Chapter 7
Modelling Continuous Cover Forests

Jerome K. Vanclay

1 Introduction

Continuous cover forestry (CCF) is desirable for many reasons, but this silvicultural approach does add to the complexity of predicting forest growth and timber yield. Many well established techniques such as yield tables and age-based growth models – techniques that are well-established and known to be useful and reliable – are not applicable in the all-aged forests that develop with continuous cover forestry. Thus CCF requires the use of alternative techniques that do not require knowledge of the age of trees, and admit the possibility of trees of all sizes and of many species. While this is not problematic conceptually, it poses some practical challenges in gathering data and calibrating the model, especially if the model deals with interspecific competition and other species interactions.

A further complexity is the need to predict regeneration. Most models for plantations and even-aged stands accept initial stocking as an input, and regeneration does not need to be predicted. However, prediction of regeneration is central to CCF, and a CCF model used for long-term simulations must be able to predict the amount and species of regeneration. This can be a complicated undertaking, and the complexity increases with the number and diversity of species (Vanclay 1992; Weiskittel et al. 2011). Because the nature of regeneration is usually dependent on stand conditions in the immediate vicinity, long-term simulations in CCF require a modelling approach that utilizes spatial data (e.g., Newnham and Smith 1964) or simulated small gaps (e.g., *JABOWA*, Botkin et al. 1972; *Sortie*, Pacala et al. 1993).

The many examples of models for CCF make a comprehensive review with case studies a daunting exercise that this chapter does not attempt, as recent comprehensive reviews are offered elsewhere (Hasenauer 2006; Pukkala 2009; Weiskittel et al. 2011).

J.K. Vanclay (✉)
Southern Cross University, PO Box 157, Lismore NSW 2480, Australia
e-mail: JVanclay@scu.edu.au

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2 Modelling Approaches for CCF

It is possible to model CCF using stand-based approaches such as transition matrices (Hool 1966; Bosch 1971) and stand table projection (Buongiorno and Michie 1980), but the utility of these approaches is limited. These were popular approaches before the advent of computers because they provide practical information with little computational effort (Vanclay 1994a, b). However, since these methods were pioneered, both information needs and computational possibilities have advanced, and most forest managers and modellers prefer to use individual-based rather than class-based models in CCF situations. Class-based approaches work best when a stand can be described with few states (hence, with a limited range of sizes and number of species), but several studies show that many of the assumptions may be questionable in CCF (Hulst 1979; Binkley 1980; Roberts and Hruska 1986). The approach may still have utility where data and computational resources are limited, and further guidance may be found in standard texts (Vanclay 1994a, b; Weiskittel et al. 2011). Despite these limitations, matrix approaches have been used to investigate a range of management options for CCF, including conversion from even-aged stands (e.g., Rojo and Orois 2005) and sustainable harvests (Lopez et al. 2007).

Individual-based approaches may take two forms – cohort-based and single-tree models. A single tree model typically simulates a sample plot of finite area, and simulates the appearance (germination or recruitment), the increment and the death of each individual tree within the plot. This approach is often used in spatial models, which simulate not only each individual tree, but often explicitly model spatial competition, sometimes down to the level of tracing rays of sunlight and their interception by individual leaves (e.g., Groot 2004). The disadvantage of single tree models is the need to model mortality, and to identify when a tree disappears from the simulation. The difficulty of predicting mortality precisely, coupled with the consequences of such a prediction on the remaining trees in the model, mean that single tree models are often stochastic, which may in turn limit the utility of these models for forest management (Vanclay 1991a). In Fig. 7.1, one of the challenging parts of the model, and the discriminator between cohort and individual tree models is the term $p \times n$: in an individual tree model, the n is always integer, and often 1, whereas in cohort models n can take any real number. This in turn implies that the survival probability p in an individual tree model is binary (0 or 1).

An alternative approach that overcomes the need for stochastic modelling of mortality is cohort-based modelling, where each individual tree is represented as a triplet comprising identity, size and abundance, where identity usually involves taxon (and sometimes spatial location), size is stem diameter and/or tree height, and abundance represents stocking (stems/plot) (Vanclay 1994a, b). Depending on the granularity of stocking, cohorts may represent a single hectare (so that stocking is an integer, effectively a single tree model), or hundreds of hectares of forest (Vanclay 1991a). While cohort models have been proven successful in several contexts (e.g., Vanclay 1994b, Ong and Kleine 1995), they may not offer the spatial precision

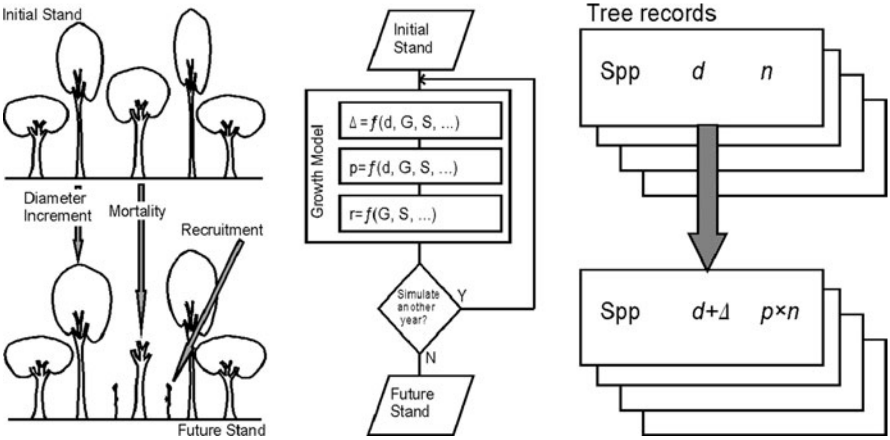

Fig. 7.1 Model components and their representation as tree records for a forest stand. Growth is modelled by incrementing the diameters in each record ($d + \Delta$) and mortality is accommodated by reducing expansion factors ($p \times n$)

needed to explore the nuances of various forms of CCF, such as different outcomes arising from individual tree selection and group selection harvesting systems.

Both cohort-based and individual tree models rely on similar components, which we will examine in turn.

3 Model Components

In a parsimonious model, it is customary to identify and model several attributes of each tree. In models that do not simulate competition explicitly, it is common to model tree size (usually stem diameter) and stocking or mortality. In contrast, models that simulate competition explicitly often model additional attributes including tree height, crown width and crown depth. In either case, a generic concept ‘size’ is refined into an attribute that is non-ambiguous, and can be both simulated and measured.

While the great majority of models take a parsimonious and explicit approach to finding the smallest number of simple relationships to describe observed changes, some modellers seek to explain observations in more detail and depth, to simulate components of tree growth in ways closer to the underlying physiology. Such models are often called physiological or mechanistic models (Landsberg 1986; Battaglia and Sands 1998). The attraction of these models is that some components of the models begin to approach stable underlying principles that may be generic and applicable to many species and situations. The disadvantage is that these approaches often require many parameters (e.g., 47 parameters for each species in the 3PG model, Sands and Landsberg 2002), including some that may be difficult to estimate.

The art of modelling is to choose a suitable level of detail, that simultaneously retains the scientific principle of falsification (able to be tested and refuted), that enables data collection and model calibration to be timely and efficient, and that achieves a utility sufficient for the model to be used to inform forest management and other user requirements. These demands are diverse, and different situations require diverse approaches.

4 Useful Relationships

There is a bewildering range of relationships that may be used in the construction of a growth model, but experience has shown that a small number of proven relationships provide robust results (Vanclay 1994a). Some of the more important of these relationships are detailed below to offer guidance for novice model builders.

4.1 *Size (Diameter)*

The growth in size of individuals lies at the heart of most growth models, and can involve the growth in height (e.g., Mitchell 1969), diameter or other parts of the trees, but it is perhaps most common to model diameter increment (Vanclay 1994a, b). Similarly, models can predict change in size (i.e., increment) or future size, and can predict diameter or some transformation of diameter such as cross-sectional area. Each approach has adherents, but the differences between these alternatives tend to be small, provided that the usual statistical assumptions are satisfied.

Modellers may estimate increment directly for a range of stand conditions, implicitly dealing with competition, or they may explicitly use a modifier to reduce potential growth to account for competition (e.g., Arney 1985). One of the difficulties of the latter approach is the need to obtain an independent and reliable estimate of potential growth. One approach is to rely on trees subjectively considered free of competition, but a better alternative is to estimate the potential growth and the modifier simultaneously.

One empirical equation that has been widely used to model diameter increment is based on a simple relationship (Wykoff 1990; Vanclay 1991b), with additional terms to include competition and site productivity:

$$\ln \Delta d = \beta_0 + \beta_1 \ln d + \beta_2 d^k + \beta_3 G + \beta_4 G_{>d}$$

where d is tree diameter, Δd is diameter increment, G is stand basal area, $G_{>d}$ is basal area in larger trees, and k is 1 (Vanclay 1991b) or 2 (Wykoff 1990). This equation is easy to calibrate, and predicts an increment pattern very similar to other equations with a strong biological basis (e.g., Bertalanffy 1942), but which are more difficult to calibrate (Ratkowsky 1983). Other equations that offer robust predictions are discussed by Weiskittel et al. (2011).

4.2 Competition and Species Interactions

In simple monospecific even-aged forests, competition is relatively easy to deal with, and simple stocking guides offer a useful way to estimate competition and manage forest stands (e.g., Reineke 1933; Newton 1997; Pretzsch and Biber 2005; Vanclay 2010). But dealing with competition becomes much more complicated in forest stands that are uneven-aged or comprise multiple species. Basal area in larger trees (Wykoff 1990; Vanclay 1991b; Vanclay 1994a, b) is a convenient non-spatial index of competition that is applicable and effective in complex forest stands. When spatial data (tree positions) are available, many more options are possible. Vanclay (1994a, b) classified spatial competition indices into six variants: the competitive influence zone (Ek and Monserud 1974), area potentially available (Moore et al. 1973), horizontal or vertical size–distance (Lemmon and Schumacher 1962), sky view (Bowman and Kirkpatrick 1986) and light interception (McMurtrie and Wolf 1983) approaches. Some of the more promising amongst the many alternatives available include the size-distance approaches based on the formulae of Miina and Pukkala (2000) and Hegyi (1974), but the specific calibration of these indices for individual species remains an important topic for further research.

Despite a wealth of literature on modelling intra-specific competition, there is no clear paradigm for modelling inter-specific competition and facilitation. While there is evidence of both facilitation (Forrester et al. 2006) and allelopathy (Blanco and Kimmins 2009), the dominant modelling approach tends to rely on a concept of strong and weak competitors built on competition indices pioneered for monospecific forests (e.g. Bristow et al. 2006), overlooking the possibility that species relationships may change over time (Forrester et al. 2011) and may not be consistent across species (Lhotka and Loewenstein 2011). To date, most models concentrate on direct species interactions, and overlook the indirect effects such as the effects of species competition on soils (Rothe and Binkley 2001).

4.3 Site Productivity

Forest modelling has a long tradition of recognising the importance of site productivity, and of using simple unidimensional indices such as site index in the prediction of plantation growth. While the utility and limitations of these indices is well established for plantation situations (Skovsgaard and Vanclay 2008), there is no dominant paradigm for dealing with site productivity in stands managed as CCF (Vanclay 1992) and many research questions remain outstanding. There are some indications that hyperspectral remote sensing may offer an efficient way to integrate the many dimensions of site productivity into an index amenable for stand growth modelling in CCF (Vanclay and Preston 1990; Turner et al. 2004), but progress with reliable site productivity assessment within CCF will depend on quality data drawn from long-term monitoring (Skovsgaard and Vanclay 2008). Long-term monitoring data, where available, provides a useful basis to formulate growth indices that may be used as a basis for calibrating other more empirical approaches (Vanclay 1989), and can be used to recalibrate and customise growth models (Trasobares and Pukkala 2004). Where dendrometric approaches cannot be used directly, indicator species and site descriptors may offer a practical way to estimate site productivity (Bergès et al. 2006).

4.4 Mortality

In even-aged forests, the self-thinning line provides an effective way to estimate mortality in forest stands, but the concept is of limited utility in CCF. With CCF, the best option is to predict tree survival from the resources deemed to be available to each tree. There are many ways to do this at the stand level (e.g. Vanclay 1991c) or individual tree level (Weiskittel et al. 2011). Most approaches tend to use a logistic model to predict survival from tree size and competitive status using variables such as relative size, basal area in larger trees, and crown ratio. Reviews (e.g. Hawkes 2000, Weiskittel et al. 2011) suggest that there is no single best way to deal with mortality, although there is an emerging consensus that empirical equations tend to perform better than theoretical (Bigler and Bugmann 2004b) and mechanistic approaches (Hawkes 2000).

Some models also deal with irregular mortality such as that arising from wildfire, pests and disease (e.g., Kobziar et al. 2006; Vega et al. 2011).

4.5 Regeneration and Recruitment

With industrial plantations, stocking is given and there is no need to model regeneration, making for a simple and robust model, but the modelling of regeneration is critical for models intending to model CCF over long time intervals. Depending on the context, regeneration models may begin with flowering and pollination, with seeding, regeneration, or recruitment (Weiskittel et al. 2011), but the most common approach in models used for informing forest management is to begin with established regeneration, often when saplings reach breast height (1.3 m) or a larger height threshold. Such models often entail two stages, reflecting the probability of a regeneration event and the abundance of regeneration given that an event occurs. The difficulty of predicting regeneration has spawned a diversity of approaches, and it is difficult to recommend any particular approach because the most promising approach depends on the forest type involved. For instance, Vanclay (1992) predicted the probability of a regeneration event using logistic equations, Hasenauer et al. (2001) used artificial neural networks, and Vickers et al. (2011) used an expert system to initiate regeneration. Similarly, modellers are divided about how to deal with regeneration once it is predicted: Vanclay (1992) recruited regeneration directly into the main model, whereas Monserud and Ek (1977) maintained a separate regeneration submodel, recruiting to the main model when trees were estimated to have reached 7.6 metres height. Miina and Heinonen (2008) offered a recent example of a stochastic regeneration simulator. The enduring principles that should guide modellers is the principle of parsimony (as simple as possible), of science (refutable), and of utility (fit for purpose).

4.6 Merchantability and Hollow Formation

It is insufficient simply to predict the existence and size of trees in a forest stand when CCF is practiced, because if is also important to estimate the proportion of merchantable timber, and to estimate some of the habitat services offered by individual trees. Despite this important need, there are relatively few such models. Strub et al. (1986) and Vanclay (1991d) offer some of the few examples of the modelling of merchantability of individual tree stems.

CCF is often adopted in favour of other silviculture alternatives because of the greater provision of environmental services, so it is important to be able to estimate progress towards these goals. In many situations, one of the key goals is the availability of hollows suitable for hollow-dependent fauna, and thus it may be useful for a CCF model to explicitly model some characteristics of tree hollows in the stand under simulation. Given the importance of these aspects, there are surprisingly few examples of such models, but representative examples are offered by Ball et al. (1999) and Ranius et al. (2009). Pukkala et al. (2005) offered a model for the spread of butt rot in even-aged conifers.

4.7 Physiological Relationships

A review of models for CCF would be incomplete without mention of mechanistic models and the relationships therein, but the task is complicated by the vast diversity of approached offered by the various adherents. Lacointe (2000) offered a comprehensive review of carbon allocation, and Weiskittel et al. (2011) offered a synthesis from a forest management viewpoint. The 3PGpjs variant (Sands 2004a) of the 3PG model (Sands and Landsberg 2002) is a widely-used open-source model that has been well documented (e.g. Almeida et al. 2004), including advice on the data gathering and model calibration procedures (Sands 2004b) needed to adapt this model for new species. This model has been used widely (e.g., Roxburgh et al. 2006; Coops et al. 2011), but primarily for even-aged plantations.

5 Validation and Implementation

Model design is but one aspect of a reliable model, and model calibration and evaluation are equally important in ensuring a serviceable and reliable model. Much has been written on model evaluation (e.g., Vanclay and Skovsgaard 1997; Weiskittel et al. 2011) and readers are directed there for technical aspects of this process which is the same for CCF models as with other models. It suffices to underscore that good data and reliable relationships are necessary, but insufficient to ensure a reliable model without careful calibration and effective evaluation.

Many of the classic growth models were implemented with thousands of lines of computer code, often Fortran (e.g., Botkin et al. 1972) or C++ (Congleton et al. 1997), and this code is sometimes re-used (Salminen et al. 2005). However, efficiencies can be gained through object-oriented programming (Sequeira et al. 1991), the adoption of modular structures (Reynolds and Acock 1997), and the use of visual modelling environments such as STELLA (Costanza et al. 1998) and Simile (Muetzelfeldt and Massheder 2003). Garcia (2003) has also offered practical suggestions for reducing the dimensionality of simulation models.

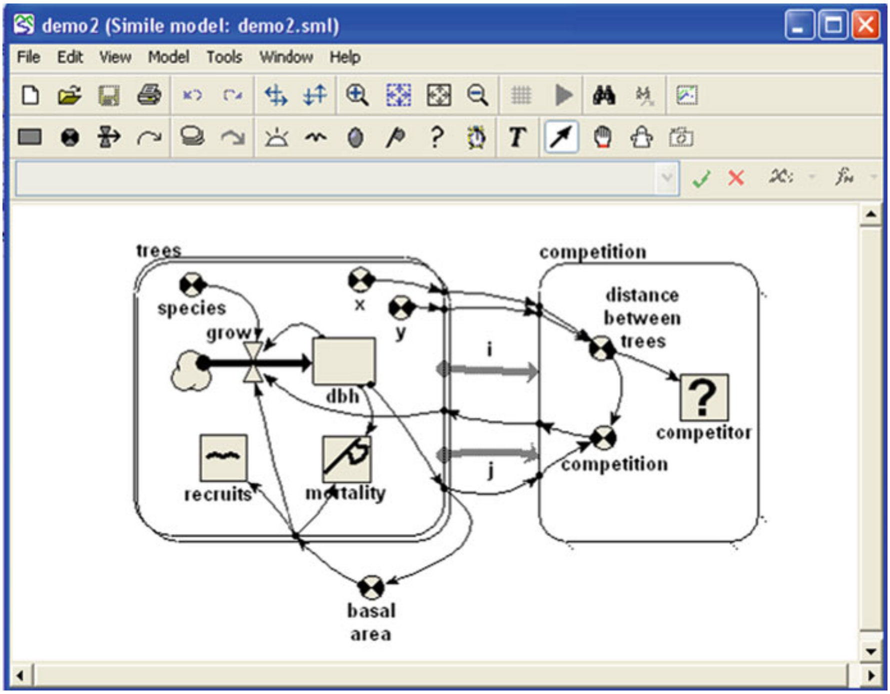

Fig. 7.2 An spatially-specific individual tree model implemented in the *Simile* modelling environment

In the past, much effort was devoted to finessing computer code to reduce memory requirements and run times, but with the advent of modern computing, these aspects are less critical and the primary consideration should be ease of understanding and of maintenance (enhancing, updating and adapting to new computing facilities). These aspects are often overlooked, but can greatly affect the utility of a model and should not be neglected. Fortunately, modern computing resources such as visual modelling environments greatly facilitate this aspect of modelling.

Visual modelling environments such as *Simile* (Muetzelfeldt and Massheder 2003), offer great potential for the rapid development, prototyping and testing of simulation models (Vanclay 2003). Figure 7.2 illustrates one example that was simple and quick to compile, but that implemented a sophisticated individual tree model to illustrate the capability of *Simile* and similar systems. This figure looks like an explanatory diagram, but is actually a model that simulates when the 'play' button (►) is pressed; it looks deceptively simple, but is in fact a sophisticated individual tree model. The point of this figure is to illustrate that powerful tools such as *Simile* make advanced modelling concepts accessible to a broader range of model builders and model users. Other more complex examples of spatially-explicit models of mixed species forests have been presented by Vanclay (2006).

6 Conclusion

There are well-established precedents for modelling uneven-aged and mixed-species forests that offer useful guidance for modelling continuous cover forests, but many challenges remain. Fertile areas for further research include site productivity assessment and the modelling of regeneration and species interactions (both synergism and allelopathy). Despite these challenges, there are good precedents for modelling timber production from CCF systems, but there remains a need for further research and development in modelling non-timber products and environmental services from these forests, and to scale up to evaluate landscape-scale implications of management options (Pretzsch et al. 2008).

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