Practical

The development of even-aged plantation forests: an exercise in forest stand dynamics

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In this paper we present a field-based practical exercise that allows students in forestry, ecology and natural resources to develop their understanding of forest stand dynamics. The exercise involves measurement of key tree growth parameters in four even-aged, single-species plantation stands of different age but occupying sites with similar soil and environmental characteristics. The selected stands represent key stages in stand development, from establishment to rotation age for maximum fibre production. In the field, students work in small teams to gather data from an equal number of plots within each stand. Tree parameters include top height, crown diameter, live crown ratio and diameter at breast height. In addition, information on stand density and understorey vegetation is collected. Plot size and number can be varied to suit the constraints of class size and available time, though circular plots of $100m^2$ are recommended. In the classroom, data are pooled and analysis focuses on presenting tree and vegetation changes through time. The simplest way of interpreting the data is to prepare graphs and charts for each of the parameters, though more advanced statistical interpretations are possible. The project as outlined here can be modified to meet the needs of different groups, and has been successfully used in undergraduate teaching of silviculture and forest ecology, as well as in postgraduate courses in natural resources management.

Key words: Applied ecology; Forest stand dynamics; Tree biology; Forest plantations; Silviculture.

Introduction

'Forest stand dynamics' is defined as the changes in forest structure, function and composition through time (Oliver and Larson, 1996). Its study draws on an understanding of tree biology and ecology, and is governed by ecological theories of competition, disturbance and succession (Kimmins, 2003). Knowledge of forest stand dynamics is applied in many areas of woodland establishment and management, including that of planted forests being cultivated for timber production (e.g. Cannell and Last, 1976), semi-natural woodlands where conservation objectives are a priority (e.g. Smith *et al*, 1997) and multi-functional woodlands managed for both timber and biodiversity values (e.g. Kerr, 1999). As such, it forms a component of forestry, ecology and natural resource management education. Traditionally it is considered to be a challenging area of learning. This is because the pace of change in forest stands is slow and seemingly imperceptible, and because teaching generally relies on interpretation of mathematical functions, growth models or analysis of data from long-term studies of forest succession (e.g., Huuskonen and Miina 2007).

The pattern of change in forested ecosystems is an important area of both theoretical and applied research (Johnson and Miyanishi, 2007; Kimmins, 2003). Ecosystems generally change through succession from one stage of development to another along a pathway that is influenced by species, site, climate and exogenous disturbance events. Each seral stage may have distinct flora and fauna, and structural characteristics.

In general terms, four major stages of development are commonly recognised in forest stands (Oliver and Larson, 1996), see Figure 1. Stand initiation corresponds to the phase of recruitment of stems to the stand. In naturally-regenerated woodlands this phase may last a number of years, but in plantations the aim is to achieve full stocking of the site in one planting operation. Stem exclusion follows as the stand develops a closed canopy; deep shade in the understorey prevents further recruitment of trees to the stand while competition, site factors and genetic differences lead to differentiation of crown dimensions and stem diameters. The stand then continues on to an understorey re-initiation stage. Herbs, shrubs and advanced regeneration of trees appear and survive as a result of gradual thinning of crowns or occasional gaps that allow increased levels of solar radiation to reach the forest floor. Finally, the stand reaches an old growth stage. Here the overstorey trees die in an irregular pattern, either from natural causes or disturbance, creating space for recruitment into the canopy of trees from lower strata.

The transition from one stage to the next generally holds true for plantations, if retained for long enough (Kerr, 1999), and those natural forests that regenerate after a large-scale, stand-replacing disturbance (Kimmins, 2003). However, each stage of the sequence may be disrupted as a result of managed interventions or natural disturbance events (Johnson and Miyanishi, 2007; Kimmins, 2003). This can result in alternate pathways of succession that do not necessarily lead to a steady-state or old-growth stage, thereby increasing the complexity of many forest ecosystems.

Planted forest stands are usually composed of one tree species, one age class and have uniform tree spacing (Savill *et al*, 1997). They are often clear-felled before reaching the understorey re-initiation stage in order to maximise the financial return on investment costs (Savill *et al*, 1997; Matthews, 1989; Evans and Turnbull, 2004). The relative simplicity of plantations makes them an ideal starting point for introduc-

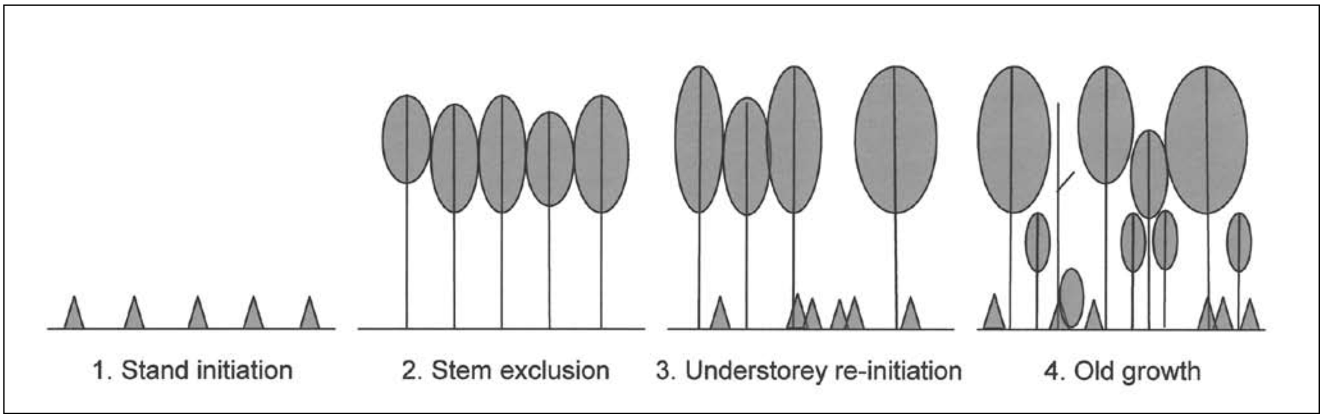


Figure 1. Schematic of the four major stages in stand development (adapted from Oliver and Larson 1996).

ing students to the study of forest stand dynamics. Individual trees in such stands undergo a variety of structural adaptations through time due to competition for space, nutrients, moisture and light (Kozlowski and Pallardy, 1997; Oliver and Larson, 1996; Larcher, 2003; Horn, 1971). Trees rely on their foliage to produce the sugars and other products of photosynthesis, collectively known as photosynthate, for maintenance respiration and for growth processes (Kozlowski and Pallardy, 1997; Wilson, 1984). Changes in the development of the crown have a profound influence on growth rates of individual trees and the economic value of any timber that might eventually be produced (Cannell and Last, 1976; Savill *et al*, 1997).

The growth of trees in forest stands usually has an impact on biodiversity (Camus et al, 2006; Kimmins, 2003). As the forest canopy begins to close, a decreasing proportion of direct incident radiation reaches the forest floor. This change in environmental conditions influences the growth rates and species composition of the ground vegetation. Species that have a low tolerance to shade soon disappear from the ecosystem. Those that can tolerate or prefer shady conditions will remain or colonise the site as the canopy closes and the stand matures. There is a succession of vegetation associated with different stand ages, stages of development and light levels (Oliver and Larson, 1996; Kimmins, 2003). Changes in microclimate, structure and ground vegetation also influence the habitat suitability for mammals, birds and amphibians.

Experiential learning strategies are considered to be of great value in professional education (Brown, 2003). These approaches integrate learning across subject areas, promote teamwork, help develop analytical skills, and boost professional and academic competency (Brown, 2003; Sungur *et al*, 2006). In this paper we describe a practical exercise designed to give students direct field experience and consolidate learning in forest stand dynamics. The exercise is aimed at introductory silviculture courses, but could be adapted for other undergraduate or postgraduate groups, or in professional development and training. Specifically, the learning objectives are:

- to develop an understanding of tree growth patterns in even-aged, single-species forest stands, and underlying growth processes
- to gain experience in tree and stand measurements
- to develop skills in identifying non-tree vegetation and monitoring changes in ground vegetation at various stages of stand development; to develop skills in sampling.

The hypothesis of this study is that stand parameters (tree height, live crown ratio, stem diameter, stand density and ground vegetation) change with age. Here we outline the design of the exercise and review the major learning outcomes. We demonstrate the approach with summary data collected by a student group at the National School of Forestry, University of Cumbria.

Methods

Site selection

For the exercise to work effectively it is important to control as many stand and site characteristics as possible. Theoretically the only variable that should change is the age of the stand. This ensures that each stand represents distinct points on a common growth trajectory. In practice, however, such control will rarely be possible due to changes that are likely to take place over time in silvicultural practices, which alter growth rates and stand development patterns. Examples include different site preparation and establishment techniques, advances in tree genetics and seed quality, and changes in spacing and thinning policies. Differences may also result from older stands being first-rotation plantations and younger stands being located on re-stocked areas, where site conditions may have been modified. In terms of the site, variation can be minimised by selecting stands located close to one another with similar soil, moisture and environmental conditions.

Stand selection

A minimum of four stands should be selected at different stages in stand development. In the UK, upland conifer plantations typically achieve their economic rotation in 40-60 years. This length of rotation means that only the first two stages of stand development, as described by Oliver and Larson (1996), are generally present in forest stands in the UK. The four stands cover the period from planting to an advanced stem exclusion stage:

1. *Stand initiation stage*. This stand should be between 3 and 6 years old. Seedlings will have overcome planting stress and the target stocking density will have been achieved. The trees will not yet fully occupy the site. Direct light on the forest floor will enable the original ground vegetation still to dominate much of the site.
2. *Stand initiation-stem exclusion transitional stage*. At this stage the trees will be large saplings and should be between 10-15 years of age. Tree crowns will be starting to interact with one another and the stand will be approaching canopy closure. Ground vegetation will be present on the site.
3. *Middle stem exclusion stage*. Trees will have grown in

height and stature, with little light now penetrating the canopy and reaching the forest floor. These strands will typically be 25-35 years of age.

4. *Advanced stem exclusion stage*. The trees will now be mature and near the end of the economic rotation. The stand will be approximately 40-60 years of age, depending on the site conditions.

If available, examples of the final two stages in stand development would also be used, providing insight into stand development through the understorey re-initiaition and old-growth stages.

Field measurements

In the field, the class should be organised in groups of two to four students. Plots are selected on the basis of a systematic or random pattern within each stand. It is advisable to establish a buffer zone between the edge of the forest and the first plot. Circular plots with an area of $100m^2$ (5.64m diameter) are recommended. Each live seedling or tree in the plot is counted. In the younger stands there may be some natural regeneration seeding in from neighbouring areas of mature trees. To simplify analysis we recommend that these trees are ignored. In the older stands it is also necessary to record any stumps from trees that might have been removed in thinning operations. This makes it possible to estimate the initial and current stand densities.

The diameter at breast height (DBH = diameter at a height of 1.3m) of each tree in the plot is recorded. Total height is measured on the three largest trees in each plot. This can be done with a measuring tape or pole in the youngest stand; a hypsometer is required in all the other stands. In addition, the height to the base of the live crown and mean crown diameter (based on two measurements per tree, taken at right angles to one another) are also recorded. Height to the base of live crown is the height to the first major live branch; adventitious or epicormic shoots are ignored. The crown diameter is measured by the horizontal distance across the crown, with the mean being taken of two measurements undertaken at right angles to one another. In the older stands there is significant crown overlap and so to an extent this can be somewhat subjective. Basic tree measurements are illustrated in Figure 2 and more detailed explanations are provided in forest mensuration texts (e.g. Forestry Commission, 2006; Husch *et al*, 2003).

In addition to information about the trees in each plot, the ground cover is assessed. Within the plot, percentage cover of ground flora is estimated for five classes using a 1 × 1m quadrat randomly located in the plot: 1 – grasses; 2 – woody vegetation (shrubs); 3 – non-woody vegetation (herbs, moss, ferns); 4 – needles/litter; 5 – bare soil. Where possible, individual species should be identified and recorded. Two scales are commonly used to describe abundance of vegetation, the Domin scale and the Braun-Blanquet scale (Williams, 1991). In this exercise we used the Domin scale which scores vegetation by percentage of ground cover as follows: 1 = <4% cover and rare; 2 = <4 % cover and sparse; 3 = <4 % cover and frequent; 4 = 4-10%; 5= 11-25%; 6 = 26-33%; 7 = 34-50%; 8 = 51-75%; 9 = 76-90%; 10 = 91-100%. Should shrubs be dominant, a larger quadrat (up to $100m^2$) may be needed to obtain an accurate measure of abundance.

Equipment required for data collection includes: prepared data sheets, 10m tape for measuring plot diameter and tree crown dimensions, 30m tape for tree height measurements, hypsometer, callipers or diameter tape, ranging pole and flagging tape for location of plot centres, and clip boards. An angle gauge is an optional tool that helps with accurate measurement of the crown diameter. Ideally, each group should be organised so that all members can practice with each piece of equipment. A minimum of four plots in each stand type is recommended. The data collected is then suitable for a variety of statistical tests.

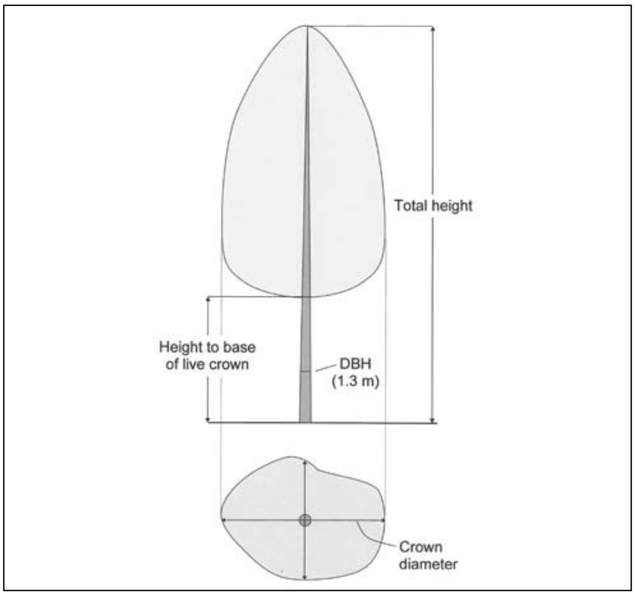


Figure 2. Diagram showing the tree measurements required for the exercise. Data include tree total height (ht), height to base of live crown (hlc), DBH and mean crown width (based on two diameter measures).

Calculations

Data for stocking density should be converted to per ha values. Mean values for stand density, DBH, total height, crown width and live crown percent are calculated for each plot, and pooled to generate mean values for each stand. In addition, basal area is calculated as an indication both of site occupancy and the level of competition within the stands. The scores from the ground vegetation should also be summarised to obtain mean values for each vegetation type in each stand. The summary values for each parameter are then plotted to demonstrate changes in tree structure and ground vegetation through time. Line graphs are drawn for age against top height, DBH and live crown percent. Additionally, bar charts can be produced for density versus stand age, and ground cover class versus stand age.

Case study

The site for the case study is located in Greystoke Forest (OS Grid Reference: NY 395330), approximately 8km from the National School of Forestry. This forest was largely established for timber production from the 1950s and the dominant species is Sitka spruce (*Picea sitchensis* (Bong.) Carr.). Harvesting and re-structuring in recent decades has created a patchwork of small even-aged stands of different ages, ideal for observing the major stages in stand development. The area of the forest selected for the exercise had four stands of appropriate age in close proximity. Although site conditions are similar on all four stands, it is important to note differences in management history in stands 3 and 4. Details of

Table 1. Stand and site characteristics.

	Stand 1	*Stand 2*	*Stand 3*	*Stand 4*
Stand location (OS Grid Ref.)	NY 387 346	NY 388 345	NY 393 340	NY 389 342
Stand age (years)	3	12	30	45
Altitude (m)	260	260	255	265
Aspect	NE	NE	NE	NE
Topography	Gentle slope	Gentle slope	Lower slope	Upper slope
Soil type	Acid brown earth	Acid brown earth	Acid brown earth	Acid brown earth
Soil texture	Loamy clay	Loamy clay	Loamy clay	Loamy clay
Rooting depth (cm)	~ 30	~30	~30	~30
Wind hazard classification	4	4	3	4
Rotation	Re-stocked	Re-stocked	Re-stocked	First
Site preparation	Mounded	Mounded	Ploughed	Turf planted
Thinning	Unthinned	Unthinned	Row thinning (1-in-6 rows) at 20 yrs. Low thinning at 28 yrs.	Unthinned
Initial density (stems/ha)	2200	2200	2000	3700
Current density (stems/ha)	2200	2100	900	1800

each stand are given in Table 1.

Once fieldwork and data analysis have been completed, students can then address the key learning objective of developing an understanding of tree growth patterns and vegetation dynamics in even-aged, single-species forest stands. The first task is to describe patterns and trends in the data. This allows students to relate their personal experience in each stand to the summary statistics generated in the classroom. Next, the group should attempt to explain the processes driving the observed changes in tree structure and stand development. Finally, students should reflect on the validity of the results with reference to their theoretical understanding of stand development. They might consider whether, in fact, age was the only difference between stands or if other site factors influenced the results.

With 20-30 students it is possible to complete fieldwork, data analysis and a class discussion in a three-hour practical and a two-hour laboratory session. Formal lectures provide the theoretical underpinnings for the exercise. Care should be taken to avoid adding too much detail or complexity to the project, as this will add significantly to the time required in the field and the classroom. Students are asked to reflect on their learning through submission of a short written report.

Results

Significant changes in mean total height, percent live crown, stem diameter (Table 2) and understorey vegetation (Table 3) were observed through time. Mean total height increased slowly in the early years before entering a phase of rapid development (Figure 3a). This phase of rapid development is often referred to as the 'grand period', occurring between years 12 and 27 in this study. Later, as the tree approaches maturity, the height increment is reduced. Overall, the developmental pattern conforms to a sigmoidal growth curve. Conversely, the percent live crown remains very high, with live branches being retained over nearly 100% of the stem, until after canopy closure. During the grand period lower branches become shaded and the percent live crown decreases rapidly. In mature trees, the percent live crown gradually levels at approximately 40% of total tree height (Figure 3b).

Mean DBH initially increases in a similar pattern to mean top height (Figure 3c). However, in the later stages of stand development the mean diameter is lower than might be anticipated. Many of the changes in tree size and form are summarised in Figure 4, which indicates the relative size and uniformity of trees as they grow through each developmental stage. Following canopy closure, after approximately 10 years of age, there are significant changes in understorey vegetation (Table 3). The grasses are first replaced by mosses, which are then replaced by a carpet of needles and leaf litter material. Initial and current stand density varied from stand to stand, especially in stands 3 and 4 (Table 1). In stand 3 the density had been reduced by thinning, while in stand 4 the high initial density was reduced by mortality of many suppressed stems. This is reflected in the significant difference in the basal area between these two stands (Table 2).

Discussion

One of the primary learning objectives of the practical is to increase the students' awareness of the link between the capture of light energy and the allocation of photosynthate at the individual tree and stand level. Foliage is the location of photosynthesis, the 'source' of energy, while the stem, branches and roots are the 'sink' where energy is consumed in growth and maintenance respiration processes. Trees allocate photo-

Table 2. Results from field assessment of each stand. The results here are the means of four plots in each stand.

	Stand 1	*Stand 2*	*Stand 3*	*Stand 4*
Mean top height (m)	0.3	4.5	22.4	23.7
Mean live crown (%)	98	97	48	39
Mean DBH (cm)	0	7.1	23.2	22.0
Mean crown diameter (m)	0.3	2.0	2.8	2.2
Basal area (m2/ha)	0	8	38	68

synthate according to an order of priority (Oliver and Larson 1996, p74-75). Those under some degree of stress will allocate resources to high priority processes such as maintenance respiration before lower priority ones such as diameter increment. The different patterns and priorities of photosynthate allocation are important in the management of planted forest stands as they influence both the volume and quality of timber being produced.

Over a wide range of stand densities on a particular site type, the height growth of dominant trees remains approximately the same and for this reason the height-age relationship is often used as a measure of site potential (Evans and Turnbull, 2004; Husch *et al*, 2003; Oliver and Larson, 1996). This can be explained in terms of photosynthate allocation. By giving priority to allocating photosynthate to height (primary) growth over diameter (secondary) growth, a tree increases its chances of maintaining a position in the forest canopy, surviving and reaching reproductive maturity. As a tree increases in height, the crown expands through an iterative and additive process of lateral and terminal shoot extension (Horn, 1971; Wilson, 1984) and competition between trees begins. This competition for resources explains why, in even-aged stands that are unthinned, there is an inverse relationship between stand density and average tree diameter (Yoda *et al*, 1963; Reineke, 1933). Trees require more space as they increase in size, and the only way they can increase in size is if the stand density decreases.

Foliage is only retained as long as it contributes photosynthate to the energy budget of the tree (Larcher, 2003). In shady conditions, the lower branches become an overall 'cost' to the tree at the point where maintenance respiration exceeds gross photosynthesis. The shedding of uneconomic shoots and foliage leads to a reduction in the percent live crown in stand conditions (Figure 3b). Foresters thin stands as they mature. The weakest trees are removed in successive interventions and spacing between the residual stems is increased to allow for a controlled expansion of the crown. Variation in mean diameter is reduced and vigorous tree growth can be sustained until the stand reaches the final harvest.

An understanding of allocation, crown development patterns and density relationships helps explain changes in stem diameter. In biological terms, diameter increases to support expansion of the shoot system and to enhance the capacity for transport of water and nutrients to the foliage (Tyree and Ewers, 1991). Diameter will increase faster in trees with full crowns than those where crown size has been reduced by competition for resources. If initial spacing and density management had been the same for each stand, we would expect the mean diameter to be lower in stand 3 than stand 4 (Figure 3c). However, the high initial density, combined with a lack of subsequent thinning has led to a high degree of crown differentiation in stand 4 (Figure 4) and a smaller mean diameter than stand 3 (Table 2). This difference can be attributed to a wider initial spacing and two thinning operations in stand 3 that have allowed residual trees to maintain larger crowns and higher individual growth rates.

Application

The exercise was piloted in January 2001 and has been successfully adopted in core teaching at the National School of Forestry. It has received positive feedback from students. Beyond direct application to forest stand dynamics, students are encouraged to consolidate and reinforce learning from other areas of the curriculum, to develop skills in critical reasoning and to become more self-reliant learners (Table 4). Formal (summative) assessment is based on submission of a written report. In their briefing instructions it is made clear that a pass grade requires a text that describes the key developmental stages and is supported by correctly labelled diagrams, graphs and tables of the main findings. A more advanced student will be able to clearly articulate some of the underlying eco-physiological processes and draw on relevant published

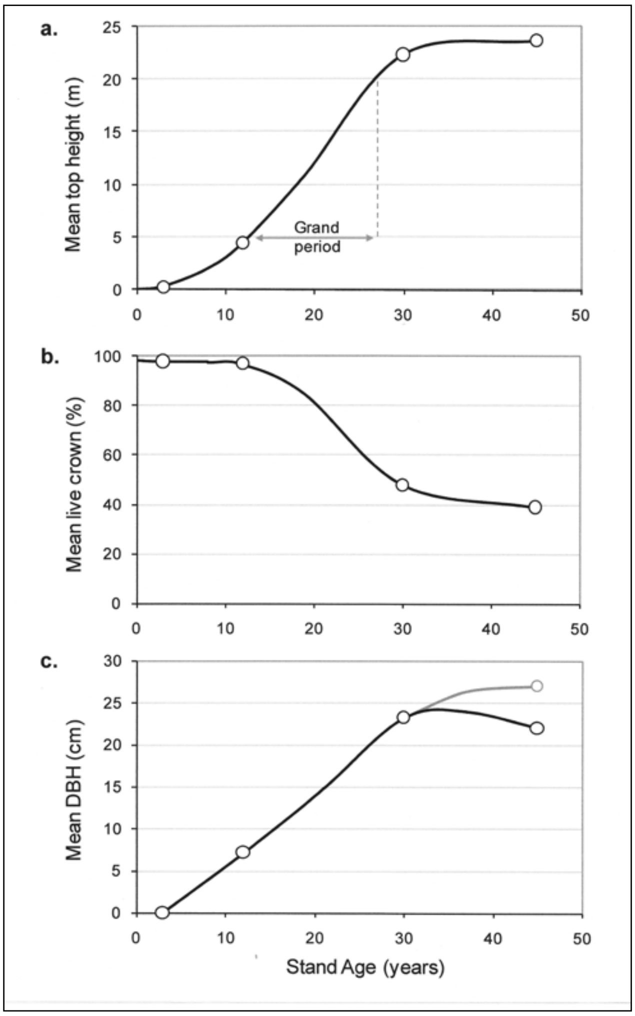


Figure 3. Stand development through time for (a) mean top height, (b) mean live crown (percent) and (c) mean diameter at breast height (DBH). Best-fit lines were fitted to mean values from four plots in each stand. The grey line in Figure 3c represents the anticipated mean diameter if tree spacing was similar in stands 3 and 4. The 'grand period' corresponds to the phase of most rapid height increment.

Table 3. Relative abundance (Domin score) of types of ground vegetation in each stand. Higher scores correspond to higher relative abundances within each stand.

	Stand 1	*Stand 2*	*Stand 3*	*Stand 4*
1. Grasses	8	6	2	0
2. Woody plants	4	0	0	0
3. Non-woody plants[1]	4	8	5	4
4. Needles/tree litter	4	4	9	10
5. Bare soil	4	0	0	0

[1] The dominant species in this group were mosses.

Table 4. Summary of activities and learning outcomes associated with completion of the exercise.

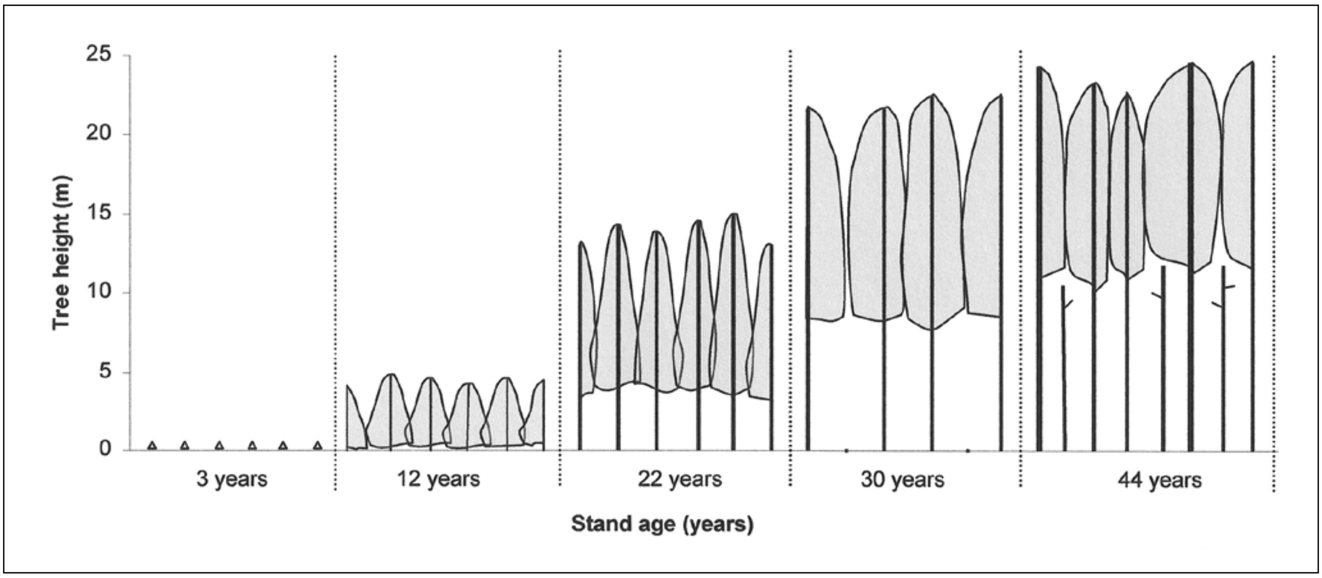
Activity	*Learning outcomes*
Understanding silvicultural relationships	• Understanding the priorities in the allocation of photosynthate • Relating the processes of self-thinning and competition to even-aged stands • Recognising the stages in the development of even-aged stands
Measurement of stand parameters	• Understanding fundamental tree parameters • Use of mensuration equipment • Basic maths (calculating heights from % and distance, live crown percent) • Ecological survey methods (quadrats and measures of abundance) • Identification of ground vegetation
Laying out plots	• Understanding of sampling • Calculation of areas
Recording field data	• Use of forms • Recording data legibly, neatly, accurately
Summarisation of data	• Use of calculators, spreadsheets • Understanding of basic statistics (mean values, but more advanced analysis possible depending on the group)
Preparation of graphs	• Use of chart function in spreadsheets • Understanding the labelling and other requirements of graphs
Interpretation of graphs	• Relating field experience to quantitative data • Understanding of the influences of age and stocking on stand and tree parameters
Describing the main results	• Scientific writing skills • Referencing
Professional competencies	• Working in a team • Critical reasoning • Organising work

literature. Linking their findings from the field project to their understanding of stand development processes provides good evidence of critical reasoning and independent thinking. Some of the technical skills being developed and aspects of working in a team can be partly assessed by asking students to include a short section in their report, a reflection, on the learning experience. Other areas of learning are developed through formative assessment.

For the project to be effective, it is important to closely match the learning objectives and workload expectations to the students' stage of progress through the curriculum. In junior undergraduate classes the exercise works best when directed by the instructor. However, it could easily be adapted as a project for different student groups. For example, in senior undergraduate and postgraduate classes more responsibility for planning, data collection and analysis could be delegated to the students. In this regard, the project may be an effective problem-based learning activity. Other modifications to the exercise are possible, including advanced statistical analysis of the data, surveying a larger number of stands to investigate development patterns in more detail, or comparison between sites of different productivity.

The exercise links to more advanced learning where forest stands are composed of more than one tree species. In an increasing number of areas, plantations are being retained beyond the economic rotation to improve the habi-

Figure 4. Schematic of stand structure at five ages from establishment to stand maturity: (1) stand age 3yrs; (2) stand age 12 years; (3) stand age 22 years; (4) stand age 30 years; (5) stand age 45 years. The diagrams accurately represent spacing, tree height and crown dimensions as measured or interpolated from data collected in the field. The diagram for stand age 30 years demonstrates the effect of thinning, which has resulted in a smaller number of trees but with large, uniform crowns. In stand age 44 years, the lack of thinning has resulted in density-dependent mortality and greater variation between trees in the canopy.



tat potential, biodiversity and landscape value of woodland landscapes. Inclusion of stands in the understorey re-initiation and old growth phases would add another dimension to stand structure analysis. A further development of the practical would be deriving the Yield Class for the stands, through the measurement of top height. Using Yield Class and species, the threshold basal area can be obtained which would indicate whether the stands required thinning. Finally, knowledge of Yield Class would allow students to compare the stands, through using yield tables, with the average tree size and stand density values under various silvicultural regimes (Hamilton and Christie, 1971).

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