Tree and Forest Measurement

P.W. West

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2nd Edition

With 33 Figures and 11 Tables

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To Mickie, for sharing so much

Preface

Since the first edition of this book was published in 2004, two areas of forest measurement have advanced considerably. Concerns about global warming and recognition that forests remove the greenhouse gas, carbon dioxide from the atmosphere and sequester it have led to a flourishing of research on the measurement of forest biomass. Also, substantial technological developments have been made with instruments capable of measuring trees and forests remotely, at scales from individual trees on the ground to large scale images of forests from satellites. Whilst neither of these developments alters the principles of tree and forest measurement fundamentally, both offer new opportunities to take better and/or more cost-effective measurements of forests to describe better their role in the world. New discussion of both these areas has been added to this edition.

The aim of the book remains to present an introduction to the practice and techniques of tree and forest measurement. It should serve the forestry student adequately in the undergraduate years and be useful as a guide in his or her subsequent professional life. It should allow practising professional foresters to keep themselves abreast of new developments. It aims also to be accessible to landholders and farmers who own and manage forests on their properties, but have no formal forestry education; they may be able to take basic forest measurements and understand the principles of more advanced measurements, which professionals take for them.

I have continued to discuss the biological principles which lead to many of the measurements which are made in forests. I believe this will help readers appreciate better why emphasis is placed on the measurement of particular things in forests.

Substantial portions of the text have been little altered. However, I have been using the book with my undergraduate forestry students and have made some modifications, where my teaching experience suggests material might be better presented.

I am indebted to Prof. H. Wiant for valuable discussion about the new approaches to 3P sampling, as described in Chap. 10. Prof. N. Coops kindly reviewed Chap. 13.

Australia P.W. West
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Contents

Chapter 1
Introduction

1.1 This Book

The measurement of trees and forests is fundamental to the practice of forestry and forest science throughout the world. Measurements are used to understand how forests grow and develop, to determine how much they contain of the products man wants from them and to ensure that they are managed appropriately.

This book introduces the techniques of tree and forest measurement (or mensuration as it is called in forestry). It covers little more than what might be taught in one semester of an undergraduate forestry course. It should be useful for students and practising foresters as well as for private landholders, who own forest and wish either to measure it or understand what professionals are doing when they measure it for them. The book is designed also to assist scientists, from other than forestry disciplines, who work in forests and need to measure them, although their interests are not necessarily in the trees themselves. It should assist them to take measurements which are consistent with, and comparable to, those which forest scientists have accumulated over many years.

Many of the things which foresters need to know about trees or forests are difficult to measure directly. For example, it is not easy to determine the amount of wood in the stem of a tree standing in a forest, simply because the tree is so tall and large. To deal with this, techniques have been developed to estimate those difficult things from simple measurements, which can be taken from the ground. Much of this book is concerned with describing those techniques and how they are applied. However, it does not discuss in any detail how forestry scientists go about developing those techniques. Students wishing to know more about that topic will need to consult more advanced texts on forest measurement (e.g. Philip 1994; Avery and Burkhart 2002; Husch et al. 2003; van Laar and Akça 2007) and the scientific literature.

It is impossible to teach forest measurement properly without a practical component to the course, under the guidance of an experienced teacher. No book can substitute for that, so the reader of this book should expect only to be exposed to the principles of the discipline, rather than to become immediately competent in its practice.

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Some terms used will be unfamiliar and a glossary has been included as Appendix A. Terms in the glossary are shown in **bold** type when they are first encountered in the text.

The metric system of weights and measures has been used throughout. To many North American readers in particular, this system will be unfamiliar and to them I apologise. I can only say with what relief, as a young forester in Australia in the 1970s, I welcomed the introduction of the metric system and could leave behind the horrors of the imperial system! A table of metric-imperial conversion factors has been included as Appendix B. Younger readers, who have grown up with the metric system, will find there also some of the relationships between units in the imperial system; they can relish the realisation that they have not had to learn by heart such arcane facts as that there are 4,840 square yards in an acre.

There is little that can be done in **forest** measurement without using some mathematics. This book is designed so that a knowledge of no more than senior secondary school level mathematics is required; much will still be understood with a lower level of mathematical ability. There are many advanced techniques of forest measurement which require much higher level mathematics; those are barely alluded to and certainly no detail is given.

Letters of the Greek alphabet are used commonly in mathematical formulae. A copy of the alphabet is included as Appendix C, so that readers will be able to give names to the Greek letters as they are encountered. Many trigonometric concepts will be encountered also. The basics of trigonometry are summarised in Appendix D.

1.2 What Measurements are Considered?

It is impossible for any book on forest measurement to cover the whole range of things which might be measured in forests. The primary focus of this book is on measuring the **trees** themselves.

A principal concern is with measurement of the amount of **wood** trees contain in their stems and the sizes of the logs that can be cut from them. It is this wood that is converted into **timber** products (lumber as it is called in America), for building and many other purposes, or that is to be used for paper-making. Wood, in the form of logs cut from tree stems, remains a valuable commercial product of forests; traditionally, courses on forest measurement have concentrated on how it is measured.

A second concern of this book is with measurement of the weight of various parts of trees, their leaves, branches, stems and roots. There are two reasons for this. Around the world, man uses about 2 billion dry tonnes of wood annually. Just over half of this is firewood, largely for domestic use, especially in Asia and Africa. That is to say, firewood is by far the biggest single use of wood by man. Firewood can be obtained from stem and branch wood of trees and, sometimes also, from large, woody roots and is usually measured by its weight.

The second reason for measuring tree weight is that about one quarter of the fresh weight of a tree (that is the weight of the wet tissue, cut directly from a living tree) consists of the chemical element carbon. Of recent times, there has been great concern around the world about global warming. This has been attributed to the release into the atmosphere of greenhouse gases from burning fossil fuels, such as coal and oil, to produce energy for human use. Carbon dioxide is one such gas. Plants in general, not just trees, take in carbon dioxide through their leaves and convert it chemically to sugar; they then use the sugar as food, for their growth and various life functions. This process of sugar production is known as **photosynthesis**. It requires energy from sunlight and releases oxygen back into the atmosphere as a waste product: it is this ‘waste’ product of photosynthesis which we animals breathe. Because plants remove carbon dioxide from the atmosphere and store it in their tissues (albeit stored in the form of other carbon containing chemical compounds), plants are now seen as tools in attempts to reduce carbon dioxide levels in the atmosphere. Thus, measurement of the amount of carbon, which trees and forests around the world can store, has assumed great importance over recent years.

There are of course many things other than tree stem wood volumes and tree weights which might be measured in forests. Information might be needed about the plants and other animals that live in forests, the soils on which they grow or the streams and rivers which run through them. These are important to understanding many of the other values that forests offer, in matters such as conservation, recreation, the supply of clean water or the rehabilitation of degraded land, forest values which are being appreciated more and more today. However, their measurement and valuation are properly the subject of other books.

1.3 Scale of Measurement

This book is concerned with forest measurement at several scales from individual trees, to **stands** of trees (a stand is a more or less homogeneous group of trees in a forest in which an observer might stand and look about him or her) and finally to large forest areas. The book is structured to consider measurements at these successively larger scales.

Individual trees occupy only a few square metres of land, whilst whole forests may cover hundreds or thousands of hectares. Thus, the measurements which can be taken at the smallest of those scales are likely to be much more detailed than those taken over larger areas. Much of the measurement of forests at larger scales is concerned with making measurements at a small scale, then using mathematical techniques to bring those measurements up to a large scale. Much of the content of the book is concerned with those techniques of scaling up.

Perhaps surprisingly, it is perfectly possible to take tree measurements using very simple equipment, like hand held tapes. These simple devices have been the mainstay of forest measurement over the last century or so. However, their use is labour intensive and requires that field measurement crews travel around the forest area being considered and take their tree measurements directly in the forest.

There is now an increasing desire to use far more sophisticated equipment in forest measurement. Of course, a computer is used generally to assist both in storing the data collected from the forest and to do the arithmetical computations needed to convert those raw data into useful information about the forest. But highly sophisticated measuring devices, ranging from **digital** cameras used on the ground, to satellite images of the forest made from space, are now being adapted for use in measuring trees and forests. Not only is this equipment likely to be labour saving, but it will allow much larger areas of forest to be measured in far more detail than was possible in the past. The final chapter of this book is devoted to a description of some of this equipment and its use from small- to broad-scale measurement of trees and forests.

Chapter 2
Measurements

2.1 Measuring Things

Measurement of things is a fundamental part of any scientifically based discipline. Some things are simple to measure, like the length of a piece of string or the time taken by a pedestrian to cross the road. Other things are very difficult to measure, like the size of an atom or the distance to Jupiter. Some things cannot be measured directly at all, like the volume of wood that might be harvested from a large forest area of thousands of hectares; there are simply too many trees in such a forest to measure them all and, as will be seen in Chaps. 5 and 6, it is quite difficult to measure the harvestable wood volume in even just one tree.

When something is difficult to measure, or cannot be measured directly at all, methods of measurement are used to approximate or estimate it. These methods often involve measuring parts of the thing, parts which can be relatively easily measured. Then, more or less complicated mathematical procedures are used to convert the measurements of the parts to make an estimate of the size of the whole thing.

Indeed, this book is concerned both with how parts of things in forests are measured, simple parts like the circumference of the stem or the **height** of a tree, and how those simple measurements are used to estimate a more difficult thing, like the harvestable wood volume in its entire stem.

Whether a simple or very complex thing is being measured, there are three things about its measurement with which we should be concerned. These are the **accuracy** of the measurement, whether or not there is **bias** in it and what is its **precision**. The rest of this chapter will be concerned with these three issues, in the context of measurement of trees and forests.

2.2 Accuracy

Accuracy is defined formally as 'the difference between a measurement or estimate of something and its true value'. In simple terms, it can be thought of as how closely one is able to measure or estimate something, given the measuring equipment or

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estimation method available. Accuracy is expressed by saying that a measurement or estimate has been made to the nearest part of some unit of measurement, for example, to the nearest 1/10th of a metre, to the nearest hectare or to the nearest microsecond, depending on what type of thing is being measured.

Suppose it was desired to measure something quite simple, like the length of the side of a field, of which the true length was 100 m. There are a variety of methods which could be used to do that. The simplest might be to simply pace the distance out yourself, having calibrated your paces by measuring their length along a tape measure. However, a result from pacing would not be expected to be very accurate, because a person is unable to keep each of his or her paces exactly the same length. Pacing would probably give a result for the length of the side of the field somewhere in the range of about 95–105 m. That is, we could then say that measuring distances of around 100 m by pacing was accurate only to the nearest 5 m.

A second method might be to use a measuring tape. Such tapes are often 30–100 m long, made of fibre-glass, or other material which is not likely to stretch, and are usually calibrated in 1 cm units. Some care is needed with their use; they must be laid carefully along the ground and pulled tight to ensure that dips, hollows and irregularities in the ground surface influence the result as little as possible. However, even taking all due care with a tape like this, it would probably give a result for the length of the side of the field somewhere in the range 99.9–100.1 m. That is, we would say the tape was accurate to the nearest 1/10th of a metre.

A third method might involve a modern **laser** distance measuring device, such as used today by professional surveyors. Lasers are becoming very important for many types of measurement, not only in **forestry**; their use in forestry is discussed further in Chaps. 4, 5 and 13.

Laser is an acronym for '**L**ight **A**mplification by **S**timulated **E**mission of **R**adiation'. Laser light involves an intense, narrow beam of light of a single colour, which can be directed very precisely. The distance from an instrument to a solid object is determined by measuring the time it takes a pulse of laser light to be reflected from the object back to the instrument. These instruments contain very accurate clocks, capable of measuring the extremely short periods of time involved, given that light travels at about 300 million metres/second. A laser distance measuring device might be capable of measuring a distance of about 100 m with an accuracy at least to the nearest 1/1,000th of a metre, that is, to the nearest millimetre.

The size of the thing being measured will immediately set some criterion for the accuracy required of the measurement. If one wishes to measure the sizes of atoms, which are of the order of 1 angstrom unit (Å) in diameter (an angstrom unit is one 100 millionth of a centimetre and was named after Anders Ångström, a Swedish physicist of the mid nineteenth century), complex laboratory equipment will be required, capable of taking measurements with an accuracy of fractions of an angstrom unit. If one wishes to measure the distance to Jupiter, which orbits the sun at an average distance of about 778 million km, a measurement method accurate to the nearest few tens of thousands of kilometres is probably what is required. However, the accuracy required ultimately of a measurement or estimate of something depends on the purpose for which the result is required. In turn, this will determine the sophistication of the equipment or estimation method required to achieve the desired accuracy.

Returning to the simple example of measurement of the length of the sides of a field, if it was desired to determine its area roughly, to work out how many bags of fertiliser were needed to cover it, the accuracy of measurement got from pacing out the sides would probably be adequate. On the other hand, if a professional surveyor wished to measure the field to establish the title to the property, a laser measuring device would probably be preferred to achieve the accuracy required by the legal system.

2.3 Bias

Bias is defined as ‘the difference between the average of a set of repeated measurements or estimates of something and its true value’. In essence, if something is difficult to measure, it may not matter how many times we attempt to take the measurement, nor how many different types of measurement equipment we use, we may simply always get the wrong answer. By ‘the wrong answer’ is meant that the results of the many attempts at measurement will be consistently larger or smaller than the true value of whatever it is that is being measured. If this is the case, the measurement or estimation method is said to be biased.

By the same token, it would be said that the measurement or estimation method is unbiased if the average of the many measurement attempts differed negligibly from the true value. How small would the difference have to be to be considered negligible? Obviously, some limit is set by the accuracy of the measurement method; we simply cannot detect differences smaller than the accuracy. Apart from that, the degree of bias that will be considered acceptable will be determined entirely by the purposes for which the result of the measurement are to be used; this issue is discussed further in Sect. 2.5.

To illustrate what is meant by bias, consider the problems involved in measuring the weight of the fine roots of a tree. Fine roots are the small (less than about 2 mm diameter), live roots at the extremities of the root system of a tree. Biologically, they are extremely important, because they take in the water and **nutrients** from the soil that the tree needs to survive and grow. Because of their importance, forest scientists need to measure them. The most appropriate way devised so far to do so is to excavate them from the soil. Obviously, this is a major task, since they will be scattered throughout a large volume of soil, extending perhaps 2–3 m or more away from the stem of a large tree and to a depth of 1–2 m. As well, so small and numerous are fine roots, it is very difficult to find all of them as one sorts laboriously through such a large volume of soil. Furthermore, in any patch of forest it is difficult to know if an excavated fine root belongs to the particular tree one is dealing with, or if it belongs to another, nearby tree or even to an **understorey** plant. So difficult are fine roots to find and measure, it is perhaps inevitable that that any attempt to do so is doomed to get the ‘wrong answer’, that is, to be a biased measurement method. Most probably, the answer will be an under-estimate of the true amount, because it is so difficult to find all the fine roots. There are various other methods used to measure fine roots (Sect. 7.2.3), all of them probably subject to bias, because of the difficulties associated with their measurement.

2.4 Precision

Precision is defined as ‘the variation in a set of repeated measurements or estimates of something’. The variation arises because of the limitations in the measurement or estimation technique, when it is used at different times and under varying circumstances, and limitations of the people taking the measurements.

Following the example in Sect. 2.3, if a number of different people set out to measure the weight of the fine roots of a tree, it is inevitable that each would get a somewhat different result. So difficult are fine roots to measure, that individuals will vary in how many they manage to find in a large, excavated soil volume.

Precision is measured by the amount of variation in the results of a repeated set of measurements of the same thing. The range of values in the set of estimates is one measure of precision. Another measure, called **variance**, is the measure used most commonly. Variance is a concept which derives from **mathematical statistics**. It is fundamental to a wide range of mathematical techniques used in science; these techniques deal with the problems that variation between natural things causes us in understanding how nature works. Variance and its use as a measure of precision will be discussed more fully in Chap. 9.

Suppose the precision of a measurement technique is low, that is, a rather wide range of different results would be obtained when the technique is used by different people or at different times. If so, we would feel rather unsure about the extent to which we could rely on any one result we had obtained using the technique. In turn, we would not be very confident that we could draw worthwhile conclusions about whatever it was that was being measured. That is why precision is important in measurement. If it is high, we will feel confident that we can use the information to draw reliable conclusions. If it is low, we will feel much less confidence in our conclusions.

2.5 Bias, Precision and the Value of Measurements

It is important to understand how bias and precision interact. This can be illustrated through an analogy used in various texts (Shiver and Borders 1996; Avery and Burkhart 2002), where a marksman is shooting at a target. In effect, the marksman is attempting to use a bullet to ‘measure’ the position of the bullseye of the target.

Figure 2.1 describes the analogy. The best possible result for the marksman is illustrated in Fig. 2.1(a). The average position of all the shots is right on the bullseye; that is, the average of the repeated attempts to measure the position of the bullseye does not differ appreciably from its true position, so it can be said to have been an unbiased measurement technique. As well, because the shots cluster closely around the bullseye, it can be said they measure its position with a high degree of certainty and so they represent measurements made with a high degree of precision.

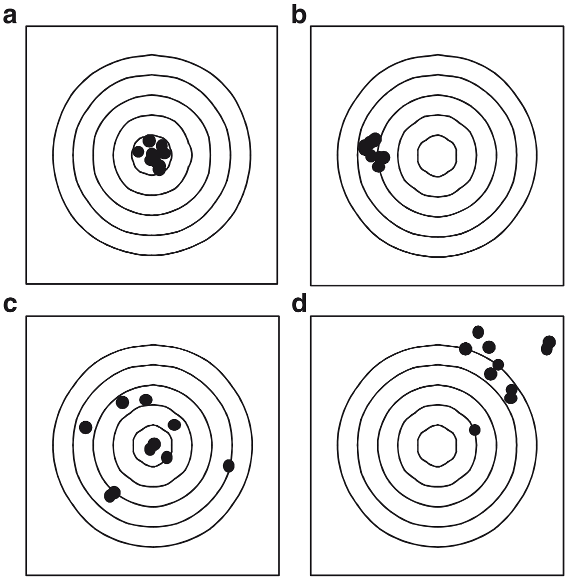

Fig. 2.1 Bullet holes in a target, as an analogy for bias and precision of measurements. (**a**) An unbiased, precise result, (**b**) a biased, precise result, (**c**) an unbiased, imprecise result and (**d**) a biased, imprecise result

In the case of Fig. 2.1(b), the shots still cluster closely around one point, so they represent measurements made with a high degree of precision. However, their average position is some distance from the bullseye, so they represent a measurement technique in which there is bias. In this analogy, the bias might have arisen because the 'instrument' being used (the gun) is not calibrated correctly, by having its sights set poorly. Or perhaps, unknown to the marksman, there was a wind blowing which pushed all the shots to the left.

Figures 2.1(c) and (d) both show cases where the marksman has produced a wide spread of shots, which represent measurements made with a low degree of precision. In Fig. 2.1(c), despite their wide spread, the average position of the shots is still right on the bullseye, so they represent measurements made without bias. This might happen to a marksman on a day when the wind varies unpredictably, so that his or her shots are spread. Figure 2.1(d) represents the worst possible result for the marksman. Not only are the shots widespread, but also their average position is a long way from the bullseye. This might happen if the sights of the gun are not set correctly and if there are unpredictable wind variations.

The important question then is whether or not a biased or imprecise measurement is still useful. Usually, it is better to have some measurement of something than no measure at all: what is difficult to judge is whether or not a biased but precise result (Fig. 2.1b) is more useful than an unbiased but imprecise result (Fig. 2.1c). Even more difficult to judge is if a biased and imprecise result (Fig. 2.1d) is better than no result at all. There are really no rules available to make these decisions. It becomes a matter of judgement for the person using the results to decide whether or not they are adequate for the purposes for which they are needed.

As discussion of various measurement techniques continues throughout this book, reference will be made to the accuracy, bias and precision involved with them.

Chapter 3
Stem Diameter

3.1 Basis of Diameter Measurement

The simplest, most common and, arguably, the most important thing measured on trees in forestry is the diameter of their stems. Amongst other things, tree stem diameter:

- Often **correlates** closely with other things, which are more difficult to measure, like the wood volume in the stem of a tree or the weight (or **biomass**, as it is called) of the tree
- May reflect the monetary worth of the tree, given that larger trees produce logs of larger sizes, from which more valuable timber can be cut and so which are more valuable commercially
- May reflect the competitive position of a tree in a stand and, hence, how well it is likely to grow in relation to the other trees.

Stem diameter declines progressively from the base of the stem, as the tree tapers. So, a standard convention has been adopted in forestry to make a basic measurement of tree stem diameter at **breast height**. This is defined as being 1.3 or 1.4-m vertically above ground from the base of the tree. The height used varies in different countries (and, in America, is actually defined in imperial units as 4 ft 6 in); the difference is generally ignored when results from different countries are compared. If the tree is growing on sloping ground, breast height is measured from the highest ground level at the base of the tree. Loose litter and debris at the base of the tree should be brushed aside before making the measurement of breast height. Of course, stem diameters may be measured also at heights along the stem other than breast height; reasons for doing so are discussed in Sect. 5.3.4.

If a tree is very young, it may not have grown tall enough to have reached breast height. If it is desired to measure its stem diameter, obviously it must be done at a lower height, at least until the tree is taller than breast height; commonly, heights of 0.1 or 0.3-m above ground are used in these circumstances. The need to do this is increasing in forestry, as some products are now being harvested from very young forests. For example, **plantation** forests are being grown for only 3–5 years to produce wood for **bioenergy** production (that is to fuel boilers or to be converted

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by fermentation to ethanol for motor vehicle fuel). However, forestry has not yet adopted any particular convention as to the height to be used for stem diameter measurement of small trees.

The rest of this chapter discusses how stem diameters are measured and the difficulties encountered in doing so.

3.2 Stem Cross-Sectional Shape

By referring to diameter, it is being implied that stems are circular in cross-section. However, the first problem with measuring stem diameter is that tree stems are never exactly circular. Certainly they are approximately so, because the principal function of the stem is to act as a pole and support the **crown** (the leaves and branches of a tree) high in the air, so that the tree can dominate other vegetation that occurs on a **site**. Engineering theory suggests that a circular pole will be stronger than poles of other shapes; thus, it can be argued that evolution has favoured the development of tree stems of the most efficient shape to perform their function.

However, all stems have some irregularities in their cross-sectional shape, simply because trees are biological organisms and nature rarely provides theoretical perfection. Those irregularities are generally exaggerated at points where branches have protruded from the stem or where damage has occurred through things like fire, disease or insect attack. As well, most stems show some eccentricity in their shape, so that they are wider in one direction than another. This is most likely a response to wind; the longest axis of the eccentric shape will correspond to the prevailing wind direction and will give the stem more strength to resist those winds. In fact, the density of stem wood has also been found to be greater along the axis of the prevailing wind direction, an effect which also increases the strength of the stem in that direction (Robertson 1991).

Particularly in tropical forests, large trees may have extensive flutes or **buttresses** protruding from their bases (Fig. 3.1). These may extend to several metres above ground. Just like buttresses used in buildings, tree buttresses are believed to give additional structural support to the tree.

Apart from these common irregularities in the cross-sectional shape of tree stems, extraordinary variations in shape occur also. Generally, these are a result of unusual **environmental** circumstances, where trees lean against one another or some other solid object, grow on steep slopes or have odd branching. In his unusual and entertaining book, Dr. Claus Mattheck has illustrated some of the extraordinary shapes which trees have been found adopting in nature (Mattheck 1991). These unusual cases are sufficiently rare that they need not be of concern for normal forestry circumstances.

Given all this discussion, it is clear that that tree stems are generally not exactly circular in cross-section. This means that stem diameter will generally be a biased measurement of the true size of the stem. The effect of this bias, on things like determining the growth in cross-sectional area of tree stems from diameter

Fig. 3.1 Buttressing on the lower stem of a large tree in subtropical rainforest in northern New South Wales, Australia. This stem is over 3-m wide at its base. The buttressing continues up the stem for more than 5 m (Photo–P.W. West)

measurements made at different ages, has been studied (Biging and Wensel 1988). However, universally in forestry and forest research, the effect of that bias is considered to be sufficiently small that it is ignored and tree stems are treated as being truly circular in cross-section.

3.3 Measuring Stem Diameter

The most common way to determine the diameter of a stem is to measure its girth with a simple tape measure, known as a diameter tape. Diameter tapes are made of steel or fibre-glass, for strength and to prevent stretching. They are calibrated in units of the mathematical constant pi (π), which is the ratio of the circumference of any circle to its diameter and has a value of approximately 3.142. That is, a unit shown as 1 cm long on a diameter tape is 3.142-cm long; when the tape is wrapped around the girth of a tree, the corresponding diameter can be read directly from the tape.

To use a diameter tape correctly, it should be wrapped firmly around the stem, perpendicular to its axis. Any loose bark should be brushed gently off the stem before making the measurement. Where a tree is to be measured repeatedly to determine its growth rate, say, at intervals of a year or so, paint or other marking material may be used to mark the point where the diameter is measured to ensure the same position is measured on each occasion.

Diameter tapes are usually calibrated at intervals of 0.1-cm diameter (that is, the calibration marks are 3.142-mm apart) and tree measurements are usually recorded to an accuracy of the nearest 0.1 cm (that is, to the nearest millimetre). Years of experience of forest scientists have shown that this accuracy is adequate generally for forestry purposes.

A second instrument used commonly to measure diameter is a caliper. Calipers are particularly useful when measuring trees of small diameter (say, less than about 5 cm), when the stiffness of a diameter tape can make it difficult to wrap the tape around the stem. However, calipers are used also to measure trees of larger diameter, the size of the calipers being chosen to suit the size of the trees being measured. Calipers are often quicker to use than diameter tapes. However, they measure stems only across one diameter of their cross-section, whereas a diameter tape measures the average diameter corresponding to the girth of the tree. To allow for this, it is usual when using calipers to take two diameter measurements, at right angles to each other. The square root of the product of the two diameters is then used as the measure of stem diameter; by calculating stem diameter this way, it is being allowed that the stem cross section may be shaped as an ellipse, rather than being circular.

Much less commonly than diameter tapes or calipers, the other instruments are used to measure tree diameters, such as Biltmore sticks or Wheeler pentaprism. They are described in some other books on forest measurement (Philip 1994; Avery and Burkhart 2002; van Laar and Akça 2007) and will not be considered further here. There are available also optical instruments, with which stem diameters can be measured high up on the tree stem. These will be discussed in more detail in Sect. 5.3.4.

3.4 Tree Irregularities

Where buttresses occur (Fig. 3.1), the stem is so irregular in shape that it is obviously quite impossible to define its diameter. To deal with this problem, measurements of stem diameter are usually made at a height on the stem above which the effect of the buttressing has disappeared and where the stem has become approximately circular in cross-section. Of course, such measurements are no longer comparable with measurements made at the world forestry standard height, that is, breast height.

When such measurements are made, they will still have local application for all the purposes that breast height diameters are used normally and which will be discussed in due course in this book. The height chosen for such measurements will be determined for the forest concerned and could be as high as several metres. A ladder may be needed to reach the required height.

In normal forest circumstances, a much more common problem is a result of the lumps and bumps, which may occur anywhere along a tree stem. They are especially common where branches protrude and may persist for some years, even after the branch has died and dropped off. When such an irregularity occurs where a diameter measurement is to be made, two measurements are usually taken, at points equidistant above and below the point. The average of two measurements is then used as the measurement of stem diameter at the required point. It is left to the judgement of the measurer to assess if such an irregularity is sufficiently large to warrant measuring diameter in this fashion.

Also common in forests is the occurrence of trees with forks in the stem, beyond which the tree has grown with two or even more stems. There are many tree species also which have multiple stems arising from ground level. The convention used to deal with these cases is to treat the multiple stems as separate trees, whenever the fork occurs below breast height.

3.5 Bark Thickness

Forestry is concerned usually with the wood in tree stems, because that is the part of the tree which is sold most commonly. Bark may be sold also, perhaps as mulching material for gardens, or it can even be burnt as biofuel. However, it is generally a much less valuable product than wood, so it is usually the wood it is desired to measure.

Between different tree species, bark varies greatly in thickness and texture, from extremely rough to quite smooth. It can be several centimetres thick, so a measurement of stem diameter made over the bark can be appreciably greater than the diameter of the wood below.

Bark thickness of standing trees can be measured with a bark gauge. This instrument consists of a shaft with a sharp point, which is pushed through the bark until the resistance of the underlying wood is felt. The sleeve around the shaft is then shifted to the surface of the bark and the bark thickness read from the calibrated shaft. Some practice is needed to get a ‘feel’ for when the point of the gauge has reached the wood. Usually, at least two measurements, at right angles around the stem, would be made of bark thickness and their average used as the measure of bark thickness.

Measuring bark thickness can be quite tedious. So, wherever possible, measurements of stem diameter over bark are preferred. As shall be seen below, over bark diameter measurements are quite adequate for many of the purposes for which stem diameter measurements are used in forestry. However, there are times when it is essential that under bark diameters be determined and so bark thickness must be measured.

Chapter 4
Tree Height

4.1 Basis of Height Measurement

The height of trees is important to forestry particularly because:

- The length of the stem is important as part of the calculation of the total amount of wood contained within it
- The height of the tallest trees in the forest is the basis of one of the most important measures used in forestry to assess **site productive capacity**. This is a measure used to asses how rapidly trees will grow on a site; it will be discussed further in Sect. 8.8.

In forestry, tree height is defined as the vertical distance from ground level to the highest green point on the tree (which will be referred to here as the tip of the tree). It might seem odd that tree height is not defined in terms of stem length (since it is usually the wood-containing stem of the tree with which forestry is most concerned) or as the height to the top of the stem itself. However, near the tips of trees of many species, it is difficult to define exactly what constitutes the stem, because of the proliferation of small branches there. Even if the main stem can be seen clearly near the tip, it is often very difficult to see exactly where it stops. This is particularly so when viewing, from the ground, a tall tree with a dense crown.

Whilst the highest green point of a tree is much easier to identify than its stem length, care must be taken to ensure that the tree is viewed from sufficiently far away so that its tip can be seen clearly. Even then, in dense forest it is often difficult to see the tip amongst the crowns of other trees; care must be taken to ensure the tip one can see is indeed that of the tree being measured.

Even if the tree is leaning, its height is still defined in forestry as the height to the highest green point, rather than by its stem length. Most trees, in most forest circumstances, stand just about vertically; if they do lean a little, perhaps in response to strong prevailing winds, the lean is usually no more than a few degrees. For general forestry purposes, it is sufficiently rare to encounter trees leaning sufficiently that special consideration has to be given as to how their height should be measured; the lean would have to exceed about 7–8° before it would be sufficient

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to affect appreciably the result of a tree height measurement. Heights of leaning trees will not be considered further here.

Direct, trigonometric and geometric methods are used to measure tree heights. Each of these will be discussed below.

4.2 Height by Direct Methods

Direct height measurement involves simply holding a vertical measuring pole directly alongside the tree stem. Devices with a telescoping set of pole segments can be purchased readily. These are able to measure tree heights to about 8 m.

Light-weight aluminium or fibre-glass poles of a constant length (1.5–2 m), which slot into each other at their ends, are available also. As many as necessary of these may be slotted together progressively and the whole lot raised until the tip of the tree is reached. The number of poles used is counted and any leftover length at the base of the tree is measured with a tape. These are effective to heights of about 12–15 m, beyond which the poles become too heavy or unwieldy to hold.

When using these devices, care must be taken to ensure the pole is raised to coincide exactly with the tip of the tree. This requires a team of two to measure heights, one to hold the measuring pole and the other to sight when the tip of a tree is reached. In windy weather, swaying of the tree tops can make this sighting more difficult.

With careful sighting of the tree tip, these devices should allow height measurements to an accuracy of about 0.1 m. For trees taller than about 12–15 m, it is necessary to use trigonometric or geometric methods, which are discussed below.

4.3 Height by Trigonometric Methods

Figure 4.1 illustrates the principle involved in measuring tree height by trigonometric methods. A vertical tree of height h_T = AC is standing on flat ground. An observer is standing a measured distance d = GC away from the tree and measures, at eye level O with some viewing device, the angles from the horizontal to the tip of the tree, a_T, and to the base of the tree, a_B. Angles measured above the horizontal should have a positive value, whilst those below the horizontal should be negative; in the case of Fig. 4.1, a_T is positive and a_B is negative.

Using straightforward geometry and trigonometry, the height of the tree can be calculated from these measurements as

$$h_T = d[\tan(a_T) + \tan(-a_B)], \tag{4.1}$$

where ‘tan’ is the trigonometric expression for the tangent of the angle. Appendix D gives some basic trigonometry and trigonometric functions.

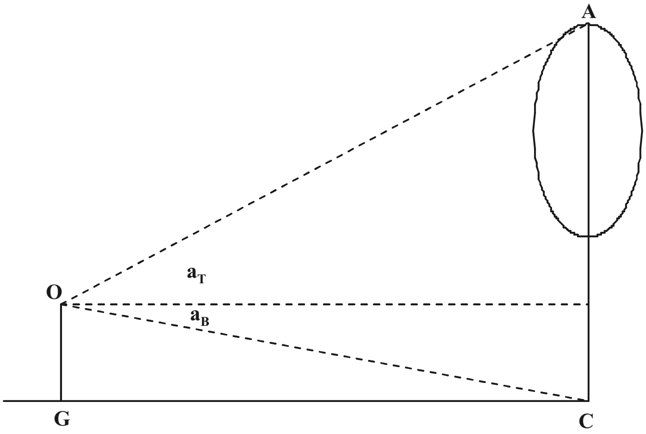

Fig. 4.1 Principle of tree height measurement using trigonometric methods

As an example, suppose the observer was standing 21 m away from the tree and measured the angle to the tip as 48° and the angle to the base as −7°. Then, the height of the tree would be calculated as h_T =21 × [tan(48) + tan(7)] = 21 × [1.1106 + 0.1228] = 25.9 m. Scientific calculators and computer programs provide the required trigonometric functions.

In dense forest, it can often be difficult for the observer to see the tip of the tree. He or she needs to move around the tree and adjust the distance from which it is being viewed to make sure that the tip of the tree can be clearly seen. These problems are exacerbated if the wind is blowing the tips about. If the day is too windy, it simply becomes impractical to undertake height measurements.

A tape may be used to measure the distance from the observer to the centre of the base of the tree. The angles may be measured with a hand-held clinometer (readily available from forestry suppliers) or, more precisely, with a theodolite. Theodolites are far slower to use and would only be countenanced if a very precise height measurement was required. Also available are various optical/mechanical instruments (Haga altimeter, Suunto **hypsometer**, Blume-Leiss hypsometer, Abney level and Spiegel relaskop), which incorporate a clinometer. These devices have scales which are calibrated so that the observer can read the tree height directly from the scale without having to do the computations required by (4.1).

For routine tree height measurements, convenient electronic instruments are available today. These combine a clinometer with a distance measuring device. Some use the time of travel of sound waves to measure the distance, whilst the most recent use a laser. In both cases, a target is pushed into the stem of the tree to reflect back to the instrument the sound wave or laser light. Because the velocity of sound varies appreciably with air temperature, the instruments which use sound need to be calibrated regularly throughout the day as temperature changes. Once distance has been measured, the instrument is aimed at the base and tip of the tree and the inbuilt clinometer measures the required angles. The tree height is then calculated electronically by the device and displayed to the user.

Heights measured by trigonometric means are often reported to an accuracy of the nearest 0.1 m. However, given the difficulties involved in sighting to the tips of tall trees, this is probably optimistic. In the example given below (4.1), a measurement error as small as +0.5° in the angle to the tip of the tree would result in a height estimate of 26.3 m, rather than 25.9 m as given in the example. In practice, an accuracy of no better than to the nearest 0.5 m might be a more realistic assessment for tree height measurements.

Often the land surface on which the tree is positioned is sloping, rather than flat as in Fig. 4.1. To allow for this, the observer needs to measure also the angle of the slope, a_S. This may be positive or negative, depending on whether the observer is positioned down- or up-slope, respectively, from the tree. The slope angle may be measured, with a clinometer, as the angle from the horizontal to a point on the stem at a height equal to the observer's eye level. The distance from the tree to the observer is then measured along the slope. Say the slope distance is s, then the horizontal distance to the base of the tree, d, can be calculated as

$$d = s\cos(a_S), \tag{4.2}$$

where 'cos' is the trigonometric expression for the cosine of an angle. Suppose the slope angle was a down-slope of −10° and the slope distance measured was 21.3 m, then the horizontal distance to the tree would be calculated as $d = 21.3 \times \cos(-10) = 21.3 \times 0.9848 = 21.0$ m. The angle to the tip and base of the tree would be measured as described before and this horizontal distance would then be used in (4.1) to calculate the tree height.

On steeply sloping ground and where the observer is standing down-slope of the tree, the angle measured to the base of the tree, a_B, may be positive, rather than negative as in Fig. 4.1. This does not affect the computation of height in any way and (4.1) and (4.2) remain appropriate to calculate the height of the tree.

The sonic or laser measuring devices described above adjust automatically for ground slope by measuring the angle up or down to the reflector on the tree, which is always positioned at a standard height above ground.

4.4 Height by Geometric Methods

Figure 4.2 illustrates the principle involved in measuring tree height by geometric methods. A vertical tree of height h_T = AC, is standing on flat ground. A straight stick of known length l_T = BC is positioned vertically at the base of the tree; such a stick would commonly be about 3–5-m long. An observer is standing a convenient distance away from the tree, with his or her eye at O. The observer holds a

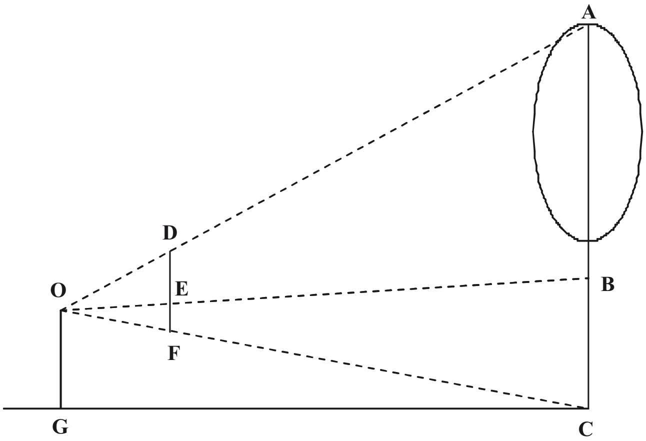

Fig. 4.2 Principle of tree height measurement using geometric methods

graduated ruler DF, positioned so that the line of sight OC to the base of the tree is coincident with the zero mark of the ruler. Without moving his or her head up or down, the observer reads from the ruler the distance l_R = FE, which coincides with the line of sight OB to the top of the stick against the tree. He or she reads also from the ruler the distance h_R = DF, which coincides with the line of sight OA to the tip of the tree. Using straightforward geometry, the height of the tree can then be calculated from these measurements as

$$h_T = h_R(l_T / l_R). \tag{4.3}$$

As an example, suppose the length of the stick standing against the tree was 5.0 m and the observer measured h_R as 41.4 cm and l_R as 8.0 cm. Then, the height of the tree would be calculated as $h_T = 5.0 \times 41.4/8.0 = 25.9$ m. Ground slope does not affect the geometry of this method.

A number of different devices are available which use this principle. Often, the ruler is graduated in such a way that the computations in (4.3) are done implicitly, so that the tree height can be read directly from their scale. These devices are known generally as hypsometers.

All the difficulties of measurement that apply with the trigonometric methods apply also with geometric methods. One advantage of geometric methods is that neither the distance from the observer to the tree nor ground slope need to be measured. A second advantage is that the equipment required is very simple (a stick of known length and a ruler only are required). Perhaps their disadvantage is that it is quite difficult physically for the observer to hold the ruler steady and, at the same time, keep in view all that needs to be sighted. However, with care, the accuracy of measurement of tree height using geometric methods should be about 0.5 m, the same as that with trigonometric methods.

Chapter 5
Stem Volume

5.1 Reasons for Volume Measurement

The volume of wood contained in the stem of a tree is one of the most important measurements made in forestry, because:

- Wood is the principal commercial product of forests
- The stem contains a very large proportion of the biomass of a tree.

Of interest is not only the total volume of the wood in the stem of a tree, but also the volumes of individual lengths cut from the stem, that is, of logs. Logs of different sizes, both in diameter and length, have different uses. Usually logs of larger diameter are required for conversion to solid wood products (that is, sawn in a sawmill to make all sorts of building materials and many other products). Generally, these larger logs attract a much higher price per unit volume of wood than do smaller logs, which may be suited only for chipping for use in paper-making. The size of a log, as well as its quality is important also. Factors such as its straightness, the presence and size of branch knots and the presence or absence of any decayed wood within the log can all be important in determining its value.

Any one tree may contain a wide range of different log sizes. Larger logs are cut from nearer the base of the stem and smaller ones from further up. There will usually be parts of the stem near the tip of the tree which are too small to use for any product; these are usually left as waste on the ground when a forest is logged.

These days, logs are often sold by weight, rather than by volume, because it is easier to allow trucks carrying logs to a mill to pass over a weighbridge than to measure the volume of the logs on it. However, the logs on any one truck will usually have been sorted at the time of felling into logs of a particular size class, hence, value. Implicitly, this means that logs have been sorted on the basis of their volumes and their conversion to weight is made simply on the basis of **wood density**. In essence then, volume remains the important variable for the characterisation of log size.

Forest science is often concerned with the production of biomass by trees; scientists who study the factors that affect tree growth behaviour often need to know how much biomass is contained in various parts of the tree (leaves, branches,

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bark, stem, coarse roots and fine roots). Chapter 7 will discuss the measurement of tree biomass. Since the stem contains a large proportion of the biomass of a tree, a proportion which increases with age as the stem continues to grow larger and larger, its correct measurement is very important. As will be seen in Chap. 7, stem biomass is often derived from stem volume by multiplying its volume by wood density. Thus, the issues discussed here for stem wood volume measurement are an important part of stem biomass determination.

This chapter will consider the various ways in which the wood volume of individual tree stems or logs is measured.

5.2 'Exact' Volume Measurement

No tree stem is perfectly regular in shape. All stems have bends, twists and lumps, where branches have emerged or there have been other environmental influences which have affected stem shape (Sect. 5.3.2). Despite this, there are at least three methods of measurement which can take into account this complexity of stem shape and, thus, can provide very precise estimates of stem volume with virtually no bias.

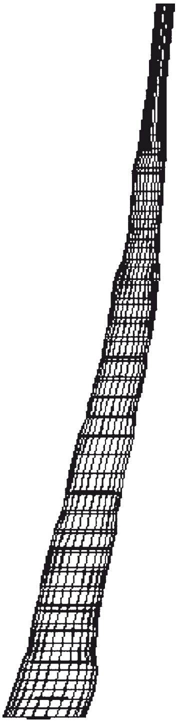
The first method involves immersion of the stem (perhaps after cutting it into bits) in water and measurement of the volume of water displaced. This is known as xylometry. Generally, it is impractical for any but exacting research work. It requires large immersion tanks, which are not portable for field use, and the tree must be felled before it can be measured. There are various examples of the use of xylometry in research projects (Martin 1984; Filho and Schaaf 1999; Özçelik et al. 2008).

The second method uses lasers and has become common in sawmills, to assist in determining the optimal set of timber products which can be sawn from a log. As a log enters the sawing line, multiple lasers scan it from several directions and measure its diameter at very short intervals along its whole length. This information is processed by a computer to produce a precise, three dimensional profile of the log, from which its volume can be determined. Because of the complex laser equipment involved, this method is not practical for field use and, as with xylometry, requires that the tree be felled before measurement

The third method can be used with standing trees in the field. Using a digital camera, a tree is photographed from at least two directions. With computer analysis, a three-dimensional view of its stem may then be produced; an example from Hapca et al. (2007) is shown in Fig. 5.1. Using a computer, the volume of the tree stem could then be determined, taking into account the fine detail of any irregularities along it. However, a standing tree still has bark on its stem, so the volume could only be inclusive of the bark and wood together. In the example in Fig. 5.1, the tree did not have a very dense crown, so the camera was able to picture the stem well up into it; this would not be the case for many other types of trees, which have much denser crowns.

These three methods are capable of making very precise estimates of the volumes of at least parts of tree stems, by taking a full account of the irregularities

Fig. 5.1 Stem profile of a standing, 70-year-old, Sitka spruce (*Picea sitchensis*) tree, derived from digital photographs of the tree. The total height of the tree was 22 m and its diameter at breast height over bark was 29 cm. This figure shows a two-dimensional profile of one side of the tree, but in fact a three-dimensional profile was obtained for it, by taking two photographs of it at right angles to each other (adapted from Fig. 4 of Hapca et al. 2007 and reproduced by kind permission of the Annals of Forest Science)



which occur along them. However, none of them is entirely appropriate or practical if it is desired to measure the wood volume of trees which are still alive and standing in the forest. Laser scanning and photography are both examples of methods known by the general term **remote sensing**, that is, measurement methods which rely on equipment which takes measurements of objects at some distance from the equipment. The use of remote sensing is a rapidly developing area of tree and forest measurement and is discussed in much greater detail in Chap. 13.

5.3 Volume by Sectional Measurement

It is very common in forestry practice to need to measure tree stem wood volumes in the field. Whilst new methods of remote sensing are being developed to aid in this (Chap. 13), it is still most common that such measurements are made directly by people. The methods they use have a long history of development, going back to the nineteenth century. They are not able to take as much account of the irregularities in shape along a tree stem as the methods described in Sect. 5.2. Fortunately however, most trees in most forest circumstances are sufficiently regular in shape that these older methods can measure stem volumes with an accuracy and level of precision which is adequate for most forestry purposes. The methods can be destructive (the tree is felled before measurement) or nondestructive (the tree is measured standing).

The principal one of these methods is known as the sectional method. It involves measuring a tree stem in short sections, determining the volume of each section and summing them to give the total volume.

5.3.1 Sectional Volume Formulae

In the sectional method, the volume, V_S, of a section of a stem is determined by measuring the length of the section, l, and some or all of the stem diameter at the lower end of the section (commonly referred to as the large end diameter), d_L, the diameter at the upper end of the section (small end diameter), d_U, and the diameter midway along the section, d_M. These measurements are used to determine the volume of the section using one of three formulae, each named after the person who first developed it. They are Smalian's formula,

$$V_S = \pi l(d_L^2 + d_U^2)/8, \tag{5.1}$$

Huber's formula,

$$V_S = \pi l d_M^2 / 4 \tag{5.2}$$

and Newton's formula,

$$V_S = \pi l(d_L^2 + 4d_M^2 + d_U^2)/24. \tag{5.3}$$

The units of the measurements used with these formulae must be consistent, say, all in metres or all in feet. So, for a 3-m long stem section with $d_L = 0.320$ m, $d_M = 0.306$ m and $d_U = 0.296$ m, its volume estimated by Smalian's formula (5.1) would be 0.224 m^3, by Huber's formula (5.2) 0.221 m^3 and by Newton's formula (5.3) 0.222 m^3. The differences in the results arise from the different amounts of information used to calculate each and natural irregularities along the stem section.

These three formulae have been an integral part of forest measurement for many years and remain so today. All three will give an unbiased estimate of the volume of a stem section if the section is cylindrical or shaped as part of what is known as a quadratic paraboloid (Sect. 5.3.2). Newton's formula will give an unbiased result also if the stem section is shaped as part of a cone. Of course, even if a stem section is shaped generally like one of these specific shapes, irregularities along the stem (Sect. 3.4) will ensure that none of these formulae can be expected to give a section volume exactly; Fonweban (1997) gives a good example of the use of these formulae, where he determined the accuracy, bias and precision of volume estimates of stem sections cut from large trees in tropical forests of Cameroon. Whilst other formulae, and indeed different methods, have been developed from time to time to be used as alternatives to (5.1)–(5.3) (van Laar and Akça 2007; Özçelik et al. 2008), none is in use consistently today and they will not be considered here.

As discussed above, these three formulae assume that tree stems have particular shapes. To understand how the formulae have become such an important part of forest measurement practice, it is necessary to consider how tree stems are shaped. Only then will it be possible to judge how appropriate these formulae really are.

5.3.2 *Tree Stem Shape*

Tree stem shape can be defined as the way in which stem diameter changes with height along the stem. Much research was undertaken in the precomputer era of the twentieth century to try to determine how tree stems are shaped. Summarising that research in modern parlance, it was believed that the stem diameter, d_x, at any distance x from the tip of a stem could be described by the relationship

$$d_x = \kappa x^{\rho} \tag{5.4}$$

where κ and ρ are **parameters** of the equation, that is, variables which take particular values in the equation for a particular stem, from which has been measured a set of stem diameters and distances from the tip. Note that Greek letters have been used to represent the parameters of this equation. Their names are listed in the Greek alphabet given in Appendix C.

The older research suggested that tree stem shape varied in different parts of the stem. It was believed that near the base of the tree stem, in the region where the butt swell occurred, the stem generally had a shape known as a neiloid, when the parameter ρ in (5.4) has the value 1.5. Above that, and for the main part of the stem of the tree, at least into the lower part of the crown, it was believed that the stem was shaped as a quadratic paraboloid, when $\rho = 0.5$ in (5.4). The top section of the stem was believed to be conical, when $\rho = 1$ in (5.4). Since the main part of the stem was believed to be shaped as a quadratic paraboloid, and particularly because that is the part of the stem which is most used for timber, this led to the use of (5.1)–(5.3), all of which will give an unbiased estimate of volume if the stem is indeed shaped as a quadratic paraboloid.

The advent of the computer has allowed much more detailed analysis of tree stem shape. In particular, it has been found that tree stems vary their shape more or less continuously along their length. Functions much more complex than (5.4), known as **taper functions** (Chap. 6), have been developed to describe stem shape.

This is illustrated in Fig. 5.2. There, the shape of the stem under bark is shown for a typical blackbutt (*Eucalyptus pilularis*) tree, a species important for wood production in subtropical Australia in both **native** and plantation forests. That shape was drawn using a taper function developed for that species. Of course, taper functions only show a smoothed stem, without the minor irregularities that will occur naturally in any real stem (Sect. 3.4).

Superimposed as dotted lines on the tree stem shape shown in the figure are the shapes that the stem would have *if* its lowest 2.5 m was shaped as a neiloid, *if* the main part of the stem between 2.5 and 35 m was shaped as a quadratic paraboloid

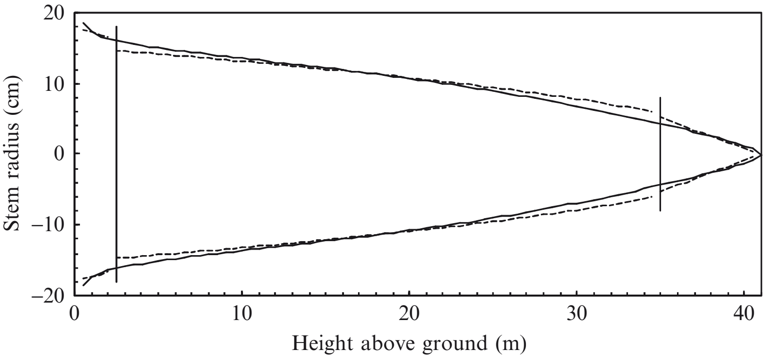


Fig. 5.2 Stem profile under bark of a felled blackbutt (*E. pilularis*) stem (*curved solid lines*), with a diameter at breast height over bark of 40 cm and a total height of 41 m. The *vertical solid lines* are positioned at heights of 2.5 and 35 m above ground. The *dashed lines* show what the stem profile would be if the stem was shaped as a neiloid between 0 and 2.5-m height, a quadratic paraboloid between 2.5 and 35 m and a cone between 35 and 41 m. Note that the *horizontal and vertical scales* of the diagram differ greatly (drawn using an unpublished taper function, developed in 1997 by E. Baalman, then of the state forest service of New South Wales, Australia)

and *if* the last 6 m of the stem was conical in shape. Whilst some deviations are apparent between these three specific shapes and the actual stem shape, the differences are not great. That is, the findings of the older research do not seem to have been violated too grossly. This has justified the continued use of (5.1)–(5.3) to determine the volumes of sections of tree stems or logs.

5.3.3 Sectional Measurement of Felled Trees

It is quite straightforward to use the sectional method to measure felled trees or individual logs lying on the ground. In both cases, the bark can be removed so that the stem wood is measured directly. Removing the bark can be quite difficult, especially at times of year when the trees are not growing rapidly and the bark may be held very tightly on the stem. However, once the bark is removed, stem diameter is measured with a diameter tape or calipers at successive heights along the stem, right to the tip of the stem or to whatever stem diameter at which it is desired to stop measuring.

Various decisions need to be made when taking these measurements. If Huber's formula (5.2) is to be used to calculate the volume of each section, only section mid-diameters are measured. If Smalian's (5.1), diameters at both ends must be measured. If Newton's (5.3), all three diameters must be measured. Newton's formula generally gives a more precise result than the other two, because it uses more information to calculate the volume.

Because of the butt swell, care needs to be taken near the base of the tree. The enlarged diameter at the base of the stem can lead to substantial bias in the estimate of the volume of the base section if that diameter is used with Smalian's or Newton's formulae. Care is needed also if the end of a section falls on a bump on the stem, such as where a branch has emerged. The usual technique of averaging two diameter measurements spaced equally above and below the irregularity must then be used (Sect. 3.4).

Perhaps more importantly, a decision needs to be made as to what length the sections should be. Mathematically speaking, the shorter and shorter the sections, the less and less important become any violations of the assumptions about stem shape which are implicit in (5.1)–(5.3) and the less will be any bias in the volume estimates made using them. Most direct tree stem volume measurements today are made using quite short section lengths, perhaps of 0.5–1 m for large trees. Shorter lengths still are necessary for small trees only a few metres tall. Usually, Smalian's formula, (5.1), is then the easiest to use to calculate the volume of each section.

Less attention is usually paid to finding the volume of the last several metres of the stem of a large tree, perhaps above the point where the stem diameter falls below 3–5 cm, than for the lower part of the stem. The uppermost part of the stem contributes very little to the total volume of the stem, so a less precise measurement of it is unimportant in adequately determining the entire stem volume. Usually, only the diameter of the stem at the base of that last section is measured, d_{T}, and the distance t to the tip of the stem is measured. Its volume, V_{T}, is then determined as that of a cone, that is,

$$V_{\mathrm{T}} = \pi d_{\mathrm{T}}^2 t / 12, \tag{5.5}$$

where d_{T} and t must have the same units.

Sometimes, it is desired to determine the volumes of particular classes of log size that occur in a tree. Nothing new in the approach is necessary to do this. Still, care is needed to make sure that the stem is divided into sections which define the different log size classes so that their respective volumes can be determined. Section lengths may then become somewhat irregular. Smalian's formula is usually the easiest to apply to obtain the section volumes, because the position of the mid-point of each section does not have to be located.

In modern forestry practice, it has become quite rare to need to measure the stem wood volumes of individual trees as part of routine **forest management**. Mostly, it is done as part of a research project to obtain the data necessary to develop a tree **volume function** or taper function for use with a particular tree species in some region of forestry interest. These functions allow estimation of stem wood volumes of standing (or felled) trees, usually from measurement only of their diameter at breast height over bark and their total height. They will be discussed in detail in Chap. 6.

5.3.4 Sectional Measurement of Standing Trees

Standing trees could be climbed and measured sectionally (measuring both diameter over bark and bark thickness) to determine their stem wood volumes. However, this is dangerous and labour-intensive work, which is done rarely today. As mentioned above, tree volume and taper functions (Chap. 6) are available now for many species of forest tree in many parts of the world to provide (usually quite precise) estimates of their volume of wood from measurements which can be made easily from the ground.

Generally, it is only in circumstances where adequate volume or taper functions are not available that stem wood volume of standing trees must be measured directly. Where it is necessary, various high quality optical instruments are available (e.g. the Barr and Stroud **dendrometer**, the Telerelaskop, the Relaskop, the Wheeler pentaprism, the laser relascope–see Kalliovirta et al. 2005) which allow stem diameters over bark to be measured from the ground at any height desired along the stem. Using such instruments to make these measurements is known as optical dendrometry. Accuracies of measurement with these devices may be to within 1–5% of the measured stem diameter.

As these instruments measure diameters over bark only, some additional method must be used to determine bark thicknesses, so that wood volume under bark can be determined. An example of the type of method used to do this is given in Sect. 5.4. Muhairwe (2000) has summarised and tested a variety of functions that have been developed from time to time for this purpose.

One difficulty with these instruments is to sight the stem clearly amongst the branches in the crown. Section lengths need to be adjusted to make measurements at heights where the stem can be seen. Care and practise are needed to use these instruments efficiently; they are slow and time consuming, but much less arduous and dangerous than climbing trees.

5.4 Volume by Importance or Centroid Sampling

A method which is much simpler and quicker than using sectional measurement with optical dendrometry (Sect. 5.3.4) is available to measure directly stem volume of standing trees. It involves one or other of what are known as importance sampling or centroid sampling.

The method requires that the stem diameter at breast height of the standing tree be measured, both under and over bark, and that its total height be measured. In addition, one further value of stem diameter over bark must be measured, high up on the stem of the tree. An optical dendrometer can be used to make this upper diameter measurement.

Not only can this method be used to measure the total stem wood volume of the standing tree, but also it can be used to measure the wood volume of any section of the tree stem, between any two heights above ground that are desired. This would allow measurement of the volume of a section of the stem from which a particular size class of log might be cut. However, an additional upper stem diameter must be measured to determine the volume of each particular stem section of which the volume is required.

The method relies on careful selection of the point at which the upper stem diameter is measured. There are two methods for selecting this point, importance and centroid sampling. Wiant et al. (1992) have published a simple exposition of how the method is applied. Their approach was followed here in describing it.

Firstly, suppose a tree has a diameter at breast height over bark of D_o and its corresponding diameter under bark at breast height is D_u. Suppose its total height (ground to tip) is H_t. Secondly, suppose it is desired to estimate its stem wood volume under bark between two points on the stem, from a lower height, H_l, to an upper height, H_u (that is, $0 \le H_l < H_u \le H_t$). Thirdly, the height, H_s, must be determined at which the upper stem diameter over bark is to be measured. This height will lie between H_l and H_u. To do this, a value, k, is determined as

$$k = 2H_t(H_u - H_l) + H_l^2 - H_u^2 \tag{5.6}$$

and this is used to determine the required height as

$$H_s = H_t - \sqrt{(H_t - H_l)^2 - \eta k}. \tag{5.7}$$

If importance sampling is to be used, then η in (5.7) should be a randomly selected value in the range 0–1. If centroid sampling is being used, then $\eta = 0.5$; the centroid is the position along the stem section being considered above and below which half of the section volume lies. The computations in (5.6) and (5.7) would be done with a calculator or computer, in the field, at the time a tree was being measured.

Fourthly, after H_s has been calculated, the diameter over bark of the stem must be measured at H_s, usually with an optical dendrometer. Suppose this is found to be D_s. Then, the wood volume of the section of the stem between H_l and H_u, V_{lu}, may be estimated as

$$V_{lu} = \pi k (D_s D_u / D_o)^2 / [8(H_t - H_s)]. \tag{5.8}$$

Note that the same units must be used throughout for each of these variables (say, all in metres or all in feet).

Two important assumptions have been made in deriving (5.6)–(5.8). The first is that the ratio of diameter under bark to diameter over bark is constant anywhere along the stem. Research with many forest tree species has suggested this is often so, at least for a large part of the stem. This assumption could be used to determine under bark diameters from over bark when the sectional method is used with optical dendrometry (Sect. 5.3.4); other methods are available to do this (Muhairwe 2000) and their assumptions could replace this assumption in the present theory.

The second assumption is that the stem is shaped as a quadratic paraboloid along its whole length. As discussed in Sect. 5.3.2, this is true generally for a large proportion of the tree stem, above the butt swell and below the crown. The method can be modified for cases where research has provided better information about either of these assumptions for any particular tree species. However, if that type of research has been undertaken, it will usually have led to the development of tree stem volume or taper functions (Chap. 6), which would be used in place of this method anyway.

Consider an example of the use of this method. Suppose a tree had $D_o = 0.423$ m, $D_u = 0.373$ m and $H_t = 38.0$ m. Suppose an estimate of stem wood volume was required for the section of the stem from $H_l = 0.2$ m above ground to $H_u = 8$ m above ground. Using (5.6), this gives a value of $k = 528.84$. If centroid sampling was being used, then the height at which the upper stem diameter over bark must be measured is $H_s = 3.9$ m, calculated using (5.7) with $\eta = 0.5$. Suppose that diameter was then measured as $D_s = 0.333$ m. Then, using (5.8), the wood volume of the required stem section would be estimated as 0.525 m^3.

Alternatively, if importance sampling was used, suppose that after choosing a random value in the range 0–1 to use for η in (5.7), the value for H_s was found to be 4.5 m and that the stem diameter over bark measured at that height was $D_s = 0.329$ m. Then, the volume of the stem section would be calculated as 0.522 m^3.

Inevitably, the two volume estimates from importance and centroid sampling will differ slightly because of the different sampling methods and because of natural irregularities along the tree stem. However, research has suggested that the differences are generally small and thus of little consequence.

The method can be used to estimate total stem wood volume from ground to tip as well as the volume of any section of the stem. Considering the same sample tree as above, this would involve setting $H_l = 0$ and $H_u = H_t = 38.0$ m. For centroid sampling, this would lead to $H_s = 11.1$ m and the stem diameter over bark would then be measured at that height. Suppose this diameter was 0.243 m, then the total stem wood volume would be estimated as 0.969 m^3. Of course, the assumptions implicit in the method (constant ratio of under to over bark diameter along the whole stem and the stem shaped as a quadratic paraboloid) are less likely to hold over the entire stem length and some bias is likely to be introduced into the estimation of total stem volume.

Research has suggested that both importance and centroid sampling have sufficiently small bias and adequate precision in estimating stem wood volumes of standing trees, that they can be used for many practical purposes (Wood and Wiant 1990; Coble and Wiant 2000). Certainly they are far quicker and easier than the use of optical dendrometry to take sectional measurements along the entire stem of a standing tree. Examples where these methods have been used in practice can be found in Dieters and Brawner (2007) and West et al. (2008). Research continues on the development of approaches such as these to stem volume estimation (Özçelik 2008).

Chapter 6
Stem Volume and Taper Functions

6.1 The Functions

As discussed in Chap. 5, stem volume measurement is a laborious and time consuming task, even for felled trees. In modern forestry practice, one of the most common reasons for taking such measurements is to develop stem **volume functions** or taper functions, for a particular tree species in a particular forest region.

Volume functions allow estimation of the total stem volume of a standing tree from simple measurements, usually its diameter at breast height over bark and its total height. Sometimes, they also allow an estimation of the volume of particular size classes of logs within a tree so that the **merchantable volume** of wood available from it can be determined.

Taper functions estimate how the diameter of the stem of a tree varies along its length. As with volume functions, they generally require that only the diameter at breast height and total height of the tree be measured. Furthermore, they can be used to estimate both merchantable and total stem wood volumes. Taper functions are rather more complex to develop than volume functions, but the data required for both is the same: sectional measurements of the stems of a large **sample** of individuals of the tree species concerned provide all the data usually required.

Volume and taper functions have been developed for a very large number of species of trees important commercially to forestry around the world. In this chapter, these functions will be described generally, with reference to just a few examples.

6.2 Volume Functions

Three variations of stem volume functions will be considered. Firstly, there are those which allow estimation of the total stem volume from ground to tip, from measurements of diameter at breast height and total tree height. Secondly, there are variations on those functions, which require that a measure of the degree to which the stem tapers be made also. Thirdly, there are functions which allow estimation of the volume of part of the stem, so that merchantable volume can be determined.

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6.2.1 Volume from Diameter and Height

Different researchers, working with different species in different parts of the world, have used various **functional forms** for stem volume functions. Generally, two basic forms have been used. Both allow estimation of the total stem volume from ground to tip (V), over or under bark, from measurements of stem diameter at breast height (D), usually over bark, and total height of the tree (H). The two functional forms are

$$V = a + bD^2 + cH + dD^2H + eH^2 + fD^2H^2 \ldots\ldots\ldots \tag{6.1}$$

and

$$V = aD^bH^c. \tag{6.2}$$

In these functions, the terms a, b, c, d,…etc. are parameters. That is, they will take particular values in the function developed for a particular species in a particular region. The string of dots after (6.1) implies that additional terms have sometimes been included in functions of this form, terms in higher powers of D and H and their products. Often, versions of (6.1) have been used which do not include all of the terms shown there. Research continues on which functional forms are most appropriate for stem volume functions in particular cases (Williams and Schreuder 2000).

Given a data set collected from a sample of trees of a species, for each of which V, D and H has been measured, the values of the parameters of functions such as these will usually be determined using regression analysis. Regression analysis is one of the most powerful tools available for the analysis of data in the natural and physical sciences. It is used to determine how variables are related to each other and to provide predictions of values of one variable from one or several other variables. There will be no further discussion here of how regression analysis works, other than to say that some knowledge of mathematical statistics and some years of experience are necessary to apply it competently. It is discussed in standard texts (e.g. Draper and Smith 1988; Freund et al. 2006). The calculations required to do it are rather tedious and are done using a computer.

Table 6.1 lists an arbitrary selection from the literature of nine stem volume functions, developed for various species of trees in various parts of the world. It illustrates both the variety of functional forms that have been used from time to time, and the variety of species and places for which volume functions have been developed.

Functions 1–4 in the table are versions of (6.1). Functions 5–8 all have the form of (6.2). Function 9 has a form quite unrelated to either (6.1) or (6.2), illustrating that individual authors have used quite different functional forms from time to time. The specific values that the parameters take for each function are shown in the table.

It is interesting to compare the functions in Table 6.1 with each other. The solid lines in Fig. 6.1 show, for trees of 30 m height, how stem volume changes as stem diameter at breast height over bark changes, as predicted by each of the functions.

Table 6.1 An arbitrary selection from the literature of stem volume functions, which allow total stem volume from ground to tip under (V_U, m^3) or over bark (V_O, m^3) to be predicted for an individual tree from its diameter at breast height over bark (D, m) and total height (H, m)

Number	Function	Species and location	Reference
1	$V_U = 0.298D^2H$	*Eucalyptus regnans*, New Zealand	Hayward (1987)
2	$V_U = 0.001 + 0.270D^2H$	*E. viminalis*, New South Wales, Australia	Bi (1994)
3	$V_U = 0.005 + 0.330D^2H$	*Pinus taeda*, Southern USA	Williams and Gregoire (1993)
4	$V_U = 0.037 + 0.28D^2H$	*Bursera simaruba*, Puerto Rica	Brandeis et al. (2006)
5	$V_U = 0.250D^{1.85}H^{1.03}$	*Picea glauca*, Canada	Morton et al. (1990)
6	$V_U = 0.128D^{1.69}H^{1.16}$	*Pseudotsuga menziesii*, USA and Canada	Rustagi and Loveless (1990)
7	$V_O = 0.450D^{1.92}H^{0.90}$	*Juniperus procera*, Ethiopia	Pohjonen (1991)
8	$V_O = 0.311D^{1.93}H^{1.02}$	*Gironnierra subaequalis*, Southern China	Fang and Bailey (1999)
9[a]	$V_u = \exp[-1.75 + 1.29/(D + 1.27)^2]\ D^2H$	*E. regnans*, Victoria, Australia	Opie (1976)

[a] The expression 'exp' in this function means that the mathematical constant '*e*' is to be raised to the power of the value calculated in the square brackets after the expression. The constant '*e*' is the base of natural logarithms. Its value is approximately 2.7183

Similar diagrams could be drawn for trees of other heights. Note that two of the functions (7 and 8) estimate over bark volume, whilst the rest estimate under bark (that is, wood) volume.

It is obvious from the figure that different species of trees have substantially different stem volumes for any given stem diameter; over the range of the data in the figure, the largest and smallest volumes for any diameter differ by around 35%. This means that the shapes of the stems of the different species must differ appreciably. It is clear that applying a stem volume function developed for one species to another species could lead to substantial bias in the volume estimates obtained for the other species.

Especially since the 1960s, when computers became available readily to allow regression analyses to be carried out, forest scientists have developed many volume functions, for many tree species in many parts of the world and continue to do so (Cordero and Kanninen 2003; Akindele and LeMay 2006; Brandeis et al. 2006; Diéguez-Aranda et al. 2006b; Vallet et al. 2006).

The dashed line shown on Fig. 6.1 is the volume function

$$V_U = 0.3D^2H, \tag{6.3}$$

where V_U is tree stem volume under bark from ground to tip (m^3), D is tree diameter at breast height over bark (m) and H is tree total height (m). This 'easy to remember' volume function gives a more or less average estimate of the tree stem wood volume for a tree of given diameter and height. Of course, I would not advocate

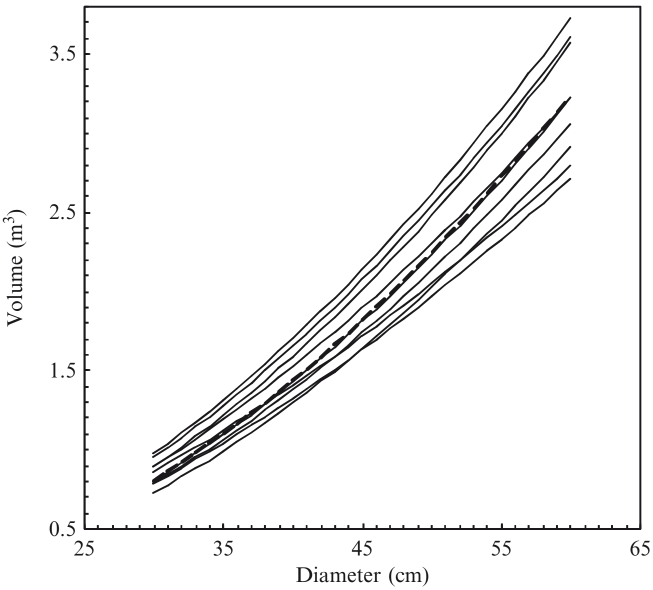

Fig. 6.1 The *solid* lines show the relationships between stem volume and diameter at breast height over bark for trees 30 m tall, as predicted by each of the nine tree volume functions listed in Table 6.1 (which function refers to which line has not been shown in the figure). The *dashed* line shows the rule-of-thumb volume function for general use, (6.3)

its use if it was desired to estimate properly the stem volume of any tree. However, it is useful as a rule-of-thumb for anyone who wishes to make a rough estimate of stem volume, for a tree for which they do not have to hand a specific volume function.

In forestry practice, it is often necessary to estimate volumes available of logs of various size classes, so that the amount of merchantable volume can be determined. The functions described in this subsection allow estimates only of the total volume of the stem. However, total volume is useful to forest scientists, because it is a good measure of tree growth. An even better measure of growth is tree biomass; as will be seen in Sect. 7.4.2, tree stem volumes can often be used to predict tree biomasses.

6.2.2 *Volume from Diameter, Height and Taper*

The volume functions considered in Sect. 6.2.1 required that only tree stem diameter at breast height over bark and total height of the tree be measured. Some researchers have developed volume functions which require measurement also of the degree to which the stem tapers.

It is well known in forest science that, as trees sway in the wind, the forces to which this subjects their stems increases their taper. In an experiment where large trees were tied with cables to prevent them swaying, the tree stems became almost cylindrical after several years, that is, to have virtually no taper (Jacobs 1954). Other experiments have shown that bending stresses in the stem due to wind sway increase both wood strength and stem taper (Valinger 1992; Osler et al. 1996a; Dean et al. 2002; Mäkelä 2002; Fourcaud and Lac 2003; Fourcaud et al. 2003; Dean 2004; Watt et al. 2006a, b).

In forestry, **management** practices are often undertaken which affect the degree to which trees are exposed to the wind and, hence, the degree to which they sway. Opening the forest, by removing some of the trees in thinning a plantation, is one of the most common of these practices. Under these circumstances, it would be expected that a stem volume function which took into account stem taper might be able to better estimate stem volumes in both thinned and unthinned stands.

The additional information required to assess stem taper usually involves measuring another tree stem diameter at some height other than breast height. The height chosen is usually not far up the stem, so that the additional diameter can be reached without too much difficulty. Two examples will be used to illustrate such functions. The first is for Douglas fir (*Pseudotsuga menziesii*) in northern USA and Canada, developed by Rustagi and Loveless (1990). Their function was

$$V_U = 0.146D^2H + 0.433D^2H_D, \tag{6.4}$$

where V_U (m^3), D (m) and H (m) are as for (6.3) and H_D (m) is the height up the tree stem at which the diameter over bark is two-thirds of the diameter at breast height over bark (a height which may be rather tedious to locate on a tree).

In this case, stem taper is being allowed for by including the variable H_D in the function; the more the stem tapers, the shorter will the distance be above breast height at which stem diameter becomes two-thirds of breast height diameter. Rustagi and Loveless found that this function gave appreciably more precise estimates of tree stem volume than a function which did not include the measure of stem taper (it was Function 6 in Table 6.1).

The second example was developed by Aleixo da Silva et al. (1994), using combined data for loblolly pine (*Pinus taeda*) and slash pine (*P. elliottii*) from the southern USA and Honduran Caribbean pine (*P. caribea* var. *hondurensis*) from Sri Lanka. Their function was

$$V_o = 0.196D^2H[1 + D_a / D_b][H / (H - 1.52)], \tag{6.5}$$

where V_O is tree stem volume over bark from ground to tip (m^3), D (m) and H (m) are as above and D_a and D_b are the stem diameters over bark (m) at 1.52 and 0.152 m above ground respectively. In this case, it is the ratio of the two diameters from two different heights on the stem, D_a and D_b, which acts as the measure of stem taper. It is interesting that this single function seemed to give reliable results for three different species of pine in two very distant parts of the world.

6.2.3 Merchantable Stem Volume

A single example will be used to illustrate the type of function that has been developed to estimate the volume of a part of the stem only. This is usually the volume to some particular diameter along the stem, which determines the point above which logs of a particular size class can no longer be cut.

The example was developed by Shiver and Brister (1992) for plantations of Sydney blue gum (*Eucalyptus saligna*), up to about 10 years of age in Kenya. Their function was

$$V_{\mathrm{d}} = 0.0950D^{1.83}H^{1.24}(1 - 1.24d^{3.49} / D^{3.37}), \tag{6.6}$$

where V_{d} is the stem volume under bark (m^3) from ground level up to the point on the stem where its diameter over bark becomes d (m), D is tree diameter at breast height over bark (m) and H is tree total height (m).

Consider how this function might be useful. Suppose that two possible products could be cut from trees in these forests, posts or **pulplogs** (small logs to be chipped and used for paper-making). Suppose posts must have a diameter over bark at their small end of at least 0.15 m and pulplogs can be cut up to a stem diameter over bark of 0.06 m. Consider a tree with $D = 0.24$ m and $H = 25$ m. Then, using $d = 0.15$ m, (6.6) shows that 0.301 m^3 of the stem could be cut as posts. With $d = 0.06$ m, the function shows 0.375 m^3 of pulplogs could be cut from the stem. If all the volume that could be used for posts was indeed used, then there would be 0.074 m^3 (=0.375–0.301) left to be sold as pulplogs. This type of information would be useful to forest planners attempting to determine what volumes of posts and pulplogs could be harvested from trees in these forests.

One of the limitations of this type of merchantable volume function should be evident from this example. Merchantable log sizes are defined usually not only by the minimum diameter they may have at the small end of the log, but also by the minimum length the log must have. Thus, it might be that a post must be at least 2 m long, say, or it would be too short to be sold as a post. Whilst the tree in the example would yield a total of 0.301 m^3 of material large enough in diameter to be posts, there might be insufficient length of material in that volume for it all to be used as posts. No information about the length available is given by the merchantable volume function. As discussed in Sect. 6.3, taper functions overcome this limitation of merchantable stem volume functions.

It should be noted also that if $d = 0$ in the example, that is, where the stem diameter becomes zero at its tip, (6.6) then gives the total stem wood volume of the tree from ground to tip. In other words, (6.6) can be used in just the same way as the other volume functions described in Table 6.1.

An additional problem in determining merchantable volume (or indeed total stem wood volume) is that trees are found quite often with their stem partially hollowed out. Termites and wood decay fungi are the most common causes of this. The damage may extend for several metres up from the base of the tree, reducing substantially the amount of usable wood which can be cut from it. Externally, the tree may appear perfectly sound. If the presence of decay is suspected, ultrasound can be used to measure it (Martinis et al. 2004). However, its presence often does not become evident until the tree is felled. Functions have been developed which can at least estimate the likelihood that a stem of a tree of particular species contains such damage; Schneider et al. (2008) give a good example.

6.3 Taper Functions

Taper functions estimate how the diameter of the stem (over or under bark) changes along the length of the stem. The reasons why stems taper, in response to the forces to which they are subjected as trees sway in the wind, were discussed briefly in Sect. 6.2.2. At present, our understanding of this process is inadequate and we have not yet developed any theory sufficiently well to describe fully how and why stems taper.

Because of this, most taper functions developed to date are **empirical** functions. That is, they have been determined by trial and error, by measuring how diameter changes along the length of tree stems and then finding some mathematical functional form which describes adequately the shape of the stem. Research has been attempting to develop taper functions from a more theoretical basis, but this work still has far to go (Sharma and Oderwald 2001; Deleuze and Houllier 2002; Ikonen et al. 2006).

In this section, some examples will be given of taper functions which have been developed for various species in various parts of the world. The way in which they can be used to predict both total and merchantable stem volumes will then be described.

6.3.1 Examples of Taper Functions

Sharma and Oderwald (2001) developed a taper function for trees in natural forests of loblolly pine (*P. taeda*) in the southern USA. It was

$$d_{\mathrm{oh}} = D\sqrt{(h/1.37)^{-0.185}(H-h)/(H-1.37)}, \tag{6.7}$$

where d_{oh} is stem diameter over bark (cm) at height h (m) above ground, D is stem diameter at breast height over bark (cm) and H is tree total height (m). Malimbwi and Philip (1989) developed a function for plantations of Mexican weeping pine (*P. patula*) in Tanzania as

$$d_{\mathrm{uh}} = 0.774D^{0.932}(H-h)^{0.610}/H^{0.448}, \tag{6.8}$$

where d_{uh} is stem diameter under bark (cm) at height h (m) above ground and D (cm) and H (m) are as above.

Figure 6.2 shows the stem shapes predicted by these functions, for example trees of a particular diameter and height. The stem profile for *P. taeda* shows clearly the butt swell near the base of the stem, but the butt swell is missing for *P. patula*;

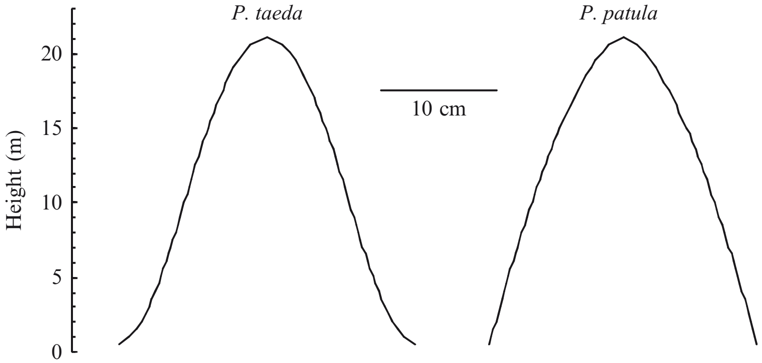

Fig. 6.2 Profiles of the stems of trees of *P. taeda* over bark (as predicted by 6.7) and of *P. patula* under bark (6.8). In both cases, the trees were assumed to have a diameter at breast height over bark of 23 cm and a height of 21 m. Note that the vertical and horizontal scales of these diagrams differ greatly (drawn using taper equations of Sharma and Oderwald 2001 and Malimbwi and Philip 1989)

Malimbwi and Philip did not describe fully how they collected the data for their *P. patula* trees and it may be that they excluded lower stem data.

Mathematically speaking, both (6.7) and (6.8) are quite simple. Functions such as these often describe tree stem shape quite well, particularly in its midsections. However, rather more complex functions seem to be necessary to ensure the shapes of the upper and lower sections of the stem are also well defined. As an example, Brooks et al. (2008) used a function, suggested by Max and Burkhart (1976), to describe shape of the stem of three commercially important species native to Turkey, Brutian pine (*P. brutia*), Cedar of Lebanon (*Cedrus libani*) and Cilicica fir (*Abies cilicica*), whilst Sharma and Burkhart (2003) used the same function for loblolly pine (*P. taeda*) from plantations in the south-eastern USA. This rather cunning function considers the tree stem to be shaped as a neiloid near its base, as a paraboloid in its midsection and as a cone near the tip, that is, consistent with the older research findings discussed in Sect. 5.3.2. The function is

$$d_{\mathrm{oh}} = D\sqrt{b_1[(h/H)-1]+b_2[(h/H)^2-1]+b_3[a_1-(h/H)]^2 I_1+b_4[a_2-(h/H)]^2 I_2}, \tag{6.9}$$

where $d_{\mathrm{oh},}$ (cm), h (m), D (cm) and H (m) have the same meanings as above, a_1, a_2, b_1, b_2, b_3 and b_4 are parameters, $I_1 = 1$ when $(h/H) \le a_1$ or zero otherwise and $I_2 = 1$ when $(h/H) \le a_2$ or zero otherwise; note that in Sharma and Burkhart's case, they predicted diameter under bark (d_{uh}, cm) rather than diameter over bark. In this function, the value of the parameter a_2 defines the relative height (h/H) at which the stem shape changes from a neiloid to a quadratic paraboloid, whilst a_1 defines the relative height above which it becomes conical. The parameter values determined for the four species are shown in Table 6.2.

Table 6.2 Parameter values of (6.9) for four tree species, as used to draw results in Fig. 6.3

Parameter	*P. brutia*	*C. libani*	*A. cilicica*	*P. taeda*
a_1	0.7313	0.7593	0.849	0.7487
a_2	0.1307	0.1116	0.171	0.0867
b_1	−3.0832	−3.6549	−2.9364	−3.3108
b_2	1.486	1.7947	1.3965	1.5745
b_3	−0.9304	−1.3658	−0.7093	−1.7299
b_4	17.9703	25.9476	5.4083	65.9168

Figure 6.3 shows the stem profiles predicted using this function, for a tree of a particular diameter and height of each of the four species. It appears that *P. brutia* and *C. libani* stems are rather similar in shape, whilst *P. taeda* has a rather more pronounced butt swell and *A. cilicica* rather less so. Note also that the stem shape defined for *P. taeda* appears rather more complex than it does in Fig. 6.2, where a more simple function (6.7) was used.

Research continues in the development of taper functions and many have now been developed for different species around the world, often using functional forms different from the examples given here (Hayward 1987; Bi 2000; Zhang et al. 2002; Bi and Long 2001; Valentine and Gregoire 2001; Garber and Maguire 2003; Ter-Mikaelian et al. 2004; Jiang et al. 2005; Teshome 2005; Diéguez-Aranda et al. 2006b; Koskela et al. 2006; Lappi 2006; Zakrzewski and MacFarlane 2006; Newton and Sharma 2008; Özçelik 2008).

6.3.2 Using Taper Functions

The function developed for Tanzanian *P. patula* by Malimbwi and Philip (1989), (6.8), will be used as an example to illustrate how taper functions are used. For the sake of the example, suppose the only merchantable log products which can be cut from *P. patula* plantations in Tanzania are **sawlogs** (logs large enough to be sawn into one or more of the many types of sawn wood used for building and many other purposes) or pulplogs. Suppose sawlogs are 2.4 m long and their under bark diameter at their small end must be no less than 15 cm. Suppose pulplogs are 3 m long and their under bark diameter at their small end must be no less than 8 cm.

Figure 6.4 shows the stem profile, predicted using (6.8), of the same *P. patula* tree as shown in Fig. 6.2, that is, with a diameter at breast height over bark of 23 cm and a total height of 21 m. The taper function may now be used to determine what sawlogs and pulplogs could be cut from this tree. Since sawlogs must have a diameter under bark at their small end of at least 15 cm, the first step is to determine how far up the stem it is before the diameter becomes less than this. This can be determined by rearranging algebraically (6.8) to give h on the left-hand side, that is,

$$h = H - [d_{\mathrm{uh}} H^{0.448} / (0.774 D^{0.932})]^{(1/0.610)}. \qquad (6.10)$$

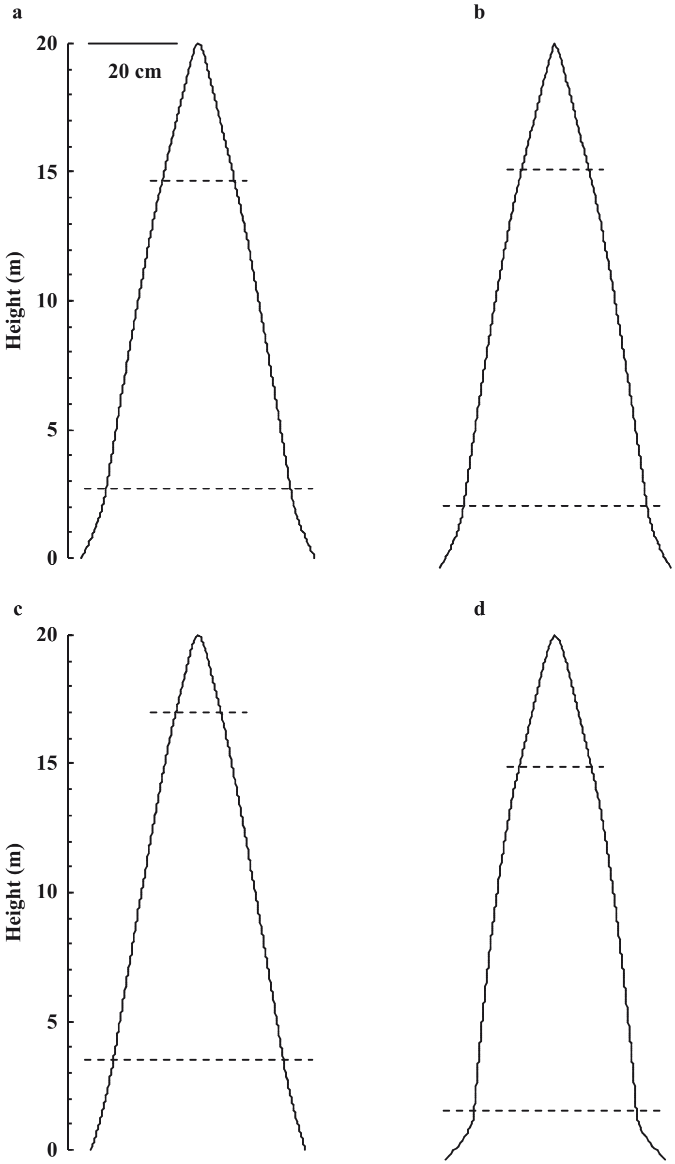

Fig. 6.3 Profiles of the stems of trees of (**a**) *P. brutia*, (**b**) *C. libani*, (**c**) *A. cilicica* and (**d**) *P. taeda*, determined using (6.9) with parameter estimates as given in Table 6.2. Each tree was assumed to have a diameter at breast height over bark of 45 cm and a height of 20 m. Below the *lower dashed line*, the stem shape is neiloidal, Above the *upper dashed line*, it is conical. Between these points, it is paraboloidal (drawn using taper equations of Brooks et al. 2008 [**a**,**b**,**c**] and Sharma and Burkhart 2003 [**d**])

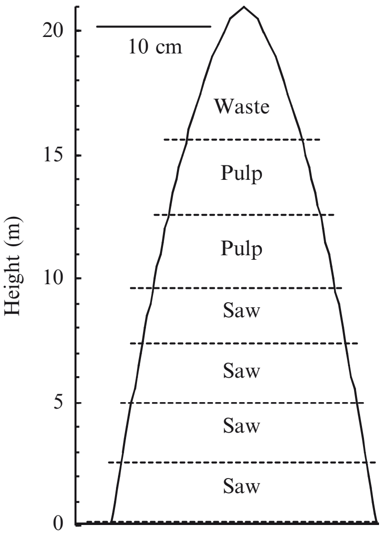

Fig. 6.4 Under bark profile of the stem of a *P.patula* tree with a diameter at breast height over bark of 23 cm and a height of 21 m. For the example described in the text, the *dashed lines* show the positions from which sawlogs (*Saw*) and pulplogs (*Pulp*) could be cut from the stem and what would be wasted (*Waste*) (derived using the taper function of Malimbwi and Philip 1989)

Using (6.10), with $H = 21$ m, $D = 23$ cm and $d_{uh} = 15$ cm, shows that the stem diameter becomes 15 cm at 11.0 m from the base. This means that, at the most, four sawlogs can be cut from the stem, since each is 2.4 m long. Of course, when the tree is felled, it will be cut some little distance above its base, usually at a height (called the stump height) of about 0.2 m above ground. Thus, the four 2.4 m sawlogs could be cut from stem sections which are positioned 0.2–2.6, 2.6–5.0, 5.0–7.4 and 7.4–9.8 m along the stem. Whilst the last part of this section of the stem, 9.8–11.0 m, has a diameter large enough to be a sawlog, it is not long enough to be so. The positions of those four sawlogs are shown on Fig. 6.4.

With four sawlogs cut from up to 9.8 m along the stem, the number of pulplogs which can be cut from the remainder of the stem can now be calculated. Using (6.10) with $d_h = 8$ cm, the smallest diameter that the small end of a pulplog may have, it is found that pulplogs cannot be cut above 17.4 m along the stem. Thus, pulplogs could be cut from the 7.6 m long section extending over 9.8–17.4 m along the stem. Because pulplogs are 3 m long, two could be cut, positioned at 9.8–12.8 and 12.8–15.8 m along the stem. Their positions are marked also on Fig. 6.4. The remaining 5.2 m of the stem, 15.8–21 m, would be wasted.

In practice, the logs which could be cut from the stem will not occupy exactly the positions determined in this example. The few millimetres width of wood lost in cross-cutting with a chainsaw would have to be allowed for in positioning the logs. Also, where there are defects in the stem, a large branch swelling say, that point would be avoided when the stem is cross-cut. Sometimes, forest planners develop functions additional to their taper function to estimate where such defects are likely to occur on the stem and improve their estimates of exactly what logs can be cut from a particular stem.

Once it has been determined from what positions along the stem logs can be cut, the taper function allows additional information to be obtained about the size of each log. Knowing the heights in the stem at which the cross-cuts are made, (6.8) can be used to determine the diameters of each log at both its small and large end. Table 6.3 lists those values for the sample tree.

Furthermore, the taper function can be used to determine the volume of each of the logs. To do this requires the use of integral calculus. Calculus in general (of which integral calculus is a part) is an extremely important and widely used mathematical tool, invented in the late seventeenth century independently by an Englishman, Sir Isaac Newton, and a German, Gottfried Leibniz. This is not the place to discuss calculus, which is a complex field of mathematical study in its own right.

However, a brief idea can be given of how integral calculus would be used, with a taper function, to calculate the volume of a log positioned in a stem at a lower height above ground L (m) and an upper height U (m). Integral calculus first imagines that a very thin disc is cut from the stem at the lower height, L. The taper function is used to determine the diameter of the disk at that height and, hence, its circular cross-sectional area. The volume of the thin disc is then calculated assuming it is cylindrical in shape.

Integral calculus then imagines that a second thin disk is cut immediately above the first, and calculates its volume also; the second thin disk has a slightly smaller diameter than the first one because it comes from further up the stem. This process continues until the volumes of all the thin disks have been calculated right up to the upper height in the stem, U. Their volumes are then added up to give the total volume of the stem section between L and U. The real beauty of integral calculus is that it is able to imagine that each thin disk is infinitesimally thin (that is, it has no thickness at all). Thus, there is no error made by assuming that each disk is actually cylindrical, whereas a thin, but finite, disk would have a slightly smaller diameter at its upper end than at its lower end.

Table 6.3 Positions in the stem and diameters and volumes of the various logs, the stump and the waste section, which would be cut from the example tree shown in Fig. 6.4. Results are shown also for the entire stem

	Position along stem	Diameter		Volume
Log	(m)	Large end (cm)	Small end (cm)	(m^3)
Stump	0–0.2	23.6	23.4	0.0087
Sawlog 1	0.2–2.6	23.4	21.7	0.0962
Sawlog 2	2.6–5.0	21.7	20.0	0.0820
Sawlog 3	5.0–7.4	20.0	18.1	0.0683
Sawlog 4	7.4–9.8	18.1	16.1	0.0550
Pulplog 1	9.8–12.8	16.1	13.3	0.0510
Pulplog 2	12.8–15.8	13.3	10.1	0.0325
Waste	15.8–21	10.1	0	0.0186
Entire stem	0–21	23.6	0	0.4123

In the formal language of integral calculus, we write this process for the determination of the volume of a log (V_{LU}, m^3) between heights L and U (m) in a stem as

$$V_{LU} = \int_{L}^{U} (\pi / 40{,}000) d_{\mathrm{h}}^{2} \mathrm{d}h. \tag{6.11}$$

In this relationship, the term $(\pi/40{,}000)d_{\mathrm{h}}^{2}$ represents the circular cross-sectional area (m^2) of the stem at height h (m), where its diameter is d_{h} (cm), and the term dh (which is read in calculus as 'with respect to changing height along the stem') represents the (infinitesimally small) thickness (m) of the disk cut at that point. Their product $(\pi/40{,}000)d_{\mathrm{h}}^{2}\mathrm{d}h$ is the volume (m^3) of the thin disk, assuming it is cylindrical. The terms L and U in (6.11) indicate that disks are to be cut between those two heights in the stem, and the special integral calculus symbol $\int$ (which is read as 'the integral of') means that the volumes of all the thin disks between L and U are to be summed to give their total volume V_{LU}.

Returning now to the example, substitute the right-hand side of the taper function (6.8) for d_{h} in (6.11), to give (with the squaring of d_{h}),

$$V_{LU} = \int_{L}^{U} (\pi / 40{,}000)[0.599 D^{1.864} (H - h)^{1.220} / H^{0.896}] \mathrm{d}h. \tag{6.12}$$

It is now possible to rewrite this integral in a normal mathematical form, which allows the volume to be calculated directly (there are mathematical text books on calculus which help you to do this integration). Doing so gives

$$V_{LU} = (\pi / 40{,}000)\{0.599 D^{1.864} / H^{0.896}\}\{[(H - L)^{2.220} - (H - U)]^{2.220}\} / 2.220. \tag{6.13}$$

Please note the erratum to this equation at the end of the book.

Given this, consider the first sawlog cut from the base of the stem of the sample tree (Fig. 6.4). It was positioned between heights 0.2 and 2.6 m along the stem, so for it L = 0.2 m and U = 2.6 m. Remembering that D = 23 cm and H = 21 m, (6.13) can be used to determine the volume of the log as 0.0962 m^3. Similarly, the volumes of each of the logs to be cut from the tree (and that of the stump at the base and waste section at the tip) can all be calculated using (6.13). The results are given in Table 6.3. Also, with L = 0 and U = 21, (6.13) can be used to determine the entire stem volume as 0.4123 m^3; of course, you will find that adding together the volumes of the various logs and those of the stump and waste will give exactly the same volume as this total.

It is important to note that it is not always possible algebraically to rearrange a taper function in order to use it directly to determine the height along the stem at which a particular diameter occurs (as was done with 6.10). Nor is it possible always to find the integral of a function as was done in obtaining (6.13) from (6.12). However, there are mathematical techniques available, called numerical techniques, which allow these heights to be determined and volumes to be calculated, even when these mathematical difficulties are encountered. These techniques are mathematically complex in themselves and can certainly be done practically only with the aid of a computer. They will not be discussed further here.

Given the discussion in this section, it can be seen that taper functions can be used to do all the things that stem volume functions can do. As well, they can be used to give additional detailed information about the logs which can be cut from a tree, information which is not available from stem volume functions. These days, most researchers prefer to develop taper functions, rather than stem volume functions.

Chapter 7
Biomass

7.1 Reasons for Biomass Measurement

Sale of logs for milling or paper-making has long been the principal market for the forestry industry and remains so. As it is the volume of a log which determines if it is large enough to be sawn to produce timber, forestry has been concerned traditionally with the measurement of the volume of the wood of the stem. That is why two complete chapters (5 and 6) have been devoted to the topic in this book.

However, there is an increasing interest in measurement of the biomass, that is, the weight of trees. Furthermore, it is not only the biomass of the stem which is of interest, but also the biomasses of the other parts of the tree, its leaves, branches and roots. Reasons for this interest include:

- All plants (including trees) produce biomass through photosynthesis. If scientists are to understand properly how tree growth occurs, they need to know how much biomass trees produce
- Concerns with global warming. There is much interest in how much carbon is sequestered in forest biomass around the world as a result of trees taking up the greenhouse gas carbon dioxide
- The establishment of plantation forests, to be grown for 3–5 years for bioenergy production. This wood is sold by weight, not volume
- Products such as firewood or wood for paper-making are often sold by weight.

This chapter describes the techniques used to measure the biomass of various parts of individual trees. It then describes functions which have been developed to estimate the biomass of trees from easily measured tree characteristics.

7.2 Measuring Biomass

Felling, dissecting and weighing trees can be a major undertaking, even more so if the root system is excavated. A large forest tree, say with a diameter at breast height over bark of 35–40 cm and total height of 30–35 m, might weigh 3–5 tonne when

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freshly cut. Of this, 2–3 tonne might be the stem, 0.5–1 tonne might be roots and 0.3–0.5 tonne might be leaves and branches. Even bigger trees than this occur in forests and their total weight can exceed 20 tonne. In contrast, very young trees may weigh only a few kilograms, so it is trivial by comparison to fell and weigh them. Even then, excavation of the root system can be a tedious task.

Usually, it is desired to measure the dry biomass of the tree, that is, its weight after the water has been removed from the fresh biomass. Water makes up about 50% of the weight of plants. Unlike nearly all the other biomass of a plant, water is not manufactured by the plant through photosynthesis or other metabolic processes. It is taken up from the soil by the roots. Thus, if the objective of the measurement is to determine what the plant has produced through its metabolic processes, it is the dry biomass that is relevant to measure, not the fresh biomass. Also, the amounts of water in plants can vary quite widely from time to time during the day or in different seasons. Thus, if consistency is required between measurements made of different trees at different times of year, dry biomass will be a more appropriate measure then fresh biomass.

To determine the **oven-dry** weight of biomass, fresh plant material is put in large laboratory ovens and dried at 60–80°C for several days, until the weight of the dried material remains constant. Laboratory ovens are limited in size, so it is obviously impractical that all of a large forest tree should be dried; some form of sampling has to be done and only the sampled material is dried.

This section describes methods to measure the biomass of large trees. The difficulty of the various procedures described will decline steadily as the size of the tree declines.

7.2.1 Branches and Foliage

There are two strategies used to reduce the amount of work required to measure the biomass of branches and foliage after a tree is felled. The first involves counting all the branches which emerge from the main stem and then selecting a sample from amongst them, usually by a random selection procedure. Mathematically formal procedures for selecting the sample have been developed (Valentine et al. 1984; Gregoire et al. 1995). Leaves are removed (usually by tedious cutting with scissors) from the sample branches and the branches themselves are cut into convenient lengths. The sample material is taken to the laboratory for drying. Sometimes also, the fresh weights of the sample leaves and branches are measured, by weighing it with a large balance in the field; a randomly selected sub-sample is then weighed fresh in the field and only this material is dried.

Given the dry weight data from the sample, and knowing the number of branches included in the sample and on the whole tree, it is straightforward to estimate the total dry weight of all the branches and foliage in the crown. Sometimes it is desired to estimate also the bark of the branch separately from the branch wood. This requires that the bark be stripped from the sample branches and its weight determined separately. Bark removal can be very difficult, particularly at times of the year when the tree is not actively growing.

The second, and probably more precise, strategy for estimating branch and foliage weight is founded on the principle that branches must be sufficiently large to support the weight of the leaves, to some distance out from the stem, and to resist the forces imposed on them by the wind. Because of this, there is usually a close relationship between both branch weight and the weight of the foliage they support and easily measured branch characteristics, such as the diameter at their base and/or their length.

Given this, the diameter at the point where they join the stem of all the branches on a felled tree would be measured, together with their lengths. Where large branches have smaller branches arising from them along their length, the length is measured of the main branch only. A sample of branches from the tree is then selected and their foliage and branch material removed to the laboratory for drying. Using the sample data, regression relationships (Sect. 6.2.1) are established to allow estimation of foliage and branch dry weights, from branch diameter and/or length, for all the other branches along the stem which were not included in the sample.

Often it is desired to measure the area of leaves, rather than their biomass. Since it is the leaf surface that absorbs light from the sun to provide the energy for photosynthesis and from which water is released by the leaves to the atmosphere, scientists studying plant growth behaviour often need to know the area of the leaves instead of, or as well as, the biomass of the leaves.

The area of samples of leaves obtained for biomass measurement may be determined by placing them on a digital scanner; computer programs are then available to determine the area of the scanned image. In essence, this means that leaf area is being defined as the area of the shadow which a leaf casts when held horizontally over a flat surface, with light shining vertically down on it. The same definition is used for both broad- and needle-shaped leaves.

Often, both leaf area and leaf oven-dry biomass are determined and the two values used to calculate the specific leaf area, which is the area of the leaves per unit of their oven-dry biomass (its inverse, specific leaf weight is often reported also). In essence, specific leaf area is a measure of the thickness of the leaves. It varies widely, perhaps in the range 2–40 m^2/kg, with tree species and tends to be lower in older trees (Holdaway et al. 2008), in trees growing in wetter environments (Gouveia and Freitas 2008), in overstorey plants growing in full sunlight (e.g. Specht and Specht 1999; Atwell et al. 1999) and in the better lit, upper parts of the **canopy** (the foliage and branches of the forest) (Monserud and Marshall 1999; Grote and Reiter 2004).

Dead branches present a problem in biomass measurement. They are usually found near the base of the crown, where the shade from the leaves higher up has led to loss of leaves from the branch. Eventually dead branches are shed by the tree but, if they are still attached to the tree at the time of measurement, it is usually considered appropriate to include them as part of the tree biomass. Such branches, and indeed branches with only a few leaves left, may have to be measured and sampled separately from other branches.

Often, there are problems near the tip of the tree. For many species, it is difficult to identify what constitutes the main stem where many small branches are growing near the tip. It may be necessary to treat the tip region separately, cutting it off and weighing all its leaves and branches, perhaps taking a sub-sample only away for drying.

7.2.2 Stems

Biomass of a tree stem is usually determined by measuring stem volume by sectional measurement (Sect. 5.3). To convert volume to biomass, stem wood density must then be determined also.

Stem wood density varies both along the length of tree stems and across its radius. For biomass estimation, some average density for the whole stem is required. Usually, a sample of stem discs, each a few centimetres thick, is cut from the stem at varying distances along it. Mathematically formal sampling strategies are sometimes used to determine the points along the stem at which the discs are taken (Valentine et al. 1984). In the laboratory, the volume of each disc is measured (by water immersion or by measuring its diameter and thickness) before it is dried. The disc is then oven-dried and weighed. This gives the **basic density** of wood, the oven-dry weight of wood per unit fresh volume. The average of all the disks is used as an average for the whole stem.

7.2.3 Roots

Root biomass measurement is vastly more difficult than measurement of the above-ground tree parts. The problems include the difficulties of physical excavation of roots from the soil and the inability to identify whether a root belongs to the tree being measured, is part of the overlapping root system of a neighbouring tree or is a root from an understorey species. These difficulties can never be solved completely. Thus, it is inevitable that root biomass measurements will tend to be less precise than above-ground biomass measurements.

One method of measuring root biomass is to undertake a full excavation of the soil around the stump of a tree. A trench might be dug around the stump with a back-hoe, at a distance (perhaps about 1–2 m) from the tree and to a depth (perhaps about 1 m) within which it is judged most of the roots of the tree are located. Hand tools and, perhaps, water or air pressure equipment or sieves would then be used to manually sift through the soil, finding and extracting the roots; obviously, this is a very labour intensive and tedious task. Di Iorio et al. (2005) gave an interesting example of such a major extraction of roots of downy oak (*Quercus pubescens*) trees in Italy, where they measured also the three-dimensional position of the roots they were extracting. Peichl and Arain (2007) attempted to estimate the accuracy of their biomass measurements when they excavated the roots in stands of white pine (*Pinus strobus*) in Canada.

The work involved in root excavation can be reduced by taking soil core samples around the stump. Usually, the stump itself will have been pulled out with a machine, removing with it as many large roots as possible. Cores may then be taken, with a hand or machine auger, to sample the distance and depth within which it is believed the roots will lie. The cores are usually taken to the laboratory to sort the roots from the soil.

It is often desired to distinguish between coarse and fine roots. Coarse roots include the large, strong, woody roots which extend immediately out from the base of the tree and anchor it firmly in the ground. An extensive web of smaller coarse roots ramifies from these larger roots. Coarse roots act also as part of the transport system of water and nutrients through the tree. Water and nutrients are taken up from the soil by fine roots and pass through the wood of the coarse roots, the stem and the branches up to the leaves. Wood consists mainly of dead tissue and water, with nutrients dissolved in it, can pass through the empty, dead wood cells; these are joined to each other by holes, to make a system of what can be thought of as hollow pipes right up the whole length of the tree.

Fine roots occur at the extremities of the coarse root system and consist of live tissue, capable of taking in water and nutrients from the soil. They have a limited lifespan, which can be as short as a few months. When they die, they become part of the organic matter of the soil and are eventually broken down by bacteria and fungi, so the nutrients they contain become available again in the soil for re-use by the tree. New fine roots then develop in their place.

When excavating roots, it is very difficult to determine exactly where, along its length, a fine root starts to develop wood and become a coarse root. In the measurement of the biomass of the root, it is common to make the rather arbitrary decision that fine roots are those less than about 2 mm in diameter and anything larger is a coarse root. It is often difficult to tell whether a fine root is still alive or dead; often its colour and its strength when pulled can be used to distinguish live from dead root tissue (Vogt et al. 1998).

It is often desired to measure both the biomass and the turnover rate of fine roots without felling a tree and excavating its root system. The three main techniques used to do so are (Vogt et al. 1998):

- Soil coring – if the fine root biomass is measured in a series of soil cores taken at several times during a year, their turnover rate can be estimated. Lee et al. (2004) give an interesting example of the use of soil cores to produce a map, at quite fine scale, of the fine root biomass distribution around individual trees in a conifer forest in north-western USA
- Ingrowth cores – a mesh sleeve, containing root free soil, is inserted into the hole left by removing a soil core. Periodic measurement of the biomass of live and dead fine roots which appear in such sleeves, as roots grow into them, gives estimates of both their biomass and turnover rate
- Minirhizotrons – these are transparent tubes inserted into the ground. Using mini-cameras or other electronic viewing devices to look down the tubes,

> recordings are made of fine roots as they grow around the outside of the tube and are visible at its surface. Flat glass plates inserted in the soil may be used also and the growth of roots along the glass surface recorded. Coupled with biomass measurements made from cores, this provides information from which fine root turnover rates may be determined.

Many refinements of these techniques of both coarse and fine root measurement have been tested from time to time for various species in many different soil circumstances. Works such as Vogt et al. (1998), Bengough et al. (2000), Snowdon et al. (2002) or Danjon and Reubens (2008) should be consulted before root biomass measurements are attempted. So difficult is root measurement, that a substantial proportion may be missed; this has often led to the under-estimation of root biomass by perhaps as much as 30–40% (Robinson 2004) or to otherwise inadequate estimates (Mokany et al. 2006).

7.2.4 Carbon Content of Biomass

As mentioned earlier (Sects. 1.2 and 7.1), concerns about global warming have led to considerable interest in determining how much of plant biomass is carbon. Direct measurement of the amount of carbon in plant biomass is a special laboratory process. It involves grinding samples of the dried biomass to a fine powder, burning the samples and measuring the amount of carbon dioxide given off, using a complex laboratory instrument known as a mass spectrometer, which ‘weighs’ atoms or molecules. Knowing the weight of the original sample, the proportion of it which was carbon can then be determined.

Table 7.1 lists numerous results of direct measurements of the carbon content of the oven-dry biomass of trees. Whilst the results vary in the range 36–61%, the carbon content is usually close to 50% of the biomass and generally varies little between species or in different parts of the tree.

Sometimes the amount of carbon stored in the biomass is reported as an equivalent amount of carbon dioxide, which the tree has removed from the atmosphere. The conversion from carbon to carbon dioxide equivalent is done simply by multiplying the carbon amount by 3.67, this being the ratio of the weight of a molecule of carbon dioxide to the weight of an atom of carbon.

7.3 Above-Ground Biomass Estimation Functions

Given the difficulties involved with direct measurement of the biomass of the tree, it is not surprising that attempts have been made to develop functions to allow tree biomass estimation from simple measured characteristics of standing trees, such as their stem diameter and height. As a part of the research on climate change, the

Table 7.1 The proportion of oven-dry biomass which is carbon, as measured in various tree parts for various tree species

Species	Carbon proportion (%)	Reference
Above –ground		
Pinus taeda	49	Kinerson et al. (1977)
Populus spp.	47	Deraedt and Ceulemans (1998)
Leaves		
Abies balsamea	53	Xing et al. (2005)
Acacia decurrens	53	Gifford (2000)
Acacia melanoxylon	52	Gifford (2000)
Callitris spp.	54	Gifford (2000)
Eucalytpus spp.	50–55	Gifford (2000)
Exocarpus cupressiformis	52	Gifford (2000)
Pinus radiata	45–53	Gifford (2000)
Branches		
Acacia decurrens	48	Gifford (2000)
Acacia melanoxylon	49	Gifford (2000)
Eucalytpus spp.	43–48	Gifford (2000)
Exocarpus cupressiformis	47	Gifford (2000)
Pinus radiata	50–56	Gifford (2000)
Branches and stem		
Abies balsamea	52	Xing et al. (2005)
Picea abies	49	Sandström et al. (2007)
Pinus sylvestris	50	Sandström et al. (2007)
Stem wood		
Acacia decurrens	48	Gifford (2000)
Acacia melanoxylon	48	Gifford (2000)
Callitris glauca	53	Ximenes et al. (2008)
Callitris spp.	52	Gifford (2000)
Corymbia maculata	49	Ximenes et al. (2008)
Eucalyptus obliqua	50	Ximenes et al. (2008)
Eucalyptus pilularis	51	Ximenes et al. (2008)
Eucalytpus spp.	40–54	Gifford (2000)
Exocarpus cupressiformis	50	Gifford (2000)
Pinus radiata	51	Ximenes et al. (2008)
Pinus radiata	48–61	Gifford (2000)
Bark		
Acacia decurrens	55	Gifford (2000)
Acacia melanoxylon	52	Gifford (2000)
Callitris spp.	50	Gifford (2000)
Eucalyptus obliqua	48	Ximenes et al. (2008)
Eucalyptus pilularis	51	Ximenes et al. (2008)
Eucalytpus spp.	38–51	Gifford (2000)
Exocarpus cupressiformis	54	Gifford (2000)
Pinus radiata	58	Ximenes et al. (2008)
Pinus radiata	45–61	Gifford (2000)
Roots		
Abies balsamea	50	Xing et al. (2005)
Fine roots		
Populus spp	36–43	Al Afas et al. (2008)

development of such functions has expanded greatly since the publication of the first edition of this book in 2004. These functions fill the same role for the estimation of biomass as the functions discussed in Chap. 6 do for tree stem volume estimation.

Perhaps most commonly, the basis of biomass estimation for a given species in a given part of the world is a function which estimates the above-ground biomass of an individual tree (its stem plus branches and leaves). The functional form used most commonly for this predicts oven-dry, above-ground biomass of an individual tree (B_A, tonne) from its diameter at breast height over bark (D, cm) as

$$B_A = \alpha D^{\beta}, \tag{7.1}$$

where α and β are parameters. There are many examples of the use of this function for many different tree species around the world (Freedman 1984; Ter-Mikaelian and Korzukhin 1997; Eamus et al. 2000; Burrows et al. 2001; Saenger 2002; Jenkins et al. 2003; Pérez Cordero and Kanninen 2003; Specht and West 2003; Van Camp et al. 2004; Xiao and Ceulemans 2004a; Hamilton et al. 2005; Montagu et al. 2005; Kajimoto et al. 2006; O'Grady et al. 2006; Wang 2006; Zerihun et al. 2006; Johansson 2007; Liddell et al. 2007; Rock 2007; Case and Hall 2008; Paul et al. 2008; Ung et al. 2008). Even in cases of multi-stemmed trees, when each stem is considered to be a separate tree, (7.1) has been found effective (Hamilton et al. 2005).

Functions, such as (7.1), that relate plant biomass to one or more other variables that reflect the size of the plant (such as its stem diameter or height) are often called allometric relationships. The term **allometry** means 'the relationship between part of an organism and its whole'. Several authors (Causton 1985; Parresol 1999; Verwijst and Telenius 1999) have reviewed the use of allometric functions for biomass estimation. Considerable care is required in applying regression analysis (Sect. 6.2.1) to obtain values for the parameters of allometric relationships (Bi et al. 2001).

Zianis and Mencuccini (2004) have suggested that it may be necessary only to measure directly the biomass of smaller trees in a patch of forest to obtain data which are adequate to fit such relationships. If this can be confirmed through additional research, it means that much of the great effort required to fell and measure the biomass of very large trees could often be avoided.

Studies around the world have found that (7.1) is usually a very adequate biomass function, when it is developed and used locally. That is, it is satisfactory when it is derived using measured biomass data at a particular time and at a particular site, and is then used to predict biomasses of other trees at the same time and site. Of course, this is rather restrictive and researchers have been seeking biomass estimation functions which can be applied much more generally, to trees at different ages, to a range of species and to trees which appear spread over some geographical region of considerable size.

An example where this was done successfully comes from Jenkins et al. (2003). They summarised results from many North American studies, all of which used (7.1), for a wide range of both **hardwood** and **softwood** species from many different locations across the USA and Canada. They identified 10 different species groups, in each of which they considered the various species should have similar characteristics and to which a common biomass function might apply (that is, with the same values of both parameters α and β in 7.1). Figure 7.1 illustrates the ten different functions they derived; the considerable differences between the functions for the different species groups are obvious there. However, Jenkins et al. were confident that these functions could be used to predict tree biomasses reliably, right across North America. Similar results have been obtained for other species in other parts of the world (Muukkonen 2007; Rock 2007; Ung et al. 2008).

Whilst these studies have had some success in applying (7.1) across a range of species and geographical regions, other authors have attempted to develop general biomass estimation functions by testing empirically functions other than (7.1) and/or by the inclusion of tree variables other than stem diameter in their function. Empirical testing involves trial-and-error testing of many possible functions, until one is found that fits the data most appropriately.

An example of this comes from Williams et al. (2005). They were concerned with estimating the above-ground biomass of trees of a variety of tree species

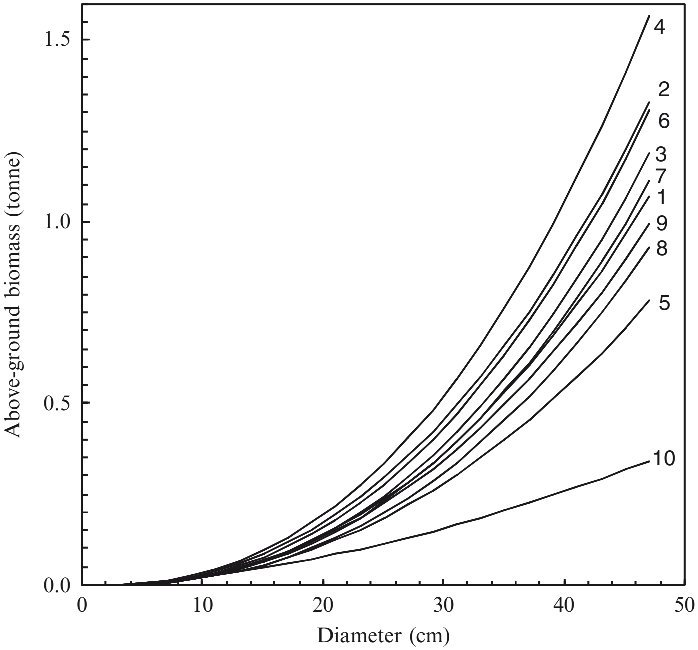

Fig. 7.1 Above-ground oven-dry biomass in relation to tree stem diameter at breast height over the bark, as defined by biomass estimation functions developed by Jenkins et al. (2003), for various North American species groups. *Numbers denote the functions for the species groups*. Hardwood groups were *1*–aspen/alder/cottonwood/willow (0.110, 2.39), *2*–soft maple/birch (0.148, 2.37), *3*–mixed hardwood (0.084, 2.48), *4*–hard maple/oak/hickory/beech (0.134, 2.43). Softwood groups were *5*–cedar/larch (0.131, 2.26), *6*–Douglas fir (0.107, 2.44), *7*–true fir/hemlock (0.079, 2.48), *8*–pine (0.079, 2.43), *9*–spruce (0.125, 2.33). Group *10* was a mixed hardwood and softwood group of species which grow in woodlands (0.489, 1.70). The values in brackets, after each species group, are the values of α and β, respectively, in (7.1), with B_A in kg and D in cm (drawn using information from Table 4 of Jenkins et al. 2003)

(mainly eucalypts) across the vast areas of **woodland** forests, which cover tropical and subtropical northern Australia. They had measured tree biomasses at 20 geographically widespread locations in these forests. They tested empirically eight different functions, which included tree diameter at breast height and/or tree height. They selected, as the best, the function

$$B_A = 0.0001275D^{2.1735}H^{0.1362\ln(H)}, \tag{7.2}$$

where H is tree height (m) and $\ln(H)$ denotes the natural logarithm of H (natural logarithms use as their base the mathematical constant known as 'e'; its value is approximately 2.7183). This function seemed to predict above-ground biomasses adequately for any tree of the many species at many sites for which they had data.

Williams et al. found there was an advantage by including both tree diameter and height in their function, rather than diameter alone as in (7.1). In working with other species and other functions in other parts of the world, other researchers have also used both tree diameter and height (Schmitt and Grigal 1981; Kumar and Tewari 1999; Saenger 2002; Carvalho and Parresol 2003; Pitt and Bell 2004; Zerihun and Montagu 2004; Khan et al. 2005; Saint-André et al. 2005; Brandeis et al. 2006; Cole and Ewel 2006; Cienciala et al. 2006; Williams and Gresham 2006; Dillen et al. 2007; Peichl and Arain 2007; Pajtík et al. 2008; Paul et al. 2008; Ung et al. 2008). However, sometimes there has been found to be little advantage from the inclusion of height (Ter-Mikaelian and Korzukhin 1997; Burrows et al. 2001; Kajimoto et al. 2006; Wang 2006) and there may even be a disadvantage (Montagu et al. 2005). Occasionally functions have been used in which diameter is the only prediction variable, but which have a form different from that of (7.1) (Droppelmann and Berliner 2000; Chambers et al. 2001; Montagu et al. 2005; Ximenes et al. 2006; Dillen et al. 2007). Sometimes other variables, which reflect environmental differences between different sites, have been included in the function (Droppelmann and Berliner 2000; Carvalho and Parresol 2003; Pérez Cordero and Kanninen 2003; Xiao and Ceulemans 2004a; Hamilton et al. 2005; Saint-André et al. 2005; Cienciala et al. 2006; Cole and Ewel 2006; Peichl and Arain 2007; Paul et al. 2008).

Pilli et al. (2006) seem to have made a further advance in the development of biomass estimation functions which apply across a variety of species and/or a range of environmental circumstances. Their approach was based on theory which considers both the engineering requirement that tree stems be big and strong enough to remain standing, given the weight they carry and the wind forces to which they are subjected, as well as the biological need for the stem to transport, to the leaves, water taken up from the soil by the roots. This theory will not be discussed in detail here, but it led Pilli et al. to suggest that the diameter of the stem of a tree, the basic density (Sect. 7.2.2) of the wood within the stem and the position of the tree within the hierarchy of tree sizes in the forest should all be important in determining the above-ground biomass of a tree.

Pilli et al. collated a large data set of biomass measurements, collected by many different researchers for many hardwood and softwood species scattered right around the northern hemisphere. Using a slight modification of (7.1), they found they could estimate individual oven-dry tree above-ground biomass as

$$B_A = \exp(\alpha_1 + \alpha_2\rho)D^{\beta}, \tag{7.3}$$

where B_A (tonne) and D (cm) are as before, ρ (tonne/m^3) is the wood basic density averaged over the whole stem of the tree and α_1, α_2 and β are parameters.

This function appeared to apply satisfactorily over all the species Pilli et al. considered and over all regions from which their data set had been collected. However, they found that the parameter values differed appreciably, depending on the position of the tree in the size hierarchy of trees in the forest where it was growing. They developed a method to determine that position for any tree. It involves measuring both the diameter and height of the trees in the forest concerned. Using quite complex methods, which will not be described in detail here, this information is used to allocate any tree into one of three size classes, based on its diameter, classes which Pilli et al. term 'juvenile', 'adult' or 'mature'. I consider these terms somewhat inappropriate, since they imply that the trees are of different ages, juvenile being young and mature being much older. That is not necessarily the case and I prefer the terms 'smaller' 'intermediate' and 'larger', respectively, terms suggesting the position of the trees in the forest size hierarchy.

Table 7.2 shows the parameter values of (7.3), as determined by Pilli et al. for trees of different positions in the size hierarchy in the forest. There were a number of tree species which were common to the data sets used by Jenkins et al. (2003) and Pilli et al. Figure 7.2 shows an attempt to compare Pilli et al's functions with those of Jenkins et al. for three of those common species, the hardwood, white oak (*Q. alba*) and two softwoods, Douglas fir (*Pseudotsuga menziesii*) and Norway spruce (*Picea abies*). There appears to be quite good agreement between the two sets of functions, at least when Pilli et al's functions for larger trees are used. There is rather poor agreement if Pilli et al's functions for smaller or intermediate sized trees are used (not shown on figure): it is probable that the data sets used to build Jenkins et al's functions were dominated by mature forests where larger trees would be most common.

Pilli et al's functions are quite general and appear to apply satisfactorily across an extraordinarily wide range of both hardwood and softwood species. However, the data set they used was dominated by species from the temperate regions of the northern hemisphere. It remains for their functions to be tested with data from a range of species from both tropical forests and temperate, southern hemisphere forests. If this can be done satisfactorily, their functions might then be used with confidence throughout the forests of the world. To do so requires that the height and

Table 7.2 Parameter values of (7.3), to predict tree above-ground oven-dry biomass (tonne) from stem wood basic density (tonne/m^3) and tree diameter at breast height over bark (cm), as determined by Pilli et al. (2006) (but for the units used here), for individual trees of different positions in the size hierarchy of trees of any particular species in a forest

Tree size	α_1	α_2	β
Smaller	−8.55	0	2.08
Intermediate	−10.42	1.27	2.64
Larger	−10.03	1.11	2.51

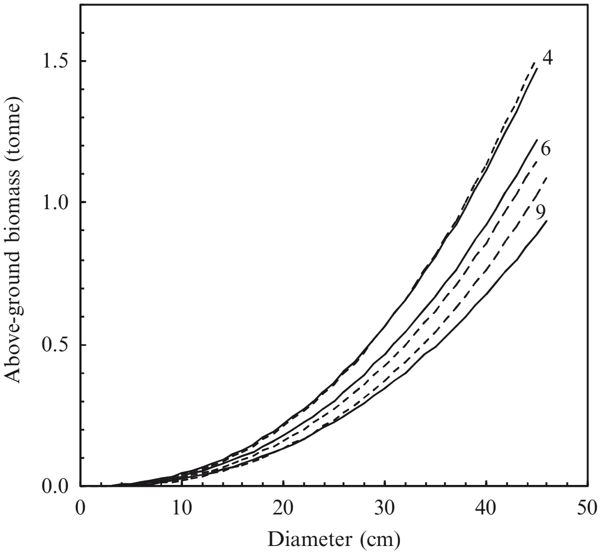

Fig. 7.2 Three of the tree biomass estimation functions of Jenkins et al. (2003) (*solid lines*), for species groups numbered as in Fig. 7.1. Corresponding functions (*dotted lines*) determined by Pilli et al. (2006) for 'larger' trees of three particular species, each of which was a member of the corresponding Jenkins et al's group. The three species were (with the stem wood basic density, tonne/m^3, assumed by Pilli et al. in parentheses) *4–Q. alba* (0.75), *6–P. menziesii* (0.50) and *9–P. abies* (0.45)

diameter at breast height of the trees in the forest concerned be measured together with the basic density of the stem wood of each species occurring in the forest. Zianis (2008) has confirmed that the principles of Pilli et al's approach show promise for the development of widely applicable biomass functions.

7.4 Biomass Estimation Functions for Tree Parts

Development of functions to estimate above-ground biomass of individual trees (Sect. 7.3) has received rather more attention than functions to estimate biomasses of other tree parts (leaves, branches, stems, roots etc.) for two reasons. Firstly, when obtaining data with which to build biomass estimation functions, it is far more common to measure above-ground biomass only, because root biomass is so much more difficult to measure (Sect. 7.2). Secondly, research emphasis has been on the estimation of the amounts of carbon sequestered by whole forests through photosynthesis, so has concentrated on functions which estimate total biomass, rather than biomass of the various parts of the tree.

Nevertheless, in scientific studies of tree growth behaviour, it is common to wish to know how the different parts of the tree develop with time. Thus, some attention has been paid to the development of functions to estimate the biomass of the various tree parts.

7.4.1 Allometric Functions

Allometric functions, of the same form as (7.1), have been used to estimate the biomasses of various parts of individual trees, with the biomass of the part concerned replacing B_A in the equation. Figure 7.3 shows a typical example, in this case for sugar gum (*Eucalyptus cladocalyx*) being grown in plantations in southeastern Australia (Paul et al. 2008). In this case, the biomass function developed for each part of the tree seemed to predict biomass satisfactorily across the three plantation sites from which Paul et al. had collected data, where the plantation age varied over the range 5–75 year.

Paul et al. determined also a function to predict above-ground biomass in their plantations, using (7.1). For interest, this function and that for large trees of Pilli et al. (2006) are compared in Fig. 7.3. There seems reasonable agreement between Paul et al's and Pilli et al's functions; as discussed in Sect. 7.3, Pilli et al's function shows potential for general use for any tree species anywhere in the world.

Of course, if the biomasses of various parts of a tree have been estimated, they may be summed to give the total biomass of the tree. So, in Paul et al's case, the estimates for leaves, the stem and branches might be summed to give the above-ground biomass of the tree. When this is done, it is found that the predicted above-ground biomass does not agree with that estimated using the function they developed to predict the above-ground biomass directly. In Paul et al's case, the discrepancy is quite small. For example, for a 47 cm diameter tree, the above-ground

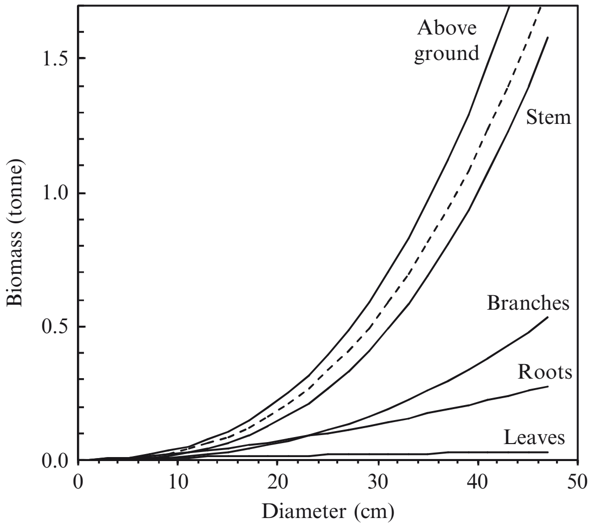

Fig. 7.3 For various parts of the tree *as marked*, the *solid lines* show the relationship between oven-dry biomass and tree diameter, as determined for *E. cladocalyx* by Paul et al. (2008). The *dashed line* shows the relationship for above-ground biomass from the function of Pilli et al. (2006) for 'larger' trees (7.3, Table 7.2); to obtain that line required use also of the function determined by Paul et al. to estimate stem wood basic density of *E. cladocalyx* trees from their stem diameter

biomass estimated by summing the estimates for the parts is 2.15 tonne, whilst that obtained directly from the above-ground biomass function is 2.12 tonne. However, such discrepancies can be larger, depending on the forest circumstances. They arise because none of the functions is an exact predictor of biomass; each function gives an estimate only. Mathematical statistical techniques have been developed to avoid this problem, and force estimates for individual parts to sum exactly to the value estimated using the function which predicts the total directly (Parresol 1999; Bi et al. 2001; Carvalho and Parresol 2003). These techniques only ensure that the sum of the estimates made for the parts equals the estimate made directly for the total: they still all remain estimates, albeit with consistency across all the functions involved.

There are many other examples where allometric functions have been developed to estimate biomasses of different parts of trees. These include cases where a function was determined from a sample of trees in one locality, for local use, or where it was attempted to develop functions which applied to a variety of species over wide geographical regions (Ter-Mikaelian and Korzukhin 1997; Droppelmann and Berliner 2000; Burrows et al. 2001; Saenger 2002; Jenkins et al. 2003; Pérez Cordero and Kanninen 2003; Pitt and Bell 2004; Xiao and Ceulemans 2004a; Zerihun and Montagu 2004; Kajimoto et al. 2006; Wang 2006; Zerihun et al. 2006; Muukkonen 2007; Coll et al. 2008; Coyle et al. 2008; Holdaway et al. 2008; Levia 2008; Paul et al. 2008; Sochacki et al. 2007; Ung et al. 2008; Wutzler et al. 2008). Some researchers have found, empirically, that inclusion of the characteristics of the tree other than stem diameter (such as tree height or the length of the crown of the tree) have improved the function, whilst others have found diameter by itself was adequate (Burrows et al. 2001; Carvalho and Parresol 2003; Pérez Cordero and Kanninen 2003; Pitt and Bell 2004; Xiao and Ceulemans 2004a; Zerihun and Montagu 2004; Khan et al. 2005; Brandeis et al. 2006; Cienciala et al. 2006; Cole and Ewel 2006; Massada et al. 2006; Tobin et al. 2006; Paul et al. 2008; Wutzler 2008). Sometimes a functional form different from the allometric form of (7.1) has been used (Jonckheere et al. 2005a; Saint-André et al. 2005; Xing et al. 2005; Kajimoto et al. 2006; Williams and Gresham 2006; Dillen et al. 2007; Muukkonen 2007; Pajtík et al. 2008; Paul et al. 2008).

7.4.2 Biomass Expansion Factors

Over the second half of the twentieth century, many tree stem volume functions (Sect. 6.2) have been developed throughout the world, for different species of tree growing under a wide range of environmental circumstances. A second form of biomass estimation function for individual tree parts exploits the availability of these volume functions. In these cases, the ratio of the biomass of one or more parts of a tree to the stem volume of the tree is determined. Such a ratio is known as a **biomass expansion factor**; multiplication of stem volume, determined using the volume function, by the biomass expansion factor provides an estimate of biomass for the relevant part of a tree.

An example can be found in Peichl and Arain (2007), for native forests of white pine (*P. strobus*) in Canada. They measured biomasses of the various above-ground parts of trees of varying ages in the forests. They found that individual tree biomass expansion factors for leaves, branches and roots varied with forest age and developed empirical functions to relate those factors to age. The results are illustrated in Fig. 7.4. Other examples can be found in Rytter (2006) and Pajtík et al. (2008).

7.4.3 Leaves

Whilst the methods described in Sects. 7.4.1 and 7.4.2 do offer functions to estimate tree leaf biomass, it is often found that the estimates they provide are not as good as might be desired. This reflects the biological circumstances of the leaves in forests.

Tree leaf biomass tends to increase with age, as a young tree grows over its first few years of life. However, eventually there reaches a point in the life of a forest when the leaf biomass over the forest as a whole reaches a more or less constant value. This value is determined principally by the availability to the trees of the water and nutrients from the soil at the site.

Once this point is reached, the stems (hence above-ground biomass), of individual trees will continue to increase in size with time, whilst the biomass of the leaves will remain more or less steady. This situation will become even more

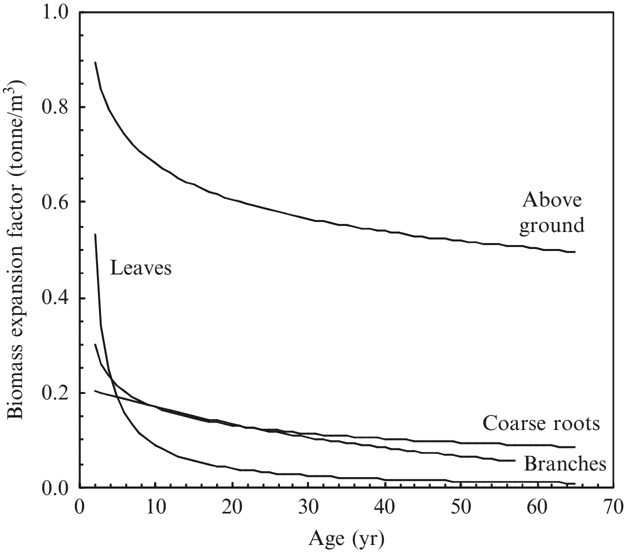

Fig. 7.4 Biomass expansion factors, as a function of the age of the tree, for different parts of individual trees of *P. strobus* in forests of southern Ontario, Canada. Multiplication of tree stem wood volume (m^3/ha) by the biomass expansion factor will give an estimate of the biomass of each part of the tree (derived from information in Table 6 of Peichl and Arain 2007)

complicated, as the competitively more successful trees in a stand outgrow their less successful rivals. The leaf biomass of a less successful tree will then decline gradually with age until the tree dies, whilst the leaf biomass of a more successful tree will increase. Examples of the effects of different competitive pressures on tree foliage biomasses can be found in Baldwin et al. (2000) and Holdaway et al. (2008).

Given this complexity, it is obvious that it will be difficult to build biomass functions generally to predict individual tree leaf biomasses over the whole life of the forest. At any one age, simple allometric equations (Sect. 7.4.1) have been used successfully for this purpose, but it is to be expected that the parameter values of these functions would change as the trees age and as their position in the stand alters. This is not always so, as the example in Fig. 7.3 illustrates, where the functions developed applied satistfactorily across a wide range of plantation ages. Nevertheless, there are many cases where it is so. For example, Holdaway et al. (2008) found variation with age in natural stands of mountain beech (*Nothofagus solandri* var. *diffortioides*) in New Zealand. For Sitka spruce (*Picea sitchensis*) in Ireland, where stand age varied over the range 10–46 year, Tobin et al. (2006) needed to include all of tree stem diameter, the length of the crown and the **stocking density** (number of trees per unit ground area) of the forest in which it occurred as variables in their biomass estimation function. Grote and Reiter (2004) related the crown biomass of individual European beech (*Fagus sylvatica*) and Norway spruce (*P. abies*) trees to the competitive influence the trees of the forest exerted on each other. There are other examples of leaf biomass functions which include various tree or stand parameters to allow for changes in age or other environmental circumstances of the tree (Monserud and Marshall 1999; Pérez Cordero and Kanninen 2003; Pitt and Bell 2004).

As mentioned in Sect. 7.2.1, it is often the area of leaves that is of interest, rather than their biomass. Arias et al. (2007) and Macfarlane et al. (2007a) developed leaf area estimation functions, using (7.1) with leaf area replacing biomass, for various species in Costa Rica and Australia, respectively.

A quite different tree variable, the cross-sectional area of sapwood in the stem, has been found particularly useful in developing leaf biomass functions. Water is transported from the roots, up through the sapwood to the leaves. Sapwood occurs in the outer part of the stem cross-section and consists of empty, dead cells through which water can pass. Heartwood occurs nearest to the centre of the stem and its cells are blocked by resins and other substances, so water can pass through it no longer. Sapwood is continually converted to heartwood throughout the life of the tree. However, the area of the sapwood in the stem at any time must be sufficient to allow passage of the volume of water necessary to supply the needs of the leaves. Thus, it can be expected that there will be a close relationship between stem sapwood area and the biomass of the leaves carried on the tree.

Stem sapwood area is usually quite easy to measure. Coring devices are available which can be screwed into the stem of a standing tree and a core of wood removed from it, without harming the tree. These devices are used regularly by scientists who study changes in climate by measuring the width of growth rings in tree stems, a field of study known as dendrochronology. The width of the sapwood can be measured from the stem core and the stem sapwood area then determined, knowing the diameter of the stem. There are numerous examples of functions developed to predict tree foliage biomass from stem sapwood area (Whitehead et al. 1984; Pothier et al. 1989; West and Wells 1990; Shelburne et al. 1993; Pereira et al. 1997; Berninger and Nikinmaa 1998; Monserud and Marshall 1999; Medhurst and Beadle 2002; Gilmour and Seymour 2004; Stancioiu and O'Hara 2005; Xiao and Ceulemans 2004b; Kajimoto et al. 2006; Tobin et al. 2006).

7.4.4 Roots

There are numerous examples (one is illustrated in Fig. 7.3) where coarse or total (coarse plus fine) tree root biomass has been estimated from tree stem diameter at breast height using (7.1), with root biomass replacing above-ground biomass (Burrows et al. 2001; Kajimoto et al. 2006; Miller et al. 2006; Wang 2006; Zerihun et al. 2006; Johansson 2007; Lavigne and Krasowski 2007; Peichl and Arain 2007; Vadeboncoeur et al. 2007; Coll et al. 2008; Paul et al. 2008), or using other functions which include stem diameter only (Tatarinov et al. 2008). Sometimes tree variables other than stem diameter have been included also (Cole and Ewel 2006; Sochacki et al. 2007; Paul et al. 2008).

However, when roots are excavated in a forest area, it is difficult to identify to which individual tree any particular root belongs (Sect. 7.2.3). Perhaps because of this, there has been an emphasis in the development of root biomass functions which estimate the root biomass per unit ground area of the forest, rather than the root biomass of individual trees. This is the next scale up of measurement to be considered in this book (Sect. 1.3); root biomass estimation functions of that nature will be discussed in Sect. 8.10.

Fine roots present rather more of a problem than coarse roots. Generally, fine roots constitute a small proportion of the total biomass of root systems, perhaps tending to decline with age to about 10% of total root biomass as the forest matures. This can vary widely with different forests in different environmental circumstances. For example, Kajimoto et al. (2006) found that the fine root biomass in Dahurian larch (*Larix gmelinii*) forests, in the cold, boreal regions of Siberia, made up 58% of the total root biomass in younger forests (trees 95–100-years-old) and 34% in older forest (trees up to 280-years-old). However, the lifespan of fine roots can be short (as little as a few months, e.g. Jourdan et al. 2008; Gaul et al. 2008), so they turn over continuously as some die and are replaced by new ones.

Development of functions to estimate the biomass of fine roots of individual trees is far less advanced than for other tree parts. However, Helmisaari et al. (2007) developed such a function satisfactorily for trees of Norway spruce (*P. abies*) and Scots pine (*P. sylvestris*) in native forest stands in Finland; they used (7.1) with fine root biomass replacing above-ground biomass. However, they found that trees tended to have greater fine root biomasses on sites which were cooler or had less fertile soil; thus the functions they developed were site specific. Others (Rytter 1999; Vanninen and Mäkelä 1999; Mäkelä and Vanninen 2000; Al Afas et al. 2008) were unable to find any relationship between fine root biomass and easily measured tree variables and so were unable to develop a biomass function for their cases.

Chapter 8
Stand Measurement

8.1 Stands and Why They are Measured

Until now, this book has been concerned with measurement of individual trees. However, forest owners and managers need to know how much timber or other forest products are available in total from their forest estate. This allows them to determine the overall value of the estate or to work out how much wood they can cut from it year by year and still be sure that the forest will go on producing timber forever.

One way to determine the total amount of wood, biomass or other tree products in an entire forest is to measure every single tree in it and add up the results. This would be an impossibly large task for any but the tiniest patch of forest. Instead, methods are used to scale up measurements made of some individual trees in the forest to estimate what is available from the whole forest. The concept of scaling up was introduced in Sect. 1.3.

The process of scaling up involves two steps. Firstly, measurements are made of individual trees in stands. Measurements made of stands are recorded usually on a per unit ground area basis, for example, the volume of stem wood per hectare in the stand. If the stand is on sloping ground, the area is taken to be the equivalent horizontal ground area. Stand measurements are sometimes recorded also as an average for the stand, for example, the average of tree stem diameters.

The second step in scaling up involves measuring many stands scattered throughout the forest. The information from those many stands is then used to estimate the total amount of whatever is being measured across the entire forest. That second step is known as forest **inventory**, which will be considered in detail in Chaps. 9–11.

8.2 Measurements Taken in Stands

The definition of a stand as a more or less homogeneous patch of forest is rather loose, in that it does not specify any particular area for the stand. In fact, the area will vary greatly, depending on how the person measuring the forest

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chooses to define ‘homogeneous’ for the forest concerned; this will be a matter of judgement and will reflect the nature of the measurements being made and their purpose.

However the stand is defined, it will not usually be the whole stand that is measured. Rather, a sample will be selected from it for measurement; that is, a relatively small part of it will be measured and the result taken as being representative of the whole stand. Often, that part will be a plot: commonly in forestry, such plots have an area of 0.01–0.1 ha (100–1,000 m^2), the actual area being chosen to suit the forest circumstances and the purpose of the measurement. However, as will be discussed below, there is at least one other way to measure a stand, which does not involve the establishment of a plot.

The measurements made most commonly in stands are:

- Tree age
- **Stand basal area** (tree cross-sectional area at breast height summed over all the trees in a stand and expressed per unit ground area)
- Stocking density (the number of tree stems per unit ground area)
- **Quadratic mean diameter** (diameter of the tree of average **basal area** in the stand)
- **Dominant height** (average height of a prescribed number per unit ground area of the largest diameter or tallest trees in the stand)
- Site productive capacity (defined in Sects. 8.7.1 and 8.8)
- Volume (the volume of the stem, over or under bark, or of some log product expressed per unit ground area)
- Biomass (the biomass of some part of the tree expressed per unit ground area)
- Growth (the change with time in variables such as stand basal area, stand volume or stand biomass).

Many other characteristics of stands can be, and often are, measured. However, those listed above are the variables used most commonly in forestry and forest science. Each will be discussed in this chapter.

8.3 Age

The age of the trees in a stand is usually most relevant when the stand is **even-aged**, that is, all the trees in the stand regenerated naturally (in native forest) or were planted (in a plantation) at or about the same time.

Even when a stand in native forest is classed as even-aged, there will have been some period of time (months to a year perhaps) over which the trees regenerated following a disturbance of the pre-existing forest, which resulted in all its trees being removed or dying. That is to say, not all the trees in an even-aged native forest will be exactly the same age. For most forestry purposes, these small age differences between individual trees are ignored and the age of the native forest stand is considered to date from the time most regeneration took place. This is often known from historical records. Other techniques may be necessary to determine stand age when the forest history is unknown, such as counting tree rings of individual trees.

In the case of plantations, stand age is usually known from planting records. Tree seedlings are often 6–12 months old, sometimes older, when they are obtained from a nursery and planted out. In most countries, plantations are aged from their date of planting. Scientifically, this convention seems to provide adequate results for practical purposes, even though it is known that the trees are generally older than the age assigned to the plantation. In some European countries, plantations are aged from the date of sowing seeds in the nursery. In colder regions, seedlings may be raised for up to 2 years in a nursery, so prescribing a plantation age by the sowing date may then be rather more realistic biologically than using the planting date.

Many native forests are **uneven-aged**. That is, trees of a wide range of ages occur in the forest. This is usual for forests such as **rainforests**, where a long process of succession occurs during the life of the forest. Following a disturbance in such forest (due to things such as fire, storm or logging), certain species, which respond to the full sunlight conditions created by the disturbance, regenerate and grow vigorously. Other species, which are more tolerant of the shade created by the light tolerant species, then regenerate and grow slowly in the shade until they eventually reach the full sun and ultimately dominate the forest. Such forests contain trees of a wide range of ages and it is impossible to assign any particular age to a stand. However, it is often useful to know the time since the initial disturbance; this may be a useful guide to what stage of development the stand has reached. Lisa and Faber-Langendoen (2007) developed a method to define the stage of development of uneven-aged forest by measurement of various characteristics of the trees within the stand.

8.4 Basal Area

Stand basal area (stem cross-sectional area at breast height summed over all the trees in a stand and expressed per unit ground area) is important to forestry because, just as tree stem diameter is often well correlated with individual tree stem volume (Sect. 6.2.1), stand basal area is often well correlated with stand stem volume.

The stand basal area of forests tends to increase with age as the trees grow. It varies also with the number of trees in the stand. For young stands, or stands with very low stocking density, stand basal area can be close to zero. For old stands and stands with high stocking densities, it can exceed 100 m^2/ha.

There are two main methods used to measure stand basal area, plot measurement and **point sampling**. These are discussed in the next two sub-sections.

8.4.1 Plot Measurement

Stand basal area may be determined by positioning a plot of known area, somewhere within the stand. The diameters at breast height (over or under bark as required) of all the trees in the plot are then measured. The diameters are then converted to stem cross-sectional areas, the results summed and divided by the plot area to give stand basal area.

There is a general discussion of plot establishment and measurement techniques in Sect. 11.6.

8.4.2 Point Sampling

A second method of measuring stand basal area is becoming increasingly important in forestry, especially in forest inventory (Chap. 11). In this book, the method will be termed point sampling. It is an extraordinarily simple technique, which does not require the establishment of a plot. The measurement is made by standing at a point, somewhere within the stand, and simply counting certain trees around the point, using an instrument which can be as simple as a small stick.

The principle of point sampling is described in Fig. 8.1. This represents a view looking vertically down on a stand. Suppose an observer standing at point O is

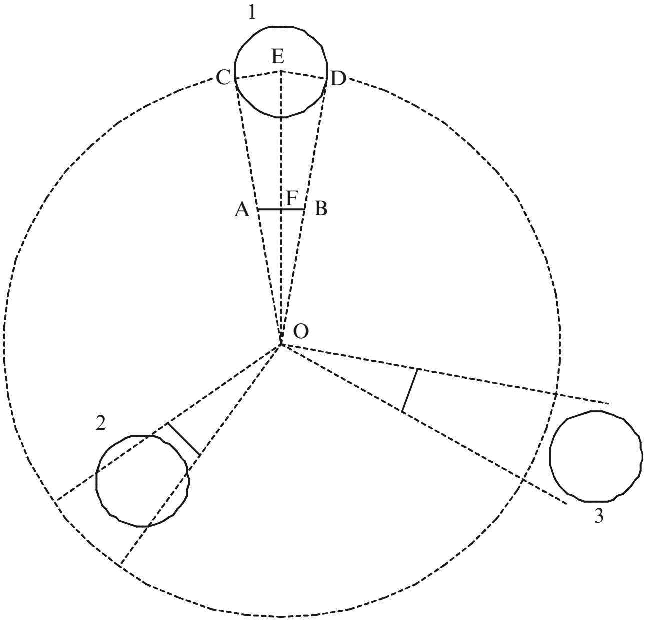

Fig. 8.1 Principle of point sampling

holding horizontally a small, straight stick AB at arm's length. In the near vicinity of the observer are several trees (3 in the diagram, but the number is not important to the argument), each with exactly the same diameter at breast height over bark; the solid circles numbered 1, 2 and 3 represent the tree stem cross-sections at breast height. The centre of the stem cross-section of Tree 1 is positioned at E.

Tree 1 has been positioned deliberately in the figure so that when the observer looks past the ends of the stick to breast height on that tree, the ends are aligned exactly with the width of the stem, as the observer sees it; that is, lines OAC and OBD are both tangents to the circular cross-section of Tree 1, touching its circumference at C and D.

The views the observer would have of Trees 2 and 3, when he or she turns in their respective directions, are illustrated also on the figure. Tree 2 is closer to the observer than Tree 1, so the stick is not wide enough to cover fully the cross-section of the tree as the observer views it; the observer will see the sides of the stem projecting past the ends of the stick. Tree 3 is further from the observer than Tree 1, so the width of the stick will more than cover the width of the stem as the observer views it.

Now, suppose all the trees in the vicinity of the observer have the same diameter as the three in the diagram. Suppose the observer turns through a full circle at O and counts the number of trees he or she sees for which the width of the stick does not cover the width of the tree stem (as for Tree 2), or just exactly covers it (as for Tree 1). He or she does not count any tree for which the width of the stick more than covers the width of the tree stem (as for Tree 3). This means that any tree of the same diameter as the 3 trees in the figure, and which is at the same distance or closer to the observer than Tree 1, would be included in the count.

Suppose the radius at breast height over bark (the radius is half the diameter) of the trees in the figure is r (cm). The radius of Tree 1 is represented by either of the lines EC or ED (geometrically, those radii will be perpendicular to the tangents to the circle OBD and OAC, respectively). Imagine that as the observer turns around at O, he or she sweeps out a circular area, shown by the large dashed circle in the figure which is of radius R (m) (the length of the line OE), and counts trees as described above. Suppose that during the sweep the observer counts n_r trees of radius r. Since all those trees are at the same distance or closer than Tree 1, their stem centres all lie within that circle of radius R.

By definition, the stand basal area of those n_r counted trees (G_r, m^2/ha) is the sum of their cross-sectional areas at breast height divided by the ground area they occupy. Knowing that the area of a circle is the product of π and the square of its radius, it then follows from this definition that

$$G_\mathrm{r} = [(\pi / 10{,}000) n_r r^2] / [(\pi / 10{,}000) R^2] = n_r r^2 / R^2 = n_r \beta, \qquad (8.1)$$

where $\beta = r^2/R^2$. The values 10,000 in this equation simply serve to convert the units of measurement (stem radii in centimetres are converted to metres and the dashed circle area in square metres is converted to hectares, there being 10,000 m^2 in 1 ha).

Consider now the right angled triangle EDO (angle EDO is the right angle), where ED = $r/100$ m and EO = R m. Let the angle EOD = θ°, so that

$$\sin(\theta) = \mathrm{ED}/\mathrm{EO} = (r/100)/R. \qquad (8.2),$$

Hence, given the definition of β above,

$$\beta = r^2/R^2 = 10{,}000\sin^2(\theta). \qquad (8.3)$$

Now, suppose the stick being held by the observer is of length AB = l_s (cm) and is being held a distance OF = l_e (cm) away from the eye. Consider the right angled triangle OFB (angle OFB is the right angle), where FB = $l_s/2$ and FO = l_e. Using Pythagoras' theorem (Appendix D), $\mathrm{BO}^2 = \mathrm{FO}^2 + \mathrm{FB}^2$, hence BO = $\sqrt{(l_s/2)^2 + l_e^2}$ Then, since angles FOB and EOD are the same angle θ,

$$\sin(\theta) = \mathrm{FB}/\mathrm{BO} = (l/2)/\sqrt{(l_s/2)^2 + l_e^2}. \qquad (8.4)$$

Hence, using (8.3) and (8.4),

$$\beta = 10{,}000(l_s/2)^2/[(l_s/2)^2 + l_e^2]. \qquad (8.5)$$

The stand basal area of the trees of radius r can now be determined using (8.1), as the product of the number of trees of radius r which were counted (n_r) and β. The importance of (8.5) is that we see that β can be determined knowing only the length of the stick the observer is holding (l_s) and the distance it is being held from the eye (l_e). That is, stand basal area can be determined with no knowledge of the tree stem radius (r) or of the radius of the large dashed circle (R) within which trees of that radius are counted.

Even more importantly, this theory works for trees of any radius, not just r. Trees with a radius larger than r will be counted within a circle of radius somewhat larger than R, whilst trees with a radius smaller than r will be counted within a circle of radius somewhat less than R. But the observer need not know the tree radius or the circle radius to apply the theory; he or she can determine β from the length of the stick and its distance from the eye. Thus, suppose the observer counts a total of n trees from the spot, a total which includes trees of any size, then the total stand basal area G (m^2/ha) will be given simply by

$$G = \mathrm{n}\beta. \qquad (8.6)$$

Equation (8.6) is perhaps the most astonishing result that has ever been devised for forest measurement. It means that stand basal area can be measured by counting trees from a single point, using an instrument as simple as a straight stick. All the observer then needs to do is measure the length of the stick and the distance it is held from the eye and use (8.5) to determine β. In point sampling, β is known as the basal area factor; in the measurement units used here, the units of β are m^2/ha.

Point sampling was invented in 1948 by an Austrian forester, Walter Bitterlich. Whilst it is referred to here as point sampling, it is also called angle count sampling, angle gauge sampling, plotless sampling, Bitterlich sampling or variable radius plot sampling.

8.4.3 Plot Measurement Versus Point Sampling

It seems amazing that stand basal area can be measured by merely counting trees from a single point, using an instrument as simple as a small stick. Even after they have tried it, my forest measurement students always have great difficulty believing that point sampling really works; it just seems too simple to be true. On the other hand, they have no difficulty accepting the results from measuring a plot (Sect. 8.4.1); they can see the plot boundaries and the trees in it, which they have measured with a diameter tape. Somehow, point sampling seems to be cheating; trees are just counted, not measured physically. However, the theory given above *proves* that point sampling works.

For both plot measurement and point sampling, one issue of concern is trees which are close to the boundary. In plot measurement, the convention adopted usually is that a tree is considered to be in the plot only if the centre of its stem lies within the plot boundary. On average then, as many trees of which only part of the stem cross-section is in the plot will be included as will be excluded. For point sampling, consider again Fig. 8.1. Suppose a tree of the same size as Tree 1 was just a little further away from the observer, so that part of its stem cross-section lay within the large dashed circle. That is, part of its stem cross-section lies within the circular area within which trees of that diameter will be counted in the point sample. However, because it is further from the observer than Trees 1, such a tree would be excluded by the point sampling process. Similarly, a tree such as Tree 1 has part of its stem cross-section outside the large circle, but is included in the count. Thus, just like plot measurement, it is the position of the centre of the tree stem cross-section which will determine ultimately if the tree is included in or excluded from the point sample count.

It is important to realise that point sampling and plot measurement will usually give somewhat different answers for stand basal area; the answers will not be vastly different, but certainly often differ by several per cent. In point sampling, the size of the circle effectively swept out by the observer in making the count differs for the different diameters of the trees being counted (circle sizes which the measurer need never know). Hence it is impossible to define exactly what area of the stand is being used to measure the stand basal area; this has led to use of the alternative name variable radius plot sampling for the technique. On the other hand, a particular part of the stand is clearly identified as being used to measure the stand basal area in the case of plot measurement.

As well, it must be appreciated that both point sampling and plot measurement are a form of sampling of the stand (Sect. 8.2). An arbitrary choice has to be made as to the location of the plot in the stand or the location of the point at which the point sample is taken. In other words plot measurement and point sampling will take samples from the stand in rather different ways. Inevitably then, they will give somewhat different results for stand basal area. That is not to say either result is wrong or one of the results is better, or more useful, than the other. They are just different results, which reflect the fact that the two methods sample the stand in different ways.

8.4.4 Practicalities of Point Sampling

One limitation of point sampling is that it can be used only to measure stand basal area over bark. If an under bark basal area is required, a method is needed to convert the over bark measurement to an under bark measurement. One system to do so involves measuring the over and under bark diameter of each tree, as it is counted. The method discussed below (Sect. 8.9.2) can then be used to find the stand basal area under bark, by replacing stem volume with stem basal area under bark in (8.10).

A number of issues need to be considered if point sampling is to be used appropriately. A straight stick is a perfectly good ‘instrument’ to use for point sampling, as indeed is the width of the observer’s thumb. Thumbs generally have a basal area factor within the range 2–5 m^2/ha, depending on the individual’s thumb width and the length of his or her arm; most foresters have worked out the factor for their thumb (using 8.5) and use it to assess, quickly and easily, the stand basal area of a piece of forest they are visiting.

Often, a small, triangularly shaped glass or plastic prism (or basal area wedge, as they are often called) is used to carry out point sampling. When a tree stem is viewed through the prism, the triangular shape of the prism causes the view of the stem section to be displaced sideways, due to light refraction by the material of the prism. If, as the observer views it, the stem section is displaced less than, or just as much as, the width of the stem, the tree is counted. Otherwise, it is not. The principle of the method remains exactly the same, but the angle of the triangle of the prism and the refractive qualities of the material from which it is made together determine the basal area factor of the prism. Forestry suppliers sell these prisms with a wide range of basal area factors. The main advantage of prisms is that it is easier to see the tree stems than it is with a stick or thumb, and so easier to judge whether a particular stem should be included or not in the count.

The instruments used for optical dendrometry (Sect. 5.3.4) are usually constructed to allow point sampling to be carried out with them. Various other (often very cheap) devices for point sampling are available also from forestry suppliers

There are always trees for which the observer will find it difficult to judge whether they should or should not be included in the count. These will be trees which are very near the circumference of a circle being implicitly swept out by the observer, such as Tree 1 in Fig. 8.1. When such cases arise, the diameter of the tree at breast height over bark and the distance from its stem centre to the observer should be actually measured. If its diameter is D (cm) and the distance to it is d (m), then it follows from the mathematics of Sect. 8.4.2 that the tree should be counted if $d \le D/\sqrt{4\beta}$ and otherwise not (this computation determines the radius, R, of the circle being swept out implicitly by the observer for trees of that particular diameter).

If the ground on which the count is being made is sloping, some of the instruments available for point sampling correct automatically for the slope. If using an unsophisticated instrument like a stick, it will be necessary to measure the diameter of each tree counted (D, cm) (or at least of those trees which are near doubtful), the distance along the slope from the observer to the tree (s, m) and the slope angle (γ, degrees). The corresponding horizontal distance to the tree (d, m) is then calculated as $d = s\cos(\gamma)$. The expression given in the paragraph above can then be used to determine if the tree should be counted or not. Generally this is necessary only if the slope exceeds about 8–9°.

It is important too that an appropriate basal area factor is used for the stand being considered. If the factor is too small, then a very large number of trees will be counted and some of the ease and speed of the method will be lost. If the factor is too large, too few trees will be counted to be a reasonable sample from the stand and the basal area determined may not represent the stand adequately. The larger the trees in the stand, the larger will be the appropriate basal area factor. In general, it might usually be considered appropriate to use a factor size which leads to a count of 10–15 trees. Many of the instruments available to carry out point sampling incorporate several factors and the user may choose one that is appropriate to the stand being considered.

Particular care needs to be taken in densely stocked forest, where some trees may be obscured from the observer's view by others. Also it is easy for the observer to lose track of which trees have been considered and which not. Under these circumstances, it is desirable to have a two-person team to carry out the measurements. One acts as the observer and the other walks about the stand, keeping track of what the observer has and has not viewed. To view obscured trees, the observer may have to move slightly away from the sampling point, but must ensure that he or she remains the same distance away from the obscured tree.

8.5 Stocking Density

Both plot measurement and point sampling can be used to determine stand **stocking density** (the number of tree stems per unit area). In plot measurement, the number of trees in the plot is counted. The number divided by the area of the plot is then the stocking density.

To get the stocking density when a point sample is taken, it is necessary to not only count the trees to be included in the point sample, but also to measure the diameter at breast height over bark of each counted tree. If there were n trees counted and the diameter of the i^{th} of those trees was D_i (cm), then the stand stocking density (S, stems/ha) can be determined as

$$S = \beta \sum_{i=1\ldots n} [40{,}000/(\pi D_i^2)], \tag{8.7}$$

where β is the basal area factor (m²/ha) used in the point sample. Note that in this equation, the mathematical expression $\Sigma_{i=1\ldots n}$ denotes the summation of the term that follows the expression, as i takes successive values 1, 2, 3….etc., up to n.

There are methods other than point sampling which also do not require the establishment of a plot and which can be used to estimate stocking density. These involve selecting a number of points at random within the stand and measuring the distance from them to neighbouring trees. Payendah and Ek (1986) describe these methods. In the past, they have been subject to bias and rather more uncertainty than counting trees in a plot or doing point sampling. However, more recent research has been addressing these limitations (Picard et al. 2005; Kleinn and Vilčko 2006a, b; Magnusson et al. 2008).

Stocking density is useful for three main purposes. Firstly, dividing some other stand estimate (say, stem volume per unit area) by stocking density gives the average volume per tree in the stand. Secondly, the stocking density of a stand is an important variable used in describing the stage of development of a stand. Third, stocking density changes with age during the life of a stand as trees die or new seedlings are recruited to the stand. Determining how and when these changes occur is an important part of forest growth modelling, where mathematical models are used to predict how stands will grow and change with time. The use of forest growth models is fundamental to modern forest management and allows managers to predict the availability of wood, or other forest products, from a forest far into the future. Growth modelling will not be discussed further in this book; there are various reviews and examples of both older and more recent approaches to forest growth modelling (Vanclay 1995; Battaglia and Sands 1998; Mäkelä et al. 2000; Peng 2000a, b; Le Roux et al. 2001; Avery and Burkhart 2002; Porté and Bartelink 2002; Pretzsch et al. 2002; Landsberg et al. 2003; Valentine and Mäkelä 2005; Cienciala and Tatarinov 2006; Richardson et al. 2006; Tatarinov and Cienciala 2006; Fourcaud et al. 2008).

8.6 Quadratic Mean Diameter

The average of the diameters of the trees in a stand is often a quite useful measurement to characterise the condition of a stand. Another measure used is called the **quadratic mean diameter**. This is the diameter corresponding to the average basal area of the trees in the stand. If a stand has a basal area G (m²/ha) and a stocking density of S (stems/ha) then its quadratic mean diameter D_q (cm) is

$$D_\mathrm{q} = \sqrt{(40{,}000/\pi)G/S}. \tag{8.8}$$

It is argued that quadratic mean diameter is often more useful than average diameter, because it relates more closely to stand volume. It is also a useful measure to give some idea of the size of the trees in a stand when their average diameter has not been recorded. It has other uses, especially in defining the density of stands (the degree of crowding of the trees) (e.g. Pretzsch and Biber 2005; Woodall et al. 2005; VanderSchaaf and Burkhart 2007). Measures of stand density will not be discussed further here; their theoretical and biological bases are discussed in West (1983, 2006) and in other forest measurement texts (e.g. Avery and Burkhart 2002).

8.7 Dominant Height

The average height of the trees in a stand can be a useful measure of stand condition. More frequently, measures known by the generic term stand **dominant height** are used to represent stand height. These are defined generally as the average height of the tallest trees in the stand.

8.7.1 Importance of Dominant Height

Stand dominant height is considered important in forestry because it reflects the site productive capacity of the species concerned, when it is growing on a particular site. By site productive capacity is meant the total stand biomass produced by a stand on a particular site, up to any particular stage of its development, when the stand has been using fully the resources necessary for tree growth which are available from the site.

Stand biomass production at any time is limited by the genetic characteristics of the species concerned, by the environmental characteristics of the site on which the stand is growing (particularly the climate and soil fertility), by the stage of development of the stand, by the stocking density of the stand and by the way in which the trees have been tended (the **silviculture** applied) (West 2006). Measurement of site productive capacity is very important to forestry, because it indicates the maximum amount of the principal forest product, wood, which might be available from that forest on that site.

Because individual trees within forest stands compete with each other for the resources of the site (light, water and soil nutrients), their sizes differ. The more successful competitors eventually become the largest in size by suppressing the smaller, less competitive trees. As a result of the competition, the smaller trees die eventually. The intensity of this competition depends both on the degree of crowding of the trees on the site and the rate at which the more successful competitors grow. The more the crowding and the faster the more successful trees grow, the more rapidly will the smaller trees succumb to the competitive pressure.

Given this, it is the characteristics of the competitively more successful trees which reflect ultimately the site productive capacity. Because the larger trees suppress the smaller ones, the characteristics of smaller trees merely reflect the fact that they are the less successful competitors. Furthermore, it is height, rather than biomass, which is the characteristic of the competitively more successful trees which best reflects the site productive capacity. Their biomass will depend very much on the stocking density of the stand in which they are growing. If, for whatever reason, the stocking density happens to be low, they may not be using fully the resources for growth available from the site. Their biomass would then be lower than it would be if there were more of them in the stand. However, much research has shown that their heights are not affected by their stocking density (although there have been exceptions to this, e.g. MacFarlane et al. 2000). Their heights will reflect the site productive capacity, even when the stocking density is sufficiently low that stand biomass is not reflecting it.

These arguments show why stand dominant height has achieved such a position of importance in forest measurement. A full discussion of how it is used to assess site productive capacity is given in Sect. 8.8.

8.7.2 Measuring Dominant Height

There are various ways in which stand dominant height is defined. One measure, **top height**, is defined as the average height of a specified number per unit area of the trees of a stand with the largest diameters at breast height (usually over bark). A second, **predominant height**, is defined as the average height of a specified number per unit area of the tallest trees in the stand. Other names and slightly different definitions are often used for these measures, but the terms and definitions used here are perhaps the most common.

It is up to the measurer as to the number per unit area of largest diameter or tallest trees to be used in these definitions for a particular forest type. The numbers used in practice vary widely from country to country, and forestry organisation to organisation. Usually, a value within the range 40–100 stems/ha is chosen. The different numbers used in different places often make it difficult to compare published results from different parts of the world.

Top or predominant height is always measured in a plot of known area within a stand. Say the plot was 0.05 ha in area (perhaps a rectangular plot of 20 × 25 m) and the definition of top or predominant height to be used specified 40 stems/ha to be measured. Then, the heights of the 40 × 0.05 = 2 largest diameter or tallest trees would be measured in that plot and their average used as the measure of top or predominant height respectively. If the plot size and number per hectare are such that a non-integer number of trees should be measured, then the number actually measured is usually taken as the nearest integer number.

Practically speaking, it is easier generally to determine top height than predominant height, because it is easier to identify the largest diameter trees in the stand than the tallest ones; diameters of all the trees in a plot are often measured anyway. Of course, the largest diameter trees in the stand are often the tallest in any case; in practice, the difference between top height and predominant height is usually small for most forest stands.

8.8 Site Productive Capacity

The concept of site productive capacity was introduced in Sect. 8.7.1. Attempts have been made often to measure the characteristics of the soil and climate at a site, and use this information to predict forest production, hence, site productive capacity.

Some work of this type has related observed growth of forest stands to observed environmental characteristics, both weather and soil (Turvey et al. 1990; Osler et al. 1996b; Hackett and Vanclay 1998; Snowdon 2001; Uzoh 2001; Ryan et al. 2002; McKenney and Pedlar 2003; Kimsey et al. 2008). Other work has involved the development of complex models which predict the physiological response and growth of tree stands in relation to the environmental characteristics (Running 1994; Coops et al. 1998; Sands et al. 2000; Ditzer et al. 2000; Mäkelä et al. 2000; Mummery and Battaglia 2001; Landsberg et al. 2003; Roxburgh et al. 2004; Buckley and Roberts 2005a; Swenson et al. 2005; Cienciala and Tatarinov 2006; Louw and Scholes 2006; Tatarinov and Cienciala 2006). Because they are based on measurement of site environmental characteristics, these methods of measuring site productive capacity have been termed ‘geocentric’ methods. They are used principally to assess whether or not particular sites are appropriate for afforestation. They are sufficiently complex to warrant a book of their own and will not be considered further here.

A different method has been used in forestry for many years to determine site productive capacity of even-aged forests. It is a ‘phytocentric’ method, that is, a method based on measurement of the growth of the trees themselves, rather than the environmental characteristics of the site. The actual growth of the trees provides a direct measurement of the productive capacity of the site, whereas a geocentric method only predicts it from the site characteristics. Therefore, a phytocentric measure should be an unbiased and very precise measure of site productive capacity. However, a phytocentric method can be used only after the forest has been established on the site. Geocentric methods allow prediction of site productive capacity before the forest is established.

The phytocentric measure used in forestry involves measurement of the top or predominant height of an even-aged forest stand, usually at an early stage of its development. Of course, top or predominant height changes with age in any even-aged forest stand as it grows. To allow for this, the phytocentric measure of site productive capacity is defined as stand dominant height at a particular age and is known in forestry as stand **site index**. For a particular type of forest in a particular forest region, the age chosen to define site index is not of any special importance; it is chosen entirely at the discretion of whoever develops the measure for that forest. Whatever age is chosen, it is termed the index age for that forest.

Thus, suppose the index age chosen for a particular forest type is 20 years. Then, a stand with a dominant height of 25 m at 20 years of age would have a site index of 25 m. Forestry research has shown consistently that site index is a very reliable measure of site productive capacity, for even-aged forest types throughout the world. The only *caveat* on this is that it is true only after the forest reaches about 5–10 years of age. In forest younger than this, the trees may not have grown large enough to be competing with each other, so that dominant height becomes a good measure of productive capacity (Sect. 8.7.1).

One way to measure site index is to wait for a stand to reach the index age and then measure its top or predominant height. However, for most of the commercially important forest types throughout the world, site index functions have been developed so that stand site index can be determined for the stand, no matter at what age it is measured. A typical example will be described here to illustrate how site index functions are used.

The example is taken from West and Mattay (1993), who developed a site index function for the commercially important species flooded gum (*Eucalyptus grandis*), which grows in even-aged, native and plantation forests in subtropical eastern Australia. West and Mattay defined stand top height in that forest as the average height of the 50 largest diameter trees/hectare, and site index as the top height at 20 years of age (the index age they chose). Their function allows prediction of the top height H_2 (m) of a stand at some age A_2 (year) from its top height H_1 (m), which was measured at some other age A_1 (year), as

$$H_2 = H_1\{[1-\exp(-0.0126A_2)]/[1-\exp(-0.0126A_1)]\}^{0.563}. \qquad (8.9)$$

Suppose a flooded gum stand was measured at 12 years of age and found to have a top height of 23.1 m. Equation (8.9) predicts that its top height would be 30.0 m at 20 years of age. Since 20 years of age was the index age used for these forests, the site index of this stand has then been estimated as 30.0 m, from a measurement of its top height at 12 years of age. The function could be used in a similar fashion to predict the stand site index from measurement of its top height at any other age.

Figure 8.2 shows how West and Mattay's site index function predicts stand top height will change with age in stands of site index 20, 30 or 40 m. Note that at the index age chosen for this forest, 20 years of age, the function predicts (by definition) that top height equals the site index. Similar lines could be drawn for any other site index. The position is indicated on the 30 m site index curve of the top height H_2, as predicted from the measured top height H_1, in the example in the preceding paragraph.

Many functional forms different from that of (8.9) have been used as site index functions by different authors from time to time, for various species in various parts of the world. Huang (1997) lists a number of these alternatives. However,

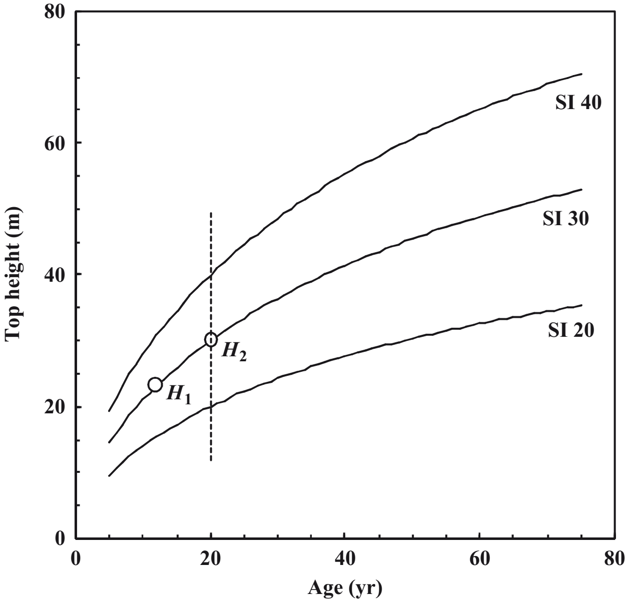

Fig. 8.2 Change with age of top height of stands of *E. grandis* of site index (*SI*) 20, 30 or 40 m, predicted using the site index function of West and Mattay (1993). The *vertical dashed line* shows the index age they used to define site index in this forest. In the example discussed in the text, the value of top height H_2 was predicted from a measured value H_1, using (8.9)

(8.9) is a commonly used function, which continues to be found useful (Diéguez-Aranda et al. 2006a; Louw and Scholes 2006; Mamo and Sterba 2006; Nord-Larsen 2006).

The importance that the use of site index has assumed today in even-aged forest management cannot be over-emphasised. It is an integral and basic part of most of the forest growth models which are used by managers of even-aged forests, throughout the world, to predict the long-term availability of wood from them.

Forestry science has paid much less attention to the development of measures of site productive capacity for uneven-aged forests. The inability to define their age makes it impossible to use the types of measure which have been developed so reliably for even-aged forest. One phytocentric measure which has been used is the stand basal area or dominant height when the forest has reached an equilibrium stage of development (see Sect. 8.11), when its basal area or height does not change with time. Other measures include the height of trees with a specified stem diameter or a complex summation of the diameters of specific 'index' species in the stand. These measures apply generally to the later developmental stages of uneven-aged forest (Sect. 8.11), and it would be difficult to use them to measure site productive capacity when the forest is at an early stage of its successional development. Vanclay (1992) has reviewed these measures. More recent work to develop geocentric measures for uneven-aged forest (e.g. Ditzer et al. 2000) may eventually provide better measures of site productive capacity than the phytocentric measures which have been developed to date.

8.9 Volume

The way in which stand stem volume is measured will depend on the resources which are available to the measurer and the precision required of the estimate. This section will consider first the case that stand stem volume is being measured in a plot and then the case that the stand is being measured using a point sample.

8.9.1 Plot Measurement

A first possible way to determine stand volume for a plot, and by far the most laborious, would be to measure directly the stem volume of each and every tree in the plot. The individual tree volumes would then be added up and the result divided by the plot area to give stand volume. The tree volumes could be found using the methods for sectional measurement of standing trees (Sect. 5.3.4), or through importance or centroid sampling (Sect. 5.4). Stand volumes, either as total stem volume or volumes of different merchantable log sizes, could be obtained with these methods. Allowance must be made if under bark, rather than over bark, stem volumes are desired; this issue was discussed in Sects. 5.3.4 and 5.4.

A second method would be to measure directly the volumes of only a sample of trees from the plot. The information from that sample could then be used to estimate the stand stem wood volume for the whole plot. There are a number of mathematically formal ways in which the trees to be included in the sample could be chosen. These are discussed in detail in Chaps. 9 and 10; an example is used in Sects. 9.4, 10.2.1 and 10.2.2 which describes the estimation of stand stem wood volume from a sample of trees taken from a plot.

A third method would also involve measuring volumes of a sample of trees from the plot. For many stands, a graph of stem volume against the square of stem diameter at breast height will show there is a very close relationship between these two variables for the sample trees. A regression equation (Sect. 6.2.1) could then be fitted to the sample data and this used to predict volumes of all other trees in the stand from measurement only of their stem diameters. An example where this method is used is given in Sect. 10.4.1.

If a tree volume or taper function (Chap. 6) is available for the species concerned, a fourth method to determine stand volume would be to use those functions to estimate total or merchantable stem volumes for each and every tree in the plot. This usually requires that only tree diameter at breast height and total height of each tree in the plot be measured (or occasionally some additional measurements, as in the examples in Sect. 6.2.2).

Measurement of the height of every tree in the plot, as required by the fourth method, can be time consuming. Particularly for even-aged forests, there is often a strong relationship between tree diameter at breast height and total height. Where this is the case, a fifth method to estimate stand volume might be used. In this case, a sample of trees from the plot would be measured for height. Then, a regression relationship could be established from the sample data, from which other tree heights in the plot might be estimated from their measured diameters. West (1979) discussed a number of regression functions which might be suitable for this purpose. Soares and Tomé (2002) also list possible functions to do this, and consider also functions which might be used to predict individual tree heights generally, for a particular species right across a particular region.

It would be expected that the precision of the estimates of stand stem volume made with these various methods would decline in much the same order as they have been presented here. More and more assumptions and regression functions are involved the further one moves through the five methods. Interestingly however, West (1979) made a study of the precision of the stand total stem wood volume estimates obtained in stands of 20–100-year-old native eucalypt forests in Tasmania, Australia, using what might be expected to be the least precise of all these methods, the fifth. He found that even for this method, the stand volume estimated nearly always lay within ±6% of the true stand volume and was often much closer. This result illustrates how reliable are the methods which have been devised for measuring stand wood volumes in forests.

A sixth possible method for measuring stand volume is worth mentioning also. Stand volume estimation functions have been developed from time to time for particular forest types in particular regions. Rather than having to measure individual trees in a stand, these functions allow estimation of stand volume (total stem or merchantable volume) directly, usually from measurement of stand basal area and stand dominant height. Whilst becoming less common today, stand volume estimation functions do continue to be developed (Brooks and Wiant 2004).

8.9.2 Point Sampling

If a point sample is being taken in a stand (Sect. 8.4.2), its method can be adapted to provide an estimate of stand volume. To do so requires measuring the diameter at breast height over bark and stem volume (total or merchantable) of each of the trees counted in the point sample. The volume measurements could be done by direct measurement with sectional measurement (Sect. 5.3), by importance or centroid sampling (Sect. 5.4), or by estimation with a tree volume or taper function (Sects. 6.2, 6.3).

Suppose n trees were counted in the sweep, the diameter of the i^{th} of those trees was measured as D_i (cm) and its stem volume was measured as V_i (m^3). Then, the stand stem volume V (m^3/ha) can be determined as

$$V = \sum_{i=1\ldots n} [40{,}000 V_i / (\pi D_i^2)], \tag{8.10}$$

Please note the erratum to this equation at the end of the book.

where β (m^2/ha) is the basal area factor. Marshall et al. (2004) have considered what basal area factor it is appropriate to use in such cases.

8.10 Biomass

The biomass of the whole or parts (leaves, stems, roots etc.) of individual trees in a stand may be obtained either by direct measurement (Sect. 7.2) or through the use of biomass estimation functions (Sects. 7.3 and 7.4). Because of the large amount of work involved, direct measurement will be rare; usually it will be done only in a research context, to obtain data to develop biomass estimation functions.

If plot measurement is being used, once individual tree biomasses have been obtained, they may be added and the total divided by the plot area to obtain the stand biomass, just as for stand basal area (Sect. 8.4.1) or stand volume (Sect. 8.9.1). If point sampling has been used, the same method is used to determine stand biomass as described for stand volume (Sect. 8.9.2), with individual tree biomasses replacing individual tree volumes in (8.10). If leaves are being considered, it is often their area, rather than their biomass that is of interest (Sect. 7.2.1). Stand leaf area is known as **leaf area index**; it can be determined from individual tree leaf areas, just as for biomass. Its value varies over a range of about 2–11 m^2/m^2 for forests of the world (Beadle 1997) and correlates closely with the availability of water or nutrients from a site. There are a number of ways by which it can be measured directly in a stand; these are forms of remote sensing and are described in Sect. 13.1.2.

An alternative to using individual tree biomass estimates to determine stand biomass is to use a stand biomass expansion factor (c.f. Sect. 7.4.2). This is the ratio between stand biomass and stand volume; the aim of using such factors is to take advantage of the many tree volume functions that are available already (Chap. 6) and which can be used to give estimates of stand volume. There are a number of examples of the use of stand biomass expansion factors in various forest types (Grierson et al. 1992; Lehtonen et al. 2004, 2007; Van Camp et al. 2004; Jalkanen et al. 2005; Cienciala et al. 2008).

8.10.1 Root Biomass

As discussed in Sect. 7.2.3, there are particular problems involved with root biomass measurement, especially the difficulty of identifying to which tree in a stand any particular root belongs. When great care has been taken to match roots with trees, individual tree biomass estimation functions for roots have been developed

(Sect. 7.4.4). However, to avoid the problem of having to match roots and trees, it has become common to develop stand based biomass estimation functions for roots, in preference to functions for individual trees.

In this sub-section, we will consider such functions for coarse or total (coarse plus fine) stand root biomass. The most common form of these functions is the simple allometric equation (Sect. 7.3)

$$B_{\mathrm{R}} = \gamma B_{\mathrm{A}}^{\delta} \tag{8.11}$$

where B_{R} (tonne/ha) and B_{A} (tonne/ha) are stand coarse or total root oven-dry biomass and stand above-ground biomass, respectively, and γ and δ are parameters of the equation. In practice, individual tree biomass estimation functions (Sect. 7.3), individual tree biomass expansion factors (Sect. 7.4.2) or stand biomass expansion factors, will be used to estimate stand above-ground biomass for the trees of a plot. That estimated value of stand above-ground biomass will then be used with (8.11) to estimate a corresponding coarse or total root stand biomass.

Mokany et al. (2006) attempted to develop a widely applicable stand root biomass estimation function of the form of (8.11). They collated root and above-ground stand biomass data, which had been collected by many different researchers from a wide range of forest and woodland stands of many different species and forest types, right across the world. Their function is illustrated by the solid line drawn on Fig. 8.3, which shows how the proportion of stand total biomass (above-plus below-ground) which is roots varies with the total biomass. Mokany et al's function predicts that stand root biomass declines progressively from around 25–30% of total biomass, in forests with a small total biomass (say, younger forest or open woodlands) to just under 20% in forests with a large total biomass (say, tall, mature forests). As shown also on Fig. 8.3, Niklas (2005) also used a data set collected widely across the world and obtained results similar to those of Mokany et al.

Mokany et al's and Niklas' results represent averages for forests generally around the world. However, there will be much variation around those averages, if one considers stands of particular tree species, of particular ages and growing in the environmental circumstances of any particular geographical region. Li et al. (2003) collated above- and below-ground stand biomass data available from the literature for forests of cold temperate and boreal regions, principally of the northern hemisphere. Their root biomass estimation functions, which also used (8.11), are illustrated also on Fig. 8.3. Their results are rather different from Mokany et al's and Niklas' results for forests of the world generally. In particular, they found a distinct difference between forests of softwood and hardwood species; neither Mokany et al. nor Niklas identified any such difference. Results obtained using (8.11) by Snowdon et al. (2000) for a wide range of forest types right across Australia are shown also on Fig. 8.3. The Australian data were probably dominated by hardwood species and there does appear to be some commonality between Snowdon et al's results and Li et al's hardwood results for northern hemisphere forests. However, the results do suggest that roots tend to make up a rather lower proportion of total biomass in Australian forests when compared with other parts of the world.

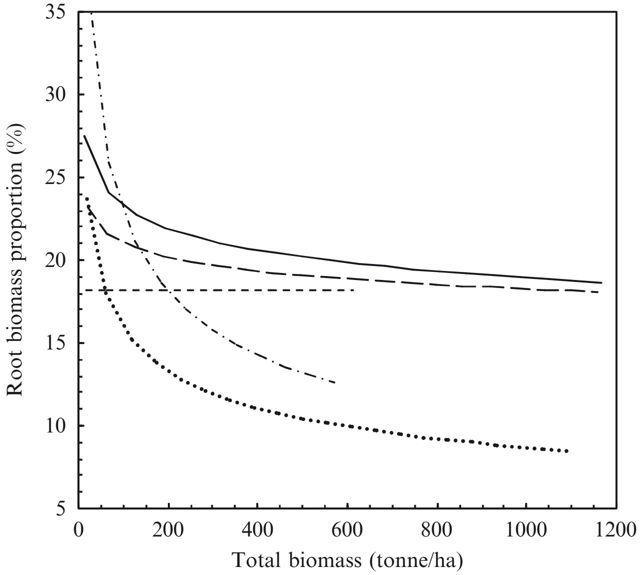

Fig. 8.3 Stand root biomass as a proportion of stand total biomass in relation to total biomass. Result are shown for an average for forests and woodlands of the world (*Solid line*) (0.489, 0.890) (Mokany et al. 2006) and (*solid broken line*) (0.372, 0.924) (Niklas 2005, Table 1, Canell data set), for Canadian softwood (*hyphenated line*) (0.222, 1) and hardwood (*solid broken line with hyphenated line*) (1.576, 0.615) forests (Li et al. 2003) and for Australian forests and woodlands (*dotted line*) (0.677, 0.712) (Snowdon et al. 2000, Table 3.6). Results were derived from functions of the form of (8.11); in each case, values in parentheses are for the parameters γ and δ of that function

Research work is continuing to develop root biomass estimation functions of this nature, for other forest types in other parts of the world, and to study what determines the proportion of stand biomass which is roots (Kajimoto et al. 2006; Zerihun et al. 2006; Cheng and Niklas 2007; Wang et al. 2008b). No consistent pattern has emerged yet to allow the development of definitive stand root biomass estimation functions.

8.10.2 Fine Root Biomass and Area

There are perhaps even greater difficulties in measuring fine roots and determining estimation functions for them than for total or coarse root biomass (Sects. 7.2.3, 7.4.4). Just as with total and coarse roots (Sect. 8.10.1) there have been attempts to develop functions to estimate stand fine root biomass directly, rather than individual tree fine root biomass.

One approach was adopted by Zerihun et al. (2007) for woodland forests of poplar box (*E. populnea*) in northern Australia. Assumptions were made about how fine roots were distributed spatially around individual trees in a stand and a model was then developed which predicted this distribution as a function of tree diameter. Applying this model to all trees in the stand gave an estimate of stand fine root biomass. The system was only partially successful in the woodlands where it was tested.

Other workers have found correlations between fine root biomass in stands and stand parameters, such as the amount of nutrients in litter falling from the above-ground parts of trees and site rainfall and temperatures (Vogt et al. 1998); these relationships tend to be specific for the site and species concerned and cannot be used to make predictions for other sites or species.

As for leaves (Sect. 7.4.4) the area of fine roots can be of great interest as well as their biomass. Fine roots absorb water and nutrients through their surfaces and so their area is an important measure of their capability to do so. Stand fine root area index is the below ground equivalent of stand leaf area index. Al Afas et al. (2008) found that it correlated quite closely with leaf area index, in a set of plots of various poplar clones (*Populus* spp. and hybrids) growing at one site in Belgium. Since it is the fine roots which must gather, from the soil, the water and nutrients required by the leaves, it might indeed be expected that fine root area index and leaf area index should be correlated. In the 2-year-old stands Al Afas et al. considered, fine root area index could be estimated quite closely as being 64% of leaf area index. It is unlikely that the same relationship would hold on different sites and would have to be evaluated separately for each site.

All these examples of stand fine root biomass (or area) estimation functions are rather specific to the site and forest circumstances for which they were derived. There remains much research to be done before satisfactory fine root biomass estimation functions become available generally.

8.10.3 Precision of Biomass Estimates

Whilst much research of recent times has been concerned with the development of biomass estimation functions, much less attention has been paid to the precision (Sect. 2.4) of the estimates that are obtained with them.

Wutzler et al. (2008) have attempted to do so, when their biomass estimation function for individual trees of European beech (*Fagus sylvatica*) across central Europe was used to predict stand above-ground biomass (by summing biomass estimates for individual trees in the stand). They found that the estimates of stand biomass were highly likely to lie within just a few percent of their true values. This is a comfortingly high level of precision for many of the practical purposes to which biomass estimation functions are being put around the world.

In another example, Case and Hall (2008) considered how the level of precision of biomass estimates changed with the scale which applied to the biomass function used to make the estimate. As might be expected, they found that a function developed using local data will give a rather more precise estimate for a stand in the same local area than will a function developed from data collected widely from many sites across a geographically large region.

Zianis (2008) has proposed theory to allow formal estimates to be made of precision of biomass estimates at single tree and stand levels, when biomass functions based on (7.1) are used. Interestingly, he showed that the most precise estimates were obtained using an approach related closely to that of Pilli et al. (2006) (Sect. 7.3). Many more such tests of precision, for many different forest types around the world, will be necessary before we will be able to use biomass estimation functions with as much confidence as we presently use stem volume estimation functions.

8.11 Stand Growth

The rate of growth of trees in forests, hence, the rate at which they produce wood, is of prime concern to anyone growing forests for commercial purposes. The rate of production of forests depends on the site productive capacity (Sect. 8.7.1), their stocking density and the way in which the trees are tended. Detailed discussion of these issues, at least for plantation forests, can be found in West (2006) and they will not be considered further here. However, there are some conventions used in forestry to refer to stand growth rates. These will be discussed here.

Figure 8.4a shows an example of how stand stem wood volume changes with age in a forest. The example is taken from West and Mattay (1993), for a typical stand of the same flooded gum (*E. grandis*) forest for which the example site index function was described in Sect. 8.8. Growth is shown only from 5 years of age, because that was the youngest age for which West and Mattay had data available. The sigmoidal (S-like) shape of the curve is common to even-aged forests throughout the world; in fact, the growth of many biological organisms displays such a shape. In the present example, the S shape is rather asymmetrical, with the bend in the S occurring at about 15 years of age. If, instead of volume, stand stem basal area or biomass was shown on the graph, the shape of the curve would be much the same.

In forestry, stand growth rate is usually expressed in one of two ways. The first, **current annual increment** (often abbreviated as CAI and also termed **periodic annual increment**, abbreviated to PAI), is the immediate growth rate of the stand at any particular age, that is, the growth rate occurring at a particular instant in time. It was this that was being referred to in using the term growth rate in the preceding paragraphs.

Trees grow too slowly to measure their growth over periods of a few seconds, as would be required in practice to determine their immediate growth rate. Hence, current annual increment is usually determined approximately by measuring a stand at intervals often of about 1 year (often longer in very slow growing forests). Current annual increment is then approximated as the change in the stand between the two measurements, divided by the length of time between them. Figure 8.4b shows how the current annual increment of the stand in Fig. 8.4a changed with age. Note that the current annual increments shown in Fig. 8.4b are exact, because

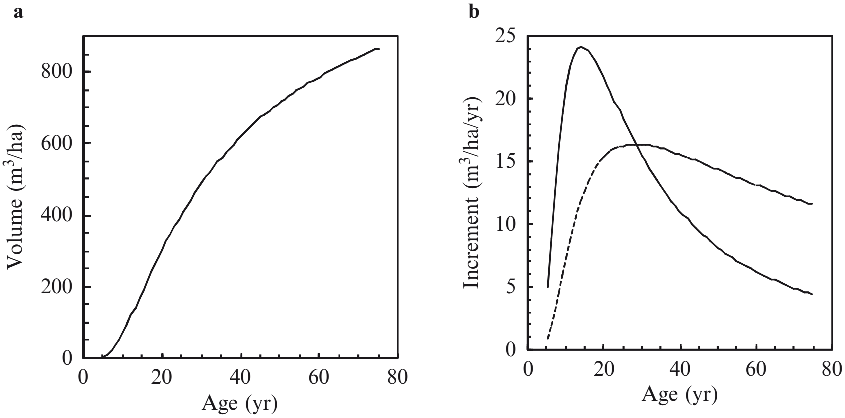

Fig. 8.4 (**a**) Change with age in stand stem wood volume of a typical stand in *E. grandis* forest in subtropical eastern Australia. (**b**) The change with age in current annual increment (*solid line*) and mean annual increment (*dotted line*) in stand stem wood volume for the same stand (drawn using Equations 8, 10 and 11 of West and Mattay 1993)

they were determined from the curve in Fig. 8.4a using the mathematical technique known as differential calculus; had they been determined by measuring the forest at annual intervals, they would have been approximate. The less mathematically inclined reader may ignore this, but should concentrate on the shape of the current annual increment curve. It shows that the current annual increment in this stand increased progressively to reach a maximum at about 15 years of age (that maximum actually occurs at the bend in the S shape in Fig. 8.4a). Thereafter, the current annual increment declined steadily. If West and Mattay had data from stands much older than the 75 years of age shown in the figure, it would be expected that their current annual increment would have declined eventually to near zero as the trees became senescent.

This pattern of growth rate is common to forests throughout the world. It would be of considerable interest to forestry to know what causes the decline in current annual increment that is apparent after 15 years of age in Fig. 8.4b. If it did not happen, the total production by forests would reach much higher levels, at much earlier ages. Various theories have been advanced to explain the phenomenon. Perhaps the most enduring has been that, as trees become larger with age, the path for water transport from the roots, through the stem and branches to the leaves becomes increasingly more tortuous. This leads to a higher level of water stress in the leaves of the tree and reduces the amount of photosynthesis, hence, production that occurs in the leaves over any period of time. Research is continuing on this and other theories (Gower et al. 1996; Ryan et al. 1997; Murty and McMurtrie 2000; Smith and Long 2001; McDowell et al. 2002; Binkley 2004; Reid et al. 2004; Ryan et al. 2004; Buckley and Roberts 2005b; Zaehle 2005; Martínez-Vilalta et al. 2007; Mencuccini et al. 2007; Vanderklein et al. 2007; Groot and Saucier 2008).

A second measure used to describe stand growth rate in forestry is called **mean annual increment** (often abbreviated as MAI). This is the average rate of production to any particular age of the stand. It is determined simply as the stand volume (or basal area or biomass) at any age, divided by the age. It is probably the most popular measure used by foresters to indicate how fast a forest grows. Mean annual increment changes with age during the life of the forest, as illustrated by the dotted line in Fig. 8.4b. The units for mean annual increment are m^3/ha/year, the same as those for current annual increment.

The most productive forests in the world are plantations, because they receive intensive silvicultural management. West (2006) has summarised knowledge on their growth rates. Plantations being grown for wood for paper-making or to be sawn into timber are usually planted at stocking densities of about 800–2,500 stems/ha. The fastest growing hardwood plantations of these have a mean annual increment which rises to a maximum of about 60 m^3/ha/yr at around 6–7 years of age, then declines steadily to just over 30 m^3/ha/yr by 30 years of age. Softwood plantations tend not to grow so rapidly at first, but the fastest growing reach a maximum mean annual increment of about 50 m^3/ha/yr at around 15–17 years of age and then decline steadily to just over 35 m^3/ha/yr at 30 years of age. Some plantations are established at much higher stocking densities, often about 10,000 stems/ha, for production of wood for bioenergy. These may have even higher mean annual increments; values as high as 100 m^3/ha/yr, to 3 years of age, have been reported (Sims et al. 1999).

The general situation for growth of uneven-aged stands is not greatly different from that of even-aged stands. If the development of an uneven-aged stand is followed starting from bare ground, its growth trajectory will usually follow a sigmoid growth pattern as in Fig. 8.4a. However, later in their life-cycle, the growth behaviour of uneven-aged stands can differ from that of even-aged stands.

An example of this is given by Moser (1972), who studied the growth over 18 years of uneven-aged stands of a mixture of hardwood tree species native to Wisconsin in the USA. Moser found that their current annual increment in stand basal area was virtually constant, at about 0.15 m^2/ha/yr, for the entire 18 years. It is clear from Moser's work that the forest with which he was dealing had reached a more or less equilibrium stage of development. Each year some trees died. Each year some new seedlings regenerated below the existing canopy to grow slowly in the shaded environment until they reached the upper canopy many years later. The remaining trees, which were already in the upper canopy, continued to grow year by year until eventually, they too, would be among the annual deaths.

Most uneven-aged forests reach this equilibrium stage at the end of the successional development stages through which they pass during their life-cycle. This final stage may last for many decades or even hundreds of years, until some catastrophic disturbance (a severe fire, a major storm or logging) destroys the forest completely. The forest then has to start its life-cycle afresh from bare ground, with rapid early growth of species tolerant of the full light conditions, followed by development of species which are able to grow under shade; sometimes this succession process is altered by smaller disturbances which are insufficient to destroy totally the forest. This is the life-cycle enjoyed also by rainforests, as discussed in Sect. 8.3. The review by Porté and Bartelink (2002) considers how growth behaviour of uneven-aged forests is modelled. They show a number of examples of how their growth behaviour changes as they pass through their various successional stages.

Even-aged forest stands may reach a stage late in their life when they have zero current annual increment, or indeed even a negative current annual increment as some trees die. However, this is only a period of old age and is not accompanied by the continuous cycle of regeneration, death and growth that occurs in the equilibrium stages of uneven-aged forest.

Chapter 9
Measuring Populations

9.1 Forest Inventory and Sampling

Discussion to this point has dealt with the measurement of individual trees and the measurement of groups of trees (stands). The next four chapters will consider the last stage in scaling up of measurements (Sect. 1.3), which is the **inventory** of forests that is, the measurement of whole forests or (as they might be called more formally) forest **populations**.

What is defined as a whole forest (forest population) is completely in the eye of the beholder. To a farmer, it might be an area of only a few hectares of plantation forest on his or her property. To a large company, it might be thousands of hectares of both plantation and native forests, supplying many thousands of cubic metres of wood annually to large wood processing plants.

There are many things an owner might want to know about the forest; these might include the availability of wood from it, the occurrence of plant and animal **ecosystems** within it or the way in which the public uses it. Whatever the owner wants to know, it is obviously impossible, even for quite small forest areas, to measure every tree or every animal in it or the activities of every person who uses it.

To make tractable the problem of measuring whole forests, we resort to **sampling**. That is, small parts of the forest are measured, usually a tiny fraction of the whole, and it is assumed that the parts measured represent adequately the whole. The measurements made on the sample are then used to make an estimate of the characteristics of the whole forest.

Sampling is not restricted to forestry. It is used to learn things about populations in all areas of human endeavour. A population can be defined as any set of things about which it is desired to know something. Populations can be big or small. Astronomers might want to know things about the stars in the Milky Way galaxy and will define them as their population; in that case it is a very large population, both in numbers and the space it occupies. Geographers might wish to know things about the people who live in Siberia; those people will constitute their population. An ecologist might wish to learn about the behaviour of ants in the root ball of a single tree which has blown over, and those ants will constitute his or her population. The most important thing about defining a population is to do so clearly. Then, it will be quite apparent what is

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and what is not included in it, and so what things within it are eligible to be included in any sample taken from it.

Speaking formally in mathematical statistical terms, populations are made up of **sampling units**. A sampling unit is any clearly defined part of, or an individual in, a population and which might be included as one member of a sample drawn from it. In the population of the Milky Way galaxy, individual stars might be the sampling units. In Siberia, individual people might be the sampling units. In ants in a root ball, individual ants might be the sampling units.

There are many ways both in which a sample can be drawn from a population and how the information derived from that sample is used to learn something about the whole population. Knowing how to sample populations is the realm of sampling theory in mathematical statistics, a complex field of study in its own right. In this book, only a tiny part of that field will be considered.

This chapter considers some basic mathematical statistical methods in Sects. 9.2–9.3. In Sect. 9.4, these methods are applied to an example, which uses the very simplest sampling method. More complex sampling methods are discussed in Chap. 10.

9.2 Subjective Versus Objective Sample Selection

The selection of a sample from a population could be done subjectively. That is, the sample selector could choose sampling units from the population which he or she considers ‘typical’. Or perhaps he or she could select samples at extreme ends of the population and assume that their average represents the population.

However, subjective selection always risks the biases of the selector’s judgement; there is no guarantee that the results from such samples will reflect properly the true characteristics of the population. Even worse, if the selector is corrupt, he or she might choose a sample which leads to an estimate of the population which is desired by the selector.

In science in general, and in forest inventory it is no different, sample selection is done objectively, so the personal prejudices or fallibilities of the selector play no part. This is usually (although not always) done by a random selection process: given the individuals in a population, tables of random numbers, or a computer random number generator, are used to select which sampling units will be included in the sample. Modern computer systems have random number generators included as a part of them.

In mathematical statistical terms, it is impossible generally to develop theory appropriate for other than objectively chosen samples. Furthermore, if the information learnt about a population from a sample is to be defensible, it must have the *imprimatur* of mathematical statistical rigour. Thus, in the discussion of sampling for forest inventory, this book will be concerned with the variety of objective strategies that are used for sample selection.

9.3 Population Statistics

Much of what is done in science involves making generalisations about things. Questions are asked like ‘how much weight does an ant carry?’, or (in a rather less scientific question), ‘how far will a family travel on a hot Sunday afternoon to treat the children to an ice-cream?’ Individual ants vary in how much weight each can carry (ants vary in strength just like people do) and families vary in just how far they will travel for an ice-cream (parents vary in their tolerance of their children’s demands and children vary in their passion for ice-cream); in science, the objective is usually to make a general statement about such things and avoid the fine detail of the variation amongst individuals.

To make these generalisations, various **population statistics** are used. These are measures used to summarise the properties of populations. Several of importance to forest inventory are described below.

9.3.1 Measures of Central Tendency

Measures of central tendency attempt to summarise the magnitude of whatever it is that is being measured in a population. The measure used most commonly is the average, or **mean**, as it is called in mathematical statistics. Then a generalisation about ants could be made by saying something like ‘on average, ants carry a load of 10 mg (milligrams)’. A generalisation about ice-cream-seeking families might be ‘the average family will not bother to go out for ice-cream if the trip involves a drive of more than 3 km, or which takes more than 20 min’, information that would be useful to an ice-cream entrepreneur considering where to set up new ice-cream stalls.

Other measures of central tendency are used for various purposes, particularly the **median** (the value in a set of data which has an equal number of values greater than and less than it) and the **mode** (the most common value in a data set). These can be particularly useful when the values in a data set are not spread similarly above and below the mean (that is, when the data have a skewed distribution).

9.3.2 Variance and Confidence Limits

It is of interest (at least to an ecologist) to know that ants carry 10 mg in weight on an average. That information will have been derived from a sample of ants in the ant population, a sample obtained by stealing the loads from some ants and weighing them. However, we cannot be sure just how representative the sample is of the whole population of ants. Maybe, over the whole population, the ants actually carry average loads of 15 mg, but the average in the sample was only 10 mg. In other words, it is necessary to recognise that any sample taken from a population can only give an approximation to the true value of the measure of central tendency which is being determined for the population.

Mathematical statistics provides an important population statistic, the **confidence limit**, which allows us to state exactly how *confident* we are that a mean obtained from a sample truly represents the actual mean of the population. It is a measure of the precision of the estimate of the population, where 'the repeated measurements or estimates of something' (see Sect. 2.4) are the measurements taken in the sample, the 'something' in this case being the population.

In turn, the confidence limit is based on a measure of precision called variance, which was mentioned also in Sect. 2.4 and was left to be considered further here. A large part of the entire discipline of mathematical statistics is concerned with how to deal with variation in natural systems and, so, with the determination of their variance.

9.4 Calculating the Population Statistics

An example will be used to illustrate the calculation and interpretation of the mean, variance and confidence limit of a population. The population to be considered will be the trees growing in a 0.25 ha plot in an area of native eucalyptus forest in northern New South Wales, Australia, a population measured for many years by my forest measurement students. There are 107 trees in this population. The diameter at breast height over bark and stem wood volume of each are given in Table 9.1. The sampling units in the population will be the individual trees. Their volumes vary over the range 0.013–1.977 m^3 and their average volume is 0.424 m^3.

Suppose the stem wood volumes of all the trees in this population had *not* actually been measured and it was desired to estimate their mean volume by selecting a sample from them. The stem wood volumes only of the trees selected in the sample would then be measured. Suppose it was decided to select 15 trees from the population as the sample and, to ensure objectivity, these trees were selected randomly. Suppose also that the sampling was done without replacement (that is, once a tree was selected in the sample, it was not considered for inclusion again); most sampling in forest inventory is done without replacement.

Table 9.2 lists a sample of 15 trees selected randomly from the population (the selection was done with the aid of a random number generator on my computer). After selecting the sample, the wood volumes of the stems of those trees would have been measured, using one of the techniques discussed in Chaps. 5 and 6.

Suppose there are n individuals in the sample ($n = 15$ in this case) and the stem wood volumes measured on those 15 trees are denoted as y_i (with i taking the values $1,2\ldots n$), so that $y_1 = 1.457$, $y_2 = 0.717 \ldots y_{15} = 0.013$ (as in Table 9.2). The average (that is, the mean) volume of the sample, Y_M, is calculated as

$$Y_{\mathrm{M}} = \left[\sum\nolimits_{i=1\ldots n} y_i\right] / n. \tag{9.1}$$

Table 9.1 The diameter at breast height over bark (DBH) and stem wood volume of each of a population of 107 trees in a eucalypt forest plot. The average volume of the trees in the plot is 0.424 m^3

Tree	DBH (cm)	Volume (m^3)	Tree	DBH (cm)	Volume (m^3)	Tree	DBH (cm)	Volume (m^3)
1	46.5	1.977	37	22.7	0.520	73	20.7	0.154
2	42.0	1.529	38	25.0	0.495	74	15.6	0.143
3	41.4	1.514	39	26.5	0.489	75	16.5	0.142
4	40.0	1.457	40	24.2	0.484	76	18.6	0.141
5	41.5	1.312	41	24.5	0.449	77	14.3	0.132
6	35.5	1.194	42	21.0	0.422	78	16.5	0.125
7	36.5	1.158	43	24.4	0.414	79	14.5	0.124
8	37.2	1.145	44	26.3	0.382	80	15.0	0.118
9	34.0	1.074	45	21.0	0.369	81	12.0	0.116
10	35.2	0.993	46	26.3	0.336	82	11.6	0.111
11	34.3	0.958	47	21.2	0.334	83	13.5	0.111
12	32.7	0.939	48	22.5	0.333	84	13.7	0.110
13	32.5	0.913	49	22.2	0.332	85	15.6	0.105
14	33.3	0.901	50	19.5	0.324	86	11.5	0.102
15	31.8	0.851	51	20.8	0.323	87	10.3	0.101
16	29.6	0.789	52	19.5	0.320	88	12.6	0.101
17	28.0	0.731	53	18.8	0.316	89	15.0	0.097
18	28.7	0.726	54	20.0	0.301	90	8.5	0.093
19	30.0	0.722	55	21.8	0.301	91	14.5	0.088
20	30.0	0.717	56	20.2	0.272	92	16.0	0.088
21	28.8	0.707	57	19.5	0.271	93	13.5	0.082
22	30.5	0.690	58	18.9	0.268	94	13.0	0.073
23	26.5	0.680	59	17.7	0.254	95	14.6	0.072
24	30.0	0.675	60	20.3	0.249	96	12.5	0.063
25	28.0	0.672	61	19.5	0.246	97	11.5	0.060
26	27.9	0.662	62	13.9	0.235	98	12.0	0.059
27	28.0	0.642	63	22.0	0.212	99	12.2	0.059
28	23.6	0.641	64	16.2	0.199	100	9.0	0.05
29	27.7	0.627	65	13.0	0.191	101	16.5	0.053
30	24.5	0.565	66	14.5	0.186	102	16.6	0.046
31	27.3	0.562	67	21.0	0.186	103	14.5	0.045
32	27.0	0.552	68	18.0	0.183	104	13.5	0.032
33	25.6	0.546	69	16.3	0.176	105	16.3	0.032
34	23.5	0.536	70	17.7	0.173	106	13.6	0.026
35	27.3	0.530	71	16.5	0.166	107	11.2	0.013
36	25.3	0.528	72	16.0	0.154			

For the sample, this gives a mean volume of 0.290 m^3, a good deal less than the actual mean of 0.424 m^3 for the whole population. This emphasises how far the estimate of the population mean determined from a sample can deviate from the true mean of the population.

The variance of the mean of the sample, V_M, is determined as

$$V_M = \left[\sum_{i=1\ldots n} (y_i - Y_M)^2\right] \Big/ [n-1]. \tag{9.2}$$

Table 9.2 Sample of trees selected by simple random sampling from the population of trees in Table 9.1

Tree	DBH (cm)	Volume (m^3)
4	40.0	1.457
20	30.0	0.717
29	27.7	0.627
41	24.5	0.449
49	22.2	0.332
67	21.0	0.186
75	16.5	0.142
85	15.6	0.105
90	8.5	0.093
96	12.5	0.063
100	9.0	0.056
102	16.6	0.046
105	16.3	0.032
106	13.6	0.026
107	11.2	0.013

For the example, $V_M = 0.155$. The confidence limit about the estimate of the mean, C_M, is then given by

$$C_M = t\sqrt{V_M / n}, \tag{9.3}$$

where t is the value of a variable known by the name Student's t. The variable t was discovered in 1908 by W.S. Gossett, who published under the pseudonym 'Student'. Its value varies, depending both on how *confident* we wish to be of our final result and on the number of observations in our sample. Suppose we choose to be 95% confident of our result and, given there are $(n-1) = 14$ degrees of freedom, as they are called, in our sample, then the value of t (which can be looked up in a table) is 2.145. So, the value of C_M for the example is $2.145\sqrt{0.155/15} = 0.218$ m^3.

These results from the sample are interpreted by saying that we can be 95% confident that the actual mean of the population lies within ±0.218 m^3 of the mean of the sample (0.290 m^3). That is, we can say we are 95% confident that the population mean lies within the range 0.290 ± 0.218 m^3, that is, within the range 0.072–0.508 m^3. This range is called the **confidence interval** about the sample mean. In this example, the actual population mean, 0.424 m^3, does indeed lie within that range; because a confidence level of 95% was chosen, it would be expected that, in 5% (100–95%) of samples taken from the population, their confidence intervals would not include the population mean. The confidence limit is our measure of the precision of the estimate of the population mean.

The determination of a confidence limit (hence, confidence interval) about an estimate of a population mean or population total is an extremely important part of an inventory of any population. It is used to indicate how worthwhile the inventory has been. If the confidence limit is small, relative to the sample mean, it can be said that the characteristics of the population have been estimated well. If it is large, it can be said that the characteristics have been estimated poorly.

In the example, the confidence limit is rather large in relation to the sample mean (it is 70% of the mean). If it was desired seriously to know the average tree stem wood volume in the example population, and the best that could be said was that it lay somewhere within the range 0.072–0.508 m^3, then we would probably not be very happy with the result. However, it is most important to recognise that it is entirely up to the person for whom the estimate is being made to judge whether or not the width of the confidence interval is adequate for the purpose for which the estimate is required.

If the confidence interval is wider than desired, there are two options available. The first is to increase the size of the sample. In our example, when a new random sample of 30 trees was taken from the population, the mean was 0.349 m^3 and 95% confidence interval was 0.189–0.509 m^3. This is still quite a wide interval, but much narrower than the range of 0.072–0.508 m^3, which was found with the sample of 15 trees. The second option is to adopt a different strategy to select the sample; options used in forest inventory to do this are discussed in Chap. 10.

It should be noted also that it is entirely up to the judgement of the person for whom the inventory is being done as to what level of confidence should be used in determining the confidence limit of the estimate. Quite arbitrarily in the example, it was chosen that we should be 95% confident about the result; that is a common level of confidence used in the biological sciences. For a forest inventory, the person for whom it is being done might be happy with a result of which he or she was only 90% confident, or he or she might demand a result of which they can be 99% confident.

The value of Student's t, as used in (9.3), varies with the level of confidence chosen, as well as with the number of observations in the sample. So, if it was desired to be only 90% confident of the result in the example, the value of t to be used in (9.3) would be 1.761, or 2.977 if it was desired to be 99% confident. These values are smaller and larger respectively than the value of 2.145 which was used to be 95% confident. The width of the corresponding confidence intervals would be progressively wider the more and more confident of the result it was desired to be. Of course, it is impossible to ever be 100% confident of the result from a sample; the confidence interval would be infinitely wide in that case. To be 100% confident, each and every individual in the entire population would have to be measured. Tables with values of Student's t are provided commonly in statistics textbooks, and computer packages often provide functions with which they can be calculated.

Chapter 10
Sampling Theory

10.1 Sampling Techniques and Their Efficiency

As mentioned in Sect. 9.4, there are various techniques which can be adopted to select a sample from a population. In the example used in Chap. 9, the sample (Table 9.2) was selected at random from the population (Table 9.1) in such a way that each and every tree in the population was equally likely to have been included in the sample. Speaking in mathematical statistical terms, this is a simple random sample (often abbreviated as SRS), that is, a sample in which each and every sampling unit in the population has the same probability of selection (or in common parlance, the same chance of being selected). In the example, there were 107 trees in the population and 15 trees were to be sampled. Thus, the probability of selection of any of the 107 trees was 15/107, that is, 0.140, or a 14% chance.

Simple random sampling is the easiest technique by which a sample might be selected, but it is certainly not the only one. Importantly, there are other sampling techniques, which have the great advantage that they lead to a reduction in the size of the confidence limit of whatever it is, that is being estimated about a population. Sampling forests can be a time consuming and expensive task. So, it is obviously desirable to obtain the most precise estimate possible of the characteristics of the forest population, with the least sampling effort. Again speaking formally, one sampling technique which leads to a more precise population estimate (that is, an estimate with a lower confidence limit) than another is said to be a more efficient technique. This chapter will describe several more efficient sampling techniques, which are used for sample selection in forest inventory.

10.2 Sampling with Varying Probability of Selection

One method to achieve more efficient sampling is to assign different probabilities of selection to the sampling units in the population, rather than using equal probabilities, as in simple random sampling (Sect. 10.1). This means that some sampling units will more likely be included in a sample than others. Obviously, there will

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have to be specific rules by which those different probabilities are assigned to the different sampling units, if this is to achieve more efficient sampling and if the sampling is to remain objective; those rules will be discussed in detail below.

Once such a sample has been selected, the computations necessary to determine the estimate of the population mean and its confidence limit, are rather more complicated than was the case for simple random sampling (Sect. 9.4); the mathematical details are given in Sect. 10.2.1. In Sects. 10.2.2 and 10.2.3, two different methods of applying this form of sampling are described.

10.2.1 The Population Mean and Its Variance

The mathematical detail and notation here follow closely those of the comprehensive and mathematically rigorous text on sampling in forest inventory of Schreuder et al. (1993). Suppose a population contains a total of N sampling units, from which a sample is to be drawn. Suppose that a probability of selection p_k ($k = 1 \ldots N$) was assigned to the k^{th} sampling unit; that is, there is a chance p_k that this sampling unit will enter any sample taken from the population. Suppose also that the probability that both sampling units k and l enter the sample is p_{kl}. Assume the sampling is done without replacement (Sect. 9.4).

Assume a sample of size n ($<N$) has been selected randomly from the population, using the probabilities of selection assigned to each of the sampling units (ways of doing this are discussed below). Suppose that some variable of interest (for example, tree stem wood volume) was then measured on each sampling unit included in the sample, and had a value y_i ($i = 1 \ldots n$) in the i^{th} sampling unit (with the corresponding probabilities of selection assigned to those sampling units now denoted as p_i, $i = 1 \ldots n$).

The mean of the variable of interest for the population, Y_{M}, can be estimated from the sample data as (adapated from 3.7 of Schreuder et al. 1993)

$$Y_{\mathrm{M}} = \left[\sum\nolimits_{i=1\ldots n} (y_i / p_i)\right] / N \qquad (10.1)$$

and its variance, V_{M}, can be estimated as (adapted from 3.9 of Schreuder et al. 1993)

$$V_{\mathrm{M}} = \left\{1 / \left(2N^2\right)\right\} \sum\nolimits_{i,j=1\ldots n, i \neq j} \{[(p_i p_j - p_{ij}) / p_{ij}][y_i / p_i - y_j / p_j]^2\}, \qquad (10.2)$$

where

$$p_{ij} = p_i p_j N(n-1)/[n(N-1)]. \qquad (10.3)$$

Note that in (10.2) the mathematical expression $\Sigma_{i,j=1\ldots n,\, i\neq j}$ denotes the summation of the term that follows the expression, as both i and j take successive values 1,2,3… up to n, except that terms where $i=j$ are not included in the summation.

The estimate of the confidence limit of the population mean, C_M, is

$$C_M = t\sqrt{V_M}, \tag{10.4}$$

where t is Student's t, for whatever probability level of confidence, is desired and with $(n-1)$ degrees of freedom.

Different sampling methods, which apply this theory, vary in the way in which the probabilities of inclusion of sampling units in the sample (the p_k) are assigned. Two such methods, useful for forest inventory purposes, are considered in Sects. 10.2.2 and 10.2.3, sampling with probability proportional to size and sampling with probability proportional to prediction.

10.2.2 Probability Proportional to Size

Sampling with probability proportional to size (often abbreviated as PPS sampling) assigns a probability of selection to every sampling unit depending on the size of the object which makes up the sampling unit. Before setting out to take the sample with this method, there must be available some measure of this size, *for each and every one* of the N sampling units in the entire population.

This measure must be easy and quick to measure and must be what is known as a **covariate** variable. A covariate is a variable which is correlated, at least partially, with the variable of interest it is desired to estimate ultimately for the population. In PPS sampling, the covariate must also be correlated positively with the variable of interest. Having a positive correlation means that sampling units with a larger value of the covariate tend to have a larger value of the variable of interest (a negative correlation would mean that a larger value of the covariate would tend to be associated with a smaller value of the variable). Furthermore, in PPS sampling the relationship between the covariate and the variable of interest should be represented reasonably by a straight-line. If the relationship is not a straight line, it can sometimes be made so by transforming the covariate values in some way, say, by squaring them or by taking their logarithms; the transformed values of the covariate would then be used for PPS sampling.

In the example used in Sect. 9.4, the diameter at breast height over bark of all 107 trees in the population had been measured (remember it is being assumed for the example that only stem volumes of trees included in a sample are actually measured). The tree diameters are listed in Table 9.1. Tree diameter is rapid and easy to measure; little time and effort would be wasted in doing so for every individual in the example population. Furthermore, we know from Chap. 6 that the diameter of the tree is likely to be quite highly and positively correlated with tree stem wood volume. However, that relationship is unlikely to be linear, whereas the relationship between tree stem wood volume and the square of tree diameter (in effect, tree basal area) is likely to be linear. That is, the square of tree diameter might be an appropriate covariate variable to use for the example, where the mean tree stem wood volume is the variable of interest it is desired to estimate ultimately for the population.

It is not uncommon to have available covariate information for every sampling unit in a forest population. For a large forest area, appropriate covariate information might be obtained from aerial photographs or satellite images of the forest. For example, suppose it was desired to undertake an inventory to estimate the wood volume of the trees in a large forest area. If aerial photographs existed of the forest, it might be possible to use them to determine the height of the trees at any point over the entire forest population. As discussed in Chap. 6, height is often correlated, at least partially, with tree stem wood volume. Hence, that information on tree height might be useful covariate information in undertaking PPS sampling to determine wood volume in the forest. In Chap. 13, there is further discussion of the various remote sensing techniques in use today in forestry and which might be used to provide covariate information over large forest areas.

Given these considerations, PPS sampling will be applied to the example in Sect. 9.4. Let the value of the covariate of the k^{th} sampling unit in the population be donated by c_k ($k = 1\ldots N$). As discussed above, the square of tree diameter at breast height over bark should be an appropriate covariate value for this example. Thus, from Table 9.1, $c_1 = 46.5^2 = 2{,}162.25$, $c_2 = 1{,}764.00\ldots$ $c_{107} = 125.44$.

Let the size of the sample to be selected be n (=15 in the example). For PPS sampling, the probability of selection of the k^{th} sampling unit is then calculated as

$$p_k = [n / N]\left[c_k / \left(\sum\nolimits_{k=1\ldots N} c_k\right)\right]. \tag{10.5}$$

For the example, $(\Sigma_{k=1\ldots N} c_k) = 58{,}939.42$ (the sum of the squared diameters over the entire 107 trees in the population), so, $p_1 = (15/107) \times 2{,}162.25/58{,}939.42 = 0.00514$, $p_2 = 0.00420\ldots$ $p_{107} = 0.000298$.

Now, a sample of size n is selected randomly from the population, except that the sampling is done so that the probability of inclusion of any particular sampling unit is determined by its assigned probability, as calculated using (10.5). To do this, when any one sampling unit is being considered for inclusion in the sample, a value is selected at random from within the range of the probabilities which have been assigned to the sampling units in the population (0.000172–0.00514 in the example, the lowest value being p_{90}, for the tree of the smallest diameter, and the highest being p_1, for the tree of the largest diameter); computer random number generation programs are adapted easily to provide such random values. If the random value is less than the value of p_k for the sampling unit being considered, then that sampling unit is included in the sample. This process is continued until the required number of sampling units (n) has been included in the sample.

In this process, it is not particularly important in which order sampling units are visited. However, to have the best chance of selecting a sample which represents reasonably the whole population, sampling units spread generally across the entire population should have been visited before the sample selection process has been completed.

Table 10.1 lists a sample of 15 trees that were selected for the example, using this process. A study of that table will show that this sampling technique has led to the inclusion of a higher proportion of trees of larger diameter in the sample than

Table 10.1 Sample of trees, selected by sampling with probability proportional to size (PPS sampling), from the population of trees in Table 9.1

Tree	DBH (cm)	Volume (m^3)
5	41.5	1.312
11	34.3	0.958
20	30.0	0.717
24	30.0	0.675
26	27.9	0.662
30	24.5	0.565
37	22.7	0.520
38	25.0	0.495
49	22.2	0.332
67	21.0	0.186
75	16.5	0.142
90	8.5	0.093
96	12.5	0.063
102	16.6	0.046
107	11.2	0.013

of trees of smaller diameter. This is a direct consequence of PPS sampling. Because of the required positive correlation between the covariate and the variable to be estimated, it favours the inclusion of sampling units which have a larger value of the covariate and, therefore, a larger value of the variable which is ultimately being estimated. It can be proved mathematically that this is likely to lead to be a more efficient sampling technique than simple random sampling.

When (10.1–10.4) are applied to the data of the sample in Table 10.1, they give an estimate of the mean stem wood volume of the population and its corresponding confidence interval, as shown in the second row of Table 10.2. Comparison of this confidence interval with that from simple random sampling (as calculated in Sect. 9.4 and shown in the first row of Table 10.2), shows it is much narrower for PPS sampling. That is, PPS sampling has indeed been a more efficient technique than simple random sampling.

10.2.3 Probability Proportional to Prediction

Before a sample was selected using PPS sampling (Sect. 10.2.2), it was necessary to have available a value of a covariate for each and every sampling unit in the population. In the case of sampling with probability proportional to prediction (often abbreviated as 3P sampling and sometimes called Poisson sampling), the advantages of the efficiency of PPS sampling can be achieved, but without the need to have the covariate values available in advance. Instead, covariate values need be determined only for those sampling units which are considered for inclusion in the sample and only at the time the sampling is being done in the field.

Table 10.2 For various types of sampling, estimates of the population mean stem volume (m^3) and its 95% confidence interval for the tree population of Table 9.1. SRS–simple random sampling, PPS–sampling with probability proportional to size, 3P–sampling with probability proportional to prediction, Stratified RS–Stratified random sampling, Model–model-based sampling. The true mean of the population was 0.424 m^3

Sampling method	Mean	95% Confidence interval
SRS	0.290	0.072–0.508
PPS	0.364	0.302–0.426
3P	0.435	0.372–0.499
Stratified RS	0.403	0.220–0.587
Model	0.403	0.365–0.441
Model (bootstrap)	0.403	0.347–0.447

Before setting out to take a 3P sample, the only extra information required about a population is to know the largest and smallest values of the covariate which will occur anywhere in the population. This will usually require that a preliminary survey be made of the population, to determine the extremes that occur in it.

Selection of a 3P sample then proceeds as follows. In the field, the sampler visits a sampling unit; as with PPS sampling, the order in which sampling units are visited is not particularly important. As a sampling unit is visited, the sampler obtains the value of the covariate for that sampling unit, using whatever quick and easy measurement technique is appropriate. Traditionally in 3P sampling, the covariate has been chosen to be the very thing which is being estimated in the inventory (in our example, the stem wood volume of a tree). The covariate value has then been obtained simply by the observer estimating its value visually; certainly, this provides the covariate value very quickly and easily. If this technique is used, the better the sampler is at making the estimates visually, the more efficient will be the result; this requires that samplers have preliminary training, to get their estimation eye ‘in’, before doing the sampling. However, it is not essential that the covariate value be obtained that way. As was found for sampling with probability proportional to size (Sect. 10.2.2) in our example, the square of tree diameter was a perfectly adequate covariate; it can be obtained quickly and easily simply by measuring the diameter of the tree concerned.

Once the covariate value has been obtained for a sampling unit under consideration, the sampler selects a value chosen at random from within the range of the minimum and maximum values of the covariate, as determined for the population before sample selection started. To provide the random values, the sampler might carry a calculator or laptop computer in the field or might simply refer to a list of such values, printed before the sampling started. If the covariate value is greater than or equal to the random value chosen for that sampling unit, the sampling unit is then included in the sample. The measurement crew accompanying the sampler would then measure the actual value of the variable of interest on that sampling unit.

If the covariate value is less than the random value, that sampling unit is simply ignored and the sampler moves on to the next sampling unit. This process continues until the required number of sampling units has been selected to make up the sample.

The disadvantage of 3P sampling is that many sampling units may be visited and rejected from the sample. If an inventory is being carried out of a large forest area, a lot of time is usually spent by the sampler and the measuring crew moving around the forest to visit sampling units, which may be located in difficult terrain. In the case of 3P sampling, a lot of time and effort can be spent getting to a sampling unit, only to have it rejected immediately from the sample. This is not a problem for our example; the population being considered there consists only of the trees in a single forest plot, so there is little time wasted by the sampler moving about the plot and finding trees to be included in the sample.

Table 10.3 lists a sample of 15 trees that were selected from the example population (Table 9.1) using 3P sampling. To make this selection, I used tree stem volume as the covariate and used visual estimation to obtain the covariate values. To select this sample, I had to visit and estimate the volume of 66 trees, a rather high proportion of the total 107 trees in the plot. Study of Table 10.3 will show that this sampling technique has led to the inclusion of a higher proportion of trees of larger diameter in the sample than of trees of smaller diameter, just as was the case with PPS sampling.

Suppose that the minimum and maximum values of the covariate which were assumed to occur in the population are denoted as c_m and c_x respectively. For the example, I assumed $c_m = 0.01$ m^3 and $c_x = 2$ m^3. Suppose a number n_v (=66 in the example) sampling units in the population were visited before the required n (=15 in the example) were selected in the sample. Suppose that the covariate value measured on the i^{th} sampling unit included in the sample was c_i ($i = 1 \ldots n$) (these values are not shown in Table 10.3, but

Table 10.3 Sample of trees, selected by sampling with probability proportional to prediction (3P sampling), from the population of trees in Table 9.1

Tree	DBH (cm)	Volume (m^3)
3	41.4	1.514
13	32.5	0.913
20	30.0	0.717
21	28.8	0.707
22	30.5	0.690
25	28.0	0.672
27	28.0	0.642
34	23.5	0.536
38	25.0	0.495
51	20.8	0.323
57	19.5	0.271
62	13.9	0.235
65	13.0	0.191
71	16.5	0.166
80	15.0	0.118

the actual, measured tree volumes y_i are). Then, for 3P sampling, the probability of selection of the i^{th} sampling unit in the sample, p_i, is given by

$$p_i = (n_{\text{v}} / N)(c_i - c_m) / (c_x - c_m). \tag{10.6}$$

When (10.1–10.4) were applied to the sample data in Table 10.3, the estimate of the population mean stem wood volume and its confidence interval were as shown in the third row of Table 10.2. In this example, 3P sampling was even more efficient than PPS sampling.

It should not be assumed from this example that 3P sampling is always more efficient than PPS sampling. The difference here simply reflects chance variation in the two processes in deciding which sampling units were to be included in the sample and how closely the covariate used correlated with the variable being measured; the higher the correlation, the more efficient will the sampling be.

It should be noted that the treatment of 3P sampling here differs from that in other texts (e.g. Shiver and Borders 1996; Avery and Burkhart 2002; Iles 2003). It contains some original elements, reported otherwise only as a conference paper (West 2005). In particular:

- Defining the probability of inclusion of a sampling unit in the sample by (10.6) allows application of the already well established, general theory of sampling with varying probability of selection (10.1–10.3)
- Visual estimation of the variable of interest on each sampling unit is not the only way to obtain a covariate value in 3P sampling. Other variables, which may be estimated visually or measured by other methods, can provide perfectly suitable covariate values
- It is unnecessary to visit and obtain a value of the covariate for each and every sampling unit in the entire population. Previously, this was the standard protocol prescribed for 3P sampling. It renders it impractical as a sampling method for any but very small populations. In the present treatment, it is necessary to visit only as many sampling units as are required to achieve the sample size desired. However, before sampling starts, failure to determine correctly the largest and smallest values of the covariate, which will be encountered in the population, will render the present method unworkable.

10.3 Stratified Random Sampling

Sampling with varying probability of selection (Sect. 10.2) is not the only way to achieve more efficient sampling. Another method used commonly is to organise the sampling units into groups, or strata as they are called, so that the variation between the sampling units in any one group (**stratum**) is less than the variation over the whole population. This is called stratified random sampling.

Consider a large area of a particular type of forest (such as a plantation forest or a rainforest). Across the area, the forest will vary in age or stage of development, as will the topography, climate and type of soil. All of these will affect the amount of wood present at any point in the forest and determine the amount of variation in wood volume across the whole area. So, stratification of the forest area into smaller areas based on these factors would be expected to reduce the variation in any one of the strata when compared with the variation over the whole population. The more and more the variation between sampling units within any one stratum can be reduced, the more efficient will stratified random sampling be.

In effect, the information used to define the strata can be thought of as covariate information, just as was required in sampling with probability proportional to size (Sect. 10.2.1). However, in stratified random sampling the covariate information might be categorical, rather than numerical; for example, different soil types might constitute different categories on which to base the stratification. Information from several different types of covariate might be used as well. Thus, strata defined by soil type might be subdivided further into strata defined also by age of the forest.

To illustrate how stratified random sampling works, it will be applied to our example from Sect. 9.4. Suppose the trees in that population (Table 9.1) were divided into three strata, based on their diameters at breast height over bark. Suppose the first stratum was made up of trees with diameters in excess of 25.5 cm (there are 35 such trees in the example); this might be called the ‘large tree’ stratum. The second stratum (the ‘medium tree’ stratum) contained trees with diameters in the range 16.5–25.5 cm (37 trees). The third (the ‘small tree’ stratum) contained trees with diameters less than 16.5 cm (35 trees).

Since the diameter of the tree is expected to be correlated with stem volume, it would be expected that the variation in stem volume in any one of these three strata would be less than the variation over the whole population. In reality, this is a most unlikely form of stratification to do; where information, like tree diameter, is available for each and every sampling unit in the population, a sampling technique like PPS sampling will make much better use of that information and would be expected to be a more efficient sampling method than stratified random sampling. However, for the sake of our example, we will persist with those three strata.

Suppose a sample of 15 trees was now selected at random from the population. In doing so, the number of trees selected from each stratum will be approximately proportional to the stratum size. The simple random sample selected earlier (Table 9.2) will serve for this purpose. From the diameters of the trees in that table it will be seen that this sample includes three trees from the large tree stratum, five from the medium tree stratum, and seven from the small tree stratum. These numbers of trees are certainly only approximately proportional to the stratum sizes, which illustrates the amount of variation that can result when random samples are selected.

Suppose there were H strata. Suppose the h^{th} stratum ($h = 1 \ldots H$) contained $N(h)$ sampling units in total and $n(h)$ of those were included in the sample. Suppose a value of a variable of interest, $y(h,i)$, was measured on the i^{th} $[i = 1 \ldots n(h)]$ sampling unit which was sampled in the h^{th} stratum. The estimate of the mean of the variable of interest in the h^{th} stratum, $y_m(h)$, is given by

$$y_m(h) = \left[\sum\nolimits_{i=1\ldots n(h)} y(h,i)\right] / n(h). \tag{10.7}$$

The estimate of the population mean, Y_{M}, is then given by (following 3.14 of Schreuder et al. 1993, but with slight modification to determine the population mean, rather than total)

$$Y_{\mathrm{M}} = \left\{\sum\nolimits_{h=1\ldots H}\left[W(h)y_m(h)\right]\right\}, \tag{10.8}$$

where $W(h) = N(h)/N$ and of its variance by (following 3.16 of Schreuder et al. 1993, with modification also for variance of the mean, rather than of the total)

$$V_{\mathrm{M}} = \sum\nolimits_{h=1\ldots H} W(h)^2 \{1 - f(h)\}\left\{\sum\nolimits_{i=1\ldots n(h)} [y(h,i) - y_m(h)]\right\} \Big/ \{[n(h)-1]n(h)\}$$

Please note the erratum to this equation at the end of the book. (10.9)

where $f(h) = n(h)/N(h)$. The confidence limit can then be determined using (10.4), with the number of degrees of freedom for t being approximately $\{\sum_{h=1\ldots H}[n(h)]\}-h$ (Satterthwaite 1946; Cochran 1977; Gregoire and Valentine 2008).

For the example, $H = 3$, $N = 107$, $N(1) = 35$, $N(2) = 37$, $N(3) = 35$, $n(1) = 3$, $n(2) = 5$, $n(3) = 7$, and the values of $y(h,i)$ are the measured tree stem volumes in Table 9.2, for the samples in the respective strata. The results of applying (10.7–10.9) to these data are shown in the fourth row of Table 10.2. In this case, stratified random sampling has produced a more precise estimate than simple random sampling, but has been less precise then PPS or 3P sampling. This is to be expected. PPS and 3P sampling make better use of the specific values of covariate information, whereas stratified random sampling only used that information to subdivide the population into three tree size strata.

10.4 Model-based Sampling

The last type of sampling to be discussed here is called model-based sampling. As with PPS sampling, model-based sampling is appropriate where the value of at least one covariate has been measured initially, on each and every sampling unit in the population. Importantly however, model-based sampling can be used to even better advantage than PPS sampling if there is more than one covariate available for each sampling unit.

In model-based sampling, the results from taking a sample from the population are used to establish a regression equation (Sect. 6.2.1) relating the variable of interest to the covariate(s). The fitted regression equation is then used to predict the values, from the covariate(s) values, of the variable of interest on each and every sampling unit in the population.

There are several advantages with model-based sampling, over other forms of sampling, as follow:

- Any number of covariates may be used, which may allow much greater sampling efficiency
- The covariates may be correlated either positively or negatively with the variable of interest in the population and still be just as useful in model-based sampling; only a positive correlation is useful in PPS or 3P sampling
- The full power of regression analysis can be brought to bear to establish a relationship between the variable of interest and the one or more covariates for which information is available in the population. This allows relationships with very complex functional forms to be used, where these provide the best relationship between the variable of interest and the covariate(s)
- The way in which the sample is selected from the population need not be as formal as in the other sampling methods. Texts on regression analysis discuss the optimum sort of information required to fit regression relationships reliably. Suffice to say that the data collected should encompass generally the range of values of the covariates that occur across the population, and that the sampler should have been objective in selecting the sample (that is, no sampling unit should have been included in the sample through any prejudice of the sampler).

10.4.1 Applying Model-Based Sampling

Model-based sampling will be illustrated for our example (Sect. 9.4), using the square of tree diameter as the covariate variable. For this illustration, suppose the sample selected for simple random sampling (Table 9.2) was available to us. Figure 10.1 shows tree stem wood volume plotted against the square of diameter at breast height over bark for the 15 trees in that sample.

For these data, there appears to be a simple straight-line relationship between stem volume (y_i, m^3) and the square of diameter ($x_i = D_i^2$, cm), where $i = 1 \ldots 15$ for the 15 observations in the sample. Hence, an appropriate regression equation to fit to those data might be a simple straight line, that is, the equation

$$y_i = a + bx_i, \tag{10.10}$$

where a and b are parameters of the equation. When ordinary least-squares regression (the form of regression analysis used normally in the biological sciences and which is discussed in all texts on regression analysis) was used to fit these data to (10.10), estimates were found for a and b of $a = -0.121$ and $b = 0.000951$. The fit to the data for this model is shown as the solid line in Fig. 10.1.

The estimate of the population mean stem wood volume, Y_M, is determined by using this model to predict wood volume of each and every tree in the population (Table 9.1) from its diameter and adding up the predicted values, so that

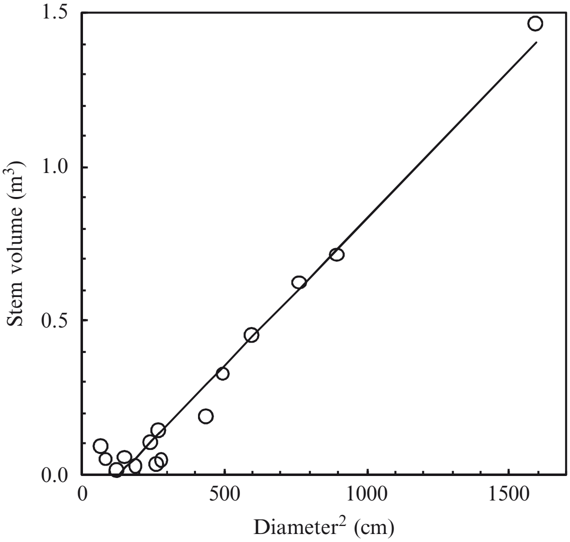

Fig. 10.1 Scatter plot of tree stem wood volume against the square of tree diameter at breast height over bark for the sample selected for simple random sampling (Table 9.2). The *solid line* shows the ordinary least-squares regression, straight-line fit to the data

$$Y_{\mathrm{M}} = \left[\sum\nolimits_{k=1\ldots N}\left(a+bx_k\right)\right]/N, \tag{10.11}$$

where x_k is the square of the diameter at breast height of the k^{th} tree in the population ($k = 1\ldots N$, where $N = 107$ in the example). The result, an estimate of 0.403 m³, is shown in the fifth row of Table 10.2.

Where a simple straight-line model such as 10.10 has been used for model-based sampling, an estimate of the variance of the mean, V_{M}, can be determined from the n observations in the sample as (see 6.17–6.19 of Shiver and Borders 1996, with slight rewriting of their 6.18),

$$V_{\mathrm{M}} = \left\{\left[\sum\nolimits_{i=1\ldots n}\left(y_i - y_{\mathrm{M}}\right)^2 - b^2\sum\nolimits_{i=1\ldots n}\left(x_i - x_{\mathrm{M}}\right)^2\right]/\left[n-2\right]\right\}\left\{\left[N-2\right]/\left(Nn\right)\right\}, \tag{10.12}$$

where y_{M} is the mean of the measured stem wood volumes in the sample and x_{M} is the mean of the squares of the diameters at breast height of the trees in the sample.

Equation (10.4) can be used to determine the confidence limit, although in this case with Student's t having (n–2) degrees of freedom; the resulting confidence interval is shown in the fifth row of Table 10.2. In this example, model-based sampling appears to have been the most efficient of all the methods tested here.

It is very important to note that (10.12) applies only when the regression model fitted in model-based sampling is a simple straight line, that is, like (10.10). If other regression models are used (perhaps a multiple regression, where other covariates are included in the model, so that it has more than two parameters, or where a non-linear regression model has been fitted – crudely speaking, a model in which the parameters are not arranged in a sequence of additive terms as in 10.10), then (10.12) is inappropriate. In general, mathematical statisticians have not yet derived equations to give the required variance estimate when regression models other than a straight line have been used in model-based sampling.

Fortunately, a technique known as bootstrapping is available to make an estimate of the variance. Bootstrapping uses the data from the sample in what is known as a Monte Carlo or simulation technique. These terms mean that bootstrapping involves averaging many trials which involve random processes; the use of 'Monte Carlo' to describe such techniques derives from the random nature of gambling at the casinos there.

For the example, bootstrapping would be applied as follows. Given the original sample of 15 trees measured for stem volume (Table 9.2), a new sample, also of size 15, would be selected from the original sample by simple random sampling from it *with replacement*. That is, when any tree has been selected from the original 15 into the new sample, it would be kept in the list of 15 and be eligible to be selected again. When this is done, about 37% of the original sample points will be duplicated in the new sample. The new sample would then be used in exactly the same way as the original sample. Model (10.10) would be fitted by least-squares regression to its data to give new values for the parameters a and b. Equation (10.11) would then be used to get a new estimate of the population mean stem wood volume.

This process would then be repeated a large number of times (say, 1,000) with different, new samples being selected with replacement from the original sample each time. The 1,000 new estimates of the population mean would then be arranged in order. The particular estimates within that 1,000 would then be found which are spaced equally above and below the estimate of the population mean from the original sample (0.403 m^3 in the example) and within which 95% of the 1,000 new estimates lie. These two values can then be considered the upper and lower limits of the 95% confidence interval. Probability levels other than 95% can be determined similarly using this process.

The bootstrap confidence interval determined for the model-based sampling example is shown in the last row of Table 10.2. It is quite close to that determined using (10.12). It is inevitable that there will be some differences between a confidence interval determined by bootstrapping and one obtained from a mathematically formulated variance predictor such as (10.12). We are not really able to say which is the 'best' estimate of the interval of confidence, although one might prefer generally the mathematically derived predictor, because its properties are known formally.

Bootstrapping has been a controversial technique amongst mathematical statisticians. However, sufficient has been learnt about its properties that it seems to be accepted now as appropriate, whenever a more formal alternative is not available. It could be applied to determine confidence intervals for any of the sampling techniques examined in this chapter. However, since formal mathematical estimators of variance have been developed for all of them, except model-based sampling, those estimators would be preferred generally to bootstrapping. The jackknife technique is an alternative to bootstrapping (Kangas 2006a), but will not be considered further here.

10.5 Choosing the Sampling Technique

The discussion of the various sampling techniques should have made it apparent when each is appropriate.

If no prior information is available about the population, there is no option but to use simple random sampling.

The technique which then requires the least prior information about the population is sampling with probability proportional to prediction (3P sampling). To apply it, an initial survey must be undertaken to determine the largest and smallest values that occur in the population of the variable which is to be used as a covariate. The better this maximum and minimum are determined, the fewer will be the number of sampling units which have to be visited to find those to be included in the 3P sample.

The other sampling techniques discussed here all require that covariate information is available for each and every sampling unit in the population. These covariates should be variables or characteristics of the population for which values can be obtained relatively easily and inexpensively. Furthermore, they should be at least partially correlated with the variable of interest to be estimated in the population.

Covariates which do not have specific numerical values, such as the type of forest or the type of soil, can be very useful in stratifying the population, so that the variation in the variable of interest is less in each stratum than it is in the whole population. When this type of information exists, stratified random sampling might be the most efficient sampling technique.

Where covariates have specific numerical values, sampling with probability proportional to size (PPS sampling) or model-based sampling might be the most efficient sampling techniques. PPS sampling would be appropriate when there is a single covariate only, which is correlated positively with and related linearly to the variable of interest. Where there are two or more covariates available, where the relationship between a covariate and the variable of interest is not linear or where the correlation between the variable of interest and the covariate is negative, model-based sampling might be most appropriate. In either case, the higher the degree of association between the covariate(s) and the variable of interest, the more efficient will be those techniques.

Apart from the sampling technique used, the other determinant of the precision of the inventory (the size of its confidence limit) is the size, n, of the sample. The larger is n, the smaller is the confidence limit likely to be. If a sample has been selected and the confidence limit is larger than is desired, then the sample size must be increased (or a different sampling technique employed) to obtain a smaller limit. Once some sampling has been done to obtain some estimate of the variation in the population, mathematical techniques can be employed to estimate how large the sample size needs to be to obtain a confidence limit of the required size. These techniques will not be discussed here; reference to them can be found in more comprehensive texts on sampling practice.

Lastly, it must be stressed that this chapter has only introduced the subject of sampling techniques. Many and much more complex variations exist to deal with the problems encountered in sampling forests; more advanced texts (e.g. Schreuder et al. 1993; Shiver and Borders 1996) should be consulted to learn more about these. However, the discussion here should give the reader a basic understanding of the principal sampling techniques used today in forest inventory.

Chapter 11
Conducting an Inventory

11.1 Objectives

Chapters 9 and 10 have established the background to undertaking an inventory of a forested area. The first practical step in doing so is to establish very clearly, with the forest owner, the objectives of the inventory, to ensure it will achieve whatever the owner has in mind.

Forest owners differ greatly both in the size and nature of their forest holdings and in the purposes for which they own them. At one end of the scale is the farmer, who may own some tens of hectares of forest being used to beautify the farm, as an 'environmental' forest or as an investment for retirement. At the other end of the scale are governments or corporations, which own large areas of native and/or plantation forests with a myriad of uses, ranging from timber production to water catchment protection, to wilderness or biodiversity conservation or to recreation for people.

The scope of the inventory task will differ greatly at these extremes. At the smaller end of the scale, a single person may be able to carry out the inventory. At the bigger end, large teams of both professional and technical staff may be employed permanently to carry out the inventory and analyse and interpret its results.

Nevertheless, whatever the scale of inventory, its objectives must be quite clear. They will determine exactly what measurements are to be made and the nature and scale of sampling necessary to estimate whatever variables are of interest across the whole forest. It may be only wood quantities in the forest that are required. However for larger and more complex forests, information on many other characteristics of the forest ecosystem may be needed.

The methods necessary to measure those different characteristics may differ so greatly that each requires a quite separate inventory. Trees do not move, so they can be easily located and measured on different occasions if necessary. Animals hide, move about and may bite, so sampling techniques necessary to locate and measure them are quite different from those appropriate for trees. If the water resources provided by a forested catchment are to be assessed, sampling may concentrate on stream outflows and water-holding characteristics of the soils within the catchment. This book concentrates on inventory of tree qualities in forests and particularly on

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wood quantities; other specialist texts will need to be consulted if the interest is in inventory of other forest ecosystem characteristics.

Once it has been established clearly with the forest owner what characteristics of the forest are to be estimated, consideration needs to be given to the level of confidence with which the owner wishes to know the answer and, hence, what width of confidence interval will be acceptable. These will determine the amount and type of sampling which will be required.

Thus an owner concerned principally as to whether or not an endangered plant species occurs within his or her forest area may require only to be 75% sure that its numbers lie within ±20% of the estimate of those numbers. A potential forest owner, wishing to value the wood resource in a forest before purchasing it, may wish to be 95% sure that its quantity lies within ±5% of the amount estimated by the inventory. The work and costs involved in undertaking the inventory will be greater the more confident the owner wishes to be of the answer.

These statistical concepts are often difficult for lay people to appreciate. Even if the forest owner does not understand them fully, the professional person undertaking the inventory needs to at least infer what the requirements of the owner are and establish what they should be in negotiation with him or her. Only then will it be possible to judge the scope of the inventory task and, hence, how much it will cost. Perhaps even more importantly for the professional, it will allow him or her to defend the quality of the results, if a legal dispute should arise with a disgruntled owner about the quantities which were estimated.

11.2 Approach and Methods

It would be possible to consider each and every tree in a forest area as being the population to be sampled in an inventory. Sampling could be done amongst those individuals and their total number would then be used to convert the results from the sample to the required estimate for the total forest.

For any but a very small forest area, this would be impractical. To travel hither and thither over a large forest area to sample individual trees would require far too much time and be unnecessarily arduous. Accordingly, forest inventory is usually carried out by sampling stands scattered throughout the forest area.

Ultimately, this provides an estimate of the stand mean and its confidence limit over the entire forest area. For example, the inventory might determine that the mean stand stem wood volume over the entire forest is 158 m^3/ha, with a 95% confidence limit of ±17 m^3/ha. To determine the stem wood volume available over the entire forest, and its confidence limit, simply involves multiplying these values by the area of the forest. Thus, if the entire forest had an area of 8,471 ha, it would be estimated that there was 1.34 million m^3 (8,471 × 158/1,000,000) of stem wood in the whole forest area, with a 95% confidence limit of ±0.14 million m^3 (8,471 × 17/1,000,000). That is, it would be estimated that we could be 95% sure that the stem wood volume in the entire forest lay within the range 1.20–1.48 million m^3 (1.34 ± 0.14).

Large forest estates often have a lot of information already collected about them. Maps may exist of forest types, soils, topography or climate variation. There may be air photos or satellite imagery available (Chap. 13). There may be reports available of previous management undertaken, of previous inventories or of ecological research done in the forest. All this information should be consulted and may prove useful in planning the inventory. At least it might provide basic maps of the forest areas being considered. Even better, it might allow stratification of the forest to allow stratified random sampling (Sect. 10.3). At best, it might provide covariate values across the entire forest estate, which could be used for sampling with probability proportional to size (Sect. 10.2.2) or model-based sampling (Sect. 10.4).

All this information will assist in defining exactly the population which is to be measured. It will help also to make decisions about what sampling technique to use and what the sample size should be; these matters were discussed in Sect. 10.5. Decisions will have to be made too about the measurement techniques to be used for stands included in the sample. Plot measurement (Sect. 8.4.1) might be used or, increasingly today, point sampling (Sect. 8.4.2) might be preferred; issues involved with measuring plots and point samples are discussed in Sect. 11.6. Ultimately, all these decisions will have to be weighed, to reach some compromise as to how to carry out the inventory in the most cost-effective way, given the prior information, equipment and staff resources available.

11.3 Forest Area

It is clearly crucial to the approach described in Sect. 11.2 that the total area of the forest population be determined. If stratified random sampling is to be used, the area of each stratum must be measured also. It is essential to have an unbiased and precise estimate of these areas, since the results of sampling are eventually multiplied by them to determine the final estimate of whatever is being measured over the whole forest. Any error in forest area is immediately transferred to the final result; poor area measurements are often one of the biggest sources of error in an inventory estimate.

For large and complex forests, measurement of area can be a difficult task. It may require the services of professional surveyors, cartographers and **geographic information system** specialists. Particularly difficult is the determination of what actually is, or is not, included in the forest population. For example, management requirements might specify that logging should not be carried out within a certain distance of streams, to avoid siltation, or on slopes above a certain steepness. Inventory of timber availability would need to exclude those areas and they would have to be mapped out of the forest area accordingly. In a forest plantation, the trees may not have grown at all on swampy areas, or refuge areas of native forest for wildlife may have been left scattered throughout the plantation. Again, these need to be mapped or, if they are not, must be included in the sampling process and wood availability from them recorded as zero when they are encountered as part of the sample actually taken.

There is a variety of more and less sophisticated surveying equipment available these days. It can range from a simple magnetic compass, clinometer and tape, to a theodolite and laser distance measuring equipment or to the **global positioning system**. The precision of the survey would be expected to increase as more sophisticated equipment is used. Nevertheless, the principles of the conduct of a survey remain the same, no matter what equipment is used; these are outlined in Chap. 12.

After the survey has been completed, the ready availability today of geographic information systems has made much easier the process of producing finished maps of complex forest areas. These systems are used universally today by organisations routinely involved with forest inventory. Description of their use is outside the scope of this book.

11.4 Sampling Units and Calculation of Results

Once issues of population boundaries, the population area and sampling and plot measurement methods have been decided, a crucial problem is then to consider the size of the population. That is, it is necessary to consider the value of N, the total number of sampling units in the population, a variable which appears in various places in Chap. 10 in the equations used to calculate the results of the inventory for various sampling methods.

If plot measurement is being used, N would be the total number of plots which could be positioned across the entire forest area. That is, N would be equal to the forest area divided by the plot area. Those N plots would then constitute the sampling units of the population from which the sample would be drawn.

If point sampling is being used, there is a quandary. Over any area, there is an infinite number of points which could be chosen as the point sample points. No area can be ascribed to a point sample (Sect. 8.4.3), so there is no opportunity to determine N in the same way as for plot measurement.

Fortunately, there is a way out of this quandary for point samples, a solution which can be applied just as well for plot measurements. It requires only that the number of sampling units in the population (N) be much larger than the size of the sample to be selected from the population (n); mathematically, this requirement is written as $N \gg n$. If this is so, the values determined for the population mean and its variance, as calculated using the equations in Chaps. 9 and 10 for the various types of sampling, are virtually unaffected by the value which is used for N in the computations. This may seem rather surprising, given that N appears in many places in those equations. However, some algebraic manipulation of the various equations will convince you that it is so; I have not shown those manipulations here, but they require appreciation of the fact that, if $N \gg n$, then $(N-n) \approx N$ and $n/N \approx 0$ (the mathematical symbol $\approx$ means ‘approximately equal to’).

In forest inventory, it is virtually always true that $N \gg n$. Usually, a sample size of some hundreds will be drawn from a forest area which is so large that it contains many tens of thousands of locations from which the sample could be drawn. Given the discussion in the last paragraph, this means it will not be important in forest inventory if the value of N is difficult or impossible to define. Virtually any large value can be used for it, as long as it is much larger than the sample size.

Having said that, it is common in preparing a forest inventory to position a square or rectangular grid over the entire forest population area. The grid need not actually be square or rectangular; any geometrically regular shape would do. However, square or rectangular grids are usually easiest to deal with in practice. In essence, the grid squares (or rectangles) will then constitute the sampling units which make up the population and from which the sample will be drawn; a plot or point sample could be measured somewhere within any grid square which has been chosen as part of the sample.

The decision about the area of each grid square or rectangle is left up to the person conducting the inventory. Let us suppose there are N' of them, which will be determined as the total area of the forest divided by the area of the grid squares. As discussed above, as long as $N' \gg n$, N' will be a perfectly good value to use in place of N, wherever N appears in the formulae to determine the population mean and variance for the various types of sampling.

These considerations lead to some minor issues with the computations necessary to obtain the results for different types of sampling, as follow:

- For simple random sampling (Sect. 9.4), N does not enter the equations to determine the population mean and its variance (9.1)–(9.2), hence its value is not an issue
- For sampling with probability proportional to size (PPS sampling, Sect. 10.2.2), it is essential to use N' for N in all the equations which apply to that form of sampling (10.1)–(10.3), (10.5)
- For sampling with probability proportional to prediction (3P sampling, Sect. 10.2.3) any arbitrary, large value may be used for N in the relevant equations (10.1)–(10.3), (10.6) as long as the value is $\gg$ n. Note that West (2005) claimed it was essential to determine N for 3P sampling, but it is recognised now that this is not so
- For stratified random sampling (Sect. 10.3), the values of $W(h)$ in (10.8)–(10.9) should be calculated as $W(h) = A(h)/A$, where $A(h)$ is the ground area of the h^{th} stratum and A is the total forest area $\left[A = \sum_{h=1 \ldots H} A(h)\right]$. As well, it needs to be assumed that the total number of sampling units in any one stratum $[N(h)]$ is much greater than the sample size selected from that stratum $[n(h)]$. For most practical forestry inventories, it will indeed be true that $N(h) \gg n(\mathrm{h})$, hence, $f(h) = n(h)/N(h) \approx 0$ and so a value of zero may be used for $f(h)$, for all h, in (10.9). With those modifications, N no longer appears in any of the relevant equations (10.7)–(10.9), hence its value is not an issue
- For model-based sampling, (Sect. 10.4), it is essential to use N' for N in all the equations which apply to that form of sampling (10.11)–(10.12).

In forest inventory today, it is common to choose the size of the grid squares to match some requirement for determining covariate values for the forest within each grid square; covariate values are necessary if sampling with probability proportional to size or model-based sampling are being used (Sects. 10.2.2, 10.4). For example, the Landsat 7 satellite (Sect. 13.3) is used often today to provide covariate values in forest inventory. This satellite produces images which cover a 30 m × 30 m ground surface area, so it will provide covariate values for forest patches of that size. Thus, a 30 m × 30 m grid would be established across the forest area concerned, to match the imagery and to give the value of N'. In Chap. 13, there is more discussion of the use of satellite imagery (as well as other forms of imagery) for forestry purposes.

11.5 Systematic Sampling

Systematic sampling is a quite straightforward variation on the method of conducting an inventory as, described in Sects. 11.2 and 11.4. It is used often in America, where many foresters make their living assessing timber availability from privately owned tracts of forests; American foresters term this timber cruising, or simply cruising.

Just as discussed in Sect. 11.4, systematic sampling involves laying out grid squares over the forest area, but with a grid size such that the number of grid squares equals the sample size required. Each and every grid square is then sampled. Because there is then no selection of which grid squares are to be included in the sample, it is a sampling technique appropriate only to simple random or stratified random sampling. As long as the location of the origin of the coordinate system used to lay out the grid squares is chosen randomly, the requirements for simple random sampling will be met; that is, each and every point in the population would have had an equal chance of being included in the sample. Usually, the intersection points of the grid lines, which make up the grid squares, are taken as the actual sample points.

The advantage of systematic sampling is that it is very straightforward to apply in the field. The sampler simply starts at a randomly chosen point, somewhere near a corner of the forest tract, and then walks along straight lines directly through the forest, measuring a plot or taking a point sample at regular intervals, as determined by the chosen grid spacing.

Foresters who do this type of work regularly will know from experience what an appropriate size is for the grid for the particular forest type within which they are working. The sample size will then be determined directly by the area of the forest. The forest area itself can be estimated by multiplying the sample size by the area of the grid squares, so avoiding the need for a separate survey to determine the forest area. The sampler might also be able to identify stratum boundaries as he or she walks through the forest, thus effectively mapping the forest as he or she goes.

The main disadvantage of systematic sampling is that it is appropriate only for forest where simple or stratified random sampling is most appropriate.

11.6 Stand Measurement

Stands are usually measured in forest inventory using plots or point samples. In doing so, a number of issues need to be borne in mind. Some of these are important for both plot measurement and for point sampling, and others only for one or the other.

11.6.1 Shape

Plots are usually square, rectangular or circular. In principle, there seems no reason in forestry to prefer one shape over the other.

There are difficulties involved with all shapes. Circular plots may be easier to establish, since their circumference can be readily identified by running a string from the centre out to the required radius. However, it is more difficult to decide which trees are inside or outside the plot, because the boundary is curved. Square and rectangular plots can be more time consuming to lay out, because they have to be established carefully with right angles at the corners. Their boundary length is also greater than that of a circular plot of the same area, so more decisions have to be made as to which trees are actually in or out of the plot; on the other hand, their straight edges can make these decisions easier. As mentioned in Sect. 8.4.3, it is usually assumed that a tree is in the plot if the centre of its stem lies within the plot boundary.

Point sampling inherently involves measuring trees from circular areas (Fig. 8.1), but care needs to be taken when deciding if borderline trees should be included or excluded (Sect. 8.4.4).

11.6.2 Positioning

Whichever plot shape is preferred, additional care needs to be taken in plot positioning when the trees are positioned with some regular arrangement, such as in a plantation. Because of the regular spacing, it is possible to position plots of the same area, but which contain different numbers of trees. However, it is usually quite straightforward to find a consistent way of positioning plot corners or plot centre and choosing the plot area so that the stocking density of the trees in the plot is similar to that of the general stocking density of the plantation.

In plot or point sampling, care must be taken where forests have some regular trends in tree size imposed on them by physical characteristics of the land or management practices. For example, where logging debris has been heaped into long rows (often called windrows) and burnt, trees in the regenerated or replanted forest may grow better on the windrows because of the soil sterilisation and nutrient release resulting from the fire. If samples were taken at spacings consistent with windrow spacing, windrows might be sampled either with higher or lower frequency than should be the case.

Trees often grow more poorly on ridges in the landscape, because water availability from the soil is often less on ridges than in the down-slope valleys. If grid lines for a systematic sample happened to be orientated so they were parallel to ridges, areas of poorer or better forest might be sampled more or less frequently than they should be.

Whatever these potential sources of bias in sampling, care needs to be taken to orient the sampling unit grid to avoid them. Sometimes long and narrow rectangular plots, oriented with their long axes perpendicular to the regularity, are used to minimise these problems.

It is common also to come across treeless gaps in the forest. They are part of the forest population and must not be ignored. They can be mapped out of the population or, if not, must be included in the sampling process and recorded as having a zero value of whatever is being measured in the inventory.

11.6.3 Size

Deciding what the area of plots should be presents several problems. In Sect. 10.5, the size of the sample to be taken in an inventory was considered, that is, the number of stands to be measured. However, ultimately it is the intensity of sampling which is rather more important than just the number of sampling units. The intensity is defined as the total area sampled divided by the total forest area. It depends on the number of plots included in the sample, their areas and the total forest area. A certain intensity of sampling will be necessary to achieve any desired precision of the final estimates sought in the inventory.

It is cheaper generally to measure fewer, larger plots than many smaller plots; the time and cost involved in moving measuring crews from plot to plot is usually much greater than taking more measurements at any one plot. However, if the sample size (that is, the number of plots sampled) is too small, the sampling may not cover adequately the range of variation that occurs across the forest. Having said that, in forestry practice plot sizes are generally chosen to be within the range 0.01–0.1 ha.

Because plot area is unknown with point sampling, sampling intensity cannot be determined. The smaller the basal area factor used for the point sample, the larger will be the number of trees measured around any point. Again, a balance will need to be drawn between the number of plots sampled and the number of trees measured in each.

If a lot of prior information is available about the forest to be inventoried, it may be possible to undertake computations to determine the optimum balance of plot size, sample size and sampling technique to achieve the most cost-efficient inventory possible. These techniques are outside the scope of this book.

11.6.4 Edge Plots

In any sampling exercise, it is inevitable that some sample locations will be positioned close to the forest edge, so that a plot established at that point would extend partially outside the forested area or trees would be missing from a point sample, as the observer looks beyond the edge. Trees along the forest edge generally grow differently from those well within the forest, because they have fewer surrounding trees to compete with them; edge trees are often larger and have bigger branches growing out into the open space. Such trees should be included in the sampling, or else some bias in the final results would be expected. Thus, it would be quite inappropriate simply to move a plot or point sample position further inside the forest to avoid an edge overlap.

Two of the more common methods used to deal with the problem will be described here. The first is known as the mirage technique. For plots, the segment of the plot lying beyond the edge is mirrored along the edge back inside the forest. Trees falling within the mirrored section are measured again and included twice in the plot measurements. The plot retains its full area. For point samples, the position of the point is mirrored from the edge into the open space beyond the edge and the point sample made from there as well as from the original point, so also measuring some trees twice. Intuitively, it may seem that measuring the same trees twice is likely to introduce bias into the results, but formal statistical analysis of the mirage technique has shown that this is not so (Gregoire 1982). The mirage technique becomes rather difficult to apply if the forest boundary is curved or cuts obliquely across the plot, or if the plot overlaps a boundary corner.

A second method is known as the walk through technique. For any tree being considered, the observer walks from the plot centre or sample point towards the tree and then continues the same distance beyond the tree in the same direction. If the observer is then positioned outside the forest boundary, the tree is measured twice. This method is rather more convenient than the mirage technique where the forest edge is curved or oblique.

There are various other methods which have been devised to deal with this problem (Kangas 2006b).

11.7 Measurement Errors

In all the discussion on inventory to here, it has been assumed that the variable of interest being measured in the sample plots can be measured directly and so is unbiased and extremely precise for each and every tree measured.

For many measurements required in inventory, such as tree stem volume, this is rarely so. It is possible to climb standing trees and measure under bark stem diameters at frequent intervals to provide a virtually direct measurement of stem volume. However, so time consuming and dangerous are such measurements, they would almost never be countenanced. Instead, variables like tree diameter at breast and tree heights would be measured directly and a pre-existing tree volume or taper function (Chap. 6) would be used to determine tree volume. Being derived using regression analysis, tree volume functions introduce 'error' in the estimates of wood volume made with them. Here, the term error is being used in its mathematical statistics context; it does not mean a 'mistake', but means there is a lack of precision of the estimate. That is, the estimate of wood volume made with a volume or taper function has a variance associated with it.

In statistical terms, the variance of the estimate of the variable of interest ultimately increases the estimate of variance of the population mean (V_M), determined as discussed in Chaps. 9 and 10 for various sampling methods. This will increase the size of the confidence intervals determined for population estimates. It is beyond the scope of the present book to discuss the statistical methods necessary to account for this. Whilst they have been used (e.g. Gertner 1990; Parresol 1999) sometimes, it may be possible to simply ignore the problem. The error associated with estimates made using a well constructed volume or taper function is usually small, so small that it is negligible in comparison to the size of the variation in the variable of interest between different sampling units in the population.

Whilst for many inventories it may be reasonable to ignore this problem, it is not uncommon to use a sampling technique known as two-phase sampling to deal with it. In the first phase, sampling is done and measurements are made, in each sampling unit, of easily measured covariate variables, such as tree diameter and height. In the second phase, a small sub-sample of the first phase samples are measured in detail to obtain values directly for variable of interest (say, by felling trees and measuring their stem wood volumes directly). The second phase sub-sample is used to establish a regression relationship between the variable of interest and the covariate variables. This relationship is then used to predict the variable of interest on the first phase sampling units. In effect, this involves the development of a tree volume function specifically for the population being sampled. The statistical theory appropriate to this type of sampling is well established and can be found in more advanced texts on forest inventory.

11.8 More Advanced Inventory

Chapters 9–11 have provided only a basic introduction to the way in which forest inventory is carried out today. Vastly more sophisticated sampling techniques and methods of conducting the inventory are used from time to time in different forest types in different parts of the world and to assess different forest characteristics.

These techniques may involve several stages of sampling. Perhaps satellite images might be used to obtain some information from a sample of the forest. Air photos, being of a smaller scale, might be able to provide more detailed measurements on a smaller sub-sample. A still smaller ground sample might then produce highly detailed measurements of the variable of interest ultimately to be determined for the forest. The earlier stages may have then provided covariate values which may be related to the variable of interest. The larger and more complex the forest concerned, the more it will be necessary to adopt these advanced techniques.

However, for relatively simple forests, for areas which are not very large and for variables of interest which are not too difficult to measure, the techniques discussed in this book should be adequate for many inventory purposes.

Chapter 12
The Plane Survey

12.1 Mapping

For most forest inventories, the area of the forest must be determined (Sect. 11.2). Generally, this involves surveying the forest boundary, drawing a map from the survey and determining the forest area from the map.

Mapping is generally the realm of the professional surveyor and cartographer. Much more information may be included on maps than just the boundaries of areas of interest. However, anyone working in the forestry needs to understand the principles at least of how a survey of a forest area is done, how a map of its boundaries is drawn from it and how the area of the forest is calculated.

Highly sophisticated instruments, including precision theodolites, laser distance measuring equipment and global positioning system receivers are the tools of trade necessary to conduct more rigorous surveys. The global positioning system has become a generally useful tool for many purposes in forestry and is discussed in Sect. 12.6. Computer-based geographic information systems are readily available to draw the maps from surveys and calculate the areas of mapped regions; they are used by most forestry organisations today. However, using even simple instruments, a good-quality magnetic compass, a clinometer and a measuring tape, any forester should be able to conduct a reasonable survey of a forest area and draw a useful, basic map of it.

The main theme of this chapter is to establish the principles of a plane survey of a modestly sized parcel of land. It is termed a plane survey, because the objective will be to draw a map of the boundaries of the surveyed area on a flat piece of paper, that is, on a plane. This means, that wherever the land is sloping, the distances measured along the slopes will all have to be reduced to a horizontal distance; this is the way most maps are presented. Where it is wished to show the topography of the land on a plane map, it is usually presented as contour lines, each contour connecting points on the map which are at the same altitude. However, we will not consider here how contour maps are drawn.

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12.2 Survey Example

Figure 12.1 shows a simple, plane map of a rather oddly shaped piece of land, which encloses an area of exactly 1.43 ha. This area will be used as an example, to illustrate how a plane survey of it could be carried out and what computations need to be done to convert the survey measurements to a map which looks like Fig. 12.1.

Figure 12.1 was drawn with *X*- and *Y*-axes which had their origin exactly at Point 1 and with the *Y*-axis running vertically along the line which joins Point 1 to Point 11. The exact *X*- and *Y*-coordinates of each of the 11 points around the boundary are shown in the last two columns of Table 12.1. This chapter illustrates how the measurements taken in a survey of this area are converted to a set of *X*- and *Y*-coordinates so that a map of it could be drawn easily.

12.3 Conducting the Survey

In principle, a plane survey is carried out by starting at any arbitrarily chosen corner point around the area to be surveyed. The surveyor then moves progressively from corner point to corner point around the survey area. The distance between each pair of corner points, the slope of the land between them and the angle by which the direction of travel changes at each point are measured. Usually at least two people are required to conduct a survey, both to move the equipment and take the required measurements.

The distances between points can be measured with a tape (many years ago a light chain, which could not stretch with repeated use, was used to measure distances and gave us the name of the old imperial unit 'link' for distance measurement). For more precise distance measurements, laser measuring devices are

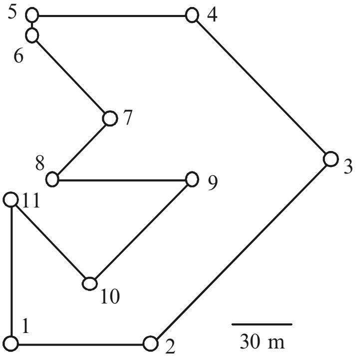

Fig. 12.1 Map of a section of land which is to be surveyed. The total distance around its perimeter is 752.5 m and the area enclosed is 1.43 ha

Table 12.1 Survey data and results of computations to find corresponding map coordinates. Values in *bold face* are measurements taken in the survey. All other values were calculated from them. The coordinates in the seventh and eight columns were determined from the survey measurements and are plotted in Fig. 12.2. The coordinates in the last two columns are the actual coordinates, as in Fig. 12.1

Survey point	Direction change at point (α_i) (degrees)	Angle line to next point made with Y-axis (β_i) (degrees)	Slope angle to next point (γ_i) (degrees)	Slope distance to next point (s_i) (m)	Horizontal distance to next point (h_i) (m)	*X*-coord. determined from survey data (x_i) (m)	*Y*-coord. determined from survey data (y_i) (m)	Actual *X*-coord. (m)	Actual *Y*-coord. (m)
1	**90**	90	**–8**	**61.5**	60.9	0	0	0	0
2	**136**	46	**0**	**128.5**	128.5	60.9	0.0	70	0
3	**89**	315	**8**	**100.0**	99.0	153.3	89.3	160	90
4	**134**	269	**3**	**70.8**	70.7	83.3	159.3	90	160
5	**89**	178	**–8**	**18.2**	18.0	12.6	158.1	10	160
6	**136**	134	**–2**	**55.0**	55.0	13.3	140.0	10	150
7	**269**	223	**–3**	**41.0**	40.9	52.8	101.9	50	110
8	**45**	88	**3**	**73.9**	73.8	24.9	71.9	20	80
9	**316**	224	**1**	**68.5**	68.5	98.6	74.5	90	80
10	**271**	315	**3**	**60.0**	59.9	51.0	25.2	40	30
11	**46**	181	**–1**	**62.0**	62.0	8.7	67.6	0	70
1						7.6	5.6		

available today and avoid the need to have to drag the tape along the ground between measurement points. Using a global positioning system receiver also avoids the need to use a tape.

For more precise surveys, a theodolite may be used to measure the angle of direction change at each point. In the example in Fig. 12.1, this would be done at, say, Point 2 as follows. The theodolite is mounted on its tripod immediately over Point 2. The surveyor looks back to Point 1 through the telescope of the theodolite and then rotates the instrument to view Point 3. The theodolite scale then gives the angle through which the instrument has been rotated and this is the angle of direction change required at Point 2. It will be assumed in this book that any such angles are measured clockwise from the line looking back to the preceding point; it does not matter if angles are measured anticlockwise, as long as the surveyor is consistent throughout the survey.

Angles can be measured also with a compass. In this case, standing at Point 2, the surveyor measures the bearing from north to Point 3 to give the required direction change. Some theodolites have an inbuilt compass and can be used to measure these bearings. Good quality, hand-held compasses can also be used, but these would not be expected to be as precise as a theodolite. A global positioning system receiver can also be used to measure bearings. For many forestry purposes, where a highly precise map is not required, a hand-held compass serves adequately. When using a compass, the user must ensure that no metal objects, such as metal fence posts, are nearby because they may influence the compass reading.

Theodolites generally allow vertical as well as horizontal angle measurements. Thus, standing at Point 2, the surveyor measures the vertical angle up or down to Point 3. This gives the required slope angle to the next point. To ensure the measurement is correct, the surveyor must sight to a point on a staff, mounted at Point 3, the same height above ground as that of the theodolite eyepiece. Hand-held clinometers can be used to obtain slope angles also. These are less precise than a theodolite, but serve adequately if a high degree of precision is not required of the survey.

If the slope angle changes appreciably (say, by more than 2–3°) along different parts of the line between any two points, the surveyor needs to establish new survey points where the slope changes; since the distance between points is measured as the distance along the slope (the tape is laid along the sloping ground), it is obviously important that the slope between any two measurement points should not vary greatly at any point between them. If there is a gully between two survey points, it is necessary to establish a new point at the bottom of the gully to deal with the different slopes on each side of it. Use of a global positioning receiver avoids the need to determine slope angles, because it provides information to allow automatic determination of the horizontal distance between survey points.

Table 12.1 lists the set of measurements that a survey team might make in conducting a survey around the area in the example in Fig. 12.1. It was assumed in this case that a theodolite without a compass was used to measure the change of direction at each point, so the angle measured was taken by looking back to the preceding point and turning the theodolite round to view the next point. The actual measurements taken are shown in **bold face** type in the table. All the other values shown were computed from them, as will be discussed in Sect. 12.4.

12.4 Calculating the Survey Results

At the start of the survey, an arbitrary decision needs to be made as to the coordinate system in which the final map is to be graphed. For convenience, the starting point of the survey (Point 1 in the example) is usually chosen to be the origin, that is, to have *X*- and *Y*-coordinate values of 0,0. It is convenient also to assume that the *Y*-axis runs along the line joining the first point to the last one (the line joining Points 1 and 11 in the example), with *Y*-coordinate values positive and increasing towards the last point. The *X*-axis is then perpendicular to the *Y*-axis through the origin.

Given these assumptions about the axes, it is possible to take the survey data, point by point in the order in which they were measured, and determine *X*- and *Y*-coordinate values for each survey point. The final map of the survey boundary can then be drawn on graph paper (or by using any of the myriad computer software packages now available to do this), using the calculated coordinate values.

For the i^{th} survey point ($i = 1\ldots11$ in the example), let the angle of the direction change at that point be α_i and the angle (clockwise from the positive direction of the *Y*-axis) that the line to the next survey point makes with the *Y*-axis be β_i. Let the angle of the slope of the ground to the next point be γ_i (it is positive for an up-slope and negative for a down-slope), the distance measured along the slope to the next point be s_i, the corresponding horizontal distance be h_i, and the *X*-and *Y*-coordinate values calculated for the point be x_i and y_i. The measurements taken in the survey provide values for α_i, γ_i and s_i for each of the survey points. Values for all the other variables must be calculated from them.

The computations begin by considering the first survey point. Because of the way it was assumed the axes were positioned, with their origin at that point, values of the various variables for that point are determined automatically. So $\beta_1 = \alpha_1$(=90° in the example) and $x_1 = y_1 = 0$. These values can be entered immediately in the results table and are shown in the first row, for Point 1, of Table 12.1. The horizontal distance, corresponding to the slope distance, to the next point is calculated as

$$h_i = s_i \cos(\gamma_i). \tag{12.1}$$

For the example, this gives $h_1 = 61.5 \cos(-8) = 61.5 \times 0.99027 = 60.9$ m, the result shown for Point 1 in Table 12.1.

The results for the remaining survey points are now considered in the order in which they were surveyed. For each, the horizontal distance to the next point is calculated using (12.1). The remaining results each depend on the results calculated for the preceding survey point. The angle that the line from the i^{th} point to the next survey point [the $(i + 1)^{\text{th}}$ point] makes with the *Y*-axis, β_i ($i = 2\ldots11$) in the example), is calculated as

$$\beta_i = \beta_{i-1} + \alpha_i - 180, \tag{12.2}$$

where all angles are in degrees (if other angular units are being used, the 180° in 12.2 would have to be replaced by the corresponding value for whatever angular units are being used). The result from (12.2) is often negative (representing an angle measured anticlockwise from the Y-axis). It can be left in that form because the subsequent trigonometric calculations give the same answers whether the angle is positive or negative. If desired, however, a negative answer can be converted to the same angle, expressed as a positive angle measured clockwise from the *Y*-axis, simply by adding 360° to the result; this conversion has been done wherever appropriate in calculating the results in Table 12.1. In the example, (12.2) gives $\beta_2 = 90 + 136 - 180 = 46$, which is the result shown in the second row, for survey Point 2, in the table.

The *X*- and *Y*-coordinates of the *i*th point are calculated as

$$x_i = h_{i-1} \sin(\beta_{i-1}) + x_{i-1} \tag{12.3a}$$

and

$$y_i = h_{i-1} \cos(\beta_{i-1}) + y_{i-1}. \tag{12.3b}$$

So, for the example $x_2 = 60.9 \times \sin(90) + 0 = 60.9 \times 1 + 0 = 60.9$ m, and $y_2 = 60.9 \times \cos(90) + 0 = 60.9 \times 0 + 0 = 0$ m, which are the results shown in the second row, for survey Point 2, in the table.

These computations are repeated for all the remaining survey points and are shown in the table. *In addition*, the computations are repeated one last time, after completing the results for the last survey point, Point 11 in the example. This gives a new pair of coordinates for the original starting point, Point 1 in the example. The resulting *X*- and *Y*-coordinates, 7.6 and 5.6 m respectively, are shown in the last row of the table. They are not the same values, 0 and 0 m, which we know are the actual coordinates of Point 1, since it was chosen as the starting point. The difference is inevitable, because the survey can never be carried out perfectly. The angles and distances will never be measured exactly, because of limitations in the measuring devices and the limitations of the people making the measurements.

Figure 12.2 shows the final plotted survey, using the coordinate values calculated from the survey data. It can be compared with the original in Fig. 12.1. The deviation of the final calculated position of survey Point 1 from its original position is obvious.

The distance between the final, calculated position of the starting point and its known position is known as the closing error of the survey. The distance can be calculated using the general function used to calculate the length of the straight line, *t*, which joins any two points of which the *X*- and *Y*-coordinates are known, (x_a, y_a) and (x_b, y_b), where

$$t = \sqrt{(x_a - x_b)^2 + (y_a - y_b)^2}. \tag{12.4}$$

For the example, $t = \sqrt{(7.6 - 0)^2 + (5.6 - 0)^2} = 9.4$ m. That is to say, at the end of the example survey the calculated position of the starting point of the survey was 9.4 m away from where it should have been, due to the errors made in taking the measurements.

In conducting the survey, a total horizontal distance of 737.2 m was travelled around the perimeter of the area being surveyed (the sum of the values h_i in Table

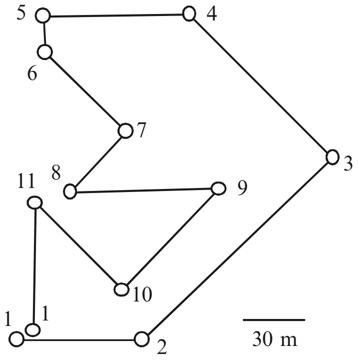

Fig. 12.2 Plotted result after conducting a survey of the parcel of land depicted in Fig. 12.1

12.1). That is to say, after travelling 737.2 m, we ended up 9.4 m away from where we should have been. So, in conducting the survey we were 1 m away from where we should have been for every 737.2/9.4 = 78.4 m travelled. This quantity, the traverse distance divided by the closing error distance, is known as the accuracy of the survey and is generally used by surveyors to judge the quality of their work.

An accuracy of 1 m in 78.4 m would be considered inadequate by most professional surveyors, who usually pride themselves on achieving much higher accuracies. However, it depends entirely on the purpose for which the survey is being done as to what accuracy is required. In the example, the missing 9.4 m of land represented by the closing error might lead to a bitter dispute between neighbours as to where the boundaries between their properties lay; for legal purposes, a surveyor would have to be more accurate than that. In contrast, for a forester making a rapid assessment of the area of a plantation, it might be quite adequate.

In the example survey, it was assumed that a theodolite was being used and the angle of direction change at each survey point was measured. If a compass (or global positioning system receiver) was being used, the bearing from north of the next survey point would be measured instead. Under these circumstances, it would be assumed usually that the *Y*-axis of the coordinate grid would be directed to magnetic north, rather than along the line joining the first and the last survey points, as assumed in the example. The bearings from north would then be direct measures of the β_i in Table 12.1 and no values of the α_i would be recorded in the survey. In calculating the coordinates of the survey points, there would then be no need to use (12.2).

12.5 Area of a Surveyed Region

Once a survey is complete, it is often desired to calculate the area enclosed by the survey. A simple way to do this is to divide the area into triangular sub-sections, calculate the area of each triangle and sum them to give the total area. Figure 12.3 shows the original example area (Fig. 12.1) divided into such a set of triangles.

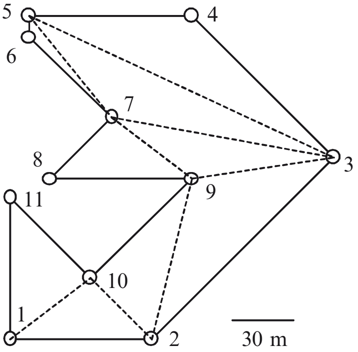

Fig. 12.3 Map of the section of land shown in Fig. 12.1, divided into triangles for area determination

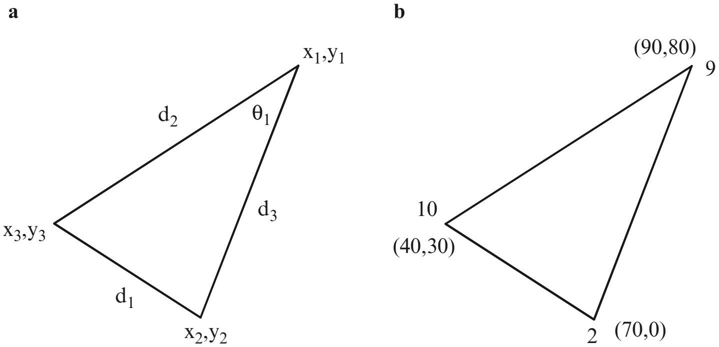

Fig. 12.4 (**a**) Arbitrary triangle, with known coordinates of its corners, and (**b**) the triangle defined by Points 2, 10 and 9 of Fig. 12.3. In (**b**), the *X*- and *Y*-coordinates (m) of each corner of the triangle are shown in parentheses

Calculation of the area of each of the triangles in the example proceeds as follows. Consider any arbitrary triangle, as in Fig. 12.4a, where the position of each corner is defined by a pair of *X*- and *Y*-coordinates. The lengths of its sides d_1, d_2 and d_3 can be determined from the coordinates of the ends of each side using (12.4).

For any triangle of which the lengths of three sides are known, the standard trigonometric function known as the 'cosine' or 'cos' rule can be used to relate the lengths of those sides to the sizes of the angles of the triangles. So, in the example, if the angle opposite the side of length d_1 is of size θ_1, then the cos rule states that,

$$d_1^2 = d_2^2 + d_3^2 - 2d_2 d_3 \cos(\theta_1). \tag{12.5}$$

This function can be rearranged and solved for θ_1 as

$$\theta_1 = \cos^{-1}[(d_1^2 - d_2^2 - d_3^2)/(-2d_2d_3)]. \tag{12.6}$$

The expression $\cos^{-1}$ in (12.6) represents the angle whose cosine is given by the expression in square parentheses [] following it; it is called the arccosine of an angle in trigonometry. All good scientific calculators and all computer systems have functions available to determine the arccosines of angles (and their arcsines or arctangents). The sizes of the other two angles in the triangle could be determined using (12.6), with appropriate rearrangement of the positions of d_1, d_2 and d_3 in the function.

If the lengths of two sides of a triangle, say, d_2 and d_3 in the example, are known, together with the size of the angle included between them (θ_1 in the example), then the area of the triangle, A, can be determined by

$$A = d_2d_3\sin(\theta_1)/2. \tag{12.7}$$

Figure 12.4b shows the triangular area delimited by Points 2, 9 and 10 in Fig. 12.3, together with the *X*- and *Y*-coordinates of each corner of the triangle. Figure 12.4b has been arranged to have exactly the same form as the triangle shown in Fig. 12.4a. Applying (12.4)–(12.7) to the dimensions of that triangle gives $d_1 = 42.4$ m, $d_2 = 70.7$ m, $d_3 = 82.5$ m, $\theta_1 = 31.0°$ and $A = 1{,}500$ m^2.

If similar calculations are done for all the triangles in Fig. 12.3 and their areas summed, the total area can be calculated as 14,300 m^2, that is, 1.43 ha.

12.6 Global Positioning System

The global positioning system (abbreviated as GPS) allows users to determine where they are on earth (their latitude, longitude and altitude). Use of the system requires a portable electronic receiving device, which can be hand-held or is easily mountable in a vehicle, boat or aircraft. The system is obviously useful as a navigational aid on land, sea or in the air, but can be used also as a surveying tool. The system is owned and controlled by the United States government, but is available for use by anyone who buys a suitable receiver.

The system works through 24 satellites which are positioned in earth orbit. Somewhere between five and eight of them are usually above the horizon at any time, as 'viewed' from any point on earth. Ground stations around the world, controlled by the system owners, track the satellites moment by moment so their positions are always known. The satellites constantly transmit radio signals about their position. These are received by the user's portable GPS receiver. As long as signals from at least three satellites are being received, the GPS receiver can calculate its position (and, hence, that of the user) on earth as latitude and longitude. If a fourth satellite is also in 'view' of the receiver, altitude above sea-level can be determined also. When more than four satellites are in ‘view’, GPS receivers combine the information from all of them to provide more precise fixes of position.

A GPS position estimate is accurate to about 20 m horizontally and 28 m vertically. This is more than adequate for general navigation purposes, but deviations as large as 20 m horizontally would obviously be inadequate for the example survey described in this chapter. However, GPS precision can be improved greatly by using what are known as differential global positioning system techniques (often abbreviated as DGPS techniques). These require much more sophisticated GPS receivers placed at precisely known reference locations on earth. These reference receivers can rationalise the satellite information to make it consistent with the precisely known position of the receiver.

Communities and organisations around the world own reference receivers and transmit radio information locally about corrections necessary to the satellite information or make the information available on the internet. Some portable GPS receivers can receive this radio information directly from a reference station and use it to correct the satellite information it is receiving This can improve the accuracy of position estimates to about ±1–5 m. With less sophisticated receivers, the corrections must be made after returning from the field, using the published information. With very expensive field GPS receivers, millimetre accuracy can be obtained, accuracy quite adequate for sophisticated plane survey.

Use of the GPS system is becoming ubiquitous in forestry. At the very least, it allows easy navigation through the forest, which would aid sample point location in an inventory. It is also being used extensively for forest mapping purposes; in conjunction with remote sensing of forests (Chap. 13), accurate maps displaying many forest attributes can be drawn without the need for ground surveys to be carried out. The GPS system is also an important safety tool to help people avoid becoming lost and to aid in crises such as fire-fighting or searches. Forest canopies can interfere with the radio signals on which the system relies, although usually this simply increases the time it takes the GPS receiver to receive sufficient information to make its estimate of position.

Chapter 13
Remote Sensing

The main emphasis of this book has been on the direct measurement of trees by people working on the ground, often using relatively unsophisticated equipment. However, there has been an increasing trend to exploit the more sophisticated devices now available, such as satellites, to measure trees and forests remotely. This means there is no need for people to handle the measuring equipment or, perhaps, to even visit the forest site where measurements are to be made.

Use of these devices has been limited in the past, perhaps because they could not measure fully the sizes of individual trees. But so rapid has been technological development that this limitation is now starting to be overcome. Over the next few decades it is conceivable that much of the relatively labour intensive measurement of individual trees on the ground will be superseded by the use of sophisticated electronic equipment, which measures trees remotely.

This final chapter summarises the principles and capabilities of the main types of remote sensing instruments available currently. Different instruments are capable of operating at different scales, from the single tree right through to large forest areas. Some operate from the ground, some are carried aloft in aircraft, whilst satellites operate from space. In this chapter, they will be discussed in that order.

13.1 Ground Measurement

Measurement of tree stems and the amount of wood they contain has been the principal focus of this book. One of the principal limitations of remote sensing instruments borne in aircraft or satellites (Sects. 13.2–13.3) is that the forest canopy obscures the stems (and branches) of the trees when viewed from above; this has been an important limitation to their use more generally in forest measurement. However, instruments which are positioned on the ground are now becoming available to allow remote measurement of the fine detail of individual trees.

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13.1.1 Tree Stems and Crowns Using Lasers

The newest, and still experimental, ground-based, remote sensing instruments use the reflection of laser light to construct a three-dimensional image of the trees in a stand. They operate to a distance of some tens of metres around a central point. From the information these instruments provide, it is possible to determine, in detail, the size of each tree stem as well as other above-ground parts of the tree.

The principles of laser light and its use to determine the position of a distant object were discussed in Sect. 2.2. In the context of remote sensing, laser measurement is often termed ‘lidar’, an acronym for **LI**ght **D**etection And **R**anging; this is analogous to the more commonly known ‘radar’, an acronym for **RA**dio **D**etection **A**nd **R**anging, which uses radio, rather than light, waves.

The laser instruments being developed for ground measurement of trees emit pulses of laser light which shine a spot smaller than 10–15-mm in diameter on an object (the size of the spot increases the further the object is away). This means that the three-dimensional position of objects as small as leaves can be measured.

Hopkinson et al. (2004) tested one of these instruments by measuring the trees in 0.12-ha square plots in each of a mature red pine (*Pinus resinosa*) forest and a complex, uneven-aged, deciduous hardwood forest, dominated by sugar maple (*Acer saccharum*) in Ontario, Canada. Their instrument could emit 2,000 laser pulses per second; the light spots were spaced apart by as little as 10 mm as the instrument scanned the three-dimensional space around it. They took six views of each plot, from points positioned outside the plots, to ensure each tree in a plot could be ‘seen’ clearly by the instrument. It required about 6 hours to get these views.

Complex computer programs are required to deal with the enormous amounts of data obtained from such instruments; in Hopkinson et al’s case, they would have accumulated data for the positions of over 30 million separate points within their two plots. When such data are analysed by the computer, they can be presented as what appears as a high contrast black and white photograph, showing quite clearly the stem of each tree and its branches and leaves. Hopkinson et al. used the data to determine the diameter at breast height of each tree in their stands and its total height. They found that the instrument gave unbiased estimates of tree stem diameters, with an accuracy quite adequate for normal forest measurement purposes. However, tree heights were under-estimated, by about 1.5 m on average. Because the view of the tip of a tree is largely obscured by the intervening foliage, relatively few laser pulses reach the tip to be reflected back by twigs and foliage there; this ‘shadowing’ of the tip led to the bias in estimates of tree heights.

Henning and Radtke (2006) tested a similar instrument in a 20-year-old plantation of loblolly pine (*P. taeda*) in Virginia, USA. They were able to measure successfully how the diameter changed along individual tree stems to a height well within the tree crown. They were also able to determine the position of branches in the lower part of the crown. However, a small degree of bias was evident in their results.

Danson et al. (2007) used both a laser instrument and a camera to take the same view, from below, of the canopy of a pine forest in Switzerland. Both images are shown in Fig. 13.1, where it is obvious how closely the laser image resembles a

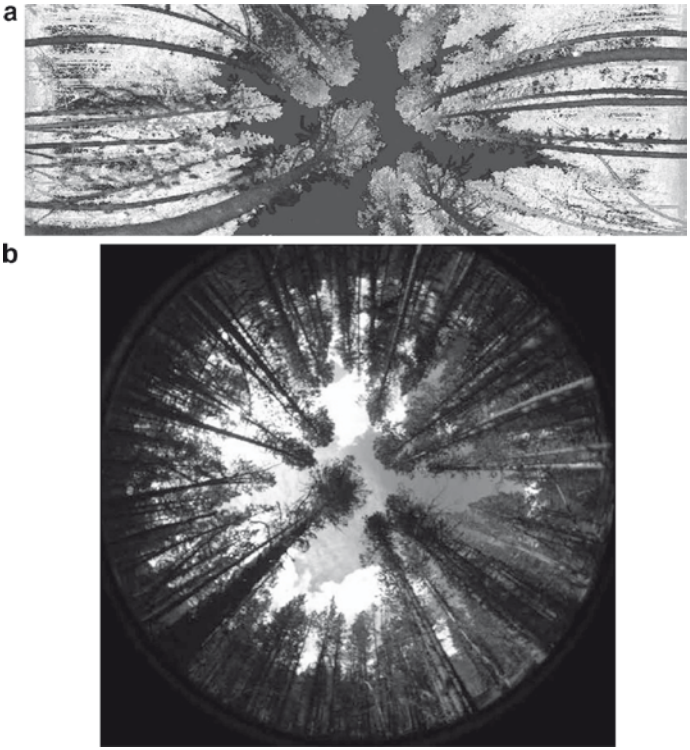

Fig. 13.1 A vertical view from below, through the canopy of a forest in Switzerland, dominated by mountain pine (*P. mugo*), but with some stone pine (*P. cembra*). Average height of the trees in the forest was about 12 m. The views are (**a**) as seen using a laser scanner and (**b**) as seen in a photograph taken with a camera with a wide-angle lens (from Fig. 2 of Danson et al. 2007, reproduced with kind permission of the Institute of Electrical and Electronics Engineers, © 2007 IEEE)

photographic image. In their case, Danson et al. were aiming to use the laser data to determine leaf area index of the forest (which can be done also from the photographic image – Sect. 13.1.2). Lovell et al. (2003) tested the ability of a similar laser instrument to measure variations in leaf area index down through forest canopies.

Tanaka et al. (2003, 2004) tested a laser instrument which operated on a slightly different principle. Instead of emitting pulses of laser light, their instrument projected a continuous laser beam, which was moved progressively around the surrounding forest. Reflections from this beam were detected by a digital camera, positioned some distance from the laser instrument. Tanaka et al. were interested particularly in measuring the leaf area index of the forest canopy (see also Sect. 13.1.2). To do so, it required leaves to be distinguished clearly from branches and the stem in the image obtained of the canopy. They found that they could do this by using laser light of two different wavelengths; leaves could be identified more clearly using infra-red light, whilst branches could be better identified when lit with visible red light. Figure 13.2 shows the clear distinction between leaves, branches and stems in an image obtained by Tanaka et al.

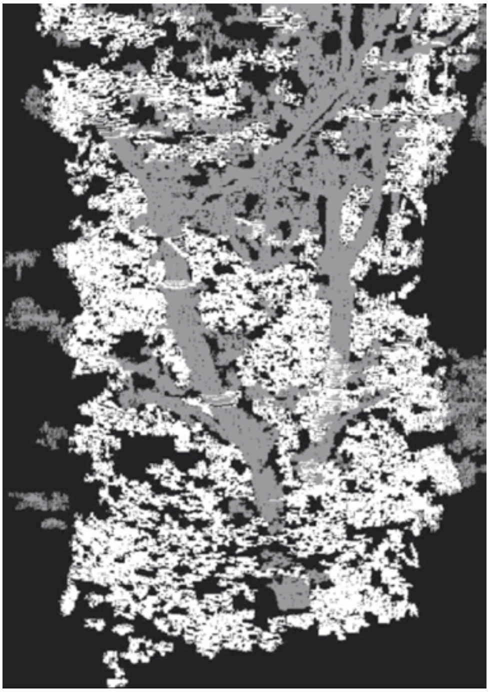

Fig. 13.2 A view through the canopy of a mixed-species, hardwood forest, dominated by Japanese oak (*Quercus serrata*) trees, with an average height of 20 m, on the campus of Nagoya University, Japan. The image was derived from laser scanning of the canopy, using light of both infra-red and visible red wavelengths. The lighter elements in the image are leaves, whilst the greyer elements are tree stems and branches. The information used to produce this image can be used also to determine the sizes of the various objects in the view (reprinted from Fig. 11 of Tanaka et al. 2004, with permission from Elsevier)

These ground-based, laser measurement instruments are clearly showing potential for detailed measurement of tree characteristics. However, they will need considerable research development before they become useful in practice for broad-scale forest inventories, where hundreds or even thousands of plots may need to be measured routinely. The instruments themselves will need to be of a size, weight and durability to allow easy transportation by hand through dense vegetation and over difficult terrain. They will also need to operate much more quickly than at present, perhaps allowing complete measurement of a stand in no more than ~30–45 min. Considerable work is also required to develop computer programs capable of analysing the enormous amounts of raw data obtained from these instruments to derive the required measurements of the individual trees. One further limitation is that they can only determine stem measurements over bark; if under-bark measurements are required, assumptions will need to be made about bark thickness (c.f. Sect. 5.4).

13.1.2 Leaf Area Index Using Sunlight

Leaf area index (Sect. 8.9.2) is an important stand parameter, useful to determine how much sunlight a stand absorbs and, hence, what the photosynthetic production of a stand might be.

Considerable effort has been made to develop methods to measure leaf area index from the ground, without having to fell trees. These have been reviewed by Fournier et al. (2003): discussion here will be restricted to the use of instruments which determine leaf area index by measuring the amount of sunlight which passes through the forest canopy to the ground below.

In essence, these instruments consider the straight beams of sunlight, coming from any point in the sky above, as ‘pointers’ which are being projected through the canopy. The path of any beam may be interrupted, by hitting a leaf so that it does not reach the ground below, or it may pass right through the canopy and reach a measuring instrument on the ground.

By measuring how many beams of light pass through the canopy, these instruments determine the canopy gap fraction (in essence, the proportion of the area of the sky above the canopy which is not hidden by any part of the canopy). If the canopy gap fraction is known, together with the angle from the horizontal at which the leaves in the forest hang, a well known law of physics (called the Beer–Lambert law) can then be used to calculate the leaf area index of the canopy. Unfortunately, this law requires that the leaves be randomly positioned within the canopy. This is generally not the case; leaves often occur in clumps on individual shoots and shoots are often clumped in different positions within the crown. Also, leaves are not opaque and a small amount of the light which hits them passes through them. In addition, some light beams are interrupted by tree stems or branches, rather than by leaves, and some light beams are scattered by reflection from several leaves. Various methods are used to allow for these complications in measuring leaf area index with these instruments (Fournier et al. 2003; Jonckheere et al. 2005a).

Perhaps the most reliable way to allow for these complications is to calibrate the instrument specifically for the type of forest in which it is to be used. This involves determining the actual leaf area index of the canopy of a particular forest type by felling trees and directly measuring the area of their leaves. These results are compared with estimates made using the instrument and a leaf area index estimation function is then determined by relating the actual leaf area index to that estimated by the instrument.

Dovey and du Toit (2005) did this in young plantation stands of flooded gum (*Eucalyptus grandis*) in South Africa. They used the LAI-2000 plant canopy analyser instrument. This has a wide-angle lens (these are also called fish-eye or hemispherical lenses, because they have an angle of view as wide as 180°) which directs sunlight passing through the canopy to one of five light detectors, depending on the angle above the horizon from which the light beam was directed. It detects light only in the ultra-violet to blue wavelengths. It is used on overcast days or at dawn or dusk, so sunlight is received from all angles of the sky, rather than being dominated by light beams directly from the sun. Using readings obtained from the instrument, Dovey and du Toit were able to develop a reliable leaf area index estimation function for their plantations. However, they found that the canopy characteristics of flooded gum plantations changed sufficiently, even between 2- and 3-year-old plantations, that separate functions were required for both ages. This emphasises how important it is to undertake the calibration process for any particular forest type in which the instrument is to be used. Using the same instrument, Battaglia et al. (1998) undertook a similar calibration task in 6–7-year-old plantations of shining gum (*E. nitens*), scattered in various locations across Tasmania, Australia. Despite the leaf area indices of the different plantations varying widely (over the range 0.5–7.5 m^2/m^2), they found that a single leaf area index estimation function could be used satisfactorily for all these plantations.

Another instrument of this type is known as the DEMON. It is carried along a transect below the forest canopy, whilst being pointed directly at the sun. It measures the change in light intensity received on the ground, from point to point along the transect. Lang et al. (1991) tested this instrument in a plantation forest of radiata pine (*P. radiata*) in Canberra, Australia and found a very close correlation between the leaf area index of the forest and the amount of light transmitted through the canopy and measured by the instrument. Lang and McMurtrie (1992) used the same instrument to measure the area of the leaves of individual trees, by moving the instrument around the ground area below a tree, on which the shadow of its crown was cast. This could be a useful method to measure individual tree crowns in open forests, where the trees are spaced widely apart; an instrument which measures light over a wide angle of view, such as the LAI-2000 plant canopy analyser, would be less suited for this purpose.

Both these methods of leaf area index estimation, that is using diffuse light from all angles of the sky and direct beams of light from the sun, were compared by Chason et al. (1991) and by Fassnacht et al. (1994). They were able to develop suitable calibrations for both pine and hardwood forests in the USA to allow satisfactory estimation of leaf area index with either method.

Another approach to measuring leaf area index from the ground is to take a photograph of the canopy, usually with a wide-angle lens, looking vertically upwards from the ground below (Fig. 13.1b). Indeed, wide-angle photography has been used for many decades to obtain information on canopy characteristics. Because they provide a visual record, photographs can be useful also in assessing other things, such as damage to the canopy by insects, storms or disease.

In the past, analysis of photographs was often done by the eye and could be very time consuming. For example, Koike (1985) determined the canopy gap fraction in his photographs by superimposing a fine, dotted grid over them and counting the number of points where sky or leaves appeared on each photograph. More recently, digitising (that is conversion to a digital form) photographs taken on film (Chan et al. 1986; Rhoads et al. 2004) and the advent of digital cameras, which provide photographs immediately in digital form, allow more rapid and thorough computer analysis of photographs. Careful selection of the sky conditions, camera settings and even the wavelengths of light detected by the camera is essential to obtain suitable contrast in the photograph between the sky and canopy elements; only then can the computer determine readily variables such as canopy gap fraction (Fournier et al. 2003; Jonckheere et al. 2005a, b, c; Zhang et al. 2005; Cescatti 2007; Chapman 2007).

Considerable research has been undertaken recently on the use of digital photography to measure leaf area index and other canopy variables. For example, Macfarlane et al. (2007b) found that digital photography, with or without a wide-angle lens, or the LAI-2000 plant canopy analyser all gave very satisfactory estimates of leaf area index in plantation stands of jarrah (*E. marginata)* in Western Australia. Keane et al. (2005) compared wide-angle digital photography, the LAI-2000 plant canopy analyser and several other instruments, which have not been mentioned otherwise here, to estimate the canopy bulk density (biomass of foliage and twigs, which will burn readily in a forest fire, per unit volume of the canopy) of coniferous forests in western USA. Both the LAI-2000 and wide-angle photography were found satisfactory for this.

There are many other examples of the use of wide-angle photography and other methods to measure leaf area index from the ground (Coops et al. 2004a; Jonckheere et al. 2004; Weiss et al. 2004; Arias et al. 2007; Macfarlane et al. 2007a; Montes et al. 2007, 2008; Schleppi et al. 2007; Wilson and Meyers 2007; Davi et al. 2008; Demarez et al. 2008; Dutilleul et al. 2008; Parveaud et al. 2008).

13.1.3 Roots

Perhaps the measurement of roots is the last frontier of remote sensing of forest characteristics from the ground. The excavation of roots, to measure directly their biomass, length or distribution down the soil profile, is an extremely labour intensive and difficult task (Sect. 7.2.3). The development of techniques and instruments to measure roots, without the need for excavation, is obviously highly desirable.

One technique which shows some promise is the use of ground penetrating radar. This technique is used commonly by people such as engineers, to locate pipes or cables which have been laid underground, or by archaeologists to locate historical artefacts which have been buried for centuries or even millenia. It involves transmitting radio signals down through the soil and recording the times for reflections to be received back from objects within the soil. The higher the energy of the radio waves used (that is, the higher their frequency), the deeper within the soil can they penetrate, perhaps to a maximum of about 10 m.

There are a number of difficulties with using radar in soil, difficulties which do not exist with the use of radar through the air. The speed of travel of radio waves in air is the same as the speed of light, but soil slows that speed considerably, perhaps by more than one half. The speed is affected particularly by the temperature and amount of water in the soil (Butnor et al. 2003). This means that a ground penetrating radar instrument must be calibrated, before it is used on any day, to determine the speed of travel of radio waves in a particular soil. Also, soils contain many irregularities, such as rocks scattered throughout it or it may have various layers, each with rather different properties. These irregularities can lead to unwanted ‘background’ reflections of radio waves. These have to be removed from the data collected by the instrument, using complex computer programs, to leave only reflections from the objects it is desired to identify.

One of the few examples of the use of ground penetrating radar to measure root systems in forests comes from Butnor et al. (2003). They attempted to estimate the biomass of the root system, to a depth of 30 cm below the ground, in a 34-year-old experimental plantation of loblolly pine (*P. taeda*) in Georgia, USA. Butnor et al. tested their system in different parts of the experiment, where the growth of the trees, hence their root biomasses, had been affected substantially by the experimental treatments. Figure 13.3 shows images they derived from their data, after computer manipulation to remove background reflections. It shows the distribution of roots down through the soil profile along transects in two plots of the experiment. In this case, fertilisation had led to a substantial increase in root biomass.

Butnor et al. identified a number of limitations of their technique. They were able to identify roots only with diameters greater than about 5 mm. This would exclude fine roots. Whilst fine roots usually make up only a small proportion of the total biomass of the root system (Sect. 7.4.4), they are a very important part of the physiological processes of a tree. Clearly, ground penetrating radar does not yet have sufficient resolution to measure these very small roots. Butnor et al. also found that they could not measure tap roots, that is, woody roots which grow more or less vertically immediately below the tree, often to considerable depth. They suggested that these roots might be ‘seen’ with the ground penetrating radar if the instrument was oriented obliquely, rather than horizontally to the ground. They also found that the ground surface over which the instrument was used had

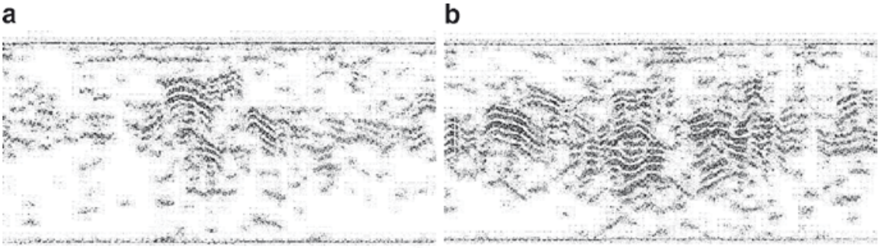

Fig. 13.3 Images, derived from a ground penetrating radar, of the distribution of roots, to a depth of 30 cm, in the soil below a 34-year-old experimental plantation of loblolly pine (*P. taeda*) in Georgia, USA. Results are shown for (**a**) an unfertilised and (**b**) a fertilised plot in the experiment. Each image represents readings taken along a 2.4-m long transect, which straddled a row of trees. The *grey* markings are the reflections from the roots of the radar signal; their relative darkness can be used to estimate the biomass of the roots at any point. The root biomass in the fertilised plot was obviously much greater than in the unfertilised. There also tends to be a greater biomass of roots near the base of a tree, which is positioned in the tree row, at the centre of each image (derived from row C of Fig. 2 of Butnor et al. 2003 and reproduced with the kind permission of the Soil Science Society of America)

to be quite smooth and free of debris; this would pose a problem to the use of the instrument in native forests where understorey plants and various sorts of ground debris are common.

Hruska et al. (1999) also tested ground penetrating radar in a small area of a 50-year-old sessile oak (*Quercus petraea*) forest in the Czech Republic. They were unable to identify roots with diameters less than about 30–40 mm, hence were unable also to identify fine roots. However, they could construct, very satisfactorily, a three-dimensional image of how individual roots were distributed around a tree down to the bottom of its root system, which was about 2 m below the ground.

It is clear from this work that ground penetrating radar has some potential, at least to measure woody root systems in forests. However, at present it cannot measure fine roots. Research in this field seems rather limited at present; clearly much more will have to be done before ground penetrating radar becomes useful generally for measurement of roots in forests. Measurement of the magnetisation properties of soil has been used to identify certain soil types in plant ecological studies (Wang et al. 2008a).

13.2 Airborne Measurement

Because of the costs involved in employing measurement crews, measurement of forests from the ground can be expected only to provide information about a limited number of individual stands within the forest. If broad-scale measurements are to be undertaken over hundreds or thousands of hectares of forests, it is practical to do so only using instruments carried aloft in aircraft or satellites. These can provide information useful for various purposes, including identifying and mapping different forest types, assessing their site productive capacity (Sect. 8.8), stratifying the forest or providing covariate variables for inventory (Sects. 10.2–10.3).

As mentioned at the start of Sect. 13.1, a principal limitation to forest measurements taken from aircraft or satellites is that the forest canopy conceals the tree stems. This prevents direct measurement of the stem sizes and, hence, the wood volumes they contain. Perhaps an exception to this is the possibility of measuring deciduous forests during winter, when they have lost their leaves and their stems can be seen directly. An example of this used aerial photographs of pedunculate oak (*Q. robur*) forest in Denmark (Tarp-Johansen 2002a, b). However, the limited number of forest types to which this applies means that little research effort has been spent on making full use of this type of imagery.

This section is concerned with the measurement of forests using instruments carried in aircraft. Most commonly, fixed-wing aircraft are used, although helicopters and even very small, remotely controlled aircraft have also been used. Different aircraft vary considerably in the speeds and altitudes at which they may fly, determining ultimately the ground area they cover in any given time and the degree of resolution of the images of the forest which they produce.

13.2.1 Aerial Photography

Photographs taken from the air have been used extensively for forest management purposes for many years. Not only can aerial photographs provide measurements of some tree and stand characteristics, but they can be used also for general mapping and for vegetation studies, perhaps identifying where different vegetation types occur across the landscape or where insect attack or disease has damaged the forest.

Of recent times, it has been felt that the revolution in various forms of digital measurement (such as laser scanning–Sect. 13.2.2) may lead to the demise of aerial photography as an important tool in forest measurement (Hall 2003). Digitally measured data are particularly amenable to computer analysis and it was felt that this might avoid the need for, and subjective assessments of, the people who have viewed and interpreted aerial photographs in the past. However, the advent of digital cameras and the ability to transform photographs taken on film to digital form, using scanners, have largely removed this objection. Also, technological developments continue in both cameras and film, which provide ever increasing quality and variety of photographic images (Hall 2003). As well, there is information captured on photographs which the human eye is able to assess better than is possible presently with computers; hence, there remains a role for air photo interpreters. For all these reasons, aerial photographs are continuing to have a major role in mapping forests and in forest measurement.

All of black and white, infra-red and colour films are used for different purposes in aerial photography; digital cameras also can take photographs using different parts of the light spectrum. Within these film types, there are many subtle variations, which react in different ways to light of varying wavelengths; the user may select film and camera types to suit particular needs (Hall 2003). For example, infra-red photographs have been found to allow better distinction between crowns of hardwood and conifer trees in mixed forests in the northern hemisphere or to identify forests which are suffering ill-health from disease (Myers et al. 1984; Avery and Burkhart 2002). The different colours of crowns of different species can aid their identification in colour photographs, even in very complex forests, such as tropical rainforest (Myers and Benson 1981).

The scale at which photographs are taken determines the resolution with which things can be seen on the ground. Both the focal length of the camera used and the altitude at which the aircraft flies determine the scale. Small-scale photographs (1:30,000–1:100,000, that is, a distance of 1 cm on the photograph represents 300–1,000 m on the ground) are suitable to recognise broadly different types of vegetation. Major types of forest cover and the species present in single-species stands can be identified from medium-scale photographs (1:10,000–1:30,000), whilst individual trees can be seen on large-scale photographs (1:2,500–1:10,000) (Avery and Burkhart 2002). Viewing the vegetation and the topography of the land on which it occurs can often be aided considerably by using pairs of photographs, which overlap partially in their view of the ground; the photo interpreter can then obtain a three-dimensional image by viewing a photo pair with a stereoscope.

To map forests adequately from aerial photographs requires considerable skill and experience by photo interpreters. They need to have knowledge of the tree species and forest types which occur in the region of interest, as well as the ecological relationships within the forests and with the environmental circumstances of the region. These give the interpreter clues as to what can be expected to appear on photographs. Such clues, together with characteristics such as the size, shape, colour and texture of tree crowns, will all help the interpreter map different forest types, or forest areas affected by disease or damaged by insect attack and so on; at present, the human eye is far superior at doing this than the computer. Such maps often form the basis for conducting forest inventories over large, complex forest areas (Sect. 11.2).

Two examples will illustrate some uses of aerial photography. The first is from Massada et al. (2006) and concerns estimation of the above-ground biomasses of individual trees in 40-year-old plantations of Aleppo pine (*P. halepensis*) in Israel. Massada et al. had available medium-scale (1:13,000) aerial photographs of the plantations. Because trees had been removed regularly from the plantations by thinning, the trees were well spaced, so that their crowns could be clearly identified in the photographs. Photo interpreters were able to determine the height of individual trees by using stereo pairs of photographs and special equipment which allowed measurement of the three-dimensional coordinates of the tip of each tree and the ground below. The diameter of the crown of each tree was also measured. Massada et al. did this for each tree in a set of plots, trees which were also measured from the ground. They found negligible differences between the ground measurements and the measurements obtained from the aerial photographs.

When ground measurements are taken, it is commonly the tree diameter at breast height and tree height which are measured. Provided a biomass estimation function is then available for the species concerned (a function such as 7.1), individual tree biomasses can then be determined. However, because the forest canopy hides the tree stems, it is not possible to measure stem diameters from aerial photographs. Massada et al. dealt with this problem by developing a new biomass function for their species, from ground measurements of biomasses, crown diameters and heights of a set of sample trees. The function they developed was

$$B_{\mathrm{A}} = 0.259C^{1.48}H^{1.67} \tag{13.1}$$

where B_{A} was the above-ground oven-dry biomass (kg), C was the crown diameter (m) and H was the tree height (m). It can be argued that larger trees will tend to have wider crowns and so tree crown diameter should be correlated quite highly with stem diameter. Thus, (13.1) can be considered as an allometric biomass estimation function, where crown diameter replaces stem diameter at breast height and which also includes tree height (c.f. Sect. 7.3). This function could now be used by Massada et al. to estimate biomasses of individual trees from the tree measurements they were able to take from their aerial photographs. Methods such as this are used commonly with various methods of remote sensing in forests. Where the remote sensing method is unable to provide some measurement, which would be taken normally from the ground, a method is developed to provide the result desired ultimately, based on those measurements which the remote sensing is able to provide.

The second example is from Harcombe et al. (2004) and concerns a problem in the native forests of mixed Sitka spruce (*Picea sitchensis*) and western hemlock (*Tsuga heterophylla*), in the mountainous coastal ranges of Oregon, in north-western USA. This region is subject to intense wind storms, which blow in from the sea during winter and may be sufficiently strong to blow down patches of forest.

Harcombe et al. had available six sets of medium-scale, aerial photographs, which covered some 500 ha of the region and which had been taken in various years between 1953 and 1993. Using stereo pairs of the photographs, photo interpreters were able to see and map patches of forest, as small as 0.5 ha in area, where tree stems were lying on the ground after being blown down by the wind. The difficulty of identifying such patches on a photograph is probably a good example where the human eye would be superior to the present capabilities of a computer.

In 1953, Harcombe et al. could identify only two small areas of blown down forest, with a total area somewhat less than 5 ha. However, over the next 40 years, additional blown down areas appeared and the existing areas expanded progressively and coalesced. By 1993, all these areas formed a single, large patch of nearly 50 ha of blown down forest. Harcombe et al. were able to correlate the location of this patch with the condition of the forest and the topography and wind intensities of the region. They concluded that the risk of forest blow down was greatest when the forest was at least 100-years-old, by which time the trees had grown to an average height of about 50 m, and where the forest was growing on particularly exposed, southerly facing slopes of secondary ridges, to the west of the main north–south ridge of the mountains of the region. This information would be useful in making decisions about appropriate management and conservation practices for these forests.

The difficulty of the terrain in this region and the long time period involved in the development of the large blown down patch would have made it virtually impossible to have accumulated ground measurement information to give these results. It was only the availability of the long-term set of aerial photographs which allowed Harcombe et al. to do so. Other interesting examples of the use of long-term sets of aerial photographs can be found in Fensham and Fairfax (2002) and Fensham et al. (2002).

13.2.2 Laser Scanning

This form of remote sensing uses laser light, transmitted from an aircraft or a satellite, some of which is reflected back when it strikes a solid object on the ground below. This is another application of lidar (Sect. 13.1.1).

Usually, for this form of remote sensing, a laser is used which emits light in pulses only some nanoseconds long (a nanosecond is one thousand millionth of a second) and which reaches the ground as a spot. The size of the spot and the distance along the ground of successive pulses varies with the speed over the ground and altitude of the aircraft or satellite and the quality of the laser equipment. At best, very fine-grained information may be obtained with spot sizes and intervals between spots of only a few centimetres.

When the object on the ground being viewed is not completely solid, such as is the case for the canopy of a forest, reflections are obtained from various light spots as they strike various solid objects (leaves, branches, understorey vegetation or the ground below) during their passage down through the canopy. The tiny time differences between these multiple reflections can be measured, so the heights of various objects within the canopy can be determined; differences in distances as small as 0.1–0.3 m can be measured using this method. The first reflections received will be from the top of the canopy and the last will be from the ground below the canopy, so that the height of the trees in the forest can be determined. An example of the type of the image of the forest canopy which can be obtained is illustrated in Fig. 13.4. St-Onge et al. (2003) and Lovell et al. (2005) have reviewed the issues surrounding tree height estimation using aerial borne lidar.

With laser data collected at sufficiently fine resolution, say with a spot size of about 0.25 m and with spots located 0.5–1 m apart, the position, height and crown spread of individual trees in stands can be determined readily. Considerable research attention has been paid to the application of airborne laser scanning to attempt to use the data to estimate many other individual tree and stand characteristics. As with aerial photographs, this often requires development of functions which relate those characteristics to the variables which are measured directly by the laser scanner. Examples of the use of aerial borne lidar, in various forest types around the world, are for the measurement of tree stem diameters, heights, stem volumes and crown structure, stand frequency distribution of diameters, wood volume, biomass, woody debris and overstorey and understorey structure and for broad-scale forest inventory (Persson et al. 2002; Holmgren et al. 2003; Lovell et al. 2003;

Fig. 13.4 A cross-sectional view of the canopy of a eucalypt forest in southeast Queensland, Australia, derived using laser scanning information from an aircraft flying at about 250 km/h at an altitude of about 1,200 m. The total distance across the image was about 500 m; the vertical and horizontal scales are the same. The *solid line* at the base of the image is the ground surface, which rises gently from right to left, then falls away quite sharply near the left hand end of the image. The *dotted points* represent the top of the vegetation canopy along the cross-section, measured in this case at about 1 m intervals; a contiguous set of 6–8 points in the upper reaches of the canopy might represent the crown of a single tree. The average height of the trees along this cross-section was measured on the ground as 24 m (from MBAC Consulting 2003, © Commonwealth of Australia, reproduced with permission)

Coops et al. 2004c, 2007; Maltamo et al. 2004, 2005, 2006a, b, c, 2007a, b; Næsset 2004, 2007; Popescu and Wynne 2004; Popescu et al. 2004; Riaño et al. 2004; St-Onge et al. 2004; Gobakken and Næsset 2005, 2008; Hall et al. 2005; Roberts et al. 2005; Chasmer et al. 2006; Falkowski et al. 2006; Mehtätalo 2006; Tickle et al. 2006; Bollandsås and Næsset 2007; Hanssen and Solberg 2007; Magnusson et al. 2007; Peuhkurinen et al. 2007; Popescu 2007; Bollandsås et al. 2008; Breidenbach et al. 2008; Briggs et al. 2008; Fujisaki et al. 2008; Heurich 2008; Hilker et al. 2008; Pascual et al. 2008; Pesonen et al. 2008).

13.2.3 Spectrometry

A spectrometer is an instrument which records the amount of light it receives at each of a very wide range of wavelengths across the radiation spectrum. Typically, it might record the light received from as many as 300 separate, narrow, wavelength bands in the visible or infra-red light regions. In this context, a spectrometer is similar to a camera, except that a camera produces an image which combines the light received at many wavelengths, whereas a spectrometer records separately the light received at each wavelength.

Spectrometers can be used on the ground, from the air or can be carried in satellites. However, for forestry purposes, there are some good examples of their use when carried in aircraft. Just as with aerial photographs, the properties of the instrument and the altitude at which the aircraft flies will determine the scale on the ground of the spectrometer recordings. At sufficiently a large scale, they can certainly record the radiation reflected from the crowns of individual trees on the ground below.

An example of the use of spectrometry concerns assessment of the health of both native eucalypt forest and plantations of radiata pine (*P. radiata*) in New South Wales, Australia (Coops et al. 2003a, b, 2004a). One common symptom of the ill-health of trees is a change in the concentration of chlorophyll in their leaves; chlorophyll is a green pigment contained in leaves and is a crucial part of their photosynthetic system. Because chlorophyll absorbs light in red wavelengths strongly, it would be expected that a tree with a low chlorophyll content in its leaves, which might then indicate its poor health, would not absorb red light as strongly; a spectrometer might then be used to identify trees which are absorbing relatively low amounts of red light.

Using an airborne spectrometer, Coops et al. (2003b) were able to identify trees in a native eucalypt forest, which had low chlorophyll contents as a result of damage to their crowns by leaf-eating insects. Coops et al. (2004b) found they could use the information from other wavelengths to identify directly individual trees which had damaged crowns. In the same forest area, Goodwin et al. (2005) found that they could use the spectral characteristics of individual tree crowns to discriminate non-eucalypt trees from eucalypts, but were unable to separate eucalypt species one from another. Similarly, Coops et al. (2003a) found that they could identify individual trees, in a radiata pine plantation, of which the crowns had been damaged and discoloured by a disease known as Dothistroma needle blight, a fungal disease which causes leaves to be shed from trees.

Another form of airborne spectrometry measures the concentrations of three elements, potassium, thorium and uranium in the top 35–40 cm of the soil on the ground below. It does so by measuring the emission of γ-rays (radiation of a rather short wavelength) emitted during radioactive decay of these elements. This can be used to infer various properties of the soil including its depth, texture and its degree of weathering. Wang et al. (2007b) used the information from such a spectrometer as a part of a system to predict the site productive capacity (Sect. 8.8) of pine plantation forests across wide areas of Queensland, Australia.

13.3 Satellites

With their world-wide coverage at all times of the year, satellites offer one of the most comprehensive forms of remotely sensed information (often referred to as satellite imagery) from forests. Some satellites are passive, that is, they sense radiation reflected from the surface of the earth. Others are active, that is, they emit radio or laser radiation which is reflected from the surface below back to the satellite.

As an example, the Landsat satellite series is one used widely for forestry purposes. It is owned by the United States Geological Survey. There have been a number of satellites in this series, launched from time to time between 1972 and 1999. Between them, they provide over 35 years of data, offering the possibility of studying changes that have occurred over that time in the vegetation at any point on earth.

The most recent in the Landsat series, called Landsat 7, carries an instrument known as Enhanced Thematic Mapper Plus (referred to commonly as ETM+). This is a passive instrument, which detects light reflected from the earth at each of a variety of wavelengths in the visible and infra-red regions of the light spectrum, as well as providing black and white photographs. Different types of vegetation and objects on the land surface will reflect light in these various wavelengths differently; it is these differences which offer the opportunity to identify and measure differences in vegetation or other land characteristics, from point to point across the ground surface.

The resolution of the Landsat 7 visible and infra-red light images is 30 × 30 m of the ground surface; that is, the images are made up of square spots, referred to commonly as pixels, which represent the intensity of radiation received from areas of the ground of that size. The photographs have a resolution of 15 × 15 m. These resolutions are inadequate to identify or measure individual trees in a forest, but are certainly adequate to identify quite fine scale variation in vegetation across the landscape. Unfortunately, there are some technical problems with the images obtained from Landsat 7, but similar images are still available from Landsat 5 (Landsat 6 was never launched).

There are now a large number of satellites, both privately and government owned, which can provide information which might be useful for forest measurement. They include, amongst many others, the Advanced Land Observing Satellite (ALOS, Japan), IKONOS (American), Indian Remote Sensing Satellite (IRS, Indian), National Oceanic and Atmospheric Administration-Advanced Very High Resolution Radiometer (NOAA-AVHRR, American), Quickbird (American) and Système Probatoire d'Observation de la Terra (SPOT, French). All these satellites produce images at each of several light wavelengths and, as their technology improves, at finer and finer resolution; some are attaining a resolution which allows individual tree crowns to be identified.

To use satellite images effectively requires specialists who can, with the aid of a computer, adjust the images to take account of various technical problems associated with them. The exact area of the surface of the earth which any image covers must be identified. Allowance must also be made for matters such as the angle of view of the image, the angle of the sun above the horizon at the time the image was taken and variations in the atmosphere.

Several examples will be used to illustrate the ways in which satellite images are being used presently. The first example concerns the monitoring of young Sitka spruce (*P. sitchensis*) plantations in Britain, to determine if they have developed adequately (Donoghue et al. 2004). The average height and stand basal area of a number of plots, located in 2–17-year-old Sitka spruce plantations, were measured on the ground. It was found that their average height correlated well with infra-red light intensity, as measured for the plots from a satellite, whilst stand basal area correlated reasonably well with light intensity measured in green wavelengths. The results were similar using data collected either by the Landsat 7 or SPOT satellites. It was concluded that the satellite information was sufficient to allow assessment of the viability or otherwise of individual plantations.

The second example is drawn from work in China (Jiang et al. 1999), where an attempt was made to assess the rate at which a wide variety of forest types, spread across the whole country, were accumulating and storing carbon through photosynthesis. Jiang et al. had available data on the annual rate of carbon accumulation (a measure known as net primary production, often abbreviated as NPP) by over 30 different forest types, both coniferous and hardwood, measured on the ground in over 1,000 plots spread around the country. Many studies around the world have found that net primary production by vegetation is related to a measure which can be calculated from satellite data, a measure known as normalised difference vegetation index (abbreviated commonly as NDVI). It is calculated, from light intensities measured in satellite data from both red and infra-red wavelengths, as

$$N = (I_\mathrm{r} - I_\mathrm{i}) / (I_\mathrm{r} + I_\mathrm{i}), \tag{13.2}$$

where N is the normalised difference vegetation index and I_r and I_i are the intensities of red and infra-red, respectively, light measured in the same pixel of a satellite image. Jiang et al. obtained their images from the NOAA–AVHRR satellite. For each forest type, they found that they could relate net primary production to normalised difference vegetation index using the function

$$N_{\mathrm{P}} = a[1 - \ln(1 - bN)], \tag{13.3}$$

where N_{P} was the net primary production, a and b were the parameters, the values of which varied with vegetation type, and ln( ) denotes natural logarithms. Given a map showing where different forest types occurred around the country, Jiang et al. were then able to use satellite images from the whole country, with (13.3), to estimate and map how net primary production of forests varied right across China.

There are many other cases where normalised difference vegetation index obtained from satellite data has been used to assess vegetation net primary production and other vegetation variables, including leaf area index, the proportion of incoming sunlight absorbed by the canopy, growth in stand stem wood volume and species richness (Gholz et al. 1991, 1999; Coops et al. 1997, 1998, 1999, 2001; Waring et al. 2002; Wythers et al. 2003; Le Maire et al. 2005; Pocewicz et al. 2004; Richards and Brack 2004; Van Tuyl et al. 2005; Volcani et al. 2005; Chirici et al. 2007; Meng et al. 2007).

The last example (Austin et al. 2003) concerns the use of an active satellite sensor, in this case the Japanese Earth Resources Satellite (JERS), which is a radar device, emitting radio waves and measuring their reflection from the earth below. Radar is sensitive to the presence of water and it is argued that this should aid its ability to detect, hence measure, fresh plant biomass. In this example, it was found that the level of radar reflection correlated reasonably well with both the stand above-ground live tree biomass and the biomass of coarse woody debris (woody material fallen from trees or in dead, standing trees) measured on the ground in a set of plots in open eucalypt forest in southern New South Wales, Australia. It was concluded that this form of remote sensing had some potential for the estimation of forest stand biomass. Coops (2002) has discussed some of the problems involved with the use of radar in assessing forest biomass. There are numerous other examples of the estimation of forest biomass using satellite imagery (Mallinis et al. 2004; Magnusson and Fransson 2005; Hall et al. 2006; Labrecque et al. 2006; Suganuma et al. 2006; Meng et al. 2007).

Satellite imagery has also been used to map different forest types (Moisen and Edwards 1999; Frescino et al. 2001; Lu 2005; Moisen and Frescino 2002), to determine the density of forest canopies (Behn et al. 2001; Baynes 2004) to determine the age structure of forests (Drezet and Quegan 2007), to identify forest suffering decline (Wang et al. 2007a), as an aid in predicting forest growth over large regions (Nightingale et al. 2008a, b; Smith et al. 2008) and as an aid in forest inventory (Köhl and Kushwaha 1994; Moisen and Edwards 1999; McRoberts et al. 2006).

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Appendix A
Glossary

Accuracy
The difference between a measurement or estimate of something and its true value.

Allometry
The relationship between part of an organism and its whole.

Basal area
Cross-sectional area at **breast height** of a **tree** stem. See also **stand basal area**.

Basic density
The **oven-dry** weight of **wood** per unit green volume.

Bias
The difference between the average of a set of repeated measurements or estimates of something and its true value.

Bioenergy
Biomass used to make energy, usually by conversion to ethanol or burning to generate electricity.

Biomass
The weight of a living organism. It may include the water in the organism, when it is referred to as fresh biomass. Often, the tissue is dried and its **oven-dry** biomass is considered.

Biomass expansion factor
The ratio between the **biomass** of some part of a tree and the volume of the stem of the tree. It can also be the ratio between the **stand** biomass of a tree part and the **stand** stem volume.

Breast height
A height of 1.3 m (or 1.4 m in some countries and 4′6” in the USA) above ground from the base of a **tree**. If the **tree** is growing on sloping ground, it is measured from the highest ground-level at the base of the **tree**.

Canopy
The foliage and branches of a **forest**.

Confidence interval
The range, evaluated with known probability, within which the true **mean** of a **population** lies, when the mean has been estimated from a sample from the **population**. It is derived from the **confidence limit**.

Confidence limit
A mathematical statistical measure to determine, with a known probability, the limits within which the true **mean** of a **population** lies, when the mean has been estimated from a sample from the **population**.

Correlation
Two variables, measured on each of a set of objects, are said to be correlated when the value of one tends to change systematically with the value of the other.

Covariate
A variable which has some degree of **correlation** with some other variable of interest.

Crown
The foliage and branches of a **tree**.

Current annual increment
The present growth rate of a **stand** at any particular age. It is often abbreviated as CAI. Also known as **periodic annual increment** (PAI).

Dendrometer
An instrument to measure **tree** stem diameter.

Digital
Forms of measurement where all the information obtained is as either one of two 'digits' only. The two digits might be recorded as a zero or a one, as the presence or absence of something and so on. These digits can then constitute a code to describe something, a code which computers are particularly efficient at interpreting. The digits are quite distinct and so are unlikely to be misinterpreted, unlike analogue measurements, which are continuously variable and so are more subject to misinterpretation.

Dominant height
Average height of a prescribed number per unit area of the tallest or largest diameter **trees** in a **stand** (see also **top height** and **predominant height**).

Ecosystem
An assemblage of plants and animals living together at a site.

Empirical
Based on experiments or observations, rather than on theory.

Environment
The other living or inanimate things amongst which a living organism grows and reproduces.

Even-aged
All the **trees** in a **stand** regenerated naturally (in **native forest**) or were planted (in **plantations**) at or about the same time. Generally there would be less than one year difference in age between any of the **trees** in the stand. (c.f. **uneven-aged**).

Forest
Vegetation dominated by plants with **woody** stems which reach a mature height in excess of a few metres.

Forest management
Activities undertaken in a **forest** to achieve the provision of the goods and services which are desired from it.

Forestry
The use and **management** of **forests** to provide goods and services to people.

Functional form
The variables included, and the way they are arranged algebraically, in a mathematical function. These determine the shape(s) the function may adopt.

Geographic information system
A computer system to store spatial data and draw maps. They allow mapping of physical features of the landscape and areal mapping of characteristics of interest which may be overlaid onto a single map as desired.

Global positioning system
A satellite-based system, deployed and operated by the United States government, which allows the user to determine where they are on earth. Anyone may purchase a hand-held, relatively inexpensive electronic device which receives satellite signals and determines their latitude and longitude and their altitude above sea-level at any instant.

Hardwood
Tree species which are flowering plants, in which the seeds develop enclosed in an ovary (cf. **softwood**).

Height
The height of a **tree** is the vertical distance from ground level to the highest green point on the **tree**.

Hypsometer
An instrument which is based on geometric or trigonometric principles for measuring **tree** height.

Inventory
Measurement or estimation of characteristics of a large forested area.

Laser
An acronym for **L**ight **A**mplification by **S**timulated **E**mission of **R**adiation. Laser light involves an intense, narrow beam of light of a single colour, which can be directed very precisely.

Leaf area index
The area of the leaves of a **forest canopy**, expressed per unit area of the ground they cover. Leaf area is defined as the area of the shadow which the leaves would cast if laid flat and lit vertically from above.

Management
See **Forest management**.

Mathematical statistics
A branch of mathematics concerned with methods to study, condense and make generalisations about information observed in natural systems.

Mean
The average of the values in a set of data.

Mean annual increment
The average rate of production (of **wood**, biomass, basal area, etc.) to any particular age of a **stand**. It is often abbreviated as MAI.

Median
The value in a set of data which has an equal number of values above and below it.

Merchantable volume
The volume of part of a **tree** stem which can be sold to convert to **wood** products by processes such as saw-milling or paper pulp manufacture.

Mode
The most common value in a data set.

Native forest
Forest which has regenerated following a disturbance (such as fire, storm or logging by man) and has been allowed to develop more or less as would happen naturally without intervention by man.

Nutrient
Any one of 15 chemical elements which are essential for plants and which play a wide variety of roles in their metabolism. They are available to land plants mainly dissolved in water in the soil and are taken up by the roots. The nutrient elements required in largest amounts by plants are nitrogen, potassium, magnesium, phosphorus, calcium and sulphur.

Oven-dry
Term to describe tissue after it has been dried (usually at 60–80°C) in an oven until its weight becomes constant.

Parameter
A variable in an equation which takes a particular value for a particular set of measured variables, the relationship amongst which the equation is being used to define.

Periodic annual increment
See **current annual increment**.

Photosynthesis
The process of chemical conversion by plants of carbon dioxide, taken into their leaves from the air, to sugars which are then used to provide energy to the plant for other metabolic processes. Light absorbed by the leaves from the sun provides the energy required in this process. Oxygen is released from the leaves as part of the process.

Plantation
A **forest** created by man, where seeds or seedlings have been planted, usually at a regular spacing.

Point sampling
A method of measuring certain **stand** characteristics from a single point within the stand.

Population
A clearly defined set of things of interest.

Population statistic
A measure used to summarise a characteristic of a **population**.

Precision
The variation in a set of repeated measurements or estimates of something.

Predominant height
Average height of a prescribed number per unit area of the tallest **trees** in a **stand** (see also **dominant height**).

Pulplog
A small log, cut from a **tree** stem, of a size appropriate for chipping to be used for making paper.

Quadratic mean diameter
The diameter of the **tree** of average **basal area** in a stand.

Rainforest
Forest which occurs in areas with high rainfall. In the tropics, rainforests contain a large number of species of tall, broad-leaved, evergreen **trees** which form a continuous **canopy**. In temperate zones, rainforests also contain many **tree** species, but are distinguished from tropical rainforests by having dominant individual species (adapted from the Merriam-Webster Collegiate Dictionary, 10th edition).

Remote sensing
Measurement methods relying on equipment which measures or detects objects at some distance from the equipment.

Sample
A set of **sampling units** selected from a **population**. They will be measured and the results used to attempt to make inferences about the properties of the whole **population**.

Sampling unit
A clearly defined part of, or individual in, a **population**, which might be included as one member of a **sample** drawn from the **population**.

Sawlog
A log cut from a **tree** stem and large enough to be sawn into one or more of the many types of sawn **wood** used for building and many other purposes.

Silviculture
The tending of **trees** in **forests** to achieve some desired objectives of management.

Site
A more or less homogeneous area of land, across which **site productive capacity** is more or less constant.

Site index
A measure of **site productive capacity**, defined as the **top height** or **predominant height** of a **stand** at a prescribed age.

Site productive capacity
The total **stand** biomass produced, up to any particular stage of development, of a **forest** growing on a particular site, when it uses fully the resources necessary for **tree** growth which are available from the site.

Softwood
Tree species which do not have flowers and in which the seeds develop without the protection of an ovary. Often these 'naked' seeds are protected by the scales of a cone (cf. **hardwood**).

Stand
A more or less homogeneous group of **trees** in a **forest** in which an observer might stand and look about him or her.

Stand basal area
Stem cross-sectional area at breast height, summed over all the **trees** in a **stand** and expressed per unit ground area.

Stocking density
The number of **tree** stems per unit area in a **stand**.

Stratum
A subdivision of a **population** containing **sampling units** which have characteristics in common.

Taper function
A mathematical function which predicts the diameter of the stem of an individual **tree** at any distance along its stem.

Timber
Wood cut from **tree** stems into sizes appropriate for its final use.

Top height
Average height of a prescribed number per unit area of the largest diameter **trees** in a **stand** (see also **dominant height**).

Tree
A **woody** plant with a distinct stem or stems and with a mature height of several metres.

Understorey
A layer of vegetation growing beneath the main **canopy** of a forest.

Unven-aged
The **trees** in a **forest stand** are of a wide range of ages. (c.f. **even-aged**).

Variance
A measure of the amount of variation in a set of measurements. It is a concept derived from **mathematical statistics** and has a formal mathematical definition as discussed in the text.

Volume function
A mathematical function which allows estimation of the volume of the stem, or parts of the stem, of an individual **tree** from simple measurements, which can be taken from the ground, such as diameter at **breast height** over bark and **tree** total **height**.

Wood
A strong material forming the greater part of the stem, branches and woody roots of **trees**. It consists mainly of dead tissue.

Wood density
See **Basic density**.

Woodland
Open **forests** in which the **tree crowns** cover 20–50% of the land area.

Appendix B
Conversion Factors

Abbreviations used commonly are shown in parentheses

Metric-Imperial Conversion Factors

1 centimetre (cm) = 0.3940 inches (in)
1 metre (m) = 3.2808 feet (ft) = 1.094 yards (yd)
1 hectare (ha) = 2.471 acres (a)
1 kilogram (kg) = 2.205 pounds (lb)
1 tonne (t) = 0.9842 tons
1 kilometre (km) = 0.6214 miles
1 litre = 0.2120 gallons (Br) = 0.2642 gallons (USA)
1 millilitre (ml) = 0.0352 fluid ounces (fl oz)

Conversions Within the Metric System

1 cm = 10 millimetre (mm)
1 m = 100 cm = 1,000 mm
1 km = 1,000 m
1 ha = 10,000 m^2
1 t = 1,000 kg
1 litre = 1,000 cm^3 = 1,000 ml

Conversions Within the Imperial System

1 ft = 12 in
1 yd = 3 ft
1 chain = 100 links = 22 yd
1 furlong = 10 chains

1 mile = 8 furlongs = 1,760 yd = 5,280 ft
1 acre = 10 chain^2 = 4,840 yd^2
1 lb = 16 ounces (oz)
1 ton = 2,240 lb
1 gallon = 4 quarts = 8 pints
1 super foot = 1/12 ft^3
1 cord = 128 ft^3
1 cunit = 100 ft^3

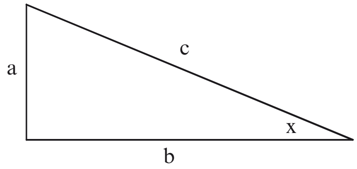
Appendix C
The Greek Alphabet

Uppercase	Lowercase	Letter
Α	α	Alpha
Β	β	Beta
Γ	γ	Gamma
Δ	δ	Delta
Ε	ε	Epsilon
Ζ	ζ	Zeta
Η	η	Eta
Θ	θ	Theta
Ι	ι	Iota
Κ	κ	Kappa
Λ	λ	Lambda
Μ	μ	Mu
Ν	ν	Nu
Ξ	ξ	Xi
Ο	ο	Omicron
Π	π	Pi
R	ρ	Rho
Σ	σ	Sigma
Τ	τ	Tau
Υ	υ	Upsilon
Φ	ϕ	Phi
Χ	χ	Chi
Ψ	ψ	Psi
Ω	ω	Omega

Appendix D
Basic Trigonometry

The Right-Angled Triangle

Consider the right angled triangle below, with sides of length a, b and c and containing an angle x, as shown.



By Pythagoras' theorem $c^2 = a^2 + b^2$

By definition, for the angle x

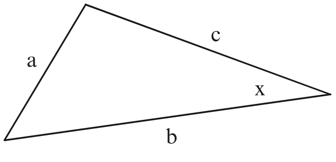
sin(x) = length opposite side/length hypotenuse = a/c

cos(x) = length adjacent side/length hypotenuse = b/c

tan(x) = length opposite side/length adjacent side = a/b

Any Triangle

Consider the triangle below with sides of length a, b and c and containing an angle x, as shown.



For any such triangle, the cosine rule states that

$$a^2 = b^2 + c^2 - 2bc\cos(x)$$

Its area (A) is given by $A = bc[\sin(x)]/2$

Some Useful Properties of Trigonometric Functions

$\tan(p) = \sin(p)/\cos(p)$
$\sin(-p) = -\sin(p)$
$\cos(-p) = \cos(p)$
$\sin(\pi/2-p) = \cos(p)$, where p is in radians ($\pi/2$ radians = 90°)
$\cos(\pi/2-p) = \sin(p)$
$\sin^2(p) + \cos^2(p) = 1$
$\sin(p + q) = \cos(p)\sin(q) + \sin(p)\cos(q)$
$\cos(p + q) = \cos(p)\cos(q) - \sin(p)\sin(q)$

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Errata to:

Tree and Forest Measurement

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On page 45 in Chapter 6, Equation (6.13) should read as:

$$V_{LU} = (\pi/40{,}000)\ \{0.599D^{1.864} / H^{0.896}\}\ \{(H–L)^{2.220} – (H–U)^{2.220}\} / 2.220 \tag{6.13}$$

On page 82 in Chapter 8, Equation (8.10) should read as

$$\mathrm{V}=\beta\Sigma_{\mathrm{i}=1\ldots\mathrm{n}}[40{,}000\mathrm{Vi}/(\pi \mathrm{D}_{\mathrm{i}}^{2})] \tag{8.10}$$

On page 108 in Chapter 10, Equation (10.9) should read as:

$$V_M = \Sigma_{h=1\ldots H}\ W(h)^2\ \{1- f(h)\}\ \{\Sigma_{i=1\ldots n(h)}[y(h,i) - y_m(h)]^2\}/\{[(n(h) -1]n(h)\} \tag{10.9}$$

The original online version for this book can be found at
http://dx.doi.org/10.1007/978-3-540-95966-3