These maps can form the basis of farm forestry planning. For each LMU an array of information, such as soil depth, fertility, salinity (current status and future risk), hydrology and geomorphology (slopes) is assembled. Soil samples are taken for soil fertility and yield predictions. Some of these factors (e.g. slope, trafficability) may not be important at establishment, but may be important at harvest.

  (c) **Evaluation and integration.** This involves the interpretation of the site survey information (chapter 5). For each LMU evaluations can be made, such as the factors that are likely to limit growth, potential productivity, drought risk, silvicultural requirements (ripping, mounding, etc), erosion hazards or likely yield (chapter 7). These can be presented as either tables or maps of individual themes. For example, a map may be used to show the distribution of those soils likely to benefit from ripping. The areas of land that require different treatments can be summarised in a table for budget calculations.

This report thus presents a set of procedures to encourage:

- **Matching species to sites:** Effective site selection will ensure that appropriate tree species and provenances are planted on particular sites. Reliably matching tree species and sites is essential to ensure sustainable enterprises are established.

- **Avoidance of unsuitable land:** Successful site selection will identify unsuitable land, where trees will grow poorly or die.
• **Appropriate site management**: Various management decisions (e.g. whether or not to cultivate, application of fertilisers, species selection and stand density) are dependent on soil and site conditions. Management should be tailored to a site’s requirements to increase profitability and maintain the resource base.

• **Characterisation of experimental sites**: With the emergence of site specific silviculture, it is important to know the relationships between site properties and tree performance. Unfortunately, many experimental sites have not been properly characterised.

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**Use of the Australian Soil and Land Survey Field Handbook**

The field survey stage of the site evaluation approach described in this report assumes that investigators use the standard Australian handbook for carrying out soil surveys:


It is available from ACLEP, CSIRO Land and Water, GPO Box 1666, Canberra, ACT 2601.

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**1.8 Boxes**

To highlight and distinguish between different types of information, three types of boxes have been used:

- **Summaries, definitions and general information**
- **Guidelines**
- **Examples and case studies**
2. Climate

T. H. Booth

Chapter outline

Climate has a major influence on the choice of species for a farm forestry project. This chapter describes the important climatic variables that affect tree growth (solar radiation, rainfall, temperature and evaporation) and discusses the impacts that El Niño events and the greenhouse effect could have on farm forestry. In most parts of Australia, rainfall is the most critical climatic factor since it is principally the amount of water available to trees that determines whether or not they will thrive. Simple water balance calculations indicate water availability much better than rainfall data alone, and the principles behind water balances are explained. Climatic data are available in a range of formats from several sources—these are listed at the end of this chapter.

2.1 Introduction

Carbon dioxide and water are the building blocks of plants. Plants obtain carbon dioxide when sunlight is available to drive photosynthesis, while water is mainly sourced from recent rainfall (rain that fell within the last few months at most) in an agricultural setting. Therefore, the vigour of vegetation in a region is closely related to the climate.

In their natural state, particular plant species are only found in certain areas—their natural distribution. One of the reasons for this limited distribution is that species that thrive in a particular area do so because they are well adapted to its climate. They do not grow so well where the climate is less favourable (in most cases, where it is drier or colder). Each species has different optimum conditions and different degrees of tolerance outside of these. This dependence on climate means that the natural distribution of a species is limited on a broad scale (i.e. the species will only grow in certain parts of Australia) and on a landscape scale (i.e. the species will only grow in certain places within a region where climatic factors change from one part of the landscape to another). However, climate is not the only factor controlling a species’ natural distribution—suitable soils, fire frequency, disease and competition from other species are also influential.

While climatic conditions within the natural distribution of a species’ requirements are useful indicators, there are some cases where research and experience have shown that plants can be grown successfully in regions with climatic conditions outside their natural range (Figure 2.1). Conversely, matching climatic conditions to those of the natural distribution does not guarantee successful tree growth. These issues are discussed in more detail in Chapter 6.

Figure 2.1: Maps of Australia showing (a) the natural distribution of *Eucalyptus globulus* subsp. *globulus* (Tasmanian blue gum) and (b) areas climatically suitable for it (Jovanovic and Booth, 2002).
Trees depend on sunlight and rainfall for growth but interactions with other climatic factors, such as temperature and evaporation, influence the rate of growth. The interactions between climatic factors are complicated because some of a site’s climatic factors may promote rapid growth (e.g. lots of sunlight), while others may limit growth (e.g. low rainfall). When planning farm forestry projects, climatic factors are considered at two stages: firstly, when deciding which species are likely to survive and grow in an area, and secondly, when attempting to predict rates of growth and yields. Rainfall and temperature indices (e.g. mean annual rainfall, mean dry season length, mean maximum temperature of the hottest month and mean minimum temperature of the coldest month) are commonly used to identify which species will survive and grow well (see Chapter 6). In addition, because rainfall (in particular) varies substantially from year to year in most Australian agricultural areas, long-term climatic records can be analysed to estimate the chances of unusually long, dry periods occurring. The analyses—which range from simple to complex—aim to calculate the net effects of some or all of the interacting climatic factors at a site. The more complex analyses are used as input to computerised tree growth models (see Chapter 7).

2.2 Solar radiation

The sun radiates energy (called solar radiation) and it is usually measured in megajoules per square metre per day (MJ/m²/d).

Photosynthesis is the process by which trees use light energy to create the carbon compounds (from carbon dioxide and water) used for maintenance and growth. Solar radiation in Australia is usually abundant. Most agricultural areas receive an average of between six and nine hours of bright sunshine a day. Slightly less, about five to six hours, is received in southern coastal areas of Western Australia, southern Victoria and northern Tasmania, but these areas include some highly productive plantation forests, indicating that solar radiation is not a major limitation to growth.

Even though solar radiation is seldom a major limitation to tree growth in Australia, its importance as the ultimate source of energy for plant growth should not be ignored. During early growth, biomass production (i.e. the total mass of the new growth of the tree including roots, stem, branches and leaves) depends on the amount of radiation intercepted by the leaves, as long as other factors, such as nutrients and water, are not in short supply (Figure 2.2). Doubling the intercepted radiation doubles the biomass production. The implication is that a tree that intercepted 100% of the available solar radiation would grow more rapidly than one that intercepted only 75% of the available solar radiation. However, a tree that grows rapidly requires more water and nutrients than one growing more slowly, and may deplete the available resources more quickly. A tree that is under stress because of lack of resources may reduce its total area of leaves, which reduces the amount of intercepted solar radiation and reduces its demand for resources. Computer models that estimate tree growth attempt to replicate the complex balances that occur between radiation interception, water and nutrient availability, and biomass production (see Chapter 7).
Figure 2.2: The relationship between above-ground biomass production and intercepted solar radiation in a fertiliser trial of *Eucalyptus globulus* at three ages. The tree ages represented are 2 years (black symbols); 4 years (green symbols); and 9.5 years (red symbols) (Linder, 1985).

Very few meteorological stations in Australia have long-term records of solar radiation, but satellite data are now used to estimate values. In addition, about 100 stations record the hours of sunshine received every day. These data can be used to estimate solar radiation at any location in Australia. Figure 2.3 and Figure 2.4 show how mean daily solar radiation in summer (January) and winter (July) change across the country.
The solar radiation values in Figure 2.3 and Figure 2.4 represent the amount of solar radiation received on a flat surface. North-facing slopes receive considerably more solar radiation than south-facing slopes. The solar radiation of the sun is important not only for photosynthesis but also for its warming effect. Computer programs are now available which can take information from digital elevation models (which are grids of ground elevation data generated using computers) and calculate the amount of solar radiation a particular site will receive during any month of the year. Some of these programs consider not only the slope and aspect of a particular site, but also whether it is shaded by its surrounding horizon. Information of this sort can be used to prepare environmental information to drive tree growth models.

Local fogs and mists may reduce solar radiation slightly, particularly in some coastal locations, but these effects are not usually a major constraint on tree growth.
2.3 Rainfall

Though solar radiation is the ultimate source of energy for tree growth, rainfall amount is probably the climatic factor most likely to limit Australian farm forestry production. Farmers and foresters tend to talk about the rainfall on a site while meteorologists refer to precipitation, which includes not only rainfall but also snow, hail and sleet.

Water is one of the essential elements of a tree—restricting a tree’s water supply not only restricts the volume of biomass the tree can produce, but also reduces the efficiency with which absorbed solar energy is used to produce biomass. Under severe conditions, the columns of water taking moisture up the stem to the leaves break down. Once an individual column is broken it cannot be restored. As more trees are being established in drier agricultural zones, spacing trials are being carried out to determine the most appropriate planting density.

Rainfall is the climatic factor with the longest measurement records and most measuring stations. The mean or median annual rainfall and the seasonality of rainfall (or rainfall regime, Figure 2.5) are commonly the first factors considered when choosing appropriate species for a farm forestry project (see Chapter 6).

Figure 2.5: Seasonal rainfall (or rainfall regime) zones. Reproduced courtesy of ACIAR from Brown et al. (1997).

High and low pressure systems track west to east across the southern part of Australia. In the middle of winter (July), the average path of high pressure cells crosses the continent from north of Perth to near Brisbane. The centres of the low pressure systems (known as mid-latitude depressions) are usually to the south of the high pressure cells. Most of the rain that falls on southern Australia comes from these winter depressions (Figure 2.6). In summer, the average paths of the weather systems move south and the centres of the high pressure cells follow a track across the Southern Ocean and through the Bass Strait. As the interior of the continent heats up, winds blow on-shore, bringing summer rainfall to the northern and eastern parts of the continent.

In the past, rainfall has been a major factor influencing site selection and the vast majority of commercial plantations were established in areas with mean annual rainfall greater than 700 mm. Now there is increasing interest in establishing trees in drier environments with, for example oil mallees for the 250 mm to 400 mm rainfall zone of Australia. It is even more important to consider climate when establishing trees in such dry zones. Simple mean annual rainfall data are still important, but they become less useful as indicators of site capability as drier sites are evaluated. The amount of moisture...
actually available to the tree can be affected greatly by the evaporation rate. Simple ways to estimate the amounts of water available to trees are described later in this chapter.

As aridity increases, so does the variability of the rainfall. In low rainfall regions it is important to take account of this. Variability can be assessed using several methods (see Box 2-1). The timing of dry years is also important. For example, three below-average years of 500 mm rainfall may be lethal to a particular tree on a particular site, while an isolated year with only 400 mm of rain may not result in tree death.

Tree root systems develop to take advantage of the rain that does fall—generally, trees in drier environments have deeper roots. It has been suggested that in areas where summer rainfall is low compared to the total annual rainfall, plants concentrate on growing deep roots and have few near the surface, whereas in an area with a small amount of reliable summer rain, roots also develop near the surface to use the summer water (Ehleringer and Dawson, 1992). Measurements of the amounts of water used (transpired) by two eucalypt species (*Eucalyptus wandoow* (wandoow or white gum) and *E. salmonophloia* (salmon gum), Figure 2.6) in an area of remnant vegetation in the Western Australian wheatbelt rapidly boosted their consumption following a large summer rainfall event (Farrington et al., 1994). The graphs show that tree water use was closely related to the distribution and amount of rainfall. Winter and spring rainfall during the first year (1989) was low and the transpiration rate rose to a low peak in late spring, and then declined until a large rainfall event in January 1990. After this, transpiration rates rose dramatically and remained high until late autumn. The winter and spring rains in 1990 were sufficient to allow high transpiration rates from late winter to late summer.

![Daily rainfall and daily transpiration graphs](image)

**Figure 2.6:** Daily rainfall (a) and daily transpiration (b) of a *Eucalyptus salmonophloia* (salmon gum) at a natural woodland site in the Western Australian wheatbelt between August 1989 and July 1991 (Farrington et al., 1994).
Box 2-1: Assessing rainfall variability

Assessing rainfall variability

One of the simplest ways to get an impression of the variability of rainfall at a location is to plot a bar chart of annual totals, with a line representing the mean annual rainfall.

Bar chart of the annual rainfalls for thirty years at Boyup Brook in Western Australia when the mean annual rainfall was 686 mm

Simple statistics such as the range (the difference between the largest and smallest values) are useful if they are compared to the site’s mean annual rainfall.

<table>
<thead>
<tr>
<th></th>
<th>1960 to 1989</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean annual rainfall (mm)</td>
</tr>
<tr>
<td>Boyup Brook</td>
<td>673</td>
</tr>
</tbody>
</table>

Sometimes the median rainfall is used to represent the rain at a site, as it is less influenced by a few extreme years than the mean. However, during the period from 1960 to 1989 the means were similar to the medians.

Percentiles (or deciles) are also used as indicators of variability. A set of data can be divided using 100 percentiles or 10 deciles. The tenth percentile (which is equivalent to the first decile) is the value below which 10% of the records in the data set fall. Since the median is the value below which 50% of the records fall, it is a percentile also, and the fifth decile. A map of the 50th percentile (or median) annual rainfall shows that for any selected location, this amount or less was received in half the years during the period of records being considered.
Annual rainfall appears to follow trends that differ from one region to another. In most eastern parts of the continent, amounts of summer rain changed more than those of winter rain during the twentieth century. The summer changes dictated the trends in total annual rainfall (Nicholls and Lavery, 1992). Conversely, in south-western Australia annual rainfall trends were strongly influenced by changes in winter rainfall. In the south of Western Australia, in areas favoured for *E. globulus* (Tasmanian blue gum) plantings, there was a substantial decrease in rainfall after the middle of the twentieth century.

Droughts in Australia appear to be associated with El Niño events. The Southern Oscillation Index (SOI) is a measure of the strength of El Niño events and its trends are often included in weather forecasts, particularly during drought periods. Droughts have caused tree deaths in plantations of *P. radiata* (radiata pine) and *E. globulus*. For example, in south-eastern New South Wales, plantations
suffered losses as a result of a run of months with below average rainfall starting in April 1997 and ending in March 1998. Rainfall at Albury was less than half the average amount from April to July (inclusive), and the total for the 12 months was only 417 mm (the mean annual rainfall was 706 mm). The dry months coincided with a period of negative SOI values that started in March 1997 and continued to April 1998 (inclusive). The greatest number of tree deaths occurred where planting densities were high, where soils were shallow and where pine aphids had also caused tree damage (H. Dunchue, pers. comm.).

Farmers change their cropping strategies depending on the pattern of rainfall in the early part of each season and on long-term forecasts. In most agricultural areas, there is local knowledge of how different rainfall patterns affect the conditions in different parts of the landscape. Some farm forestry projects may be flexible—for example, plantings in a range of landscape locations may be planned. In such situations, it may be practical to decide on the order of planting according to the rainfall conditions over the previous months and the forecast conditions. Similarly, where it is intended to plant several different areas over a number of years, a few months warning of the next season’s likely conditions can be taken into account in choosing that year’s project. Some government agencies and research institutions have produced tools for assessing the probability of specific rainfall amounts falling in the following months based on the rainfall in the preceding months (see Section 2.9). They may be based on comparing the rainfall conditions in the few preceding months to similar periods in the rainfall record, or doing the same with recent SOI conditions.

### 2.4 Temperature

Temperature has an important influence on tree growth. A tree grows and photosynthesises fastest at specific temperatures (Figure 2.7), but these optimum temperatures change according to a tree’s stage of growth. For some locations and species, frost damage may be a problem.

![Figure 2.7: The effect of temperature on the increase in diameter of grafted clones of Pinus radiata (radiata pine) trees during a ten-week period. Grafts were allocated to one of 14 treatments consisting of five different day-time temperatures and night-time temperatures that were 3°C, 6°C or 9°C lower than the day temperature. Each point represents the mean value for 8 replicates. The graph shows that there are optimum combinations of day and night temperatures for growth. For example, for day temperatures of 15°C, the greatest growth was with the warmest night temperature (12°C, 3°C below the day temperature). Conversely, when day temperatures were hotter (30°C), the greatest growth was when the night temperature was coolest (21°C, 9°C below the day temperature) (Booth and Saunders, 1979).](image-url)
Temperature data are available for many locations around Australia. Some useful indicators, such as mean annual temperature, mean maximum temperature of the hottest month and mean minimum temperature of the coldest month, can be calculated from them. Using these helps to identify species suited to the climate of a particular location (see Chapter 6). Mean monthly maximum and minimum temperature data are also required for several tree growth models (see Chapter 7). Figure 2.8 shows the mean daily maximum temperature for January, which is the hottest month in most locations across Australia. Figure 2.9 shows mean daily minimum temperature for July, which is the coldest month in most locations across Australia.

Figure 2.8: Mean daily maximum temperature for January (isotherms in °C).

Figure 2.9: Mean daily minimum temperature for July (isotherms in °C).
The actual site being evaluated may be some distance from the meteorological station where temperature measurements were taken. Differences in elevation are particularly important. The rate of change in temperature on moving upslope is known as the *lapse rate*. The rate varies in different parts of the country and at different times of year, but is commonly a fall of about 0.5°C per 100 m rise in elevation. So, if a potential planting site is 200 m higher than a meteorological station, both the mean monthly maximum and minimum temperature values at the planting site are likely to be about 1°C below those at the meteorological station. However, as lapse rates are variable, it is advisable to obtain estimates from computerised models that interpolate between recording stations and take elevation into account (the *ESOCLIM* program is one such model—see the section on data sources near the end of this chapter).

Frost damage is important as one very cold night may, in the worst case, kill a complete stand of trees. The record minimum temperature recorded at a particular site is one useful indication of likely frost damage. This is sometimes referred to as the absolute minimum temperature. Similarly, the seasonality of frosts is important in relation to a tree’s stage of growth. Some species are more susceptible to frost damage than others and the record minimum temperature provides a simple measure of the capability of a site to grow a particular species. For example, sites where the absolute minimum is below minus 8°C are probably unsuitable for spotted gum (*Corymbia maculata*). Absolute minimum temperatures cannot be mapped usefully at the continental scale. Instead, the duration and timing of the frost period is shown in Figure 2.10 to give a general idea of the severity of frost risk across the continent. However, from 1957 to 2000, the annual number of frost days and the mean duration of the frost season both declined (Collins et al., 2000).

**Figure 2.10:** Duration and timing of frost period. “0-50 days July” means that frost has occurred during the 50-day period centred on July. Reproduced courtesy of ACIAR from Brown et al. (1997); adapted from Fitzpatrick and Nix (1970).

Considerable caution is necessary in interpreting frost data. Frost effects can be highly variable over short distances and are greatly influenced by topography. For instance, frost-prone hollows may experience minimum temperatures several degrees below those of nearby ridges. Temperatures experienced in the previous few days influence the effects of frosts on trees. Frost will be much more damaging if it is preceded by a warm period than by a gradual drop in temperature over several days.
The latter allows the trees to ‘harden’ and they can then withstand much colder temperatures than if temperatures drop suddenly (this is illustrated in Figure 2.11).

![Figure 2.11: Modelled frost hardening for *Eucalyptus pauciflora* (snow gum) for temperatures measured between August 1984 and July 1985 at Toulouse in France. The graphs indicate that hardening starts when minimum daily temperatures gradually decrease to just a few degrees below 0°C. Because of the increasing hardiness, there is initially no frost damage, but two extremely cold days take temperatures below the hardiness threshold, implying that such conditions would have produced frost damage. The model results were supported by tree deaths recorded in the region after those days. Modified from Hong (2001).](image)

### 2.5 Evaporation and vapour pressure deficit

While rainfall adds water to the environment around a tree, evaporation removes it. The rate of evaporation at a site is determined by temperature and atmospheric pressure. When raindrops form, water changes from a gas to a liquid. During evaporation, the reverse happens and water changes from a liquid to a gas (called ‘water vapour’). Water vapour pressure is the pressure that is exerted by water vapour in the atmosphere. The *saturation vapour pressure* (*svp*) is the water vapour pressure when the atmosphere has accepted the maximum amount of water vapour possible at a particular temperature. If the atmosphere is close to saturation, then it does not readily accept more water, so the evaporation rate will be low. If the air is not saturated then the water vapour pressure will be below the *svp*. The difference between the water vapour pressure and the *svp* is the *vapour pressure deficit* (*vpd*)—the greater the *vpd*, the greater the evaporation rate.

The *svp* changes when the temperature changes: the atmosphere cannot hold as much water when it is cold as when it is hot. This means that evaporation rates are lower when it is colder.

Evaporation rates are estimated by measuring the loss of water from an open-topped pan that is regularly refilled with measured amounts of water (the standard is called a *class A pan*, and the measurements are called *pan evaporation*). Estimates of *vpd* can be calculated from relative humidity, which in turn is calculated using measurements made with wet and dry bulb thermometers. Some tree growth models (Chapter 7) require *vpd* data because *vpd* influences evaporation rates, which in turn influence rates of biomass production.

As can be seen by comparing maps of Australia’s median annual rainfall and mean annual evaporation (see figures in Box 2-1 and Figure 2.12), annual evaporation over most of Australia is much greater...
than annual rainfall. Annual rainfall exceeds annual evaporation only in the mountains of south-
eastern Australia and western Tasmania.

Figure 2.12: Mean annual evaporation in millimetres. Modified from (Bureau of Meteorology, 1989).

2.6 Wind

Wind tends to hamper tree growth. Wind can cause physical damage by sand-blasting or burying
seedlings under sand drifts, by causing trees to lean, by breaking parts off trees, or by blowing trees
down. It also increases evaporation rates, which could increase stress on trees on hot days. Following
rainfall, wind removes intercepted water before it can drip or flow down the stem to the ground.
However, trees are useful as windbreaks to protect crops, stock and buildings from similar impacts—
the JVAP book *Trees for Shelter* (Cleugh, 2003) describes the information required to design effective
windbreaks.

Wind is recorded at some meteorological stations, but the strength of wind varies locally because of
the shape of the land. Directions of damaging winds commonly change with the seasons—an area that
is sheltered from hot dry summer winds may be exposed to cold winter winds. Land managers are
usually aware of where and when wind causes problems on their properties.

2.7 Balancing rainfall and evaporation

In addition to rainfall and evaporation, many processes (interception, stem flow, leaf drip, surface
ponding, run-off, run-on, infiltration, percolation, lateral unsaturated subsurface flow, perching,
groundwater recharge and discharge) determine the amount of water that finally becomes available for
a tree to use and the amount of water that a tree transpires. There is a hierarchy of water balance
calculations for estimating the available water—from very simple sums that subtract evaporation from
rainfall to complex computerised models that attempt to account for all of the processes and their
interactions. Two types of calculations are described below. The more complex ones, which form parts
of tree growth models, are described in Chapter 7.
2.7.1 Comparing the magnitudes of rainfall and evaporation

The ratio between precipitation ($P$) and evaporation ($E$) is sometimes used as a simple measure of aridity. Commonly, the year is divided into relatively dry months in which evaporation is more than three times the rainfall (the $P:E$ ratio is less than 1:3 or 0.33) and relatively wet months in which it is less than that (the $P:E$ ratio is more than 1:3). In some of the most agriculturally productive areas of eastern Australia and in a small area in the south-west of Western Australia, the $P$ to $E$ ratio is over 1:3 for more than nine months of the year. In some of the drier areas being considered for farm forestry, $P$ to $E$ ratios are over 1:3 for less than six months of the year.

2.7.2 Accounting for evapotranspiration

When water evaporates from plants, the process is called transpiration. The term evapotranspiration is used to describe all the water that is evaporated from an area and usually consists of transpiration and evaporation from the soil surface. Most of the evaporative loss from tree leaves takes place through stomata. These small openings are also the places through which the carbon dioxide necessary for photosynthesis enters the leaf, and the oxygen produced by photosynthesis exits. Some trees, such as E. grandis (flooded gum), will close their stomata in response to dry air conditions. Interestingly, irrigation experiments have shown that the trees do this even if they are irrigated and their roots have ample water supplies. It is likely that trees have evolved this response to avoid the breakdown of water conductance in the cellular columns that transport water through the tree.

If soil and tree surfaces in Australia evaporated as much water as is lost from an open pan, their supplies of water would soon run out. The amount of water actually removed from soil and plant surfaces is often much less than pan evaporation. Actual evapotranspiration depends on the characteristics of the plant and the soil (in simple terms, how quickly they can transmit water) and the amount of water available. Even when a plant has access to ample water, its transpiration rate is usually less than the pan evaporation rate—this rate is called the potential evaporation rate ($PE$). During rainless periods, plants have access to a finite amount of soil water. If this water is all used, the plants cannot transpire. However, as a soil proceeds from containing ample water towards having no water, it becomes increasingly difficult for plants to draw out what water there is. So, when the soil water store is full, a plant transpires at a rate close to its potential rate. As the soil dries out, the evapotranspiration rate decreases, so the actual evapotranspiration rate ($AET$) is less than the potential rate.

Water balances that include evapotranspiration processes require estimates for both $PET$ and relationships between available soil water and $AET$.

Researchers use a range of techniques to estimate the evapotranspiration from an area and the transpiration from plants. For many plant species, reviewers of experimental data have arrived at simple coefficients that can be applied to pan evaporation data to estimate $PE$ and have derived relationships for calculating the $AET$ value, based on soil water contents. $PE$ is usually in the region of 80% of pan evaporation for a cereal crop in winter in southern Australia, and about 70% of pan evaporation for trees and shrubs, year round. Most computerised water balances include an $AET$ relationship in their calculations. In more complex models, relationships between solar radiation, air temperature, dew point temperature, wind speed and crop properties are used.

Water balance calculations can be carried out using just mean rainfall and pan evaporation data, or using actual annual, monthly, weekly or daily readings. The choice depends on the purpose. Simulations for agricultural crops usually require daily or weekly data, but for land evaluation for farm forestry in areas not prone to drought, calculations based on mean monthly data may be adequate.

Box 2-2 describes the mechanics behind the many computerised versions of simple water balance models. Government agencies, research bodies and individuals have made some of these computerised models generally available (see Section 2.9 on data sources).
Comparing rainfall and evaporation data provides some indication of moisture conditions at a particular site, but a simple water balance can provide a much better estimate of the moisture available to trees. A water balance can be used to calculate the change in the amount of water stored in the soil from, for example, one day to the next or one month to the next. This can then be used to estimate the ratio between the actual and potential evapotranspiration (which is called the \textit{plant water status}). In agricultural areas, water balances are also commonly used to estimate the amount of groundwater recharge that occurs below different types of plants. The following equation is the basis of water balance calculations:

\[ \Delta S = P - (I + ET + RO + L) \]

where

- \( \Delta S \) = the change in the amount of soil water stored in the root zone;
- \( P \) = precipitation;
- \( I \) = the amount of precipitation intercepted by the foliage and evaporated from it;
- \( ET \) = evapotranspiration (both evaporation from the soil surface and tree transpiration);
- \( RO \) = run-off;
- \( L \) = leakage out of the root zone.

Most tree growth models used for farm forestry site evaluation, such as 3-PG or ProMod (see Chapter 7), use a simple, single layer ‘bucket’ water balance calculation. More complex soil water models move water between several soil layers, but single layer models are easier to set up and have been found to produce useful results for site evaluation.

Water is added to the soil water store as a result of rainfall or irrigation. Models usually deduct interception by the tree canopy and surface run-off from the rainfall. For eucalypts, the interception loss is generally about 10% to 15% of rainfall, while for pines it is about 20% to 30% (Myers, B. J., pers. comm.). Commonly, run-off is assumed to occur only when a large amount of rain falls in a day and the process is ignored in some simple balances.

Before the water balance can be performed, the site’s soil textures and the depth intervals over which they occur must be identified so that the \textit{maximum plant-available soil water storage} (maximum PASWS) can be estimated. Obtaining this estimate is an important part of site evaluation (see Chapters 3 and 4).

An initial value of soil water storage is assumed at the beginning of a model run—for example, if the model is being run for somewhere in southern Australia and is to start at the end of winter, then it is assumed that the regolith is ‘full’ and the soil water storage is equal to maximum PASWS. For each time step (usually time steps are days or weeks), the water available as a percentage of maximum PASWS is calculated. If the store is full, it is assumed that excess water is lost as a result of run-off or leakage. \( PE \) is estimated from pan evaporation. The ‘fullness’ of the soil water store is then used to calculate a coefficient (called the \textit{AETCF}), which is multiplied by the \( PE \) value to estimate the \textit{water demand}. If there is enough soil water to meet the water demand, then the \( AET \) is assumed to be equal to the water demand. If the water demand is greater than the available stored soil water, then the actual evapotranspiration is assumed to be equal to the available water. The plant water status is calculated by dividing \( AET \) by \( PE \) (it is expressed as a percentage). The monthly or annual plant water status usually provides a much better indicator of likely tree water stress than a simple consideration of precipitation or the ratio of precipitation to evaporation.

The remaining soil water is calculated by subtracting \( AET \) from the soil water storage. Commonly, any leakage is viewed as potential groundwater recharge.
2.7.3 Using the output

The information gained from water balances has three main uses in site evaluation for farm forestry:

- the changes in the amount of soil water available to the roots can be used to assess the frequency and duration of dry periods, which helps in choosing species suited to a site;
- the ‘leakage’ values indicate whether trees can be expected to reduce or eradicate groundwater recharge below an area (the use of water balances to assess the impacts on salinity of planting trees on farms is discussed in detail in the JVAP book *Trees, Water and Salt* (Stirzaker et al., 2002));
- the results can be included in the input to tree growth models to assess the economics of a site (see Chapter 7).

Box 2-3 shows the results of two simple water balances carried out using the outlined procedures.
We assumed that we were assessing whether to plant a tree species that is found naturally near Dowerin, in the Western Australian wheatbelt, at a site on the Riverine Plain around Merbein (near Mildura) in northern Victoria. The mean annual rainfalls at the two locations are similar (314 mm at Merbein and 320 mm at Dowerin for the period from 1950 to 1979), but the mean evaporation rates are lower at Merbein (about 1858 mm at Merbein, about 2378 mm at Dowerin). Dry periods in northern Victoria tend to be shorter than those experienced around Dowerin. We ran a simple water balance to assess whether the periods when soils were dry at Merbein were also likely to be shorter. The water balances were run for the thirty years between 1950 and 1979 and the results were compared. It was assumed that each site had the same maximum soil water storage (1000 mm). This meant that differences in the results were solely the effects of different rainfall patterns and evaporation rates.

The computer runs using the Dowerin data produced substantially more days with extremely low soil water storage (e.g. less than 10 mm) than those run using the Merbein data (Figure 2.13). However, the results were similar for ‘moderate’ amounts of stored water (e.g. about 50 mm), while in most of the years modelled, the Dowerin runs produced more days with relatively high soil water storages because a large proportion of the rain fell during short periods in winter months.

<table>
<thead>
<tr>
<th></th>
<th>No. of days with 10 mm or less in storage</th>
<th>No. of days with 50 mm or less in storage</th>
<th>No. of days with more than 150 mm in storage</th>
<th>No. of days with more than 200 mm in storage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dowerin</td>
<td>2282</td>
<td>5692</td>
<td>741</td>
<td>140</td>
</tr>
<tr>
<td>Merbein</td>
<td>647</td>
<td>5613</td>
<td>372</td>
<td>9</td>
</tr>
</tbody>
</table>

Not only did the modelling estimate that Dowerin had more days with extremely dry soil than Merbein, but they were clustered into longer stretches. There was low rainfall in 1972 in Dowerin and the model produced 142 days with soil water storage below 10 mm, 105 of them being in two long stretches separated by one day with 11 m in store. In comparison, at Merbein the greatest number of days with less than 10 mm of water stored in the soil in one year was 74 (in 1965). Fourteen of the thirty years modelled at Dowerin had more dry soil days than that. The implication was that trees at Merbein would be less likely to suffer water stress than trees on similar soils at Dowerin. Conversely, the model indicated that a soil profile at Merbein would contain substantially less available water for long periods during most years than a similar one at Dowerin. The impact these differences would have on tree growth could be estimated using models described in Chapter 7.
2.8 Climate change

It is expected that both atmospheric and climatic conditions will change over the next fifty or so years as a result of changes in atmospheric concentrations of some gases, largely due to the burning of fossil fuels. Increasing levels of atmospheric carbon dioxide may assist tree growth, particularly in drier areas, as tree stomata will not have to open as widely to take in the carbon dioxide required for photosynthesis. Water losses through stomata will, therefore, be reduced. The magnitude and persistence of these changes is not clear. The greenhouse effect is also expected to change patterns of temperature and rainfall. The likely effects of climate change in Australia are summarised in CSIRO (2007). Reliable regional or local predictions are not yet available, so possible changes cannot be taken into account during site evaluation.

2.9 Data sources

Most of Australia’s climatic data are collected by the Bureau of Meteorology.

The basic climatic information required for species selection is mean monthly values for maximum temperature, minimum temperature and precipitation, from which the important factors of mean annual rainfall and temperature, rainfall regime and dry season length can be calculated (see Chapter 6). Data on the lowest recorded minimum temperature are also useful to assess frost risk. Information on evaporation (or relative humidity) is required to run simple water balance models, while solar radiation and daily temperature and rainfall data are needed for the more complex simulation models described in Chapter 7.

Generally, the most useful source of climatic information for a site is data from the nearest recording station. Sets of daily recordings can usually be purchased from the Bureau of Meteorology (contact one of their offices), but mean annual and monthly data for many locations are published and are available in print and on the internet (see below). Be aware that many of the daily data sets contain
gaps in the record (measurements at many stations are made by volunteers). The Bureau of Meteorology has a network of ‘official’ meteorological stations, and these record a wider range of variables.

Landholders will often record rainfall and will also have a good idea of variations in major climatic factors across their property.

One of the best sources of published climatic data is *Climatic averages Australia* (Bureau of Meteorology, 1988). This book contains monthly mean values for maximum and minimum temperatures and rainfall for nearly 1000 locations. Similar data for many locations across Australia are now available from the Bureau of Meteorology website. The website also contains lowest minimum temperature data for each month and mean monthly evaporation for some of the major meteorological stations.

CSIRO Plant Industry in association with the Bureau of Meteorology and Horizon Technology (PO Box 598, Roseville, NSW 2069) has produced the *MetAccess* system (Donnelly et al., 1992). This can analyse weather records including rain, evaporation, temperature and radiation. The program will display data either for daily, monthly or yearly averages or actual series of observations. The program allows the likelihood of various events, such as drought or frost risk, to be calculated on the basis of previous measurements. There is a charge for the program and for the data, which are available for climatological districts (which are regions defined by the Bureau of Meteorology). The Western Australian Department of Agriculture has produced a free program called *TACT*, which was designed to aid Western Australian wheat farmers with sowing decisions. However, it is also useful for farm forestry site evaluation because it analyses the likelihood of receiving rainfall within a given time period and the probability of experiencing frost (see <www.agric.wa.gov.au> for information on obtaining the program).

The Queensland Department of Natural Resources and Water generates two types of daily climatic data, called the *Patch Point Dataset (PPD)* and *Data Drill* (Jeffrey et al., 2001). The PPD contains daily rainfall, minimum and maximum temperatures, radiation, evaporation and vapour pressure. The data are from Bureau of Meteorology stations but any gaps in the records have been infilled by modelling. The Data Drill program generates the same climatic variables, but does so for any location in Australia, which makes it useful for evaluating sites that are not close to stations. It does this by interpolating between the Bureau of Meteorology stations. The SILO web site (<http://www.nrw.qld.gov.au/silo/datadrill/index.html>) discusses which data source is best suited to which types of analyses, and gives details of costs and how to order data.

A source of mean monthly data for any Australian location is the *ESOCLIM* program, which is part of the ANUCLIM package developed by the Fenner School for Environment and Society (formerly Centre for Resources and Environmental Studies) at the Australian National University. With appropriate site data for latitude, longitude and elevation the program will provide monthly values for maximum temperature, minimum temperature, precipitation, solar radiation and evaporation.

The PPD, Data Drill and ESOCLIM sources are useful as they provide all the climatic variables required to run computerised growth models. The ESOCLIM package is widely used to provide estimates for thousands of locations as part of broad-scale land evaluation assessments. It does not, however, give an indication of the variability or the range of extreme values of these climatic attributes at any particular site (because of its similar nature, Data Drill also tends to mask any extreme events if they did not affect all of the nearby stations).
3. Soil Water, Nutrients and Site Hazards

P. J. Ryan, M. F. Lewis, N. J. McKenzie, R. J. Harper and R. J. Gilkes

Chapter outline

The land’s characteristics at and around a site can dictate the success or failure of a farm forestry project. This chapter introduces the key conditions (soil water regime, nutrient regime and site hazards) that affect tree growth and management and explains why they are important. A range of land properties determines key conditions (for example, the soil water regime is partly dependent on the depth to bedrock or other impediment to root growth). The chapter focuses on the most influential ones.

3.1 Introduction

Trees depend on the land around and below them for water and nutrients. The land can also present hazards to tree growth (e.g. saline soils). The key land properties that affect tree growth and dictate the practices used to manage them can be grouped into three sets according to their influence on the soil water regime, the nutrient regime and site hazards. As discussed in Chapter 1, site evaluations for farm forestry focus on identifying any properties that could prevent tree survival or limit tree growth.

Substantial changes in conditions can occur over small distances, and the land evaluation should take this into account. A particular place is affected not only by the characteristics of the underlying materials, but also by those of the surrounding area (from a few square metres for some properties up to several hectares for others) because surrounding landforms and land uses can influence microclimate, surface water flows, erosion and deposition.

Regolith and bedrock are the terms used to describe the materials underlying the ground surface. The soil is the upper part of the regolith. Box 3-1 illustrates their differences. The regolith provides trees with support, water storage and nutrition.

Box 3-1: Bedrock, regolith and soil

Bedrock, regolith and soil

Bedrock is solid rock below which there are no unconsolidated materials. It may not have a direct influence on tree growth. However, it affects site characteristics in two important ways:

- bedrock may be the main source of the regolith, in which case its characteristics will influence those of the regolith;
- bedrock type and structure have commonly influenced the formation of the landscape upon which any farm forestry project is sited.

Regolith is all of the mineral material covering the bedrock. It consists of materials formed by the breakdown of the underlying bedrock and materials transported from elsewhere. Therefore, it may consist of just a thin veneer of weathered bedrock, only centimetres thick, or a thick pile of sediments (deposited by wind, water or gravity) hundreds of metres thick. Although regolith is predominantly unconsolidated, processes such as compaction and cementation can result in hardened layers or zones within it.

Usually, the upper part of the regolith has been transformed into soil. According to some definitions, the A and B horizons of a profile make up the soil, and the underlying parts of the regolith are called the subsoil. Other definitions consider everything below the A horizon to be subsoil. In this report, the B horizon is included in the soil, and the parts of the regolith below the B horizon will be called the subsoil.
The characteristics of the complete regolith profile are more important for forestry than for traditional farming. Most agricultural crops and pastures are annual species that have shallow root systems (generally less than 2 m deep) and require ready access to nutrients and water during a growing season of just a few months. Trees are long-lived and pass through several stages that exploit different parts of the regolith. They are normally planted as seedlings, and at that stage their root systems have similar requirements to those of most annual crops. However, the root systems soon expand to exploit a relatively large volume of regolith. Leaf litter builds up below trees and, as it decomposes, adds to the nutrients available to the trees. Finally, as trees age and die the roots decompose and return large amounts of carbon to the regolith, where it plays an important role in increasing biological activity and the processes of weathering and mineral breakdown. Thus, tree root systems can extract nutrients and water from parts of the regolith not accessible to agricultural crops, as well as incorporate both into their biomass. However, trees may die or their growth may be limited if the volume of regolith accessible to roots is inadequate.

Regolith properties commonly vary substantially (both horizontally and vertically) over distances as small as a few centimetres to many metres. Such regolith variability can create management problems and irregular stand growth. In addition, some of the conditions that are hazards to tree growth (e.g. salinity, shallow bedrock, waterlogging) may be present for just a few square metres or cover tens of hectares; comprising a small percentage of or dominating a project area. The impact of a particular property may change with tree species—for instance, there are trees adapted to alkaline conditions, while others are not (see Chapter 6). Therefore, any limitations to tree growth should be gauged according to the species under consideration.

Management techniques can be used to improve some adverse conditions (for example, surface water drainage, deep ripping, fertiliser applications—see Chapter 5) and it may or may not be economical to use them.

Operations associated with farm forestry have the potential to create environmental degradation (such as soil erosion and soil compaction). The risks associated with such hazards should be assessed during the site evaluation so that the operations can be planned to minimise the potential damage.

Chapter 4 describes the procedures used to evaluate sites for farm forestry. The purpose of this chapter is to provide the background information on site properties that is required to carry out those procedures. For each of the three key site conditions (soil water regime, nutrient regime, site hazard), this chapter:

- describes how the condition affects tree growth and the management of trees;
- describes the main site factors which influence the conditions; and
- describes ways of quantifying the conditions.

### 3.2 Soil water regime

Box 3-2 explains the difference between the terms *soil water* and *groundwater*, which are sometimes confused.
Box 3-2: Soil water and groundwater

**Soil water and groundwater**

The term *soil water* is used to describe the water that is in the regolith above the watertable, whether it is within the actual soil layers or the subsoil zone.

The watertable marks the boundary between the soil water and groundwater zones. Groundwater exists below the watertable—all voids are filled with water and conditions are said to be *saturated*. Commonly, the degree of saturation increases downwards from the ground surface to the watertable. Along with this increase in the degree of saturation, there is an increase in the pressure exerted by the water. The position of the watertable is defined as the level at which the water pressure is equal to the atmospheric pressure. If a hole was dug down to it, water would flow into the hole at that level.

However, the watertable does not coincide with the level at which the material changes from being unsaturated to saturated. That level is above the watertable, and the distance between it and the watertable depends on the characteristics of the regolith. This saturated zone of soil water is called the *capillary fringe* or the *capillary zone*. The water pressure in the capillary fringe is less than the pressure of the atmosphere, and so water will not flow into a hole. The water in the capillary fringe is held where it is by forces of surface tension.

Describing the properties that dictate a site’s soil water regime helps us to address questions such as:

- How much water can be stored in the regolith around the roots of the planned trees and under what conditions is it accessible to the trees?
- Will trees be able to make use of groundwater (either directly or by drawing on soil water supplied by capillary rise from the groundwater)?
- How much of the rain that falls on a site infiltrates there?
- Does all the water that infiltrates at the soil surface come from rain that falls at the site, or are there additions from surface flows?
- How does the soil water regime change with landscape location? Is there ever too much water for trees?
- How will all of these factors change after trees are established?
- If trees can access groundwater either directly or from the capillary zone, is it usable (is it too saline, too acidic)?

At some sites, the crucial question is the first—how much water can the regolith store in the places accessible to tree roots? The amount of water is called the *maximum plant-available soil water storage* (which is shortened here to ‘*maximum PASWS*’); in most cases it depends on two factors: the regolith depth and the type of regolith material. Groundwater is not usually included in estimates of maximum *PASWS*.

In regions with low rainfall, the maximum *PASWS* may be large compared to the amount of water available from rainfall. However, in higher rainfall areas the maximum *PASWS* may be too small to store all the available rainfall, and this could limit the potential for tree growth. This introduces a problem with site evaluations for farm forestry. How small is too small? A few investigations have aimed to determine the relationships between maximum *PASWS* and tree performance, but these have resulted in broad generalisations. For example, Harper et al. (1998) considered that *Eucalyptus globulus* (Tasmanian blue gum) in south-western Western Australia required an unimpeded rooting depth of greater than 2 m. Therefore, the effort expended in determining the maximum *PASWS* at sites being investigated should be related to the accuracy and precision of the knowledge about the
limitations of the species under consideration. Where no information on a tree’s maximum PASWS requirements are available, one option is to make simple assessments of the maximum PASWS values at the sites being investigated, and use a ranking system to differentiate between the ‘best’ and ‘poorest’ of the sites assessed. Lacking more information, this approach provides a framework to aid evaluation.

The following sections firstly examine factors affecting the maximum PASWS (regolith depth or volume and regolith materials), giving an example of a simple, generalised method of calculation. This is followed by discussion on issues of water availability (including groundwater, waterlogging and surface water factors).

3.2.1 Regolith depth and volume

Drought deaths are periodically reported in areas with shallow regolith—examples have been recorded in *Pinus radiata* (radiata pine) and *E. globulus* plantations in south-western Western Australia (Harper et al., in review; McGrath et al., 1991) and south-eastern New South Wales (Dunchue, H. pers. comm.). Estimating the regolith volume that can be reached by tree roots is complicated in places where it contains boulders, gravels, hardpans or cemented zones (see Box 3-3). Such constituents may have relatively few pore spaces or cracks, so roots are less able to explore them than the surrounding regolith materials. In places with these features, it may be useful to estimate the effective regolith volume (see Box 3-4). Other complications affecting the estimation of regolith volume include:

- factors that could impede root growth are not always obvious (e.g. zones with extreme pH, intermittently waterlogged zones); and
- pits and holes dug to assess the regolith may be shallow compared to the regolith’s depth and such excavations only sample a small area of the site under investigation.

**Box 3-3: Cemented zones and hardpans**

Cemented zones and hardpans

Silica, calcite, iron minerals and accumulations of organic material form the most common types of cement in the regolith, and where they form hard layers, the layers are called hardpans or duricrusts.

Iron-cemented duricrusts are called ferricretes, silica-cemented duricrusts are called silcretes, and calcite-cemented duricrusts are called calcretes (Goudie and Pye, 1983).

The term laterite is sometimes applied to the ferricretes, which are common in the Western Australian agricultural regions and in the south-west of Victoria, but the word was coined for a different, softer regolith material found in India. For clarity, this report will call the material ferricrete.

The term hardpan is also used to refer to hard layers that develop below agricultural land as the unintentional result of compaction from the weight of farm machinery rather than by cementation. Hardpans of all types can prevent roots growing downwards, but they can be ripped if they are shallow (the deepest ripping used for trees is about 1.3 m). Suitable machinery is available and cost-effective.
Box 3-4: Effective regolith volume

**Effective regolith volume**

The *effective regolith volume* can be defined as the below-ground volume that trees can exploit to obtain water and nutrients. Where below-ground conditions are uniform, such as where impenetrable bedrock exists at a constant depth below a consistently porous regolith, then the effective regolith volume below a specified area of land can simply be calculated by multiplying the area of land by the regolith depth. However, where below-ground conditions are not uniform, such as where cemented layers are patchily developed or the bedrock surface is uneven, then the effective regolith volume below a certain area of land will change from place to place.

### 3.2.2 Regolith materials and water storage

The type of regolith materials matter because some have more or larger pores or other types of spaces that can hold more water. Pore size is generally related to grain size and grain shape, and some materials are more likely to host larger voids than others.

There are many grain-size classification systems but most use the term *clay* to describe the smallest, or finest, grains, and *silt*, *sand*, and *gravel* for increasingly larger particles. The classification systems differ because they were designed by different people to best suit the conditions under which they were working. One commonly used in Australia, and recommended in the *Australian Soil and Land Survey Field Handbook* (McDonald et al., 1990) is shown in Figure 3.1.

**Figure 3.1: The grain size classification system recommended in the *Australian Soil and Land Survey Field Handbook* (McDonald et al., 1990)**

Grain shape is influenced by its composition. Quartz grains tend to be more or less spherical, while clay minerals are commonly platelets. Therefore, the pores that exist in a clay-rich material have different characteristics to those in quartz-rich sand.

**Clay-sized grains and clay minerals**

The word *clay* is used in two ways. It denotes a particular range of small grain sizes and it is the name of a group of minerals that form minute platy crystals. Clay minerals are common constituents of regolith profiles. Being very small, clay mineral grains are commonly clay-sized. The meaning of the term is usually clear from the context in which it is used.

A typical volume of clay consists of between 40% and 70% pore space, whereas a volume of sand has pore space between about 25% and 50% (Freeze and Cherry, 1979).

The grain sizes and types, and the ways in which they are packed together, affect tree root penetration. *Soil structure* is the term used to describe the way the different sand, silt and clay particles are joined together into structural units called *peds*. Some clay-rich regolith materials have no discernible peds and are said to be *massive*. Others have many, well-defined peds and are said to be *strongly structured*. In strongly-structured clays, roots readily penetrate between the peds. In weakly-structured or massive
clays, penetration may be impeded. The grains of sandy soils are commonly loosely held together and do not form peds. Roots can usually penetrate them unless they have been hardened by compaction or cementation.

3.2.3 Water flow through the regolith

The types and sizes of grains influence the volume of water that can be stored in the voids in a regolith profile. They also affect how much and how quickly water can move through the regolith (the terms used to describe the different stages of water moving down through the regolith are explained in Box 3-5). Some of the pore spaces in a regolith material are ‘inactive’: they may fill with water moving from above but have no outlet at the base for that water to continue to move. Some pore spaces are not connected to others at all, and so play no part in water flow. Regolith dominated by awkwardly stacked plates (such as clay particles) is likely to have more inactive pores than regolith consisting of rounded spherical grains (such as sands).

Box 3-5: Infiltration, percolation and recharge

Infiltration, percolation and recharge

When water enters the regolith at the ground surface it is said to infiltrate. As it passes down to the watertable, it is said to percolate. As it enters the groundwater system at the watertable, it becomes recharge.

The term infiltration is commonly considered to include water passing from the ground surface as far down as the base of the root zone. Below this, water percolates. The amount of water percolating is sometimes called ‘leakage’ or ‘deep drainage’.

3.2.4 Estimating maximum PASWS

Water may be retained on the surfaces of grains by surface tension. The smaller the pore sizes and the greater the total surface area of grains in a given volume of material, the greater the amount retained by tension (or suction). This has an important effect on plants. As regolith dries it becomes harder for the roots to draw the remaining water away from the grains. There is a limit to how much suction a plant can exert. In most cases it is less than the suction holding the last remnants of water to the mineral grains. Because a volume of clay grains usually holds more water by suction than the same volume of sand grains, there is more water left in a clay than a sand when a tree can no longer draw water.

Measuring soil water characteristics requires specialised techniques. Therefore, measurements have only been carried out in limited areas, usually as part of research projects. When values are required for sites where measurements have not been made, it is common to estimate them using published data that relate the grain-size of the material to the soil water property. The simple calculations used to estimate the maximum PASWS are illustrated in Box 3-6.
Box 3-6: Estimating maximum PASWS

Estimating maximum PASWS

The gravimetric water content of a soil or regolith sample can be measured by weighing the wet sample, then drying it (it is standard practice to place it in an oven at 105°C for 24 hours), then weighing the dried sample. The weight of water that has been lost can be calculated. Dividing it by the dry weight of the sample gives the gravimetric water content. This can be converted to a volumetric water content by multiplying by the bulk density of the dry soil (bulk density is explained in Box 3-9).

How much water can a regolith profile of known depth store, and how much of this can a tree access? Imagine a soil sample in a container is saturated, and then water is allowed to drain from its base. Not all of the water drains away. The water content of the soil after it has drained this far is called the soil’s upper storage limit. Trees draw water from soil by suction, but the amount of suction they can exert is limited. The drier the regolith, the greater the suction required to withdraw the remaining water. At some point, the tree can draw no more. The regolith’s water content at this point is called the lower storage limit.

These simple concepts of water storage in a regolith profile allow the amount of ‘tree-available’ water that can be stored in a profile (maximum PASWS) to be estimated. The calculation is done by subtracting the lower storage limit from the upper one for each layer of the profile, converting the answer to an equivalent volume of water, and adding the results up for the whole profile. To do this, the upper and lower limits for each of the regolith layers have to be measured or estimated. For general purposes, it is usual to rely on estimates based on tables of published figures that give the water content limits for a range of soil textures.

The following table illustrates the process of estimating the maximum PASWS of a hypothetical regolith profile.

<table>
<thead>
<tr>
<th>Regolith texture</th>
<th>Depth interval (m)</th>
<th>Layer thickness (m)</th>
<th>Effective layer thickness (m)</th>
<th>Volumetric lower storage limit (%)&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Volumetric upper storage limit (%)&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Estimated maximum PASWS of layer (mm)&lt;sup&gt;b&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sandy loam</td>
<td>0.0-0.3</td>
<td>0.3</td>
<td>0.3</td>
<td>10</td>
<td>20</td>
<td>30</td>
</tr>
<tr>
<td>Loam</td>
<td>0.3-0.6</td>
<td>0.3</td>
<td>0.3</td>
<td>15</td>
<td>30</td>
<td>45</td>
</tr>
<tr>
<td>Clay loam</td>
<td>0.6-1.0</td>
<td>0.4</td>
<td>0.4</td>
<td>25</td>
<td>40</td>
<td>60</td>
</tr>
<tr>
<td>Clay</td>
<td>1.0-2.0</td>
<td>1.0</td>
<td>1.0</td>
<td>30</td>
<td>40</td>
<td>100</td>
</tr>
<tr>
<td>Sandy clay with 20% low-porosity rock fragments</td>
<td>2.0-5.0</td>
<td>3.0</td>
<td>2.4</td>
<td>15</td>
<td>25</td>
<td>240</td>
</tr>
</tbody>
</table>

Total estimated maximum PASWS: 475

<sup>a</sup>: Estimated from graph above

<sup>b</sup>: In this example, maximum PASWS is expressed in millimetres so that it is easy to compare it to rainfall. Maximum PASWS was calculated by converting column A to millimetres by multiplying by 1000, then multiplying the result by the difference between the upper and lower storage limits (column C minus column B, divided by 100 to convert from per cent to a fraction): maximum PASWS = (column A x 1000) x ((column C – column B)/100).
3.2.5 Preferred path flow

The above sub-section presented a simplified description of regolith. There are many processes operating under field conditions that alter the way water moves through regolith profiles. When features of the regolith cause more water to flow along some routes than others, it is termed *preferred path flow*. The preferential flow may be initiated by irregularities both at the soil surface and below ground.

Examples of surface irregularities that affect the distribution of water entering the soil include:

- plants (from small plants, like clover, to trees), which concentrate intercepted rainfall by leaf drip and stem flow;
- areas of surface ponding (from tiny pools to lakes), which provide relatively large sources of water for infiltration, compared to areas with no ponding;
- patches of non-wetting soils, which inhibit infiltration and soil water flow;
- areas sheltered from rainfall (below parts of plant canopies not affected by leaf drip or stem flow; below pieces of gravel, cobbles, stones, boulders);
- compacted surface soils (such as, below wheel ruts), which inhibit infiltration; and
- rip lines and cultivation lines, which encourage infiltration.

Similarly, irregularities within the regolith can influence the flow paths of water, including:

- roots;
- non-uniform initial soil water distribution;
- patches of non-wetting soils;
- irregular arrangement of grains;
- zones with different combinations of grain-sizes;
- non-uniform degrees of cementation; and
- irregular distributions of large voids (called macropores), such as burrows, cracks and rip lines.

3.2.6 Uneven root distribution

The simple calculations used to estimate maximum $P_AWS$ in Box 3-6 carried the implication that roots have uniform access to all parts of the soil water store. However, tree roots are not uniformly distributed throughout regolith profiles. There is evidence that several Australian woody perennial species, including eucalypts, develop mats of fine roots near the ground surface and tap roots or sets of sinker roots, which reach greater depths. This implies that even if both the regolith materials and the water distribution within them were uniform, trees would have easier access to some parts of the profile than others. Knight (1999) summarised the available information on how roots are distributed throughout the regolith and on their water-uptake patterns.

3.2.7 Dealing with variability

Recognising that regolith, root and soil water systems vary over short distances is important because the recognition is likely to lead to:

- sampling strategies suited to the land’s characteristics;
- interpretations of site data that are more realistic than interpretations based on over-simplistic models of uniform profiles; and
- an understanding of the limitations inherent in the simple models used to calculate tree growth.
Heterogenous regolith materials, soil water distribution and root distribution mean that representative quantifications of maximum \(PASWS\) are difficult to obtain. Fortunately, precise quantifications are rarely warranted for farm forestry projects because, as mentioned earlier, the precise requirements of the trees being considered are usually unknown. And in places where the maximum \(PASWS\) is large compared to the annual rainfall (which is commonly the case in low rainfall regions), determining the water storage properties of the materials making up the regolith will be less crucial than in areas where the maximum \(PASWS\) is low relative to the available rainfall and could limit tree growth.

3.2.8 Soil water, groundwater, waterlogging and surface water

In a simple view of a farm forestry situation, the only source of soil water is rainfall that enters the soil and remains in the unsaturated zone within reach of the tree roots until it is used. The volume of water available for trees will be less if water flows away from the site as surface run-off before it infiltrates. Conversely, if the rainfall at a site is supplemented by surface run-on or groundwater, tree growth can benefit. Although it is thought that roots of some trees do not function well in saturated regolith, capillary rise can draw water upwards from the watertable to replenish the soil water store above as the trees dry the profile. Issues associated with groundwater and surface water are discussed below.

3.2.8.1 Groundwater and waterlogging

Under some circumstances, problems caused by groundwater may worsen even after trees are planted at a site. Groundwater levels are rising in many agricultural areas of Australia, and they could continue to rise after trees are established on a site if the source of the water recharging the groundwater system is elsewhere. Since saturated conditions may be a barrier to the roots of many tree species, the effective regolith depth decreases with a rising watertable. If tree roots access soil water drawn from a saline groundwater system by capillary rise, then the salinity of the soil water around the roots could increase with time. This is because trees use the water but leave the salts behind, which increases the concentration of salts in the soil water. Once the soil water becomes too saline, trees can no longer extract the water, and suffer drought symptoms. The interactions between trees, soil water, groundwater and salt are explained in Chapter 7 of the JVAP book *Trees, Water and Salt* (Stirzaker et al., 2002).

When saturated conditions occur in the regolith near the ground surface, it may be referred to as waterlogging. Although waterlogging can take several forms, two are common in Australian agricultural areas:

- waterlogging caused by a shallow permanent groundwater system, and
- waterlogging caused by a temporary perched groundwater system.

Waterlogging resulting from either cause is likely to limit the depth of regolith that roots can explore. Temporary perched watertables may exist for only a few days or weeks, but the conditions can encourage extensive shallow root systems to develop at the expense of deeper ones. This means that the trees may not have enough deeper roots to support them when the saturated conditions end. However, there are tree species that are not adversely affected by temporary waterlogging which grow poorly where there are permanent shallow watertables.

Groundwater levels can be measured using piezometers, and in some cases, wells and bores (Box 3-7).
Piezometers, wells and bores

The terms well, bore and piezometer are sometimes used interchangeably although they have distinct meanings. Wells are usually installed just below the watertable. Where deeper holes are required, drilling equipment is used to produce bores—these can intercept multiple water-yielding layers (or aquifers). Casing is pipe that is installed into wells and bores to prevent the holes caving in. When wells and bores are installed for water supply purposes, the aim is to collect as much water as possible, so most of the casing below the watertable is slotted to allow water to enter the hole. This means that water from different depths is mixed. Therefore, the value of any data collected from wells and, in particular, bores, such as groundwater levels or groundwater chemistry, may be limited.

A piezometer (the word means ‘pressure meter’) is intended to provide information from a particular depth. Piezometers are constructed by drilling a hole to the required depth and placing casing (usually PVC pipe of 40 or 50 mm diameter, which is narrow compared to that used in water supply bores and wells) in the hole, which is slotted over only a short interval – usually between 1 and 3 m. To make sure that only groundwater from the intended depth enters the casing, a gravel or sand ‘pack’ is poured into the annulus around the slotted section, and then a seal is placed on top of the pack. Bentonite clay is commonly used as a seal. It can be bought as pellets, which are easy to pour around the annulus. When it is wetted, bentonite swells and becomes relatively impermeable. In a deep piezometer the annulus above the seal is back-filled with drill spoil to near the ground surface, and then a cement collar is poured to prevent surface water leaking down the outside.

The level to which the water in a piezometer rises reflects the pressure of the groundwater at the inlet depth. The groundwater level is only that of the watertable if the piezometer inlet is at the watertable depth.

Observation wells are sometimes installed to measure watertable levels, rather than piezometers. As their name implies, observation wells are constructed like wells in that they do not have a seal placed in the annulus above the level of the slots, although small-diameter PVC pipe is used as casing. Therefore, they may appear similar to piezometers from the surface, but data collected from them should be interpreted differently.

Soil colour can indicate the state of soil drainage, particularly the hazard of waterlogging. A series of soils which are progressively less well-drained follow the sequence from red to yellow to grey. Waterlogged areas often have grey or greenish soils at depth and very dark surface layers which have formed as a result of the accumulation of organic material. Mottling may indicate a fluctuating watertable. The strength of any relationship between colour and waterlogging or watertable fluctuation will depend on the nature of the regolith material and the amount of organic matter. Many Australian soils are very old, and have been subjected to quite different hydrological regimes in the past, and their colour may reflect this past history.

3.2.8.2 Surface water

If water temporarily covers the ground surface, it may or may not indicate a problem for tree growth. Surface water may result from:

- rainfall which accumulated where it fell or which flowed to the site after hitting the land surface elsewhere (run-on); or
- groundwater discharge.
Short-term shallow inundation by good quality water resulting from rainfall ponding or run-on may not be damaging to trees, and could provide a bonus source of water for growth. Rainfall accumulates on the ground surface when there is either too much to infiltrate into the soil in a given amount of time (e.g. when particularly heavy rain occurs) or when the soil at the ground surface is already saturated. Depending on the landform and land surface conditions, the surface water may flow away from the site (becoming run-off) and be lost to the regolith on which it fell. Conversely, a site downslope of one that generates run-off may have soil and landform conditions that encourage the run-on to infiltrate the soil and add to the soil water store. This would be a benefit at sites where water is in short supply, but could be a problem if it exacerbates waterlogging.

If the surface water is from groundwater discharge, it could be an instance of where the watertable has risen above ground level or it could have emerged via preferred paths from a deep system under pressure. Under these circumstances, the surface water may indicate a problem for tree growth. Groundwater discharge is commonly saline in Australia, and the wet conditions are likely to be more permanent than those caused by ponded rainfall. Even in situations where the surface water is known to have resulted from rainfall ponding, it may indicate a shallow watertable. This is because regolith above shallow watertables needs little rain to become saturated, so further rain results in ponding on the surface.

Identifying the source, permanence and quality of any surface water or groundwater and the trend of groundwater pressures below a site provide valuable information for a farm forestry project. These issues are the focus of the JVAP book *Trees, Water and Salt* (Stirzaker et al., 2002).

### 3.3 Nutrient regime

The chemical properties of the regolith are important for tree growth because they dictate the nutrient regime and may also present hazards such as salinity, acidity, alkalinity and sodicity.

Although trees have access to much greater volumes of soil than shallow-rooted annual agricultural plants, the top few centimetres of the soil are the source of most of their nutrients. This is because organic matter is concentrated near the ground surface and acts as a reservoir of nutrients.

The nutrient regime changes with time because it is influenced by temperature, soil moisture, biological activity, land use and management practices. For example, nutrients are inaccessible to plants if the soil is dry. This means that even if there are adequate nutrients stored at shallow depths, seasonal drying of the shallow soil can limit the access that trees have to them (Dell, B., pers. comm.).

Computer models have been developed which estimate the changes in nutrient availability or mineralisation rates with changing conditions, but most of these have focused on processes affecting shallow-rooted annual plants rather than on those affecting deep-rooted perennials such as trees.

Deficiencies in minerals result in a variety of unhealthy symptoms in trees (Dell, 1996; Dell et al., 2001). The elements which Dell (1996) associated with deficiency symptoms in eucalypts are:

<table>
<thead>
<tr>
<th>Macronutrients</th>
<th>Calcium (Ca)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnesium (Mg)</td>
<td></td>
</tr>
<tr>
<td>Nitrogen (N)</td>
<td></td>
</tr>
<tr>
<td>Phosphorus (P)</td>
<td></td>
</tr>
<tr>
<td>Potassium (K)</td>
<td></td>
</tr>
<tr>
<td>Sulphur (S)</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Micronutrients</th>
<th>Boron (B)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Copper (Cu)</td>
<td></td>
</tr>
<tr>
<td>Iron (Fe)</td>
<td></td>
</tr>
<tr>
<td>Manganese (Mn)</td>
<td></td>
</tr>
<tr>
<td>Molybdenum (Mo) – if N is applied as nitrate</td>
<td></td>
</tr>
<tr>
<td>Zinc (Zn)</td>
<td></td>
</tr>
</tbody>
</table>
However, different plants have different nutritional requirements, and some species can survive, or even grow relatively well, on nutritionally-poor locations. For instance, *E. occidentalis* (swamp yate) is better adapted to sodic and saline soils than *E. grandis* (flooded gum).

Mycorrhizal associations between fungi and tree roots are known to increase plant growth rates by increasing the supply of nutrients to the trees (Brundrett et al., 1996). Many types of fungi have been found in mycorrhizal relationships with tree roots in Australia, but individual taxa are adapted to specific soil and environmental conditions and tree hosts. Some farmland may contain fungi which can form associations with trees, or be close enough to remnant vegetation or other tree plantings to be colonised by beneficial fungi existing in them (Lu et al., 1998). In addition, tree nurseries may inoculate seedlings with suitable fungi.

In most agricultural areas of Australia, chemical fertilisers have been used to make the land suitable for the required crop and pasture species and to boost their yields. Some of the added fertilisers are retained in the soil for many years, and residues will be available to trees planted on the land. In some cases this is considered to be beneficial, but high nutrient loads can also cause growth problems. For example, B. Dell (pers. comm.) has noted that eucalypts with high concentrations of N in their leaves may have imbalances of other nutrients, resulting in deficiency symptoms—for example, weeping branches associated with low levels of copper in leaves.

Soil acidity, alkalinity and sodicity affect plant growth because they decrease or increase the availability of elements, leading to deficiencies or toxicities. Similarly, salinity can lead to toxicity, but it also causes damage by inhibiting the ability of roots to obtain water from the regolith. It does this because saline solutions have high osmotic potential, which means plants require greater suction to take in the water. The processes involved are described in Chapter 7 of the JVAP book *Trees, Water and Salt* (Stirzaker et al., 2002). Different tree species, and different provenances of species, are known to vary in their tolerances to high and low levels of elements. However, in many cases only limited specific data are available. Although most tree species are considered to have a broad tolerance of pH variation, a soil layer with an extreme pH value may act as a barrier to roots.

Published soil and landscape surveys usually note limiting chemical soil factors that have been identified in a region, but the scale of the mapping is mostly too broad to provide information on specific sites. Therefore, information has to be obtained during field surveys.

### 3.3.1 Indicators of nutrient conditions

Currently, the value of using nutrient soil tests to assess the suitability of a site for trees is limited. Although there is a general understanding of the range of nutrients that are important for plant growth, there is little information available on the specific requirements of different tree species under different conditions. The problem is recognised and research has begun into some of the questions, but for most situations neither the concentrations required for optimum growth nor the maximum and minimum concentrations that limit growth are known. Therefore, even though the nutrient regime can be manipulated by adding fertilisers, the relevant prescriptions for specific site conditions have not been developed.

An alternative to testing for nutrients in soil samples is to wait until trees are growing and then analyse their leaves (*foliar analysis*) if they show signs of deficiencies. It is good practice to test leaves even if no deficiency symptoms are present because tree growth may be affected before symptoms develop. Symptoms vary with the nutrient that is lacking, the tree species and the tree age, and for some tree species (the common plantation eucalypts, for example) visual leaf keys have been developed to identify the deficient nutrients in the field (Dell et al., 2001). Laboratory plant analyses depend on knowing the limiting values of the various nutrients for leaves of specific ages for the relevant species.

In addition to laboratory analyses, there are qualitative indicators of chemical conditions that are relatively easy to identify or measure (). However, values of indicators change with time and those that were obtained during a site evaluation may not represent the conditions at the time of tree planting or during tree growth.
Table 3.1: Qualitative indicators of soil nutrient regime

<table>
<thead>
<tr>
<th>Indicator</th>
<th>Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Bedrock type</strong></td>
<td>The minerals present in the rock that was the source of the regolith (whether transported or residual) dictate the chemical character of the regolith, especially if they are not highly weathered. A quartz-rich source rock is likely to produce a quartz-rich regolith; an iron-rich source rock is likely to produce an iron-rich regolith. However, the processes of weathering are complex and variable, and although some generalisations may hold in some situations (e.g. soils recently formed from basalt are likely to have more phosphorous and calcium than soils recently formed from sandstone), they should only be extrapolated with caution.</td>
</tr>
<tr>
<td><strong>Prior land use</strong></td>
<td>Different prior agricultural land uses leave different nutrient legacies. Legume pastures or crops increase nitrogen levels and superphosphate and nitrogen fertilisers are applied to most crops and pastures. However, farmers tailor their application rates according to the soil properties, the crop or pasture requirements, and the expected yield improvements, so fertiliser history may vary markedly over short distances. In addition, nutrients may have been leached or eroded more readily from some areas than others and subsequent accumulation and deposition are likely to be uneven.</td>
</tr>
<tr>
<td><strong>Effective regolith volume</strong></td>
<td>Effective regolith volume dictates the overall volume that tree roots can exploit to access both water and nutrients.</td>
</tr>
<tr>
<td><strong>Regolith effervescence</strong></td>
<td>Calcium carbonate effervesces if diluted hydrochloric acid (usually 1 molar) is applied. Therefore, the acid is used to test for the carbonate in the field by adding two or three drops to samples of regolith materials. Certain tree species do not grow well in calcareous soils.</td>
</tr>
<tr>
<td><strong>Regolith colour</strong></td>
<td>Colour reflects the mineral and organic components of the regolith. In surface soils, black indicates the presence of organic material and, indirectly, relatively high nutrient contents. Note that the carbon to nitrogen ratio varies depending upon the nature of the organic matter. Some earthy forms of iron oxides (haematite and goethite in particular) are common in soils and have colours in the red, yellow and brown ranges. Some iron-rich rocks also contain phosphorous and calcium, so soils with the iron oxide colours may also contain these nutrients. However, iron oxides adsorb phosphorous, so it may be unavailable to plants (the iron oxides can also reduce the effectiveness of applied phosphorus fertilisers). Pale grey colours above a clay-rich B horizon can indicate strong leaching and removal of nutrients. Anaerobic conditions (which are produced by waterlogging) may result in gleyed colours (commonly greys and greens). Anaerobic conditions can limit root access to oxygen and produce high concentrations of soluble metals (manganese and iron).</td>
</tr>
<tr>
<td><strong>Regolith texture</strong></td>
<td>The more clay, the greater the regolith’s ability to retain and provide cations to roots.</td>
</tr>
<tr>
<td><strong>Regolith structure</strong></td>
<td>Well-structured regolith has regularly spaced cracks that allow roots to penetrate clay-rich materials and access nutrients (and water) held by the clay. Clay-rich materials with massive or weak structure, or with widely spaced cracks, will limit root penetration and growth. Root access will be relatively easy where cracks are less than 50 mm apart.</td>
</tr>
<tr>
<td><strong>Regolith drainage</strong></td>
<td>Poorly drained regolith can limit root growth and nutrient access in both fertile and non-fertile soils.</td>
</tr>
<tr>
<td><strong>Biological activity</strong></td>
<td>Biological activity in the regolith is often a function of available nutrients. Earthworm casts are more prevalent in soils with high organic matter and thus higher fertility. Ant and termite activity is less indicative.</td>
</tr>
</tbody>
</table>
3.4 Site hazards

For farm forestry projects, two types of site hazards should be evaluated:

- pre-existing hazards which could decrease tree growth or hamper forestry operations; and
- degradation hazards which could be caused or increased by the establishment of a farm forestry project.

Pre-existing hazards may be natural or induced by previous management. The former type may include inundation (flooding, and in situ ponding), waterlogging, shallow or exposed bedrock or hardpans, water repellence, salinity, alkalinity, acidity, sodicity, low fertility, erosion (by water, wind, landslides, soil creep) and sedimentation. Previous land management may have exacerbated or even created some of these types of hazard, as well as additional ones such as soil structural decline, soil compaction, loss of soil fertility and pollution of waterbodies by fertilisers and pesticides. The operations involved in establishing, growing and harvesting an area of trees may worsen or improve degradation problems; however, once identified, the risks of most land hazards can be reduced by management.

Other hazards that can affect the productivity of farming enterprises include pests, weeds, diseases and fire, and those which can be caused by establishing agriculture include loss of biodiversity, weed invasion and habitat loss, increase in methane generation, decrease in carbon dioxide extraction from the atmosphere, and increase in run-off. Reforestation can reverse some of these degradation trends, but there are farm forestry tree species (e.g. some *Pinus* species and *Chamaecytisus palmensis* (tagasaste)) that can become weeds in remnant vegetation.

There is little quantitative information available on the impact that site hazards have had on tree growth. Some of the issues (waterlogging, shallow bedrock and hardpans, acidity, alkalinity, sodicity, low fertility) were discussed in previous sections, and others are beyond the scope of this report. The rest of this section discusses some ways in which the risks posed by salinity, water repellence, soil structural decline, soil compaction, erosion and flooding can be assessed. Although published soil and landscape surveys provide information on the soil degradation hazards associated with mapped soils and landscapes, a field survey is required to evaluate the hazards associated with most farm forestry projects because the degree of risk is commonly site-specific.

3.4.1 Salinity

There are vast quantities of salt (mostly sodium chloride) stored in the regolith below some of Australia’s agricultural areas. Soil water and groundwater flush a proportion of this salt towards the sites where groundwater discharges. Where the groundwater discharges by evaporation from a shallow watertable, the salt remains in the soil and concentrations rise and reach levels where they adversely affect plant growth and soil structure. The soil surface then becomes more prone to wind and water erosion. Salt accumulates on the ground surface and has the potential to salinise surface water systems, as does saline groundwater which discharges as springs. The groundwater processes involved in the salinisation of land are the focus of the JVAP book *Trees, Water and Salt* (Stirzaker et al., 2002).

The risk of future salinity should be assessed by considering landscape position, clearing history and, if available, groundwater level records. Salinity could develop even after tree establishment because the groundwater system could be receiving recharge from elsewhere in the landscape.

There is a wide range of ways of assessing the degree of land salinisation, from field observation to analysing satellite imagery. For farm forestry purposes, field observation, soil sample analyses, ground-based electromagnetic surveys and groundwater levels are likely to be the most useful indicators. Each method has its advantages and disadvantages, and interpretation of the results is not easy because the salt stored in a volume of soil is likely to change with the season A certain level of salinity may have different impacts in different places, and the tolerances of particular tree species are only known broadly (see Chapters 7 and 8 of the JVAP book *Trees, Water and Salt* (Stirzaker et al., 2002)).
Most of the information on tolerances of tree species is based on salinity levels measured in samples of soil. Two ways of preparing samples for laboratory salinity measurement are used:

- 1:5 soil:water suspensions, and
- saturation extracts.

Preparing a 1:5 soil:water suspension is simpler than obtaining a saturation extract, but in both cases, the salinity measurement of the sample is made using an electrical conductivity meter. The units usually used for the electrical conductivity of soil and water samples are milliSiemens per metre (mS/m). Since the electrical conductivity of a solution increases as its salinity increases, relationships have been developed enabling electrical conductivity to be used as a surrogate for salt concentration. The electrical conductivity of a saturation extract is abbreviated to $EC_e$, and because it is considered to be a better indicator of a plant’s response to salinity than the electrical conductivity of a 1:5 soil:water suspension ($EC_{1:5}$), it is the preferred indicator. Equations which take soil texture into account have been developed to convert $EC_{1:5}$ values to $EC_e$ values. Table 3.2 lists corresponding $EC_{1:5}$ and $EC_e$ values for soils with a range of clay contents.

Table 3.2: Electrical conductivity values of saturation extracts ($EC_e$) corresponding to electrical conductivity values of 1:5 soil:water suspensions ($EC_{1:5}$) of soils containing different percentages of clay-sized particles. Source: adapted from McKenzie et al. (2004)

<table>
<thead>
<tr>
<th>$EC_e$ (mS/m)</th>
<th>10 – 20% clay</th>
<th>20 – 40% clay</th>
<th>40 – 60% clay</th>
<th>60 – 80% clay</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;95</td>
<td>&lt;7</td>
<td>&lt;9</td>
<td>&lt;12</td>
<td>&lt;15</td>
</tr>
<tr>
<td>95 – 190</td>
<td>7 – 15</td>
<td>9 – 19</td>
<td>12 – 24</td>
<td>15 – 30</td>
</tr>
<tr>
<td>190 – 450</td>
<td>15 – 34</td>
<td>19 – 45</td>
<td>24 – 56</td>
<td>30 – 70</td>
</tr>
<tr>
<td>450 – 770</td>
<td>34 – 63</td>
<td>45 – 76</td>
<td>56 – 96</td>
<td>70 – 118</td>
</tr>
<tr>
<td>770 – 1220</td>
<td>63 – 93</td>
<td>76 – 121</td>
<td>96 – 153</td>
<td>118 – 187</td>
</tr>
<tr>
<td>&gt;1220</td>
<td>&gt;93</td>
<td>&gt;121</td>
<td>&gt;153</td>
<td>&gt;187</td>
</tr>
</tbody>
</table>

Salinity can be assessed in the field using hand-held or vehicle-based instruments that measure the apparent electrical conductivity of a volume of the ground after generating currents using electromagnetic induction. Results of surveys were related to the performance of E. globulus in southwestern Australia by Bennett and George (1995), and subsequently the instruments have been used in some site evaluation surveys. However, the instruments require calibrating against soil sample measurements of $EC_e$, and knowledge of the likely underground regolith and groundwater conditions is needed to interpret results.

### 3.4.2 Water-repellent soils

Water-repellent soils are also called hydrophobic soils and non-wetting soils. Sandy soils are particularly susceptible to the problem (Harper et al., 2000a). It is caused by water-repellent coatings on soil particles, but researchers are not yet certain of all of the sources of the coatings.

Water-repellency causes non-uniform infiltration and wetting of the soil profile. If a tree seedling is in an area where water does not readily infiltrate, it will be disadvantaged. However, if a tree seedling is in a location where water-repellency has caused surface water to concentrate, it may benefit. This is more likely to occur where trees are planted in troughs or depressions rather than on high points such as mounds. Once trees are established and have widespread root systems, water-repellency is less likely to be an issue.

To have a water-repellency problem, soils need to have a source of the hydrophobic coating, and this means that the lower the surface area of the soil particles in a given volume of soil, the greater the risk
of repellency, as the same amount of coating material can cover a greater proportion of the available surfaces. A given volume of sand has a lower surface area than the same volume of clay particles, and this is the reason they are more susceptible to water repellency. Therefore, soil grain size (or texture) can be used as an indicator of susceptibility to water repellency.

The effects of repellency vary during a year: they are most pronounced after prolonged dry periods. Therefore, the hazard may not be evident in mid-winter or early spring. The effects can also change over a series of years, depending on land management. Landowners are often aware of the problem, and laboratory tests can be carried out if it is considered to be a crucial issue.

3.4.3 Soil structural degradation

Soil structural degradation is also known as soil puddling. When the structure of soils is damaged, the soil surface develops crusting and hard-setting characteristics. These cause several problems for plant growth and trafficability. Those that have the greatest impact on farm forestry are decreased infiltration and aeration, increased run-off, increased soil strength (inhibiting root growth), and increased risk of vehicle bogging.

Soil structure decline can occur under both agricultural and forestry operations; however, management can be adapted to improve the condition and to pre-empt further degradation.

Clay-rich soils are most susceptible to structural damage since coarser-grained materials have little structure. A well-structured soil consists of clusters, or aggregates, of clay grains and the structure is damaged when these aggregates are broken down. The breakdown can be caused by a physical process (slaking) or a chemical process (dispersion). Both processes reduce the porosity of the soil. Some of the management practices that lead to these processes are cultivating soils when wet (see Box 3-8), mixing surface and underlying soils during cultivation, and trampling by stock.

Box 3-8: Plastic limits

Most soils that have high proportions of clay- or silt-sized grains are plastic (i.e. they can be moulded) when their water contents are within particular ranges. The ranges vary with the type of clay minerals present and the proportions of the different grain sizes. The water content of a soil that can just be rolled into a thread 3 mm in diameter without breaking is called the plastic limit of the soil. At lower water contents, the soil is friable rather than plastic.

Laboratory tests can be used to assess the stability of soils; however, for most farm forestry projects, field observations and land manager experience will provide adequate information.

3.4.4 Soil compaction

Soil compaction is the result of the breakdown on the arrangements of soil particles in response to applied external forces (e.g. the passage of heavy machinery). It is the physical processes of soil compaction that result in hardpans, called plough pans and traffic pans. Mostly, pans develop some tens of centimetres below the surface of the soil. Although the main cause of the degradation is heavy vehicles, cultivation and stock trampling may also provide the stresses.

Compacted soils can retard tree growth because they have reduced porosity, which inhibits root growth and prevents them accessing moisture and nutrients below the pan. Compaction can occur in most soils, but wet soils and sandy soils with a small percentage of clay appear to be most susceptible.

Compacted layers are usually easy to identify in a soil pit, but measuring the strength and bulk density of soils (see Box 3-9) may provide further evidence.
Box 3-9: Bulk density and soil strength

Bulk density and soil strength

Dense and strong soils can inhibit the growth of roots.

The bulk density of a soil is used as a measure of its density. It is calculated by dividing its weight by its volume. Usually, the dry bulk density (that is, the weight of the oven-dried sample divided by its original volume) is used for comparing the properties of materials from different places. Common ranges of bulk density values are 1.2 g/cm³ to 1.5 g/cm³ for clay-rich soils and 1.6 g/cm³ to 1.9 g/cm³ for sandy soils.

Soil strength is measured in the field or laboratory using instruments called penetrometers. As the name suggests, penetrometers measure the effort required to push a rod into soil. Each measurement tests only a small volume of soil, so many are required to characterise a regolith profile.

If the bulk density of sandy soils is greater than about 1.6 g/cm³, the growth of roots may be restricted; if it exceeds about 1.8 g/cm³ then root growth may be prevented (Vepraskas, 1988). Bulk densities greater than about 1.4 g/cm³ may restrict growth in clayey soils, while values above 1.6 g/cm³ could prevent root growth (Vepraskas, 1988). Although Robinson et al. (2006) found evidence of root activity, in the form of moisture removal, in soils with bulk densities of up to 1.9 g/cm³. In this case, roots may be penetrating the sub-soil via cracks and other preferred pathways.

3.4.5 Erosion

The dominant forms of erosion are caused by water, wind and gravity. They are most likely to occur during establishment, pruning and harvesting phases. Erosion hazard assessment involves considering:

- the energy source (wind, water (rainfall or run-on) and gravity);
- landform factors (e.g. slope angle and length);
- erodibility (i.e. resistance to erosion); and
- management practices which can be used to ameliorate the hazard (e.g. contour banks).

Soil erodibility in relation to water and wind erosion is related to the amount and type of vegetation cover (generally, the more cover, the less erodible) and the surface soil properties, condition and stability. In general, for water erosion, a loose sand is highly erodible; a firm, non-dispersible clayey sand or sandy clay has low erodibility; while a firm but dispersible sandy clay is highly erodible.

For wind erosion, a loose sand is likely to be more erodible than a firm sandy clay, especially if it has a hard-setting surface.

The erodibility of a slope in terms of landslides (mass movement) is related to the types of bedrock and regolith, structure and strength (which is related to soil water content). Signs of previous mass movements are commonly used as indicators of hazard. However, afforestation of land with high mass movement hazard is one of the best stabilisation strategies.
3.4.6 Flood hazard
Landowners are usually the best source of information on the areas affected by flooding and the frequency and duration of such events because there are few instrumented watercourses in agricultural areas. Landforms and soil profiles can also be used as a guide.

3.4.7 Exposed bedrock
In addition to indicating that surrounding regolith is shallow, areas of exposed bedrock may make vehicle access difficult.

3.5 Summary
The three key land conditions that affect tree survival and growth are soil water regime, soil nutrient regime and site hazards. Various site properties (e.g. slope of ground surface, bedrock depth) influence the key conditions, but there is a lack of detailed knowledge on the effects of the various site properties on tree performance. Therefore, many site evaluations aim to identify those properties that could limit tree survival or growth, rather than the optimum conditions for tree growth.
4. Site Evaluation Procedures


Chapter outline

This chapter discusses collecting and interpreting site data. Existing information may be used to evaluate regions, individual farms, or just parts of farms. It is analysed and interpreted prior to carrying out site surveys. Site surveys are designed to collect specific information that is not already available. This chapter then describes how information collected during the desk study and field survey stages is used to draw maps which delineate areas suited to the forms of farm forestry being considered and requiring distinct management operations.

4.1 Introduction

Chapter 3 explained why particular land characteristics are important for farm forestry. This chapter describes how to obtain and interpret information on them. For most regions of Australia, some information on land conditions is available and it is usually summarised in the form of maps. Unfortunately, most existing maps are not detailed enough to provide the level of information required for individual farm forestry projects. This means that field surveys of the prospective sites are needed to supplement the available mapped information. Surveys can be simple, quick and based on field observation, or they can be exhaustive, time-consuming, expensive and involve specialised equipment and laboratory analyses. The choice of methods is dictated to a large degree by the level of investment to be made and by the expected returns on the investment (Figure 1.1). However, the emphasis in this report is on collecting information that has ‘demonstrated benefit’ rather than following a prescribed list.

The approach to data collection also depends on the purpose of the investigation—that is, whether land is being sought to grow a particular species (e.g., *Eucalyptus globulus*, Tasmanian blue gum), or whether a particular area of land has been selected and suitable species are to be identified. If the aim is the former, then the emphasis will be on differentiating between sites that are predicted to have different productivities. If the aim is the latter, then the emphasis will be on differentiating between those conditions that limit the growth of some tree species but not others.

Much more information is available on the site requirements for the common plantation species than for the other species that may be used in farm forestry (this is discussed in Chapter 6). For the main plantation species, lists of site criteria have been developed for the various regions where they are grown across Australia, and so it is straightforward to list the data with demonstrated benefits that should be collected in a site survey for a farm forestry project. For other species, a more generic set of data with demonstrated benefits should be collected.

Once data have been collected on the relevant landscape features, hydrology and soil properties, it can be classified and similarly classed sites can be grouped together using mapping units. Maps can be based on:

- *individual site properties* (e.g. one map could show salinity classes, another could show slope classes, and another could show soil classes), or
- *combinations of properties* relevant to tree performance and management (e.g. areas prone to waterlogging but not salinity; areas prone to both waterlogging and salinity; areas prone to salinity but not waterlogging; areas unaffected by waterlogging and salinity but with shallow impeding layers, and so on)—that is, *land management units* (LMUs); and
• land suitability for particular tree species—these are derived from the LMU maps and lists of site requirements for particular species.

The maps form the basis of planning farm forestry layouts and management inputs and for estimating budgets and potential productivity. The process emphasises that management decisions should be made for each LMU on the basis of requirement and not general prescription. This means that it is particularly important to document:

• the survey methods used;
• the assumptions made in interpreting the field data; and
• the results of the interpretations.

This chapter describes how existing information can be interpreted for farm forestry purposes (Section 4.2), then the processes involved in carrying out a field survey for farm forestry (Section 4.3), followed by the development of maps for planning and evaluating farm forestry projects (Section 4.4).

4.2 Using existing information

A desk study—the collecting, analysing and integrating of existing information—is the first step in a site evaluation. This section firstly describes common sources of existing information on land conditions and then gives simple examples of using the information as the basis for a regional assessment and for designing a field survey.

4.2.1 Information sources

For farm forestry, land evaluation may cover a large region, a watershed or a whole property, or it may just cover a few small areas already selected for planting. It may focus on finding suitable sites for just one species, or on identifying the species suited to different types of sites.

Site-specific information on the main factors affecting the soil water regime, the nutrient regime and the site hazards is required, but is not likely to be available for most potential farm forestry sites. Some background may be obtained from published maps and reports on geology, topography and landscape features, soils and hydrogeology, but it is rarely at a relevant scale and has to be interpreted in terms of the implications for farm forestry. The shortcomings of published soil and soil-landscape maps mentioned in Box 4-1 apply to most other types of published maps. Conveniently, many agricultural areas now have excellent aerial colour photography coverage, usually at scales of about 1:25 000.
Box 4-1: Usefulness of existing soil and soil-landscape maps

Usefulness of existing soil and soil-landscape maps

Soil and soil-landscape maps are now available for much of Australia. Soil-landscape maps show areas of land in defined, recognisable positions in the landscape and contain specific sets of soils. An example of the use of such information to predict fibre production and carbon sequestration is given by Harper et al. (2005).

The maps are better-suited to regional or district level evaluations than to providing information useful at the paddock level:

- Commonly, the maps are at scales of between 1:50 000 and 1:250 000 and do not contain enough detail for farm forestry site selection or management. For instance, a 100 ha paddock is only 1 cm² on a 1:100 000 map. Maps are required at scales between 1:5000 and 1:20 000 to adequately portray the soil variation at the paddock scale.

- The site and soil properties used to construct the maps may not be relevant to tree performance. Soil surveys designed for agriculture usually concentrate on the properties of the surface horizons to depths of less than 1 m. Trees are affected by soil properties at depths much greater than this. Properties that are important for tree performance (regolith depth, soil fertility, salinity) are often omitted.

Interpretation of maps is difficult without an understanding of the landscape features that are found in the area being evaluated. The reports that are produced in association with published soil and soil-landscape maps commonly contain descriptions of the predominant landscape features of the region. They are likely to note or illustrate the parts of the landscape where shallow rock is common—for example, along steep ridgelines. They may describe the characteristics of areas prone to waterlogging, the parts of the landscape underlain by hardpans of specific types, and the types of sites where salinity develops (indicating the areas likely to be underlain by shallow saline watertables). This helps a person unfamiliar with a region to interpret the features seen in the field, even though the published maps are not precise enough for farm forestry site evaluation.

In the last 10-15 years, land management units have been mapped on many farms and catchments. Some of the maps have been produced by landholders, while others by government agencies. Their quality is variable, but the best are excellent. The scales are usually between 1:5000 and 1:25 000, and most were prepared as overlays on aerial photographs. They aim to divide the farming properties into zones requiring different management practices, based on soil properties and problems such as shallow rock, steep slopes, soil erosion, waterlogging, flooding and salinity. Although most unit boundaries are drawn based on field observations and aerial photograph interpretation, in some cases, backhoe pits have also been used to distinguish between zones. If landscape management unit maps are available, field surveys should be planned to check their accuracy. It is likely that some mapping units will need adjustment for farm forestry purposes. For example, a farmer may have mapped an area where rock is too shallow for annual cropping, so it would be reasonable to assume that the area unsuited to trees would be larger. Field checking should address these possibilities.

There are some regional-scale maps and reports available on watertable depth and salinity in agricultural areas, but only limited information can be extracted from them for planning farm forestry projects. Most are based on networks of bores and piezometers installed to monitor groundwater levels and salinities. Landholders are usually aware of monitoring sites on or near their properties, and most government agencies maintain groundwater databases. Be aware that in some regions (e.g. some hillslopes in the Western Australian wheatbelt) groundwater behaviour can differ greatly over short distances, whereas in others (e.g. broad valley floors in some of the Murray-Darling Basin river catchments) groundwater behaviour is similar below large areas. In some regions groundwater (fresh and saline) can occur at shallow depths below locations high in the landscape, not just below valley
floors. The differences between local-scale, intermediate-scale and regional-scale groundwater systems are explained in Chapter 3 of the JVAP book *Trees, Water and Salt* (Stirzaker et al., 2002). Where there is no nearby groundwater information, aerial photographs can be used to identify possible groundwater discharge sites (fresh and saline) and these should be field-checked.

As mentioned above, aerial photographs are one of the simplest and quickest ways to gain an appreciation of the scale of variability of an area of land and its major features. They are particularly good at showing problem areas—deep sands, saline zones, shallow rock, waterlogging—at scales useful for farm forestry. They should therefore be inspected prior to site visits, and preliminary boundaries of mapping units should be marked. These can then be checked in the field. Preparations for site visits are discussed further in Section 4.3.

Landholders are possibly the most valuable sources of information, particularly for water issues. They are usually aware of how frequently an area is inundated and whether the water is saline or fresh. If the reason for planting trees is to reduce groundwater recharge or to revegetate a saline area, the landholder probably has some knowledge of groundwater conditions already, and may even have installed piezometers and kept groundwater level records. Since groundwater behaviour below two nearby areas with similar surface characteristics can be very different, caution should be used in extrapolating information from one site to another.

Measurements of surface water inputs and exports for agricultural land are usually only made for research projects. However, qualitative generalisations can be based on the surface soils and landforms, and commonly landholders are aware of which parts of their properties shed and gain water, and how regularly this occurs. These generalisations may be adequate for some farm forestry projects. Computerised models have been developed to make quantitative estimates of surface water run-off and run-on, but they rely on:

- accurate values of soil and landform properties being available; and
- accurate representations of the processes involved.

Where a site’s loss to run-off or gain from run-on is substantial, the yield of trees will be affected. If computerised tree growth models (such as those discussed in Chapter 7) are used to predict yields, they should incorporate any available information on the site’s potential to shed or collect water. The possibilities of changing run-off or run-on characteristics by changing land management and the changes likely to result from the establishment of a farm forestry project should be taken into account.

### 4.2.2 Integrating information

The next step in the desk study is to bring together and interpret the available information and summarise it in a form that is useful for planning the farm forestry project. Some of the information may also guide the field survey. Box 4-2 is an example of using maps to summarise the available information.

**Box 4-2: Hypothetical desk study 1: Regional evaluation for *Eucalyptus globulus***

**Hypothetical desk study 1**

**Regional evaluation for Eucalyptus globulus**

The investigator has been asked to make a broad-scale evaluation of the area of land suitable for growing commercial *Eucalyptus globulus* in a specific region of Australia. The investigator has been given a set of criteria and plans to use a geographical information system (GIS) to produce maps of land that satisfied each criterion and combinations of them. An example of this approach is detailed in Harper et al. (2005), used to estimate wood production, carbon sequestration and recharge control in the Collie catchment of Western Australia.
<table>
<thead>
<tr>
<th>Given criteria</th>
<th>Information source</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Select land with &gt;600 mm mean annual rainfall</td>
<td>Digitised mean annual rainfall contours produced by the Bureau of Meteorology or packages such as ESOCLIM</td>
</tr>
<tr>
<td>2. Select land with &lt;1500 mm mean annual evaporation</td>
<td>Digitised mean annual evaporation contours produced by the Bureau of Meteorology or packages such as ESOCLIM</td>
</tr>
<tr>
<td>3. Avoid limestone, deep sands, bedrock less than 3 m deep and hardpans more than 1 m deep</td>
<td>Digitised geology maps (based on 1:250 000 mapping) produced by the government geology agency for geological units incorporating limestone or deep sands; digitised soil-landscape maps (based on 1:100 000 mapping) produced by the government agriculture agency for soil-landscape units incorporating calcareous material, deep sands or hardpans of any sort, or units associated with shallow bedrock, and the proportions of the units consisting of such features</td>
</tr>
<tr>
<td>4. Avoid wetlands, flood-prone areas, waterlogged areas</td>
<td>Digitised topographic maps (based on 1:50 000 mapping) produced by the government land agency for wetlands and other land subject to inundation; digitised soil-landscape maps (based on 1:100 000 mapping) produced by the government agriculture agency for soil-landscape units incorporating land prone to waterlogging or floods and the proportions of the units consisting of such features</td>
</tr>
<tr>
<td>5. Avoid areas with saline watertables within 5 m of surface in summer</td>
<td>Digitised hydrogeology maps (based on 1:250 000 mapping) produced by the government groundwater agency; digitised soil-landscape maps (based on 1:100 000 mapping) produced by the government agriculture agency for soil-landscape units incorporating land underlain by shallow saline watertables and the proportions of the units consisting of such watertables</td>
</tr>
<tr>
<td>6. Avoid areas with slopes steeper than 15°</td>
<td>Digitised slope maps (based on 1:50 000 mapping) produced by the government land agency</td>
</tr>
<tr>
<td>7. Select land being used for agriculture, but not horticulture</td>
<td>Digitised land use maps (based on 1:50 000 mapping) produced by the government land and agriculture agencies for agricultural and horticultural units</td>
</tr>
<tr>
<td>8. Select land within 200 km of the regional woodchip export port facilities</td>
<td>Digitised map of the region with location of woodchip port</td>
</tr>
</tbody>
</table>

The available information allowed firm lines to be drawn for some criteria, such as 1, 2, 6, 7 and 8. Since one soil-landscape unit can contain a wide range of soils, regolith depths and soil salinities, the mapped units were graded as ‘most land suitable’ and ‘most land unsuitable’ according to the given descriptions and proportions of constituent soils. A GIS was used to draw the final maps. The accompanying report emphasised that the information was only relevant for regional assessments because of the broad scales of the information sources used.
4.3 Field survey

Field surveys require planning. Planning steps include identifying the site conditions and properties that have ‘demonstrated benefits’ (see Section 4.3.1). If practical, a reconnaissance site visit is valuable (Section 4.3.2).

Field surveys concentrate on collecting data from a selection of small areas (sites). The ways in which the sites can be chosen are discussed in Section 4.3.3. At most sites, the regolith will be excavated for examination and sampling and there are a range of techniques for doing this (Section 4.3.5). Further information can be gained using laboratory analyses for soil samples collected during the field survey (Section 4.3.6).

4.3.1 Deciding which data have ‘demonstrated benefits’

Which data have ‘demonstrated benefits’? The aim of the field investigation is to answer several questions, and these dictate which data to collect.

If the primary purpose of the farm forestry project is to establish a chosen tree species for wood products (e.g. *Pinus radiata* (radiata pine) or *E. globulus*) the first consideration will be whether the farm is in a district that has a suitable climate for the chosen species (see Chapter 6). If it is, then a list of the species’ site requirements should be developed.

If the land for a project has already been selected, the first considerations will be the species that will grow well under the district’s climatic conditions and are thus potential choices, and the information available on their site requirements (see Chapter 6). Potential species should be considered before the practical site survey because different species have different site requirements. The survey should incorporate observations or measurements to check all of the site factors that could be relevant.

The other main questions will be similar for both cases:

1. Where on the farm will the chosen species or selection of potential species survive and produce the expected benefits? (i.e. which areas match the site requirements of the species?)
2. What management inputs will be required to maximise tree survival and produce an acceptable yield?
3. Are there any hazards for tree growth? (e.g. drought, wind, erosion, flooding)
4. What is the best layout of trees for the purpose of the project?

These questions revolve around the issues of soil water regime, soil nutrient regime and degradation hazards. What do we look for in the field to answer these questions? Some of the data requirements are straightforward (e.g. whether a site is on a floodplain or not), but some are not easy to obtain directly. For instance, Chapter 3 discussed how important soil water is for tree growth, but measuring the ability of the soil to store water can be expensive and time-consuming. Instead, related but simpler properties can be described or measured (e.g. soil texture and depth) and used to estimate the profile’s capacity to store water.

There is a long tradition of using such easily described soil properties (called surrogates) to estimate soil water regimes, soil nutrition regimes and soil degradation hazards (see Chapter 3), but the reliability of surrogates varies (Gibbons, 1961). The following is a list of some that are considered to be reliable:

- soil texture can be used as a surrogate for soil hydraulic properties (Smettem et al., 1999a; Smettem et al., 1999b);
- effective regolith depth can be used as a surrogate for available soil water storage (Harper et al., 1998; Harper et al., in review).

The strength of such relationships differs from area to area and local calibrations may be required. For example, Harper et al. (in review) found that a regolith depth of at least 2 m is necessary for reasonable survival of *E. globulus* in south-western Australia. In that case, regolith depth was a
surrogate for available soil water storage. However, the features that limit the effective regolith depth vary from location to location—at one site it might be shallow bedrock, at another it might be a cemented layer. Therefore, a site survey using regolith depth as a surrogate should aim to identify anything that would limit root penetration within the first two metres of the profile, and determine the depth, thickness, continuity and distribution of any such feature.

Some site attributes, such as the frequency and intensity of waterlogging, cannot be measured on a routine basis over large areas of land, but can be inferred from soil profile observations and landscape position. Soils from waterlogged sites, for example, commonly have gleyed colours (i.e. greyish, bluish or greenish colours resulting from periods of reducing conditions when water replaces air in the soil pores).

Researchers have considered whether various types of remotely sensed electronic information (from satellite or airborne surveys) are more cost-efficient and more accurate than site surveys. Unfortunately, the remotely measured data still have to be calibrated against field measurements, the results then need to be checked against field evidence, and since they do not directly measure the properties we require (e.g. available soil water storage), they also rely on relationships between the instrument output and the required property.

Box 4-3 and Box 4-4 use two hypothetical cases to illustrate the processes involved in listing the data requirements and planning survey procedures.

**Box 4-3: Hypothetical case 1: Species already chosen–Land to be selected**

**Hypothetical case 1**

*Species already chosen–Land to be selected*

The investigator is to survey a farm near Manjimup in south-western Western Australia to find about 50 ha of land for *Eucalyptus globulus* for woodchips. The aim is to maximise profits.

There is an established *E. globulus* plantation industry in the district, but the investigator was conscientious and checked that the climate is suitable for the species, that the farm is within economic distance of a port exporting woodchips, and that no local government restrictions would affect site choice. The investigator then checked around the local industry bodies and government agencies to find out what criteria they used for site selection, and asked them about any sites that had failed. He was given a checklist and survey procedure that was developed by Harper et al. (1998), so used it to plan the site survey.

**The FPC quick site selection procedure for *E. globulus* in south-western WA**

1. Identify farmed areas with slopes <15% which are unlikely to be inundated with water or which would respond to surface drainage and which have no rock outcrop. These areas will be surveyed in more detail.

2. Survey site at scale of 1:10 000 using aerial photograph interpretation and ground survey. Undertake ground survey using a drill rig or back-hoe and an electromagnetometer.

3. Identify sites with shallow (<2 m) regolith, saline soil (EC >50 mS/m measured with a magnetometer) or sandy soils with sand horizons >2 m deep. Do not plant these.

4. Identify sites with hardpans within 1.3 m of the soil surface that can be rectified by ripping. *Hardpan* includes ironstone (ferricrete) and coffee rock. If hard material is basement rock, or >1.3 m deep, ripping will not increase soil depth – do not plant these sites.

5. For sites that have no overt limitations, take soil samples from between about 0 cm and 10 cm deep. Take 15 to 20 samples in a Z-shaped pattern. Send samples to laboratory, with location details. These samples will be used to predict site index and fertilizer requirement.
Box 4-4: Hypothetical case 2: Farm forestry sites provisionally selected–Species not yet chosen

Hypothetical case 2

Farm forestry sites provisionally selected–Species not yet chosen

The investigator planned a survey of several sites that a landholder selected on her farm near Donald in northern Victoria. The landholder wanted to plant specific areas for wind erosion control, shade and shelter, a buffer around a wetland, and fodder, and wanted to plan plantings for recharge reduction. She wished to produce a small amount of high quality timber from as many of the plots as possible.

The aim of the investigation was to find out which tree species would grow well in each of the chosen locations. The first step was to assess the climatic conditions of the sites, then use the available information (see Chapter 6) to draw up a short-list of species that would thrive in the region. For each of the potential choices, its known preferences and dislikes in terms of site conditions (e.g. salt tolerance) were then listed. A full list of relevant site properties was then compiled from all of these and used as the basis for field investigations.

In a perfect world, reliable information would be available for every species on both the conditions that best suit its various provenances and the conditions causing different provenances to grow poorly or die. This information would be based on analyses of many plantings over a wide range of climate, ground and management conditions. Unfortunately, because the history of growing trees in the agricultural areas of Australia is short, there is only limited information available for most species and provenances of species. Basic criteria lists have been produced for some, while those available for commercial species are more comprehensive (see Table 6.1 and the section headed Species grown primarily for wood products).

The rainfall on the property at Donald had averaged about 380 mm over the previous 30 years. The investigator looked up the mean daily maximum and minimum temperatures at Donald on the Bureau of Meteorology website and averaged them to estimate the average annual temperature at the farm (15°C). The investigator then referred to Trees, Water and Salt and selected all the species (there were 13) considered ‘reasonably suited’, ‘suited’ or ‘very suited’ to areas with less then 400 mm average annual rainfall. Most of these were also considered ‘suited’ or ‘very suited’ to the average annual temperature in the district, so he copied the table to start a criteria list (the following table illustrates the entries made for three of the 13 species as examples). He then checked with the landholder to see if she or her neighbours had any additional information on how these species or any other relevant ones grew under local conditions.

Examples of entries in the table the investigator extracted for his site from Trees, Water and Salt (Stirzaker et al., 2002)
The table indicated that the site survey should differentiate between:

- low, moderate and high frost-risk areas (the investigator planned to check with the landholder, who had been on the farm for over forty years);
- slightly, moderately, severely and extremely saline areas (the investigator planned to check aerial photographs for signs of salinity, ask the landholder about any salt-affected crop and pasture growth, and to take soil samples for measurements);
- areas with different pH ranges (the investigator planned to ask the landholder for the results of any soil tests she had made and to take soil samples for measurements);
- areas subject to waterlogging periods of only a few days, a few weeks or several weeks (the investigator planned to check aerial photographs for signs of waterlogging, ask the landholder where the susceptible areas were, to inspect the landforms for areas where water was likely to accumulate, and check for gleyed or mottled soils).

The investigator could find no specific information on the requirements of the species for many of the factors discussed in Chapters 2 and 3. He therefore decided to draw up a generic list of data to collect that would indicate site suitability for trees in general. He considered which factors would be most likely to influence the success of trees on the farm.

**Solar radiation**: Solar radiation was unlikely to be in short supply. Since the district around Donald has no steep hills, even south-facing slopes would have abundant light.

**Wind**: The landholder was concerned about wind erosion in some parts of the property, and had also commented that her sheep would benefit from some protection from hot winds in summer and cold winds in winter. So the investigator planned to map the areas susceptible to wind erosion.

**Soil water regime**: Since the farm was in a low rainfall zone, the investigator considered that adequate soil water would be an important factor. He planned to estimate available soil water storage using regolith texture and effective regolith depth. He did not know what the requirements of each potential species would be, but could use his estimates of available soil water storage to rank different sites. He also considered adjusting the rankings depending on whether a site was likely to receive additional water from surface run-on, lose water due to surface run-off, or be exposed to hot dry winds. To gauge these factors, he would record a site’s slope position and landform element, the condition of the surface soil and texture of the upper parts of the regolith profile. He would also note the main pasture species to assess whether weeds would create competition for stored soil water.

**Soil nutrient regime**: The farmer had regularly carried out standard soil testing and had applied fertilisers accordingly. The farmer did not consider nutrients would be deficient anywhere, but suggested that she would watch for signs of deficiencies as the trees grew. She thought some of the soils were getting more acidic with time. Therefore, the investigator did not plan to test for nutrients but he would test for acidity (which was already on his list).

**Soil degradation and other hazards**: The farmer had mentioned that wind erosion occasionally occurred, and the investigator was aware that there was the potential for most of the soil degradation hazards to occur on some parts of the property, so he planed to assess the hazards from wind and water erosion, flooding, soil
compaction, structural decline and water repellence (salinity was already on his list). In addition, the farmer had mentioned that there was a rubbish tip in an adjoining area of remnant vegetation, and that fires were often started there. Rabbits in neighbouring bushland also caused adverse impacts. The investigator planned to note these areas as hazards, and to check other parts of the property for signs of rabbits (especially near sandy road verges and remnant vegetation). The farmer did not anticipate that weeds would be a serious problem.

The investigator drew up a check list based on the above considerations and based his field survey on it.

4.3.2 Farm reconnaissance and map preparation

The farm reconnaissance provides an initial familiarisation with the features likely to promote or limit tree productivity. It involves making a brief ground inspection and may take place before, during or after the desk study. Insights and information gained during the visit are used in planning the field survey.

Base maps are for recording information during both the reconnaissance and the field survey. Enlargements of aerial photographs are ideal, particularly if recent colour photography is available. If possible, this mapping base should be digitally corrected for distortion and have ground contours overlaid. Stereo-contact prints can also be used for aerial photograph interpretation using a stereoscope. Historical photographs can be valuable if they indicate former patterns of land use and native vegetation.

The reconnaissance evaluation should consider and map factors such as:

- slope limitations;
- areas required for firebreaks around the property boundaries and around any areas already chosen for farm forestry;
- areas of remnant vegetation and the scope for linking these together;
- easements for powerlines and roads;
- unplantable areas (e.g. lakes, exposed rock); and
- areas that appear to be affected by problems (e.g. waterlogging, salinity, erosion) or appear to have soils requiring special management practices (e.g. zones underlain by ferricrete sheets or deep sands).

For projects where the layout has not already been chosen, some preliminary options for shapes and distributions of planting can be contemplated at this stage.

4.3.3 Choice of survey method

The purpose of the field survey is to obtain information on the above- and below-ground properties relevant to farm forestry for an area of land (such as a farm). One of the assumed advantages of specifying survey procedures is that different people using the recommended methods produce similar results. The *Australian Soil and Land Survey Field Handbook* (McDonald et al., 1990) provides standard ways of describing many of the relevant landscape and soil features and is recommended.

The field assessments and measurements are made at a range of scales. For instance, for landform and vegetation features it is recommended that the general characteristics of the feature in the surrounding 25 m by 25 m area are described, whereas for the soil and regolith profile descriptions are made at a ‘point’. The surveyor then extrapolates the information from these assessment areas and points across larger areas, and illustrates the results using maps.

The following sections describe the processes involved in selecting the sites to be surveyed.
4.3.3.1 Picking points to survey

The three main methods of selecting sites to survey in detail are described below.

**Grid surveys** involve routinely sampling the area under consideration in a grid and then interpolating between observations. This is useful for those soil properties with strong variability or no obvious relationship to the landscape. It also allows the use of software packages to draw maps using simple interpolation procedures. Similarly, it is a useful technique if only one or two soil properties are known to limit tree growth in a particular region, such as soil depth or salinity. Gridding allows the use of less skilled personnel to systematically describe the soils at pre-ordained sampling sites. It also allows the generation of unbiased summaries of soil properties in a particular area. The major disadvantage of grid surveying is potential over-sampling (i.e. more holes are dug than are necessary).

**Free surveys** involve both field observations and interpretation of aerial photography and landscapes. Stereo-contact prints are used for aerial photograph interpretation of major mapping units, using a stereo-viewer prior to fieldwork. This relies on the relationship soils often have with the landscape and on the surveyor understanding how soil properties vary across the landscape. This approach can save significant time but requires some training in soil science or local experience. It is not a statistically sound method of sampling and can produce bias if care is not taken. Random checking across the mapped area can prove or disprove whether the surveyor’s reading of the landscape is in fact correct. Different surveyors will produce a different map based on their understanding of the landscape. Many landscapes do not have consistent relationships between soil properties and landforms.

**Stratified random sampling:** While simple random sampling is feasible, efficiency is nearly always improved by using stratified random sampling. Stratification means dividing the landscape up into broad zones (strata) with similar features, usually based on landform, geology or vegetation. Within each stratum, randomly located observations can be made.

4.3.3.2 Intensity of field observations

The density of field observations will depend on the variability of the paddocks being examined. As a general rule, a mapping scale of 1:10 000 requires an observation density of at least one hole per hectare (or a 100 m grid). With free survey, where there are discernible relationships between soil attributes and landforms and the operator has experience, only one observation may be required every 10 ha to 15 ha. In some areas (e.g. where there is shallow bedrock, but its depth varies) more observations will be required, whereas in others fewer are needed (e.g. deep regolith, relict sand dunes).

4.3.3.3 Method of recording field data

Field data can be recorded on the field data sheet provided in the *Australian Soil and Land Survey Field Handbook* (McDonald et al., 1990), or a purpose-designed field sheet for the surveys. Some organisations have developed systems to allow the direct entry of data into portable computers in the field.
4.3.4 Site coordinates

The location of the observation sites should be recorded on an aerial photograph.

Site investigation may involve combining the field observations and analysis with data from other sources, such as digital elevation models, climatic models and remotely sensed imagery. This requires accurate location of field observations.

It is recommended that sampling points and any relevant site boundaries be located to within 5 m, and preferably within 1 m, of their true position. This can be achieved using Differential Global Positioning Systems (DGPS) or, less reliably, with a single GPS unit. For the best results, the position of the DGPS base station within the standard topographic survey (geodetic) framework should be known precisely. In some circumstances (e.g. remote areas), the DGPS base station may be tied into a local or temporary benchmark and the recommended accuracy will then only be achieved when the local benchmark is tied into the standard framework. The local benchmark must, therefore, be clearly identified so that it can be located at a later date.

4.3.5 Field techniques for inspecting and sampling soil profiles

Once the above-ground properties of the site have been recorded the soil should be described and quantified. This means that the regolith will have to be exposed in some way. The common methods are back-hoe pits, which expose a few square metres of a profile but usually do not reach as deep as roots can penetrate, and drilling rigs of different types. Care is required in interpreting soil material from drill spoil. A drilling rig can easily penetrate horizons that are impenetrable to roots, but the properties relevant to tree growth (e.g. soil structure) may be disturbed or destroyed by the time a sample reaches the surface. Conversely, drill holes can be impeded by discontinuous rocks or hardpans that would not limit root penetration markedly (Figure 4.1). The following text discusses other advantages and disadvantages of the various methods of observing the regolith and obtaining samples.
4.3.5.1 Back-hoe pits

Pits dug by a back-hoe or excavator are best and should be used when financial and time constraints permit. The pits are usually backfilled once sampling is completed.

Pit safety

It is unsafe to enter deep pits. Some guidelines consider that pits greater than 1.0 m deep should not be entered unless properly stabilised against collapse by shoring. Be aware of your organisation’s or government’s safety regulations.
The main advantages of pits are that the regolith and its variability (horizontal and vertical) can be rapidly observed and sampling is simplified with little or no compaction or contamination. ‘Undisturbed’ samples can be taken for soil physical measurements and exposures are easy to photograph.

The main disadvantages of pits are that they can be costly if contractors have to be engaged, or organisations face the capital cost of purchasing a back-hoe. Some areas are too steep or inaccessible for other reasons (e.g. wetlands) and there is a substantial labour requirement when pits are dug by hand.

4.3.5.2 Coring

Coring aims to obtain uncontaminated samples of soil from a known depth at a site. In areas with shallow watertables, coring may have advantages over pits. To reduce field costs, core tubes can be taken to a regional centre to abstract samples and record descriptions.

Cores of 50 mm to 75 mm diameter can be obtained using thin-walled sampling tubes that are pushed into the ground with hydraulic rams or jack hammers. Cores abstracted in this way are usually disturbed and not suitable for physical soil measurements. Intact cores can be abstracted using specially designed drills and sampling tubes. The cores may be larger (diameters of 100 mm to 150 mm or more) and are generally suitable for physical soil measurements.

Coring is a quick and easy method of sampling and a large number of places can be sampled. The main disadvantages of cores are:

- they sample only small volumes of the regolith so provide little information on regolith variability;
- the samples may be compacted during abstraction;
- the tube emplacement and core recovery can be hampered by gravels;
- the total depth of sampling is restricted in some soils, especially for push-sampling;
- coring using drill rigs generally requires sites to be accessible to vehicles and drill rigs; and
- drill rigs are expensive to buy.

4.3.5.3 Existing exposure

Existing exposures (e.g. road or railway cuttings, gully banks, sand or gravel pits, cliffs) are sometimes used as they provide ready access. The major advantages of exposures is that they are often deep, expose the underlying geology, give an indication of the lateral variability of soil morphology and expose the root systems of prior native vegetation.

Exposures provide a biased sample of soil and regolith because roads and quarries occupy particular parts of the landscape for a reason (e.g. avoidance of wet areas). Care must be taken at these sites to ensure that there has not been addition to or removal of surface materials and that soil properties (e.g. salts) have not changed due to exposure. The exposed soil face has to be cut back sufficiently to minimise the effects of exposure, leaching, or mechanical disturbance prior to sampling.

4.3.5.4 Hand auger

Hand augers are often used in soil surveys and have the advantage of being a rapid method of making shallow examinations and there are few problems with site access. The ease of augering depends on the nature of the soils being examined. It is relatively easy to sample to several metres in sandy soils, but features such as hardpans, dry subsoils and watertables impede augering. Augering is often terminated at shallow depths (<1 m) in clayey soils. Disadvantages include: undisturbed samples cannot be collected, lateral variability cannot be observed and soil structure cannot be described reliably. Another disadvantage of augering is that it is labour-intensive.
4.3.5.5 **Steel rods**

In some site assessments, steel rods can be pushed by hand into the soil to depths of up to 1 m to detect hard zones. This technique is not recommended, unless the only likely site limitation is compacted or cemented soil layers within the first metre of the surface.

4.3.6 **Analysing soils in a laboratory**

Sampling and submitting soils to a laboratory can be appropriate in some circumstances, and particularly where there are no, or poor, relationships between descriptions of soil morphological properties and the property in question. In such circumstances soil analysis can be used to provide further information about the paddock under consideration. Examples include:

- assessment of chemical factors likely to affect growth such as extremes of pH, salinity, or gross nutrient deficiencies (in most soils used for agriculture, nutrient contents are related to past fertiliser applications rather than soil parent materials);
- determination of the fertiliser requirements of the soils, but only when an appropriate calibration curve between fertiliser application rates and tree growth response has been established; and
- provision of data for growth models (Chapter 7) and hydrological models (such as those described in the JVAP book *Trees, Water and Salt* (Stirzaker et al., 2002)).
- Using soil analyses in site evaluation has several limitations. These include:
  - the financial and time costs of sampling and analysis;
  - large variations of some attributes over short distances and with time of sampling. For example, it has been illustrated that some soil attributes may vary by as much as 50% over a scale of several metres (Webster, 1985). Spatial variation can to some extent be compensated for by increasing the number of samples taken. However, the number of samples needed to estimate the values of some attributes may be of the order of tens or hundreds (Beckett and Webster, 1971). Seasonal variation can be expected in commonly measured aspects of soil fertility such as potassium (Roberts, 1968) and phosphorus (Jessop et al., 1977); and
  - knowing how to interpret the information. For some analyses, unambiguous interpretations are not possible and the analysis provides only a general indication of likely response.

Thus, although laboratory analysis appears to be more accurate than field assessment, it does have limitations, and in some cases the values should be regarded as indicative only.

4.4 **Developing Land Management Units and land suitability maps**

For management purposes, the site and soil information from one place has to be extrapolated to larger areas (aided by aerial photographs and field observations of the landscape) and sites with similar properties are grouped together in mapping units. The size of the smallest practical mapping unit will vary with the project. If a farmer has a one-hectare area prone to waterlogging in a cropping paddock that is otherwise well-drained, he or she may just treat it in the same way as the rest of the paddock. In contrast, it may be practical to change tree species at intervals of only a few metres.

After the field data has been collected, individual site and soil properties are classified using systems relevant to the tree species being considered. Some of these were introduced in Chapter 3. For example, sites can be classed as slightly, moderately, severely or extremely saline, according to salinity measurements; sites can be classed as having bedrock or hardpans less than 2 m deep or greater than 2 m deep; and so on. Classification systems for soils are numerous, and most were designed for a specific purpose. A classification developed to predict the growth of *P. radiata* in southern Australia is described by Turner et al. (1990).

The next step is to produce maps. Most projects will require LMU and land suitability maps, but in some cases, maps of *individual properties* may be drawn first—for example, one map could show...
level areas, areas with gentle slopes (e.g. <3°), areas with moderately inclined slopes (e.g. between 3° and 10°) and steep slopes (e.g. >10°). Another map could show the distribution of different soil classes, and so on.

LMUs are based on combinations of properties—they are commonly defined using the properties considered to limit the growth or management of any of the species being considered. Chapters 3, 5 and 6 discuss the site and soil properties affecting tree performance and site management, and the hypothetical cases in Box 4-4 and Box 4-5 illustrated listing the properties to evaluate during field surveys. These sources of information form the basis for defining LMUs. For example:

- if two sites have similar regolith profiles, but one has steep slopes which pose an erosion hazard and one site is level, then different LMUs can be defined to distinguish between them.
- if LMUs are being defined for tree species which are all considered to require regolith depths greater than 2 m, then it would be reasonable to allocate all areas with less than that depth to one LMU. However, if the same land was being divided into LMUs for a range of annual crops or pastures in addition to tree species, then areas with regolith less than 2 m deep may be divided between two or more LMUs. For instance, there may be one LMU for regolith between 1 m and 2 m deep; one for sandy regolith less than 1 m deep and one for clayey regolith less than 0.5 m deep.

Suitability maps are then drawn by grouping together LMUs that are unsuited and suited for each species. Several LMUs may be suitable for the species, but they may require different inputs to optimise profitability (site specific silviculture) and different types of hazard-reduction management.

As in most mapping projects, drawing lines to divide areas for different treatments is basically a matter of individual interpretation and judgement because it is not practical to survey the entire boundary of every mapping unit. However, during the field survey it is wise to think ahead and consider where boundaries may fall, and to check any areas that could prove critical. It is also preferable to field check the drafted maps. The implications of unclear boundaries should be discussed with landholders and land managers.

It is hard to produce reliable LMUs if the conditions which suit trees are not well-known, and if the relationships between those conditions and the surveyed site and soil properties are not well-understood. Where compromises and assumptions have to be made, it is important to discuss these with the landowner and to record them on the maps and in accompanying documents.

Once the land suitability map has been finalised (it may be necessary to produce different maps for different proposed tree species), alternative farm forestry layouts can be discussed (the JVAP books Design Principles for Farm Forestry (Abel et al., 1997) and Trees, Water and Salt (Stirzaker et al., 2002) contain relevant information). Then tables summarising the areas of different units can be prepared, management inputs can be estimated (see Chapter 5), tree growth modelling can be carried out (see Chapter 7), and the economics of various species and layout options can be calculated.
5. Planning Farm Forestry Operations

P. J. Ryan and N. J. McKenzie

Chapter outline

This chapter is concerned with soil management practices for farm forestry. It lists the site information needed to plan common management operations and describes how this information is obtained by interpreting the data collected during the desk study and field investigations.

In many cases, specific relationships between site properties and tree performance are not known. Those relationships that are in use are mostly empirical and location-specific and were developed for large-scale forestry operations. Transferable relationships based on well-documented, physical principles are still to be developed. In the absence of these relationships we suggest using a ranking approach where extreme values are regarded with caution.

5.1 Introduction

Site information can be used to improve site management and apply inputs where they are required, rather than on a routine basis. The information in this chapter can be applied in the design of plantings for demonstration and research purposes as well as for general farm forestry projects. However, there is little specific information available on how management changes improve tree performance or reduce soil degradation, so the emphasis in this chapter is on identifying limiting or extreme conditions.

Although field surveys can be used to collect information on hazards posed by pests, diseases and fire, these are beyond the scope of this report.

Site management decisions should be based on the answers to the following queries:

- what site properties are you trying to modify?;
- will the planned operation be effective?; and
- will there be adverse effects from this operation?

Adverse effects (such as increased run-off and erosion) can cause substantial off-site problems as well as decrease tree growth. The operations that have the greatest off-site impacts are:

- site preparation (e.g. ripping, mounding);
- roading (construction, usage and maintenance);
- tree harvesting; and
- burning.

This chapter shows how to use the information collected from the desk study and site investigation stages of the site evaluation to plan site-specific management. The management practices are divided between site preparation and amelioration, and thinning and harvesting. Trafficability is also discussed.

The site properties mentioned in this chapter were explained in Chapter 3.
5.2 Site preparation and amelioration

Site preparation and amelioration operations occur at the establishment of the first or subsequent rotations of the farm tree stand. They are some of the most disruptive operations that the land will endure while under trees until tree harvest: ripping, cultivation, mounding, scalping, fertilisation, weed control and drainage.

5.2.1 Ripping

Ripping refers to deep tillage operations that aim to affect the regolith to depths below 0.3 m. The reason for ripping is to make it easier for roots and infiltrating water to penetrate hard layers and reach the underlying regolith. It includes operations with blade ploughs and wing-rippers. The depth that is disturbed by ripping is about two-thirds the depth reached by the ripper.

The locations of rip lines dictate the locations of mound and tree rows.

Table 5.1 summarises the criteria for ripping operations.

<table>
<thead>
<tr>
<th>Table 5.1: Ripping</th>
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<tbody>
<tr>
<td><strong>Aim</strong></td>
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<tr>
<td><strong>Key soil properties for modification</strong></td>
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<tr>
<td><strong>Limiting site properties</strong></td>
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<tr>
<td><strong>Limiting soil properties</strong></td>
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<tr>
<td><strong>Cautions</strong></td>
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</tbody>
</table>
5.2.2 Discing and other cultivation

Discing is a cultivation system that only affects the surface soil (less than 0.3 m deep). Its use in farm forestry preparations should be limited to specific problem surface soils or vegetation control (Table 5.2).

**Table 5.2: Discing**

| Aim | To break up surface soils and the roots of any competitive vegetation.  
|     | To improve water infiltration and thus conserve moisture on site. |
| Key soil properties for modification | High surface soil strength (e.g. hard-setting crusts).  
|     | High surface soil bulk density.  
|     | Low surface macroporosity.  
|     | Structure: massive apedal grade.  
|     | Presence of competitive tussock grass (*Poa* species), bracken fern or other vegetation with thick surface root systems. |
| Limiting site properties | Steep slopes.  
|     | Drainage lines.  
|     | Exposed or very shallow bedrock. |
| Limiting soil properties | Water content: wetter than plastic limit.  
|     | High coarse fragment content.  
|     | High clay content.  
|     | High dispersivity. |
| Cautions | Discing requires less fuel than ripping but it is still expensive and can easily be misused.  
|     | Discing is a major disturbance to the surface soil and, therefore, increases the site’s erosion hazard.  
|     | Discing wet soil can produce smearing and the formation of large clods - effects that are detrimental to soil quality.  
|     | Discing will not alter subsoil properties and if the subsoil is of high bulk density or has a low percolation rate then discing can produce a plough-pan at the disturbed-undisturbed soil interface that can adversely affect root growth. |

5.2.3 Mounding

Mounding refers to any surface cultivation operation that piles up surface soil for seedling beds (Figure 5.1). Table 5.3 lists the soil management criteria for mounding operations. Mounding is often combined with ripping, the mound being formed over the rip line.

If a site is inaccessible to normal tractors because of steep slopes, exposed bedrock or retained slash, *spot cultivation* can be used to form mounds. Spot cultivation is generally done by excavators with auger attachments. These implements can disturb the soil up to between 0.6 and 1 m depths at a ‘spot’, producing a circular mound.
**Table 5.3: Mounding**

| **Aims** | To produce an elevated seedling bed of finely tilthed surface soil.  
To concentrate available nutrients for early seedling growth.  
To encourage rapid seedling root growth.  
To improve soil drainage for seedlings.  
To control weed competition. |
| **Key soil properties for modification** | Thin A horizon.  
Low density of organic matter and associated nutrients.  
Slow mineralisation of organic nutrients.  
Poor drainage.  
Shallow depth to watertable or both. |
| **Limiting site properties** | Steep slopes (dependent on erodibility or regolith stability).  
Deep and closely-spaced erosion gullies.  
Drainage lines.  
Rough ground surface.  
Exposed or shallow bedrock. |
| **Limiting soil properties** | High water content.  
High coarse fragment content.  
Thin A horizon.  
Low organic matter content.  
High dispersivity.  
Texture: fine sandy and silty surface soils with low organic matter are prone to erosion (water and wind) if disturbed and exposed. |
| **Cautions** | Mounding is a major site disturbance that can increase erosion hazard. Mounds should be aligned close to the ground contours, with falls of about 1 to 2°. On wet sites the fall should be towards the drainage lines whereas on dry sites the fall should be away from drainage lines to distribute water.  
The scalped gutters can expose erodible and dispersive subsoils.  
Increased mineralisation of the mound organic matter can lead to rapid removal and leaching of nutrients.  
Ex-agricultural soils may require two passes over the planting rows to produce fine tilth.  
Air pockets in the mound can lead to poor seedling survival. |
5.2.4 Scalping

Displacement of surface soil and vegetation using a near-horizontal blade is known as scalping. This practice has only limited impact on soil physical and chemical properties and so should only be considered for specific circumstances where ripping, discing or mounding are deemed inappropriate (Table 5.4).

Table 5.4: Scalping

<table>
<thead>
<tr>
<th>Aim</th>
<th>To displace the upper soil (vegetation and litter) layer and expose the lower A or B horizons.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Key soil/site properties for modification</td>
<td>Weed competition.</td>
</tr>
<tr>
<td></td>
<td>Surface roughness.</td>
</tr>
<tr>
<td>Limiting site properties</td>
<td>Steep slopes.</td>
</tr>
<tr>
<td></td>
<td>Exposed or shallow bedrock.</td>
</tr>
<tr>
<td>Limiting soil properties</td>
<td>Thin A horizon.</td>
</tr>
<tr>
<td></td>
<td>Poor aggregate stability.</td>
</tr>
<tr>
<td></td>
<td>High erodibility.</td>
</tr>
<tr>
<td></td>
<td>High coarse fragment content.</td>
</tr>
<tr>
<td>Cautions</td>
<td>Displacement of thin A horizons will degrade the seedling bed.</td>
</tr>
<tr>
<td></td>
<td>Removal of nutrients from near to seedling sites may slow early growth in less fertile soils.</td>
</tr>
<tr>
<td></td>
<td>Exposure of dispersive or erodible soil will increase the erosion hazard.</td>
</tr>
<tr>
<td></td>
<td>Recommended only for ex-pasture sites with soils not prone to wind erosion.</td>
</tr>
</tbody>
</table>

5.2.5 Fertilisation

Fertilisation covers the addition of various compounds (organic and inorganic) at different stages in the life of a farm forestry project to maximise tree growth and avoid nutrient deficiency. As noted in Chapter 3, there is little information available for most tree species on the relationships between nutrient levels recorded in soil analyses and growth rates under specific site conditions. However, for situations where reliable information exists, Table 5.5 lists the properties to take into account when planning fertiliser applications at the time of tree establishment.
Table 5.5: Establishment fertilisation and soil modification

| Aim | To increase the availability of specific elements required for tree nutrition.  
To modify the soil chemical regime: to enhance soil structural stability, nutrient holding capacity or change acidity, alkalinity or sodicity status. |
| --- | --- |
| Key soil properties for modification | Concentrations of the required plant macronutrients and micronutrients (B, Ca, Cu, Fe, Mg, Mo, Mn, N, P, K, S, Zn).  
 pH: ameliorate extremely high or low values.  
 High sodium adsorption ratios (SAR) or exchangeable sodium percentages (which indicate low soil structural stability and can be improved by adding gypsum). |
| Limiting site properties | Strong weed competition. |
| Limiting soil properties | Coarse textured soils are prone to excess leaching of added nutrients.  
 Abundant sesquioxides can increase anion adsorption rendering some nutrients (P, S and B) unavailable to plants.  
 High C:N ratios in surface soils can immobilise added nutrients. |
| Cautions | Fertiliser effects are optimal when weed control is good and there is adequate soil water available.  
 Determining meaningful available nutrient indices for tree crops from soil analysis is harder than for agricultural crops because of tree longevity and extensive root systems. Foliar (leaf) analysis can be a more efficient means of determining tree nutrient status.  
 The nutrient levels in tree crops change with time. Nutrient demands in seedlings differ from saplings and mature trees.  
 Ex-agricultural soils can have adequate to excessive concentrations of N and P from past practices. Establishment fertilisation may not be required.  
 Overabundance of N or P in ex-agricultural soils can produce nutrient imbalances in trees leading to micronutrient deficiencies, excessive branching, excessive leaf area and water use, and other structural deformities. |

5.2.6 Weed Control

Weeds can compete with tree seedlings for light, water and nutrients. Weed control in the tree establishment phase can be critical to the survival and productivity of the project. Table 5.6 lists the soil management criteria for weed control.

Table 5.6: Weed control

<table>
<thead>
<tr>
<th>Aim</th>
<th>To reduce the vegetative competition for radiation, nutrients and water.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Key properties for modification</td>
<td>Root concentration.</td>
</tr>
</tbody>
</table>
| Limiting site properties | Weed cover too high or too low for treatments, untreated weed type, weeds too young or too old for treatments.  
 Presence of drainage lines, streams, lakes, swamps or other open water that potentially could be affected by herbicide contamination.  
 Human habitation. |
| Limiting soil properties | Low soil organic matter contents and coarse sandy textures can facilitate leaching of herbicides into subsoils and drainage lines. |
| Cautions | Most herbicides are hazardous materials. Adherence to best management practice is essential. |
5.2.7 Drainage for waterlogging reduction

If the farm forestry project is only concerned with tree species that are not tolerant of waterlogging, it may be best to exclude sites prone to the condition. In many cases, it is possible to install drains that reduce the hazard, but drains can be costly and in some locations there are restrictions on draining water, especially if it is saline. Since the cause of the waterlogging dictates the design of drains, it should be identified before any drainage is considered.

Tree-planting can change the surface drainage processes of a site. For example, mounded tree rows placed on the contour can retain more water on slopes.

5.2.8 Later age fertilisation

The decision to fertilise trees post-establishment is usually made on the basis of leaf analysis where standards have been developed (Dell et al., 2001) In addition, if the trees are to be thinned, N fertiliser (often in combination with other elements such as P or K) may be applied to maximise the ability of the remaining trees to expand their leaf area to exploit the available gaps. This type of fertilisation aims to supply readily available nutrients for rapid growth rather than overcome a clear deficiency. Where water is not limiting growth, the soil nutrient capital (that has been built up over decades of farming) is often inadequate to sustain the performance of fast-growing trees in the mid to late stages of the rotation. Foliar standards are being developed for these periods.

Soil information is not commonly used to determine the efficacy of later-age fertilisation. Smethurst (1998) produced an indication of the critical levels of some commonly analysed elements (Table 5.7). This table only deals with extreme ranges: if intermediate results are obtained then expert advice should be sought.

One of the critical factors that will affect the ability of trees to respond to fertiliser at the time of thinning is the availability of soil water. If the stand has dried out the regolith prior to thinning, any applied N fertiliser will have minimal effect until the soil water storage refills.

<table>
<thead>
<tr>
<th>Analysis</th>
<th>Method no.</th>
<th>Level</th>
<th>Likely problem</th>
<th>Level</th>
<th>Likely problem</th>
</tr>
</thead>
<tbody>
<tr>
<td>P-CaCl extract</td>
<td>9F1 or 9F2</td>
<td>&lt;0.2 mM</td>
<td>P deficiency</td>
<td>&gt;20 mM</td>
<td>Induced deformities with P fertiliser</td>
</tr>
<tr>
<td>N-KCl extract</td>
<td>7C1 or 7C2</td>
<td>&lt;5 mg/g</td>
<td>N deficiency</td>
<td>&gt;50 mg/g</td>
<td>Induced deformities with N fertiliser</td>
</tr>
<tr>
<td>pH in water</td>
<td>4A1</td>
<td>&lt;4</td>
<td>Nutrient imbalances, e.g. Al and Mn toxicities</td>
<td>&gt;6.8</td>
<td>Nutrient imbalances e.g. deficiencies of Cu or Zn</td>
</tr>
</tbody>
</table>

5.3 Thinning and harvesting

Thinning and harvesting operations can have a major impact on the site. If not planned properly, these operations can cause soil damage and diminish the productivity of the existing stand and subsequent rotation crops.

These operations aim to decrease or remove the merchantable stem volume from the stand as quickly and efficiently as possible. This aim should be constrained by the following soil management goals:

- allow traffic when soil is strong (drier than plastic limit) to minimise soil deformation and compaction;
- reduce contact between machine and soil as much as possible by encouraging branch mulch as a track surface;
- minimise and localise machine traffic; and
• retain non-merchantable biomass (leaves, branches, bark) on site, distributed as evenly as possible; note that certain smooth-bark eucalypts can accumulate Ca in the bark and removal of this bark from the site can constitute a major export of the site’s nutrient capital that may require replenishment in subsequent rotations to maintain productivity.

• The major site and soil considerations for planning thinning and harvesting operations are: 
• managing the organic matter left on the site;  
• trafficability;  
• erosion;  
• soil structure decline and compaction; and 
• soil hygiene.

Assessing erosion and soil degradation hazards were briefly discussed in Chapter 3. Systems for rating hazards specifically for farm forestry operations do not exist. Guidelines produced by state forestry agencies for operations in native forests may be relevant for some farm forestry situations.

5.3.1 Organic matter management

It has become common practice to retain and grind up logging ‘slash’ on the site after harvest as part of the preparation for the following rotation in *Pinus radiata* plantations. This followed evidence that second rotation decline in South Australia was linked to nutrient loss. The practice of soil organic matter retention has been reinforced with recent concerns of Ecological Sustainable Forest Management and the use of soil carbon as an indicator of sustainability (Canadian Forest Service, 1995). Soil carbon is one pool of carbon that may have to be considered in future carbon accounting systems for tree plantations.

The retention of organic matter on the soil surface is especially critical for sites that have low nutrient capital or have high erosion hazard.

Retained logging waste can restrict second rotation site preparation and access because of its size and uneven distribution. Slash size also limits the rate of organic matter decomposition. Chopper rollers can be used to crush, break-up and partially incorporate logging slash into the soil (Table 5.8).

<table>
<thead>
<tr>
<th>Table 5.8: Chopper rolling</th>
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<tbody>
<tr>
<td><strong>Aim</strong></td>
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<tr>
<td><strong>Key soil properties for modification</strong></td>
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<tr>
<td><strong>Limiting site properties</strong></td>
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<td><strong>Limiting soil properties</strong></td>
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<tr>
<td><strong>Cautions</strong></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
</tbody>
</table>
5.3.2 Trafficability (establishment, thinning and harvest)

Trafficability depends on the machinery to be used (see Box 5-1) and is limited by exposed or shallow bedrock, steep slopes, drainage lines and erosion gullies, and high soil water contents.

Box 5-1: Trafficability

Trafficability

The ability to drive machinery onto a site without damage to the machinery or to the soil is referred to as trafficability.

The type of machinery changes with each stage of the farm forestry project:
- site preparation: tractor with plough, ripper or mounder, excavator, utility or tractor with herbicide spray equipment;
- site establishment: tractor with planting machinery;
- fertilisation: utility, truck or tractor with blower and flingers;
- insect control: utility, truck or tractor with misting equipment; and
- thinning and harvest: skidders, harvesters, processors, feller-bunchers, cable logging systems.

Technology is improving the ability of forest machinery to traverse difficult terrain. Cable logging systems are advantageous in steep, dissected country and have been used in pine plantations in eastern Australia. Cable logging systems have also been used in plantations on gentle to flat terrain that have high compaction or erosion hazard.

As an example, Table 5.9 provides a rating system designed for the hazards associated with the machinery used in forestry operations in Tasmania.

Table 5.9: Site factor assessment criteria for trafficability hazard ratings for forestry operations in Tasmania. Source: adapted from Laffan (1997).

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Trafficability hazard rating</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Negligible</td>
</tr>
<tr>
<td>Slope angle (%)</td>
<td></td>
</tr>
<tr>
<td>&lt; 20</td>
<td>20 – 30</td>
</tr>
<tr>
<td>Exposed bedrock (%)</td>
<td></td>
</tr>
<tr>
<td>&lt; 10</td>
<td>10 – 20</td>
</tr>
<tr>
<td>Drainage</td>
<td>Rapidly drained</td>
</tr>
<tr>
<td>Well-drained</td>
<td>Moderately well-drained</td>
</tr>
</tbody>
</table>

69
Chapter outline

The first stage in selecting the species for a farm forestry project is to decide the purpose for which trees are being grown. The JVAP book *Design Principles for Farm Forestry* (Abel et al., 1997) discussed the common reasons for planting trees on farms, including growing wood products, controlling dryland salinity and waterlogging, soil conservation, shade and shelter, producing fodder, nature conservation and scenic quality. This chapter describes some of the site characteristics that suit different tree species. Detailed information is available for the small number of species that currently dominate commercial wood production in Australia and this information is summarised in this chapter. Brief notes are also provided on about 25 other species used less commonly in farm forestry plantations, but some additional sources of information are suggested.

6.1 Introduction

Some farm forestry enterprises are part of established industries, such as *Pinus radiata* (radiata pine) for sawn timber, paper and cardboard, and *Eucalyptus globulus* (Tasmanian blue gum) for paper and cardboard. Others are involved in developing industries, such as mallees for electricity, activated carbon and eucalyptus oil. Generally, there is more information available on site suitability for species that are part of established industries than for the less widely-grown species. Some Australian tree species grown commercially in other parts of the world are not commonly planted in Australia. Examples include *Acacia mearnsii* (black wattle), *E. diversicolor* (karri) and *Grevillea robusta* (silky oak). These overseas experiences may be relevant in considering such species for farm forestry plantings in Australia.

If production of a commercial product is the primary aim, and only one species is acceptable to a local processing centre, then the selection process will be simple. If several species are being considered then this chapter will provide some basic introductory information about site requirements and help to identify which species are suitable for particular regions and sites. However, this short chapter can only provide a brief introduction to species selection and further information should always be sought from local advisory officers before planting commences.

The first part of the chapter summarises the site requirements of the nine tree species and one hybrid favoured by the plantation industry. The following sections discuss the information available for additional species that could be used in farm forestry projects. The importance of selecting the most suitable genetic material of a particular species is emphasised.

6.2 Species grown primarily for wood products

Industrial forest plantations in Australia are dominated by nine species: *P. radiata*, *E. globulus*, *P. elliottii*, *P. caribaea*, *P. pinaster*, *E. grandis*, *E. nitens*, *E. pilularis* and araucaria species (especially *Araucaria cunninghamii*). These species and hybrids such as *P. elliottii* x *P. caribaea* account for about 88% of the area of commercial plantations in Australia.
Access to processing facilities is an important factor for all commercial plantings. The distance between where the trees are grown and the processing facilities is a crucial factor in determining whether a farm forestry project with the primary aim of producing wood for income will be economically successful. Preferably, a plantation should be located less than 50 km from processing facilities, but distances up to 100 km or 150 km may also be suitable, depending on factors such as the value of the product and the quality of the roads. Where processing plants have been established, the companies running them usually require wood from particular species, so choosing those species provides growers with some assurance that they will find a market for their product.

The following descriptions are based largely on a report prepared by Jovanovic and Booth (2002). The climatic requirements were determined by assessing the conditions in the areas where the species grow naturally, where plantations have been established, and where successful trials exist. They are defined in terms of six simple factors:

- mean annual rainfall;
- rainfall regime: a site’s rainfall regime is classed as summer, winter or uniform – if the mean rainfall of the May to October period at a particular site exceeds the mean rainfall of the November to April period by more than 30% then the site has a summer rainfall regime; if the mean November to April rainfall exceeds the mean May to October rainfall by more than 30% then it is a winter regime; otherwise, the rainfall is uniform;
- dry season length (the number of consecutive months with less than 40 mm of rainfall);
- mean maximum temperature of the hottest month;
- mean minimum temperature of the coldest month; and
- mean annual temperature.

Descriptions of climatic conditions give a general indication of areas where the species may be worth considering, but results from any existing local plantings should always be considered before selecting a particular species.

6.2.1 Pinus radiata (radiata pine)

*Pinus radiata* is found naturally in a small area of California but it dominates commercial plantations in Australia: in 2000 the species accounted for about 717,000 ha or about 48% of the total plantation area (Wood et al., 2001). Softwood plantations were developed initially to complement the large existing source of hardwood from native forests. Many softwood species were tested, but *P. radiata* was found to be an outstanding performer under temperate conditions (i.e. warm summers, cool winters). It is typically grown in rotations of about 30 years with one or two thinnings. The thinning operations produce pulpwood and poles, while the final harvest produces timber suitable for uses such as house framing and relatively low-cost furniture. Table 6.1 lists the ranges of conditions for *P. radiata* and contains a map showing the distribution of the areas in which these conditions are found.
Table 6.1: Climatic conditions and maps of areas suitable for the ten most favoured plantation species (mean maximum temperatures are for the hottest month; mean minimum temperatures are for the coldest month)

### Pinus radiata (radiata pine)

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
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</thead>
<tbody>
<tr>
<td>Mean annual rainfall (mm)</td>
<td>650 – 1800</td>
</tr>
<tr>
<td>Rainfall regime</td>
<td>winter/uniform</td>
</tr>
<tr>
<td>Dry season length (months)</td>
<td>0 – 5</td>
</tr>
<tr>
<td>Mean maximum temperature (°C)</td>
<td>18 – 30</td>
</tr>
<tr>
<td>Mean minimum temperature (°C)</td>
<td>-2 – 12</td>
</tr>
<tr>
<td>Mean annual temperature (°C)</td>
<td>10 – 18</td>
</tr>
</tbody>
</table>

### Eucalyptus globulus (Tasmanian blue gum)

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
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</thead>
<tbody>
<tr>
<td>Mean annual rainfall (mm)</td>
<td>600 – 1500</td>
</tr>
<tr>
<td>Rainfall regime</td>
<td>winter/uniform (winter only in NSW)</td>
</tr>
<tr>
<td>Dry season length (months)</td>
<td>0 – 5</td>
</tr>
<tr>
<td>Mean maximum temperature (°C)</td>
<td>13 – 29</td>
</tr>
<tr>
<td>Mean minimum temperature (°C)</td>
<td>-1 – 12</td>
</tr>
<tr>
<td>Mean annual temperature (°C)</td>
<td>4 – 18</td>
</tr>
</tbody>
</table>
### Pinus elliottii x Pinus caribaea var. hondurensis hybrid (hybrid of slash pine and Caribbean pine)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean annual rainfall (mm)</td>
<td>750 – 1700</td>
</tr>
<tr>
<td>Rainfall regime</td>
<td>summer</td>
</tr>
<tr>
<td>Dry season length (months)</td>
<td>0 – 5</td>
</tr>
<tr>
<td>Mean maximum temperature (°C)</td>
<td>27 – 31</td>
</tr>
<tr>
<td>Mean minimum temperature (°C)</td>
<td>5 – 13</td>
</tr>
<tr>
<td>Mean annual temperature (°C)</td>
<td>18 – 23</td>
</tr>
</tbody>
</table>

### Araucaria cunninghamii (hoop pine)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean annual rainfall (mm)</td>
<td>900 – 2700</td>
</tr>
<tr>
<td>Rainfall regime</td>
<td>summer</td>
</tr>
<tr>
<td>Dry season length (months)</td>
<td>0 – 2</td>
</tr>
<tr>
<td>Mean maximum temperature (°C)</td>
<td>24 – 34</td>
</tr>
<tr>
<td>Mean minimum temperature (°C)</td>
<td>2 – 19</td>
</tr>
<tr>
<td>Mean annual temperature (°C)</td>
<td>15 – 26</td>
</tr>
</tbody>
</table>
### Pinus pinaster (maritime pine)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean annual rainfall (mm)</td>
<td>400 – 1200&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>Rainfall regime</td>
<td>winter/uniform</td>
</tr>
<tr>
<td>Dry season length (months)</td>
<td>0 – 8</td>
</tr>
<tr>
<td>Mean maximum temperature (°C)</td>
<td>22 – 31</td>
</tr>
<tr>
<td>Mean minimum temperature (°C)</td>
<td>0 – 8</td>
</tr>
<tr>
<td>Mean annual temperature (°C)</td>
<td>13 – 18</td>
</tr>
</tbody>
</table>

### Eucalyptus pilularis (blackbutt)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean annual rainfall (mm)</td>
<td>730 – 2460</td>
</tr>
<tr>
<td>Rainfall regime</td>
<td>summer/uniform</td>
</tr>
<tr>
<td>Dry season length (months)</td>
<td>0 – 4</td>
</tr>
<tr>
<td>Mean maximum temperature (°C)</td>
<td>22 – 31</td>
</tr>
<tr>
<td>Mean minimum temperature (°C)</td>
<td>3 – 12</td>
</tr>
<tr>
<td>Mean annual temperature (°C)</td>
<td>10 – 22</td>
</tr>
</tbody>
</table>

### Eucalyptus grandis (flooded gum)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean annual rainfall (mm)</td>
<td>725 – 3730</td>
</tr>
<tr>
<td>Rainfall regime</td>
<td>summer/uniform</td>
</tr>
<tr>
<td>Dry season length (months)</td>
<td>0 – 7</td>
</tr>
<tr>
<td>Mean maximum temperature (°C)</td>
<td>22 – 34</td>
</tr>
<tr>
<td>Mean minimum temperature (°C)</td>
<td>0 – 16</td>
</tr>
<tr>
<td>Mean annual temperature (°C)</td>
<td>12 – 25</td>
</tr>
</tbody>
</table>
**Eucalyptus nitens** (shining gum)

<table>
<thead>
<tr>
<th></th>
<th>700 – 2300</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mean annual rainfall (mm)</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Rainfall regime</strong></td>
<td>winter/uniform/summer</td>
</tr>
<tr>
<td><strong>Dry season length (months)</strong></td>
<td>0 – 5</td>
</tr>
<tr>
<td><strong>Mean maximum temperature (°C)</strong></td>
<td>19 – 29</td>
</tr>
<tr>
<td><strong>Mean minimum temperature (°C)</strong></td>
<td>-3 – 4</td>
</tr>
<tr>
<td><strong>Mean annual temperature (°C)</strong></td>
<td>5 – 17</td>
</tr>
</tbody>
</table>

*a: When planting *P. pinaster* in low rainfall environments, care should be taken to ensure that local conditions are suitable and appropriate planting densities are used.*

A system was developed to rank the suitability of sites for *P. radiata* (Turner et al., 1990; Turvey, 1987). The evaluation is related to parent rock, soil depth, impeding layer, texture of surface soil and surface condition (Turvey et al., 1990) and it is described in Chapter 7.

More recently simulation models, such as ProMod and 3-PG (see Chapter 7), have been calibrated to provide evaluations of site potential for *P. radiata*. For example, a simplified version of ProMod was produced for evaluating sites in Tasmania as part of *The Farm Forestry Toolbox* compact disc (Private Forests Tasmania, 1999; Warner, 2007). Maps indicating the broad-scale capability of land for *P. radiata* have been produced for several regions as part of the comprehensive regional assessments carried out in preparation for Regional Forest Agreements.

### 6.2.2 *Eucalyptus globulus* (Tasmanian blue gum, blue gum)

The National Plantations Inventory (Parsons et al., 2006) found that in 2006, *E. globulus* plantations covered over 454 000 ha, which accounted for 26% of Australia’s industrial and farm forestry plantations. Much of this expansion was in broad-scale plantations established by companies leasing or buying agricultural land for the purpose.

*Eucalyptus globulus* trees are usually grown in short rotations of about 10 to 12 years and most of the wood is used to produce pulp for making paper. The conditions where it is grown in Australia are listed in Table 6.1. *Eucalyptus globulus* subsp. *Globulus* is the subspecies most widely planted because it grows the fastest. The map in Table 6.1 shows where it is commonly planted. The subspecies *pseudoglobulus*, *maidenii* and *bicostata* may be worth investigation in Gippsland, mid coastal areas of New South Wales and around Dubbo, respectively. Overseas, *E. globulus* is sometimes grown in places with summer rainfall climates, such as Yunnan in China, but almost all plantations in Australia are currently in winter or uniform rainfall climates.

Harper et al. (1999) analysed climatic and soil factors affecting the growth of *E. globulus* at over 450 sites in Western Australia. They found that climatic factors (rainfall and evaporation), soil volume (estimated from the soil depth and the proportion of ferricrete gravel), soil fertility (assessed from the total nitrogen content) and the number of trees per hectare were particularly important.

Computer models, such as ProMod and 3-PG, have been calibrated to evaluate the capability of sites for *E. globulus*. *The Farm Forestry Toolbox* compact disc developed for Tasmania (Private Forests
Tasmania, 1999; Warner, 2007) includes a simple version of ProMod that is suitable for evaluating sites for E. globulus. Mummery and Battaglia (2001) generated a map of Tasmania predicting mean annual increment (the average annual increase in stand volume over the life of a plantation) for E. globulus across the state. This was produced by running the ProMod model for locations at intersections of grid lines 1 km apart. Several broad-scale land capability maps for E. globulus in other areas of Australia have been produced by the Bureau of Rural Sciences as part of the Regional Forest Agreement process (Waring and Baker, 1998).

6.2.3 Pinus elliottii x Pinus caribaea var. hondurensis hybrid (slash pine and Caribbean pine)

In the past, P. elliottii (slash pine) was the predominant plantation tree in south-eastern Queensland. P. caribaea (Caribbean pine) was and continues to be used in warmer climates further north in Queensland. However, the hybrid between the two species is now favoured for planting in south-eastern Queensland as it has superior growth rates, tolerance of poorly drained sites, wind-firmness and stem straightness and also has uniform wood quality. The individual species and the hybrid are grown in rotations of about 30 years for timber products used for house framing and furniture. Together these species comprise around 144,000 ha of plantations (Parsons et al., 2006). Areas where the hybrid is grown are usually within the climatic ranges listed in Table 6.1.

Low phosphorus levels can cause needle shortening, crown thinning and reduced growth. Poorly drained soils with accumulations of organic matter (classified as Podosols) are sometimes subject to copper deficiencies causing stem deformities and poor growth. Mycorrhizal fungi (which enhance a tree’s ability to absorb nutrients) are required on some low phosphorus soils.

6.2.4 Araucaria cunninghamii (hoop pine)

Araucaria cunninghamii (hoop pine) and other araucaria species accounted for about 45,600 ha of plantations in 2000 (Parsons et al., 2006). These plantations are mostly in south-eastern Queensland. Major new plantings are unlikely because the trees take a long time to reach maturity but the species does have potential for use on suitable agricultural land. The species is usually grown in rotations of about 60 years and the timber is used for furniture, panelling and plywood. Climatic requirements of A. cunninghamii are listed in Table 6.1.

In Queensland and northern New South Wales the older A. cunninghamii plantations (established before 1970) were planted on sites that were originally occupied by sub-tropical rainforest. In the southern areas these sites were mostly deep, fertile red or brown iron-rich soils (classified as Red and Brown Ferrosols). In Queensland, there was expansion of plantings onto non ex-rainforest sites, but there was still a preference for deep, fertile, well-drained red iron-rich and clayey soils (Red Ferrosols, Dermosols and Kandosols). In general deep, moist but well-drained soils of reasonable fertility are required for good growth and A. cunninghamii generally requires better sites than those used for exotic pines.

6.2.5 Pinus pinaster (maritime pine)

Pinus pinaster (maritime pine) is a species of major importance in Europe with about two million hectares of plantations in France. In Australia it is planted mainly in Western Australia and South Australia. The total plantation area in 2006 was estimated to be about 44,195 ha (Parsons et al., 2006). Share cropping schemes with farmers are being used to establish the plantations, with trees grown on 30- to 40-year rotations with at least two thinnings to produce a range of products, including sequestered carbon, pulpwod, wood panels and sawlogs (Ritson, 2004; Ritson and Sochacki, 2003). Western Australian plantings are also aimed at producing environmental co-benefits by lowering watertables and helping to control salinity problems.

Pinus pinaster has been successfully planted in Australia on well-drained, deep profiles of uniform sands and gradational loams (those fitting the Rudosol, Tenosol, Aeric Podosol Dermosol and
P. pinaster has been planted on soils considered too poor for P. radiata (Havel, 1968). It does not grow well on clayey or texture-contrast soils, but is particularly suitable for sandy and sandy loam soils.

6.2.6  **Eucalyptus pilularis** (blackbutt)

*Eucalyptus pilularis* (blackbutt) is found naturally in coastal areas from southern New South Wales (around Bega) to south-eastern Queensland (around Fraser Island). Managed natural forests of the species provide the main commercial source of sawn hardwood in northern coastal New South Wales and south-eastern Queensland. It has great potential as a plantation species for coastal areas within its natural distribution. The combined plantation area of *E. pilularis* and *E. grandis* was estimated to be 28 000 ha in 2006 (Parsons et al., 2006). The estimated climatic requirements of *E. pilularis* are listed in Table 6.1.

For good growth, *E. pilularis* requires deep, well-aerated soils. The species occurs naturally on well-drained, mid and upper slopes on sandy and earthy uniform or gradational profiles (soils in the orders Tenosol, Kandosol and Dermosol and Kurosols in which the clayey B horizon will not inhibit root growth or drainage). Any poorly-drained sites will not be suitable.

6.2.7  **Eucalyptus grandis** (flooded gum)

*Eucalyptus grandis* (flooded gum) is one of the most widely planted eucalypts with well over two million hectares of plantations around the world. In Australia there were estimated to be about 13 000 ha of plantations in 1994. Most plantations are in the Coffs Harbour area.

On the basis of an analysis of its natural distribution and the results of successful trials in Australia and overseas, Jovanovic and Booth (2002) estimated the climatic requirements for *E. grandis* plantations (Table 6.1). The map in Table 6.1 indicates areas climatically suitable for growing the species under rain-fed conditions. The species is also suitable for growing under irrigated conditions in dry parts of southern New South Wales and Victoria under the temperature conditions shown.

*Eucalyptus grandis* prefers lower slope, deep colluvial and alluvial soils (those classed as Tenosols, Kandosols, Dermosols and some in the Kurosol order) that have high moisture content, but are not saturated continually or show anaerobic features (i.e. not those classed as Hydrosols). Loam to light-medium clay B horizons are suitable but deep sands should be avoided. *E. grandis* also requires soils with moderate to high fertility. Despite its common name (flooded gum), it will only withstand very brief periods of flooding.

6.2.8  **Eucalyptus nitens** (shining gum)

*Eucalyptus nitens* (shining gum) is a significant plantation species in Tasmania and a small area of plantations has also been established in Victoria. Parsons et al. (2006) estimated the total Australian plantation area in 2006 to be about 143,000 ha. It is also used overseas in plantations, particularly in South Africa and Chile. In Australia and overseas it is used both for pulpwood and sawlog production. Table 6.1 shows estimates of the climatic requirements for *E. nitens* plantations based on an analysis of its natural distribution and the results of successful trials in Australia and overseas (Jovanovic and Booth, 2002). *Eucalyptus nitens* may grow successfully at the warmer end of the range of conditions shown in Table 6.1 but its main potential is at the cooler end on sites that are too cold for *E. globulus*.

*Eucalyptus nitens* grows best on well-drained, deep, earthy gradational and uniform soils (those in the orders Dermosol, Ferrosol or Kandosol). Texture-contrast soils and uniform sandy soils should be avoided. *Eucalyptus nitens* also requires moderate to high fertility soils.
6.3 Other species

The species described so far dominate commercial wood production. In terms of establishing a commercially viable farm forestry project, they will often be the safest options. In the appropriate areas, there is considerable experience in site selection, establishment and management of plantations of these species. There are also established markets for selling timber. There are, however, other species worth considering for commercial farm forestry.

Three species of particular interest are Corymbia maculata, Eucalyptus cloeziana and E. pellita. There has also been increasing interest in species suitable for low rainfall areas. The Australian Low Rainfall Tree Improvement Group (ALRTIG) has identified several species particularly suited to 400 mm to 600 mm mean annual rainfall environments. These include E. cladocalyx, E. occidentalis, E. sideroxylon and E. tricarpa, E. camaldulensis, P. brutia and several mallee eucalypts. ALRTIG are also working with C. maculata and P. pinaster. At the other extreme, a range of rainforest tree species are being used in farm forestry projects in northern Queensland. These are not discussed further in this report, but the JVAP report *Growing rainforest timber trees—A farm forestry manual for north Queensland* by Bristow et al. (2003) provides a guide to the site conditions suitable for different species based on natural distributions.

6.3.1 Corymbia maculata, Eucalyptus cloeziana and Eucalyptus pellita

The species formerly known as *Eucalyptus maculata* (spotted gum) has been split into three species belonging to a new genus *Corymbia*. *Corymbia maculata* occupies the part of the distribution of *E. maculata* south of the Manning River in New South Wales (Taree). The other two species are found further north: *C. henryi* is mainly along the coast and *C. citriodora* subsp. *Variegata* is inland. North of a line running inland from Fraser Island, *C. citriodora* subsp. *Variegata* merges with the closely related *C. citriodora* (lemon scented gum, also known as spotted gum in Queensland), which is generally found further north. Samples of *C. maculata* timber from plantations in low to medium rainfall environments (about 580 mm to 750 mm mean annual rainfall) of the southern Murray Darling Basin have produced good recovery rates of high-quality solid wood products. The species is best-suited to reasonably deep, well-drained soils of moderately heavy texture. Frosts are few and mild in its natural distribution and seedlings are vulnerable to frost damage. It is probably unsuited to areas where the absolute (i.e. record) minimum temperature is below –3°C. *Eucalyptus cloeziana* (Gympie messmate) is suited to sawlog production in high rainfall areas, such as parts of south-eastern Queensland. Spencer et al. (1999) have mapped areas suitable for *E. cloeziana* and also *C. citriodora* in south-eastern Queensland. *Eucalyptus pellita* (red mahogany) occurs naturally in north-eastern coastal Queensland and southern New Guinea. It has considerable potential as a plantation species for humid and subhumid tropical areas (mean annual rainfall of 1200 mm to 3000 mm, summer or uniform rainfall regime, dry season of 1 to 5 months, mean maximum temperature of hottest month of 24°C to 38°C, mean minimum temperature of coldest month of 10°C to 19°C and mean annual temperature of 19°C to 29°C). Harwood (1998) has reviewed the species characteristics. It grows best on well-drained clay loam soils, but reasonable growth can be obtained on less fertile sands and sandy loams if adequate fertilisation is provided. Its timber can be used for pulpwood or solid wood products.

6.3.2 Species for low rainfall zones

This section describes species suited to low rainfall zones, firstly mentioning those being investigated by ALRTIG.

*Eucalyptus cladocalyx* (sugar gum) occurs naturally in limited areas of South Australia on the eastern side of the Eyre Peninsula, towards the top of Spencer Gulf and on Kangaroo Island. It produces a heavy durable timber suitable for construction. The species is noted for its drought tolerance and its ability to grow on alkaline and saline soils. About 1000 ha have been planted near Colac in western Victoria and some encouraging results have been reported from trials near Mumbil and Condoblin in
New South Wales (Marcar, N., pers. comm.). This has also been planted in several projects in the medium rainfall (400-600 mm) zone of Western Australia.

_Eucalyptus occidentalis_ (swamp yate) is widely distributed in south-western Western Australia. The species is tolerant of poorly drained conditions and will withstand moderate to high levels of salinity (_EC_ up to about 1000 mS/m). The full range of its environmental requirements are yet to be determined, but it is worth considering for planting in areas with winter and uniform rainfall regimes in South Australia, Victoria, New South Wales and Western Australia. Its timber is durable and suitable for construction purposes.

_Eucalyptus sideroxylon_ and _E. tricarpa_ (red ironbark) are two closely related species. The natural distribution of _E. sideroxylon_ covers the area from Wangaratta in northern Victoria through the western slopes of New South Wales to south-eastern Queensland, while _E. tricarpa_ is restricted to central Victoria, Gippsland and south-eastern New South Wales. Both species prefer relatively well-drained sites. The species are worth considering particularly in areas within the 500 mm to 800 mm mean annual rainfall range. They produce wood suitable for posts, poles and construction, as well as furniture.

_Eucalyptus camaldulensis_ is the eucalypt with the widest natural distribution and is found in all states except Tasmania. It is widely grown around the world in arid and semi-arid conditions. The Petford (Queensland) and Katherine (Northern Territory) provenances are favoured in hotter environments and the Lake Albacutya (Victoria) provenance has been outstanding among samples from southern Australia. Like _E. occidentalis_, the species can tolerate waterlogging and moderate salinity, but poor stem form is a problem. Hybrids and clones are being developed to produce trees that are faster growing and better adapted to marginal sites. The wood is suitable for flooring, framing, railway sleepers, fencing and charcoal.

The ALRTIG project is also working with _P. brutia_ (brutian pine). Its natural distribution includes eastern Mediterranean countries such as Italy, Greece, Iraq, Syria, Lebanon and Turkey. Although not widely tested in Australia, it is expected to be suitable for winter rainfall sites with mean annual rainfall around 350 mm. Unlike _P. pinaster_ it is suitable for shallow, heavy clay and highly alkaline sites.

Since the early 1990s, there has been a concerted effort to establish an oil mallee industry in the wheatbelt of Western Australia (Bartle, 2001) with the combined aims of producing oil, fuel wood and activated charcoal and of reducing groundwater recharge. Several species of oil mallees are being planted in the Western Australia wheatbelt as short rotation crops in areas with mean annual rainfalls around 400 mm. The recommended layout is belts about 10 m wide and about 100 m apart (Bartle and Shea, 2002). They are being grown to supply biomass for electricity generation, eucalyptus oil and activated carbon. Mallees have also been planted as a carbon sink in several projects across Australia. The ALRTIG project includes several oil mallee eucalypts from Western Australia including _E. angustissima_, _E. horistes_, _E. kochii_ subsp. _Kochii_, _E. kochii_ subsp. _Plenissima_, and _E. loxophleba_ subsp. _Lissophloia_, and _E. polybractea_ from eastern Australia.

_Santalum spicatum_ (southern sandalwood) has traditionally been harvested from natural stands in Western Australia. Since the late 1990s, it has been planted on farmland in the agricultural areas of southern Western Australia, and _Santalum album_ (Indian sandalwood) has been established in plantations in the Ord River Irrigation Area in the north of the state. The trees are harvested for the aromatic oil held in their heartwood. Since sandalwood trees are parasitic, their roots need a host tree, and for _S. spicatum_, the usual hosts are acacias and allocasuarinas. Denham (1998) recommended that, for commercial plantings, mean annual rainfall of at least 350 mm was required, although in its natural range it is found in areas with as little as 200 mm mean annual rainfall. He noted that even though the trees can take decades to reach harvestable size, the high value of the oil meant that they could compete favourably with grazing and cropping enterprises in higher rainfall zones. One additional advantage is that they can be established in areas of degraded or sparse remnant vegetation if suitable hosts are present. The best soils are those that suit the host species, usually sandy soils formed on granitic rocks which have pH values in the neutral to slightly acidic range (Denham, 1998).
There are many other species that can be considered for commercial wood production in farm forestry projects. They include species that produce high-value timbers, but such trees usually need higher-quality sites and take longer to grow than the most common commercial species. Species that produce less wood than commonly planted commercial species may have additional advantages, such as being more tolerant of particular environmental conditions. The JVAP book *Trees, Water and Salt* (Stirzaker et al., 2002, p. 116) summarises the environmental requirements and potential uses of some of these species.

Information on a wide range of species is available electronically:

- most RIRDC publications are available at www.rirdc.gov.au; and
- the REX revegetation database and associated software is available as a compact disc.

Information in-print includes:

- *Trees for Rural Australia* (Cremer, 1990);
- *Trees for Saltland: A Guide to Selecting Native Species for Australia* (Marcar et al., 1995);
- *Australian Trees and Shrubs: Species For Land Rehabilitation and Farm Planting in the Tropics* (Doran and Turnbull, 1997); and
- *South West Slopes Revegetation Guide* (Stelling, 1998), which was produced for southern New South Wales.

### 6.4 Species/provenance trials and genetic improvement

Trees of the same species, but collected from different parts of its natural distribution (different *provenances*), may not respond in the same way to a particular set of climatic and ground conditions. For instance, some may be more vigorous under nearly all circumstances, while some may be less susceptible to frost or salinity. Therefore, if the aim of the farm forestry project is to produce commercial products, then identifying a suitable species is only the first stage in selecting the best tree for a particular site. It is important to select the best genetic material from the chosen species. The cost of seedlings is a very small fraction of the total cost of growing a tree crop. The best provenance of a particular species will be much more productive than a poorly adapted provenance. It usually costs as much to plant, manage and harvest a poorly selected provenance as it does a high performing provenance.

In the past, selecting the best provenance has been enough, but increasingly improved genetic material is becoming available as a result of tree breeding (Eldridge et al., 1993). The ALRTIG was established with the aim of ‘producing genetically improved planting material for farm forestry in low rainfall areas of southern Australia, and inform tree growers of its availability’ and now has information on its ten key species (Harwood and Bush, 2002).

Improved genetic stock may come in the form of improved seed produced by tree breeding, interspecific hybrids or clones. Hybrids include crosses such as *E. camaldulensis x E. grandis*, which has been used in Brazil and South Africa in areas too dry for *E. grandis*. Clonal material is genetically identical and requires mass vegetative propagation. Extensive clonal plantations of eucalypts have been established in locations such as Aracruz (Brazil) and Pointe Noire (Congo), but have so far been little used in Australia because of the costs of propagation and the difficulties of propagating temperate eucalypts. Research that compared seven cloned selections of *E. camaldulensis* concluded that there was potential for commercial wood production on land with shallow saline watertables (Bennett and George, 1996).

Genetically modified forest trees are not yet available in Australia, but experiments have been carried out overseas, for example to provide eucalypts with resistance to the herbicide glyphosate. Whether improved seed, hybrids or clones are selected it is important to determine their suitability for the selected site. A particular hybrid may perform magnificently at an overseas site, but that is no guarantee that it will be the best tree to plant at an Australian site. It is important to choose the best possible material, but it is also essential to consider results from local trials.
7. Estimating Tree Growth Using Site Variables

T. H. Booth, P. J. Ryan, R. J. Harper and R. J. Gilkes

Chapter outline

A major task facing managers of commercial farm forestry projects is to predict tree performance from site factors and management. A range of assessment systems has been developed to assist in evaluating the potential productivity of a site. The purpose of this chapter is to provide some introductory information about the systems and the relevant computer models. The aim is to outline the input data required, the main features of how each system and model works and the output produced. The descriptions also indicate which methods are suited to different tasks.

7.1 Introduction

This chapter focuses on those farm forestry projects designed to generate wood products for profit. To estimate the income that a farm forestry project is likely to produce, the yield has to be estimated. Chapters 2 and 4 described how to collect most of the information that the various tree growth models require as input. During the life of a farm forestry project, the model results can be checked by periodically measuring tree growth.

The systems and models developed to estimate the potential productivity of sites include:

- regression models;
- ratings systems; and
- simulation models.

Regression models and ratings systems are called empirical methods because they rely on relationships derived from measuring the performance of existing trees. Simulation models using calculations that attempt to replicate the processes that produce tree growth under the conditions existing at a particular site are called physiological models. It should be stressed that the output from these approaches is often only indicative, and detailed work is required in a region to produce accurate models.

For example, assessments of many plots in mature plantations were needed to produce rating models for *Pinus radiata* in South Australia, such as described in Lewis et al. (1976). Usually, when a new species is introduced into a region, calculations of its potential yield are based on scanty information and a limited number of trial plots. In such circumstances it is important that results of calculations are not used without noting the assumptions involved.

For farm forestry, the effort expended on predicting yields will depend on the purpose of the planting and the size of the investment being made. The choice of model will depend on whether the model was designed as a researcher’s tool or was intended for wide use.
The term *site index* is used throughout this chapter. It is explained in Box 7-1.

**Box 7-1: Site index**

*Site index* is an expression of the site quality of a forest stand, at a specified age, based on the *top height*. Top height is the average height of the hundred trees of largest diameter per hectare. Typically, the specified, or *index*, age is at least two thirds of the rotation age (i.e. the period between establishment and final harvest). For example, 20 years is commonly used for *Pinus radiata* (radiata pine) stands grown for sawlogs, but 10 years may be used for short rotation *Eucalyptus globulus* (Tasmanian blue gum) trees grown for pulp. Site index is a useful measure because it provides a good indication of the quality of a site relatively unaffected by the stocking rate (i.e. number of trees per hectare).

This chapter aims to introduce the topic of yield estimation, list the data required to make calculations, outline the mechanics of the main methods used, discuss the situations in which they are appropriate, and describe the results that can be produced. It firstly covers empirical methods, and then physiological ones.

### 7.2 Empirical models

#### 7.2.1 Regression studies

Regression studies relate a *response variable* (e.g. growth of trees) to one or more *explanatory variables*, such as rainfall and soil volume. Regression models have been used in many overseas studies to predict tree performance (Carmean, 1975). Australian examples include models for *Eucalyptus globulus* (Tasmanian blue gum) (Inions, 1992) and *Pinus pinaster* (maritime pine) (Ritson, 2004) in south-western Australia, based on a range of soil and climatic attributes. Booth et al. (2007) assessed growth and environmental conditions at 97 farm forestry plantation sites in south-eastern Australia. The site index of these stands ranged from 3 to 25 m at 10 years of age. They used multiple regression analysis to relate the site index measurements to factors indicating the different species (*E. grandis* (flooded gum), *E. globulus*, *E. saligna* (Sydney blue gum), *E. camaldulensis* (river red gum) and *Corymbia maculata* (spotted gum)), soil salinity, soil pH, and indices related to temperature, solar radiation, soil moisture and evapotranspiration. The regression model accounted for about 70% of the variance in the data (100% would be a perfect fit) and the mean error was 2.74 m (Figure 7.1).
The nutrient content of the soil is a major component of many of the regression equations that have been developed (Burkhart and Tennent, 1977; Schmidt and Carmean, 1988). Despite the strong correlations between the nutrient content and tree production that researchers have observed, there are limits on the use of soil nutrient analyses for making yield predictions. Chemical properties of soils are known to vary greatly over short distances and short time spans. Webster (1985), for example, illustrated that some soil attributes may vary by as much as 50% over a scale of several metres. Another reason for caution when interpreting relationships between soil nutrient status and tree growth is that a strong correlation does not necessarily imply 'cause and effect'. Site index studies are performed on mature stands of trees. Trees can modify soil fertility (Barth, 1980; Turner and Kelly, 1985), and fertilisers can be applied to trees during the course of the rotation (Flinn et al., 1979; Hunter and Graham, 1983). Therefore, the nutrient status used in regression studies may be different to that which influenced tree growth. It may not be valid to predict the site index based on the nutrient content of an unplanted area using relationships developed by analysis of nutrient content under mature trees.

Similarly, regression studies include measurements of nutrients in the soil such as nitrogen and phosphorus, but care is needed in interpreting these factors. Whereas attributes such as available water storage are characteristic of a site and cannot be easily modified, the content of N and P can be readily manipulated by the application of fertilisers. Sites will have a particular potential (often strongly influenced by their available water storage), and the degree to which this potential is met will depend on variables such as nutrient content.

As an example, consider identical soils on land previously cleared and developed for agriculture and land remaining uncleared. The fertility levels of the two sites will be quite different, and so will potential growth. The site with lower fertility will, with a regression equation, have a lower apparent yield, and may be rejected despite the potential for nutrient response. The decision to accept or reject should be based on the economics of the likely response of trees to fertilisation, and this can only be derived from soil analysis and comparison with calibrations between nutrient content and plant response. It is therefore desirable to indicate the potential of a site and the inputs needed to reach that potential. Potentially productive sites should not be discarded on the basis of requiring fertiliser, as nutrient status should be viewed as a variable that can be modified to produce a particular level of production.
7.2.2 Site ranking systems

Ranking systems divide land into areas according to their potential productivities. Three ranking systems are used as illustrations of the approach: one, designed by Baker and Broadfoot (Baker and Broadfoot, 1977; Baker and Broadfoot, 1979), was intended for commercial hardwoods in the United States of America; one, designed by Turvey (1987), was designed for pine plantations; and the third, by Laffan (1997), was aimed at tree farms in Tasmania.

The Baker and Broadfoot (1979) empirical site classification system was designed to:

- accurately predict site index under any soil or site condition;
- use soil properties important to tree productivity; and
- provide guidelines for soil management and amelioration.

These design criteria made it one of the first soil technical classifications tailored for commercial forestry. The Baker and Broadfoot (1979) classification assumed that four main soil ‘factors’ affected stand site index:

- soil physical condition;
- water availability during the growing season;
- nutrient availability; and
- aeration.

Each of these factors was assumed to be responsible for a certain percentage of tree growth (selected qualitatively). Each of the soil factors was considered to be affected by a set of soil ‘properties’, so the percentage of tree growth resulting from each factor was further divided between the relevant soil properties (Table 7.1).

Table 7.1: Contributing soil factors and properties and their relative percentage contributions to the estimation of southern hardwood site index for cottonwood (Baker and Broadfoot, 1979)

<table>
<thead>
<tr>
<th>Physical condition (35%)</th>
<th>Moisture availability (35%)</th>
<th>Nutrient Availability (20%)</th>
<th>Aeration (10%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>soil depth and pans (53%)</td>
<td>water table (20%)</td>
<td>geologic source (30%)</td>
<td>structure (25%)</td>
</tr>
<tr>
<td>texture (25%)</td>
<td>pans (20%)</td>
<td>past use (20%)</td>
<td>swampiness (25%)</td>
</tr>
<tr>
<td>compaction (20%)</td>
<td>topographic position (15%)</td>
<td>% organic matter (15%)</td>
<td>mottling (25%)</td>
</tr>
<tr>
<td>structure (10%)</td>
<td>microsite (15%)</td>
<td>topsoil (10%)</td>
<td>colour (25%)</td>
</tr>
<tr>
<td>past use (10%)</td>
<td>structure (10%)</td>
<td>soil age (10%)</td>
<td></td>
</tr>
<tr>
<td>texture (10%)</td>
<td>pH (10%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>flooding (5%)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>past use (5%)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Each soil property would then be categorised into three classes (best, medium and poor) based on specific criteria, and the contribution of the soil property to tree growth (and site index) was adjusted according to the class. Choice and relative ranking of each soil property was based on field experience of each tree species. Therefore, relevant and reliable information is required before the system can be applied. This is the main weakness of the system. Emphasis on soil factors influencing the soil water and nutrient regime of the tree species plus the use of soil properties that could be determined in the field are notable strengths of this system. However, it is questionable whether it is appropriate to use such an arbitrary classification to estimate an indirect productivity measure such as site index.
The second system, called the Technical Soils Classification (TSC), was designed to provide a means of objectively classifying land already under, or being considered for, pine plantations in eastern Australia, using soil attributes observable in the field. The objectives of the TSC were stated by Turvey (1987) as:

- to allow stratification of forest areas into uniform units for scheduling wood production and soil-based silvicultural management;
- to provide a basis for extrapolation of research results within and between forest areas; and
- to allow for a systematic accumulation of soil information relevant to forest productivity, nutrition and management practices on a computer database.

Eight soil properties were chosen and divided into two groups:

**Group A**

- parent rock: type and degree of consolidation;
- soil texture profile form; and
- effective regolith depth: depth to root impeding layer and type of impediment.

**Group B**

- texture of the uppermost 10 cm of soil;
- condition of the uppermost 10 cm of soil;
- character of surface soil horizons or layers;
- condition of subsoil; and
- colour of subsoil.

Group A attributes alone were considered relevant at small scales (for state or regional forest management), while Groups A and B combined were important at large scales (for plantation land unit or compartment management). Each attribute is described in detail by Turvey (1987) and reasons for their selection are outlined by Turner et al. (1990).

A series of 11-year-old *P. radiata* stands (unfertilised and unthinned) were chosen across New South Wales, Victoria and South Australia to test the a priori assumptions that the eight chosen soil properties were the most important ones for predicting plantation productivity. For 181 sites measured, Turvey et al. (1990) showed that all eight TSC soil properties except for texture profile were significantly related to **merchantable volume** (i.e. the amount of sound wood in a single tree or stand that is suitable for marketing under given economic conditions). Statistical analysis showed that the combined effect of all the TSC soil properties accounted for 75% of the variations in plantation productivity.

It was intended that the TSC be used within a climatic envelope suitable to pine species. However, the TSC did not include climatic variables or a direct measure of available soil water storage and these were large weaknesses if it was to be applied to potential farm forestry areas.

The third system was based on the Food and Agriculture Organisation’s classification system for land suitability (FAO, 1976; FAO, 1984) and was applied to the assessment of land for tree farms in Tasmania by Laffan (1997). Laffan proposed that a land suitability classification for plantations should consider land qualities that affect:

- site productivity; and
- plantation management and land degradation.

These land qualities are listed in Table 7.2.
Table 7.2: The main land qualities influencing land suitability for farm forestry in Tasmania (Laffan, 1997)

a: Land qualities affecting site productivity

<table>
<thead>
<tr>
<th>Land Quality</th>
<th>Component Land Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature regime</td>
<td>Altitude; aspect; landform</td>
</tr>
<tr>
<td>Moisture availability</td>
<td>Mean annual rainfall; soil moisture storage based on field texture, regolith depth and stone content; drainage; native vegetation</td>
</tr>
<tr>
<td>Drainage</td>
<td>Soil drainage</td>
</tr>
<tr>
<td>Rooting Conditions</td>
<td>Effective rooting depth; ease of root penetration based on texture, soil structure and stone content</td>
</tr>
<tr>
<td>Nutrient availability</td>
<td>Total phosphorus; total nitrogen; organic carbon</td>
</tr>
</tbody>
</table>

b: Land qualities affecting plantation management and land degradation

<table>
<thead>
<tr>
<th>Land quality</th>
<th>Component land characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trafficability</td>
<td>Slope; exposed bedrock; surface boulders; drainage</td>
</tr>
<tr>
<td>Flood hazard</td>
<td>Landform; soil profile development</td>
</tr>
<tr>
<td>Erosion hazard</td>
<td>Water-stable aggregates; permeability; drainage; soil strength; stone content; frequency of high intensity rainfall</td>
</tr>
<tr>
<td>Landslide hazard</td>
<td>Geology; soil properties; slope angle; landslide history</td>
</tr>
</tbody>
</table>

The Productivity Class (in terms of maximum mean annual increment, $MAI$, Table 7.3) of a site is assessed from the various soil and climatic attributes affecting tree growth. Site suitability is then assessed by taking into account management constraints and land degradation hazards in addition to site productivity (Table 7.4). While all the critical land qualities relevant to plantations can be described and a number of land characteristics can be proposed for each land quality, the actual ranking or rating can be specific to a region or a species.

Table 7.3: Site potential productivity classes for farm forestry in Tasmania (Laffan, 1997). Note that Class 1A and 1B can be combined.

<table>
<thead>
<tr>
<th>Productivity class</th>
<th>Productivity (m³/ha/y)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1A</td>
<td>very high</td>
</tr>
<tr>
<td>1B</td>
<td>high</td>
</tr>
<tr>
<td>2</td>
<td>medium</td>
</tr>
<tr>
<td>3</td>
<td>low</td>
</tr>
<tr>
<td>4</td>
<td>very low</td>
</tr>
</tbody>
</table>
Table 7.4: Site suitability classification for farm forestry in Tasmania (Laffan, 1997)

<table>
<thead>
<tr>
<th>Class</th>
<th>Designation</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Highly suitable</td>
<td>Land having negligible or slight limitations affecting site productivity (Productivity Class 1), and with negligible or slight management limitations or degradation hazards.</td>
</tr>
<tr>
<td>2</td>
<td>Moderately suitable</td>
<td>Land having moderate limitations affecting site productivity (Productivity Class 2), or land having higher productivity but with moderate management limitations or degradation hazards.</td>
</tr>
<tr>
<td>3</td>
<td>Marginally suitable</td>
<td>Land having severe limitations affecting site productivity (Productivity Class 3), or land having higher productivity but with severe management limitations or degradation hazards.</td>
</tr>
<tr>
<td>4</td>
<td>Unsuitable</td>
<td>Land having very severe limitations affecting site productivity (Productivity Class 4), or land having higher productivity but with very severe management limitations or severe to very severe degradation hazards.</td>
</tr>
</tbody>
</table>

7.3 Physiological models

Recently, simplified physiological models of forest growth have been developed. These simulation models can be used to assist site evaluation. This section provides some introductory information about a selection of the models.

7.3.1 Growest

The Growest (Fitzpatrick and Nix, 1970) model was one of the first computer models to be used experimentally for assisting land evaluation in Australia. The model calculates a weekly growth index ranging between zero (no growth) and one (maximum growth) by multiplying light, temperature and moisture indices (each ranging between zero and one). The weekly growth indices can be summed to give an annual index, which can be related statistically to actual growth at different sites. The relationship for the moisture index uses a simple water balance similar to that described in Chapter 2. The relationships for light and temperature are shown in Figure 7.2. The temperature index is the main factor that can be changed for different species. Minimum, optimum, and maximum temperatures for growth define the temperature response.

The growth index accounted for growth across 18 _P. radiata_ sites much better than simply using mean annual rainfall (Booth and Saunders, 1980). Its capacity to account for annual variations in _P. radiata_ growth was also tested using annual data for more than forty years from 85 permanent plots in four forests in the Australian Capital Territory. The index was far superior to either total rainfall or seasonally effective rainfall when accounting for annual variations in growth, reducing the total residual sum of squares by almost 20%.

Growest was designed as a general plant growth prediction model and it has been largely superseded by specialised models for predicting tree growth. However, indices from Growest were used in the regression analysis of farm forestry sites in south-eastern Australia described by Booth et al. (2007) (Figure 7.2). Growest and its associated climatic database were also developed into the Climex package (Sutherst and Maywald, 1985) by the addition of factors to account for the extremes of hot and cold as well as wet and dry conditions. The Climex package continues to be widely used to assess pest and disease risks.
7.3.2 Plantgro

The Plantgro model (Hackett, 1991) was originally developed to assist the selection of plants for growing in village gardens in Papua New Guinea. The developer recognised that a small number of highly detailed models were available for the dozen or so crops that dominate world agricultural trade. In contrast, no general system existed to simulate the growth of the hundreds of other plant species, including trees. The aim was therefore to develop a system for which preliminary descriptions for lesser-known species could easily be created. The program comes with data for about fifty species, including some trees. Preliminary data files for over 400 tree species have been created, though it is important to emphasise that most of these files need testing and further refinement.

The water balance calculations of Plantgro have already been described in Chapter 2. The solar radiation calculations use a relationship much like that used by Growest (Figure 7.2). The temperature relationship is similar to the degree day system, where units are accumulated above a defined base temperature. For example, a 12°C day would contribute two day-degrees if the base temperature was 10°C. Plantgro uses a slightly more complex calculation which assumes a curvilinear relationship.
between development and temperature, thus allowing for changes in temperature through the day. *Plantgro* can be run using monthly, ten-day or weekly climatic data.

Unlike *Growest*, which only considers available soil water storage and the effects of soil texture on water retention, *Plantgro* evaluates 11 soil factors, including nitrogen, phosphorus, potassium, pH, and salinity. These are evaluated along with the climatic factors using *notional relationships*, which are simple graphs representing what are often best guesses for likely responses. For example, Figure 7.3 shows the notional response for soil pH (i.e. soil acidity or alkalinity) for *Eucalyptus grandis*. If a particular site had a soil pH of 5 then Figure 7.3 would indicate a limitation rating of 6. Limitation ratings for several factors are estimated. *Plantgro*’s limitation ratings are constrained between zero and nine. As they are limitations, a rating of zero indicates ideal conditions and a rating of nine indicates totally unsuitable conditions (i.e. plant death). Factors are combined using Liebig’s *Law of the Minimum*. This simply means that the most limiting factor determines the growth rate. The presence of other factors in excess quantities does not compensate for limitations with another factor.

![Figure 7.3: An example of a Plantgro notional relationship for soil pH for Eucalyptus grandis. The optimum soil pH for this species is between 5.5 and 6.5.](image)

*Plantgro* is relatively easy to understand. Models such as *ProMod* and *3-PG* probably provide more accurate growth predictions for well-known trees species, but *Plantgro* encourages the use of preliminary estimates and may be easier to set up for lesser-known species. It may also be of interest to farmers as the model can also predict the growth of farm crops other than trees.

A simplified version of *Plantgro* has been incorporated into a simulation mapping program which allows limitation ratings to be estimated for over 11 000 locations across Australia (Booth, 1996). The model has also been used to evaluate farm forestry potential in southern Queensland and northern New South Wales (Norman et al., 2002).
7.3.3 ProMod

A 1995 workshop identified that forest managers needed a simulation model and ProMod was developed to meet this need (Battaglia and Sands, 1997). Unlike either Growest or Plantgro, ProMod was designed from the outset as a tree growth model.

As mentioned in the climate section (Chapter 2), the ability of trees to capture solar radiation is an important influence on tree growth. ProMod calculates closed-canopy leaf area index from mean annual rainfall and temperature at a site, and a simple index of site fertility (Figure 7.4). Day-to-night temperature variations are taken into account in a similar way to that in Plantgro, but possible seasonal adjustments of photosynthesis to current conditions are also assessed. A simple water balance calculation is made, but this includes a relationship to take into account vapour pressure deficit effects. The main output from the model is peak annual increment, which is the mean annual increment at the age at which mean annual increment has its maximum value. For most sites in Australia, peak MAI is usually close to MAI at 10 years. An analysis of the relative limitations of various environmental factors on growth can also be produced.

![Figure 7.4: Summary of the conceptual relationships in ProMod. Source: adapted from Battaglia and Sands (1997).](image)

Input data required by ProMod are generally simpler than Plantgro. The aim was to only use data that would be readily available to forest managers or data that could be cheaply obtained. Site factors include the latitude, longitude and elevation of the site and the number of trees per hectare.
Soil factors include texture, stoniness, depth of soil, presence or absence of any features impeding root development and a salinity measure. In contrast to the detailed soil chemical information required by Plantgro, ProMod uses only a simple index of soil fertility with grades of 0 to 4 (where 0 represents fully fertilised sites, 1 represents the most fertile sites and 4 represents the least fertile sites). Climatic factors include monthly mean values of daily maximum temperature, daily minimum temperature, solar radiation, precipitation, pan evaporation and number of rain days. These can be obtained from local records or estimated from the site location data using ESOCLIM (see Chapter 2). For land evaluation purposes the program is usually run with monthly mean data, but actual daily measurements can be used for detailed growth studies.

ProMod was originally calibrated to predict the growth of E. globulus using data from research sites in Tasmania and Western Australia. Testing of the model has shown that it can provide good predictions of tree growth. However, care is needed when it is used for the first time in a new area. As with any model, incorrect estimates may be made if locally important factors are not taken into account. For example, it was necessary to add a salinity factor when the model was first used in some areas of Western Australia as the simple soil fertility factor did not consider this limitation.

ProMod settings have been developed to simulate E. nitens and P. radiata as well as E. globulus and settings for other important species are under development. Developing appropriate settings for other species (parameterisation) requires detailed information on factors such as canopy development. It is more complex than the notional relationship approach of Plantgro, but should provide more reliable growth predictions.

ProMod is well suited to site evaluation studies involving species of major importance. It has been used for studies of small numbers of sites as well as evaluating thousands of sites to provide maps of growth potential for a 1000 m grid across the whole of Tasmania (Figure 7.5). It has also been used to estimate the potential productivity of P. radiata, E. globulus and E. nitens in a 2.8 km grid across areas of the Murray Darling Basin receiving more than 400 mm annual rainfall (Booth et al., 2007). As it concentrates on predicting peak mean annual increment it does not include predictions of stand development, but these can be provided by linking the program’s outputs with conventional forest growth models. It has also been used to predict the effects of irrigation on the growth of farm forestry plantations.
A simplified version, suitable for use by extension workers and farmers in Tasmania, has been circulated on *The Farm Forestry Toolbox* compact disc (Private Forests Tasmania, 1999; Warner, 2007).

### 7.3.4 3-PG

Following the development of *ProMod*, Landsberg and Waring (1997) developed another simple tree growth model called *3-PG* (*Physiological Principles in Predicting Growth*). Its components are summarised in Figure 7.6. Gross primary production is predicted by adjusting light interception for the effects of soil moisture, vapour pressure deficits and stand age. Two major differences compared with *ProMod* are the treatment of respiration and stand development. *3-PG* does not make separate calculations for respiration, assuming that the ratio between net and gross primary production is constant. In contrast to *ProMod*, *3-PG* does not concentrate on the prediction of peak mean annual increment, but simulates stand development over time. Input data requirements are similar to *ProMod*.

Like *ProMod*, *3-PG* is well suited to site evaluation either for small numbers of sites or for broadscale assessments using GIS. In collaboration with CSIRO, the Bureau of Rural Sciences has written a version of *3-PG* called *3PG-Spatial* for use within a GIS. This enables the model to be run for thousands of locations, and maps to be generated indicating potential productivity across particular
regions. Evaluations of plantation potential were made for several regions as part of the Regional Forest Agreement process.

There are two key soil attributes required to run 3-PG. The first is plant available soil water holding capacity and the second a fertility index. If 3PG-Spatial is to be used then these soil data need to have a spatial context. McKenzie and Ryan (1999) and Ryan et al. (2000) have shown how such spatial soil models can be developed over forest areas using modern digital technologies.

A modification to 3-PG allows potential forest productivity to be checked against actual forest productivity. 3PG-Spatial uses satellite remote sensed data to estimate leaf area index (Coops, 1999; Coops et al., 1998). This is another important means to enable this physiological model to be run spatially to monitor and predict actual and future forest growth (Coops, 1999).

There are, however, several limitations with both 3-PG and ProMod that require further development for their full spatial application to most farm forestry sites.

Figure 7.6: Diagrammatic representation of the inputs, constants and sequence of calculations used in the 3PG-Spatial model. Source: Landsberg and Coops (1999).

7.3.5 CABALA

Both ProMod and 3-PG were designed initially as simple models to assist land evaluation. The CABALA (CArbon BALAnce) model has been developed to simulate stand growth in more detail so that the effects of silvicultural decisions, such as thinning and fertilisation, can be simulated (Battaglia et al., 2004). It can also provide managers with valuable information on the potential impact of frosts, drought, pests and disease. It is being used in some circumstances for site evaluation, though its requirements for data are considerably greater than those of either ProMod or 3-PG. The current
version is calibrated for *Eucalyptus globulus*, but work is underway developing versions for *Eucalyptus nitens*, *Pinus radiata* and sub-tropical eucalypts.

### 7.3.6 APSIM

APSIM (the Agricultural Production Systems Simulator) is designed to combine the computer operations of sets of modules to simulate the productivity of agricultural crops (Keating et al., 2003). Modules include, for instance, soil water, nutrient cycling and crop growth models. A forestry module has been developed (Huth et al., 2002). It calculates daily growth using relationships between the amount of solar radiation intercepted and the efficiency with which the radiation is used, adjusting for limitations imposed by temperature, nutrients, vapour pressure deficit and soil water supply. The daily growth is divided between leaf, stem, bark, branch, taproot, and roots according to the tree’s size and the available water and nutrients.

APSIM is more versatile than individual models such as 3-PG and ProMod because more than one type of module is available for both soil water and nutrient processes. This allows the selection of appropriate modules for the available data and the purpose of the modelling. It has been used to simulate the production of plantation trees under different irrigation and fertiliser regimes, the growth of plantation trees and accumulation of salt in the soil at a site with a shallow saline watertable, and the competition between annual crops and trees in agroforestry systems (Huth et al., 2002). One of the main limitations in applying the APSIM process to modelling agroforestry systems is the lack of data on tree-crop interactions.
8. Summary

This report has described the procedures involved in evaluating sites for farm forestry projects. The procedures can be applied to all farm forestry projects, whatever their aims and expected financial returns.

The main stages in evaluating sites can be summarised as collecting and interpreting relevant data and information.

Collecting data and information is relatively straight-forward. In general, climatic data are readily available for most farming districts in Australia and they can be supplemented by local experience of conditions such as frost. However, field surveys will usually be required to collect information needed on the other main site conditions—soil water regime, soil nutrient regime and site hazards.

Interpreting the collected information relies on knowing the conditions best-suited to different tree species, and knowledge is lacking for all but the most common plantation species in the areas where they have traditionally been grown. This means that the site evaluations carried out in a district in the early days of farm forestry should aim to identify any conditions likely to limit tree growth, rather than look for conditions that might be optimum for growth. However, as farm forestry research trials are completed and operational experience is gained by growers across the district, we can expect more sophisticated interpretations of site evaluation information. The procedures outlined in this report are intended to be applicable across the range of stages of development of farm forestry enterprises.
9. References


Hong, Y., 2001. Frost prediction for Australian tree species in China, Australian National University, Canberra.


