CHAPTER 5 A REVIEW: FROM CONCEPTUAL MODELLING TO AGENT - BASED SIMULATION

5.1 Introduction

Ecological rehabilitation is a long-term process with spatial and temporal variations that are difficult to study using a traditional experimental approach. In particular, the successional process to reach the rehabilitation goal takes considerable time and is difficult to predict and judge the success of the rehabilitation on the basis of a few years monitoring in the early stages of development. Simulation models provide an alternative approach, particularly if a process-based model is used. A modelling approach provides the opportunity to test how rehabilitation will progress from establishment to maturity under a range of different conditions and management strategies.

A range of models can be used to study ecological rehabilitation based on the purpose and application of its use. Models may be classified in many ways according to selected criteria (Urban & Shugart 1992). In fact, it is problematic to place them into classes because of their multi-aspect form. In this thesis, models are grouped into conceptual models, mathematical models and simulation or tactical models.

5.2 Conceptual Models

A conceptual model is commonly used in rehabilitation and is based on simple hypotheses or guidelines as to how rehabilitation strategies may allow systems to progress to end goals by presenting flow charts and network diagrams. Most theoretical concepts adopted in rehabilitation can be explained in this way. For instance, Clements (1916) succession theory can be described as a relay floristic model (Egler 1954). Westoby *et al.* (1989) proposed a state-and transition model of succession for rangelands. Hobbs and Norton (1996) illustrated the succession threshold according to the ecosystem transition from a degraded state to the desired state. The conceptual model by Yates and Hobbs (1997) presented the process of woodland rehabilitation in the Western Australian wheatbelt. Grant *et al.* (2001) developed a state-and-transition model for open-cut mining rehabilitation, which started from the initial state and moved through a range of conditions to the desired state along the successional trajectory. Connell (1978) and Huston (1979) used graphs to explain the equilibrium and non-equilibrium model of competition resulting from succession. Huston (1979) also presented the "Intermediate Disturbance Hypothesis (IDH)" graphically. Other applications include the Vital Attribute Model (Noble & Slatyer 1981) and Initial Floristic Composition Model (Purdie & Slatyer 1976). Conceptual models tend to focus more on description rather than providing operational or mechanistic solutions and they are more likely to be metaphysical with limited practical use in predicting outcomes under different sets of conditions. However, the model descriptions and hypotheses on which they are based can be used as guidelines for rehabilitation planning. Finally conceptual models generally form the basis for the development of other forms of ecological models.

5.3 Mathematical Models

Mathematical models may take a range of forms and all are commonly used in ecology research. They can be classified as linear or nonlinear models, static or dynamic models, deterministic or mechanistic models etc. In this thesis, mathematical models are grouped according to procedures adopted to describe population dynamics within the model.

Statistical models are based on statistical analyses of population dynamics and are usually represented by linear or polynomial equations. Such equations are used to describe density-dependent functions of populations, such as growth, development and regeneration, or to present the correlation between population density and various factors that change over time and/or in space (Sharov 1997).

Most statistical models commonly use regression functions. For example, population density for the next year can be predicted from the current density at the same location where predictions of statistical models are based on the presumption that the previous behaviour of the community is similar to the future behaviour. However, if the past system exhibited specific behaviours that are likely to be different than future behaviours, it is possible future predictions will provide misleading results. Such models are limited in their ability to predict the future behaviour of the system.

Analytical models are similar to statistical models but generally describe average case changes in populations. Exponential and logistic growth models are typical examples of analytical models.

The Volterra-Lotka model, which is a simple two species predator-prey model developed by Lotka (1925) and Volterra (1926) independently, used non-linear and differential equations to describe the interactions of a predator and its prey. However the use of either population equilibrium or stabilities of fixed points make the model unrealistic but the concept behind it has provided a valuable reference for more recently developed models. Ezoe and Nakamura (2006) developed size structured models for single species, and analysed the impact of dispersal on metapopulation by assuming each subpopulation grows in a logistic manner.

Stochastic models are the models that include random, probabilistic or stochastic processes. For instance, stochastic models describe the system behaviour between neighbouring units or events which depend on interaction rules expressed by probability (Camporeale & Ridolfi 2006). The Markov model, for example, is a classic stochastic model (Horn 1975). A stochastic model is more appropriate for expressing discrete events, particularly when it is necessary to take account of events occurring randomly over time. In a stochastic model different outcomes can result from the same initial conditions. Sometimes a stochastic model may also be a simulation model, e.g. a stochastic model for rehabilitation is EMBYR (1997), developed by the Oak Ridge National Laboratory, and is a landscape model developed for fire disturbance.

In contrast to stochastic model, the variable states in a **deterministic model** are determined by parameters or by sets of previous states of these variables (Vogel 1999). Therefore, when initial conditions are same or similar, deterministic models will perform the same way and produce the same or similar results.

5.4 Simulation Models

Due to the long time span involved in rehabilitation practices for establishing natural ecosystems, the outcomes of initial rehabilitation strategies are often uncertain in relation to reaching the desired goal. In order to be sure that chosen rehabilitation practices are likely to be successful, ecologists, social communities, regulators and industrial companies need to track and manipulate rehabilitation processes to achieve success. Simulation models with strong predictive functions can be used to predict the future results of rehabilitation measurers.

Most simulation models are sophisticated and process-based in relation to biotic and abiotic factors and their interaction, and how they may change over time and space. Although Cairns (1991) noted that predictive models are not common in rehabilitation ecology, simulation models should be designed to predict rehabilitation outcomes based on the mechanisms associated with vegetation succession. Unlike analytical models that show prediction by extrapolation, the process-based models use outputs of previous stages as input for further steps in the simulation (Martineau & Saugier 2007). The advantages of simulation models are evident as they can be used to examine rehabilitation mechanisms without disrupting an actual ecosystem to predict the rehabilitation process beyond current experience and experimental evidence.

Early simulation models described the vegetation as a mosaic of closed canopies and gaps. The theory behind this is that light is critical to the success of most species and those interactions between individuals and species is mostly driven through competition for light. Although such models used discrete cells as plants to represent the vegetation, there was no direct communication between cells (Shugart 1984) and it ignored the explicit spatial structure. Since models need to track interaction and competition of individuals and species in space and express the dynamic processes over time, Agent-based Models (ABM) were introduced into ecological research (Grimm 1999).

Models have been used in rehabilitation studies for different purposes. Most have been based on knowledge associated with natural vegetation succession. Conceptual and empirical or deterministic models that have been developed can provide an overview of rehabilitation. To describe the rehabilitation progress in relation to degradation intensity, various mathematical models may be appropriate to quantify ecosystem dynamics in terms of criteria proposed by ecologists. Simulation models are useful to examine rehabilitation mechanisms and to predict the future outcome of those processes.

5.5 Agent – Based Model

Rehabilitation can be considered as an essential practice in ecosystem repair and a section of vegetation succession (Hobbs & Harris 2001). Succession consists of invasion, colonisation, persistence and establishment at the population level (Arnold *et al.* 1992), such that population dynamics are derived from individual behaviour. Therefore, the understanding of the dynamics of individuals and simulating individual plant growth and development forms the basis of Agent-based Models.

Although the individualistic concept in ecology was raised in the 1920s (Gleason 1926, 1936), it was not seriously considered by many ecologists. With the development of the representative gap model – JABOWA established by Botkin et al. (1972, 1979), researchers reconsidered the importance of individuals in developing ecological communities (Pickett 1985; Glenn-Lewin 1980, Pacala *et al.* 1993 & 1996). Gap models are based on the gap theory (Watt 1947) to simulate community succession by means of modelling individual behaviour, and view vegetation succession as a stochastic process (Botkin 1979, Urban *et al* 1991). Although these kinds of models use discrete cells to represent individual plants, there is no close communication between cells (Shugart 1984) so that the interaction between individuals was not explained well. However, the concept of describing ecosystem dynamics from the view of individuals has now emerged, and the function of individual plants in the ecosystem has been studied (Pacala & Deutschman 1995), particularly with the introduction of Agent-based Models into ecology (Grimm 1999, Uchmanski & Grimm 1996).

An Agent-based Model is sometimes called as Individual-based Model. In relation to the term ‘agent’, there is no clear and general definition (Gilbert & Troitzsch 1999). Franklin and Graesser (1997) considered all different definitions and concluded that entities having autonomous, reactive, goal-oriented, communicative and temporally continuous properties, or having mobile, flexible, and learning characteristics, that can sense and react to the environment are agents. Each agent has states (properties/characteristics) and behaviour (actions) in their environment. For example, individual plants or animals in an ecosystem, individual people in a society, individual cars in traffic, etc. have 'agent' characteristics and can be set as agents.

The application of an Agent-based Model to ecology can be expressed as individuals in an ecosystem that have different life spans and behaviours, both temporarily and spatially. The population is the aggregation of individuals that occupy the niche. However, a population is not just a simple collection of individuals; but it is the result of individual growth, competition and interaction. Competition occurs among individuals within and between the populations (Bampfylde *et al.* 2005). For plants, the competition is for space, light, water and nutrient, but for animals, the competition is for food, habitat and space. Within an ecosystem, individuals sense and react to environmental changes and to other individuals that surround them. The dynamics of individuals also translates into energy and nutrient flows within the system. Changes within individuals also have an impact on population dynamics. Moreover, population fluctuations influence other populations which are then reflected at the ecosystem level. Therefore, an Agent-based Model is a bottom-up model compared with traditional population or community models. Thus ecosystem dynamics are explained by understanding changes of the individuals and their interactions (Winkler & Heinken 1997)). Stochastic characters can be built into the process of an Agent-based Model, which means that modelling results may be different even with similar initial conditions. Thus an Agent-based Model in this way can also be considered as a stochastic process-based model.

5.5.1 Agent-Based Models and Object-Oriented Programming

Obviously, the key task for the Agent-based Model is to correctly track individual behaviour, competition and interaction.

Computer programming languages, especially Object-oriented programming (OOP) such as 'Java' , 'C++' , and 'Object C' provide tools for Agent-based Model development. An agent in an Agent-Based Model can be simulated through the main characteristics of OOP (Eckel 2002). The relationship between an agent and an object is:

- The Object-oriented programming contains a set of objects (e.g. plant or soil); Agent-based Models have a set of agents.

- Each object has its own attributes/states (i.e. plant age or property of soil) and methods (which may be the behaviour of the object, i.e. plant growth, reproduction, and mortality or soil pH changes). Each agent has its own attributes and behaviour.

- Objects determine their behaviour and respond to other objects through information transfer built as program parameters and rules (i.e. how plants compete for light, space and nutrients). Agents interact with others based on logic rules.

- Objects that have the same or similar attributes are classified as a class (i.e. Tree Class, each instance of the 'Tree Class' (a tree) will have the same definition of attributes and behaviour, but the detailed value and action varies). Class is an abstract of similar objects, and an object is created from it.

- All objects in a class share the same information;

- The attributes and behaviour in the super-class can be generated by a sub-class (i.e. a 'Young Forest' Class may generate all the attributes and behaviour from its super-class 'Forest'). Inheritance and encapsulation are the major characters in OOP and that can be generated to the agents.

These characteristics of Object-oriented programming are compatible for Agent-based Models in formulating a complex system in 'reality' and it does not need to create a new programming language for Agent-based Models. An object has similar characters to an agent. In some ways, an agent can be derived from an object but it is different from an object because of its unique features. An agent can be considered as an autonomous object or an intelligent object. In an ecosystem, an individual plant is an agent. It has age, DBH and height attributes, it germinates, grows, dies, senses to and learns from the environment surrounding it, responds to other plants and adapts to the environment. The common characteristics of these agents is collected and created as an agent class. In the model, we called it as *Plant* class (Chapter 6). An agent is an instance of agent class. The environment in which a plant agent lives is an object rather than an agent because it does not have the features to be an agent. The interactions within agents, between agents and other objects are expressed through logic rules. The logic rules are from biological and ecological principles. Therefore, Agent-based Models are rule-based.

5.5.2 Framework/toolkits of Agent-based Model

The Agent-based Model is built mainly in two ways; one is establishing a model by means of writing an Object-oriented Programming language for a particular domain and the other is to modify and develop it from similar existing models. In the first case it requires someone with a strong programming background and the ability to compile all the modules that the model requires besides the model itself, i.e. data input, establishment, compile, display, data and graph output modules. However, most potential users are from different professional research fields (except computer science) and may have the ability to understand and write the basic program but are not professional computer programmers. Because of this, some programmers have developed toolkits or Special Object-oriented programming frameworks since the 1980s that can be used widely in Agent-based Models to simulate complex ecosystems. A framework contains a library of programming codes, user interface and a development environment for programming. Frameworks for Agent-based Models provide basic modules for users who have some background in appropriate computer programming languages and good knowledge of their own fields. The user can then write their own rules in the existing framework, or can modify and extend the framework to establish their own particular models or even develop their own framework. In this way, users do not need to write program codes for the basic modules (i.e. data entering, compiling, display, or output modules), but need some basic knowledge of programming languages to complete the task. It is important and necessary to choose a suitable framework that has desirable functions for model development and application. People without a background in computer programming would have to use an existing model with the option to change some parameters rather than changing the programming codes. Such an option has a high risk because models are built for a particular purpose. Since Agent-based Models simulate an ecosystem by using rules that express ecosystem development and dynamics, different applications require different rules.

In order to satisfy the diverse requirements from different users, many different frameworks for Agent-based Models have been developed and applied in ecology, social sciences, and economics. Common frameworks are ASCAPE, REPAST, AGENTSHEET, GECKO, SWARM, CORMAS and STARLOGO etc. Some Agent-based Models have been developed using these frameworks and applied in ecology, such as ECOTALK (Baveco & Lingeman 1992), HOBO (Lhotka 1994), OSIRIS (Mooij 1997), and ECOSIM (Lorek 1998). However, most frameworks have their problems when they are adapted to different circumstances because they: 1) are designed for particular problems or models, and therefore difficult to transfer to other models; 2) are only used under a special operating system; 3) lack how-to-use documents; and 4) provide incomplete functions.

Table 5.1 provides some basic information on major frameworks. **Swarm** is one of the best known multi-agent simulation platforms and was originally created by the Santa Fe Institute, United States, and is now maintained by the Swarm Development Group. It has representation / infrastructure and a schedule for actions, offers model building, analysing, displaying and controlling functions, with a set of complex object oriented libraries. The original Swarm was compiled in 'Object C', and subsequently in 'C++' and 'Java'. Swarm contains a main simulation module (Simulation Swarm) to create and control objects' behaviour; a basic module to collect data from simulations and draw graphs; an observation module to display images and graphs (Display Swarm); and a time schedule for system time control and updating agents. Since its design in 1994, Swarm has possessed powerful functions and proven to be successful, and also served as a model for other toolkits. The application of Swarm has touched many fields from economic, social and environmental sciences to ecology. It has multiple functions with complex mixing schedules of structures including distribution across the multilevel swarms. It also has the function to represent the model as an XML document tree, but many of its structures have not been completely used in most applications. Swarm is used mainly in the field of Artificial Intelligence (AI). However, because of some disadvantages it has been limited in its utilisation by potential users. For instance, it has complex and large toolkits which in some way make it difficult to understand. In addition to 'Object C'/'Java'/'C++' programming code, it also has its own codes. Unfortunately, the 'Java' version has not been entirely independent from 'Object C', which confuses the user who can only understand Java. However, its design concepts have impacted on other toolkits, and even served as a model for other toolkit development.

Table 5.1 Agent-based Toolkits/Framework

Toolkits	Developer	Computer language	Application Fields	Open Source Codes (Yes or No)
Swarm	Santa Fe Institute, USA	Objective C/C++/Java	Natural, Economic, Social sciences	Yes
Ascape	Brookings Institute, Washington DC	Java	Natural, Economic, Social sciences	Yes
Cormas	CIRAD, France	Smalltalk	Natural, Economic, Social sciences	No
Xraptor	University of Mainz, Germany	C++ (only for UNIX with X Window System & Motifl.2)	Continuous Events	Yes
Starlogo	Massachusetts Institute of Technology	LOGO	Discrete Events, Mainly used as teaching tool	No
AgentSheets	AgentSheets Inc.	Visual programming paradigm	Teaching/ demonstration	No
Repast	University of Chicago, USA	Java	Discrete Events, Natural, Economic, Social sciences	Yes

Ascape is another framework that was developed initially by Parker (1998, 2001) from the Brookings Institute for the artificial society study. Ascape was developed from Swarm but is easier for the user to develop models. Ascape supports complex model design and the end-user tools make it an option for non-programmers. However, it does not provide detailed documents associated with its structure and application.

Cormas was developed by CIRAD, France, based on the Smalltalk language (Bousquet *et al.* 1998). It provides a programming environment for multi-agent systems, and develops simulation models to express relationships between individuals and groups, and between societies and their environment.

Xraptor was conceived by Bruns *et al.* (2003), and provides a simulation environment for continuous virtual multi-agent systems. It is written in C++ for UNIX platforms with the X Window System and Motif 1.2

In addition, **Starlogo** (Colella *et al.* 2001) and **AgentSheets** (AgentSheet 2006) are more suitable for non-programmers to create agents with behaviours and missions, and teaching goals etc.

Repast is an agent-based simulation environment developed and maintained at the Social Science Computing Department of University of Chicago and Argonne National Laboratory to support design, analysis and distribution of the model. The original Repast framework was generated from Swarm, and has a representation/infrastructure similar to Swarm. It has an independent framework written in 'Java' and is designed for simulation of discrete events with time units that are called 'ticks'. It attempts to develop an easy to use simulation environment with abstraction of simulation infrastructure, extensibility and appropriate performance (Collier 2003). It contains most of the elements that agent-based simulation needs and expresses them through Java classes. The classes are sorted into different packages so that the modeller can establish his or her own Agent-based Model using different packages;

i.e. the 'Engine Package' is mainly used for setting up, manipulating and running a simulation; the 'Analysis Package' is for gathering, recording and figuring data; the 'GUI Package" contains classes for visual graphing, taking snapshots and making QuickTime movies; the 'Space Package' is used for building special agent simulation relationships and the environment; the 'GIS Package' includes node, line and polygon features for GIS application and integration in the model; the 'Network Package' aims to build a network simulation environment and the 'UTIL Package' has different utility classes such as random number distribution, display dialogs etc. (Collier 2003).

A typical Repast Agent-based Model has a collection of agents and objects that are defined as the agents' environments. Each agent has attributes and behaviour that the models want to explore. Logic statements are used as the rules and descriptions for each agent, the relationships between agents and agents and their environments. Logic statements control the agents' behaviour and actions to others and their environment, which are expressed through different classes and packages. "Scheduling" is the core part of Repast, which contains model establishment and agent behaviour execution.

Repast provides detailed "how-to" documents to start with and an online supporting mailing list to provide updated information and technical assistance for the user, which makes it better than other frameworks. In addition, besides the demonstration models provided by Repast at Repast web site, it also provides numerous models published by Repast users for downloading.

5.5.3 Application of Agent-based Models

Having a process simulation function, an Agent-based Model can simulate the lifestyle and span of individual plants (i.e. EFIMOD for Scots Pine (Chertov 1999)) or the interaction and competition among neighbouring plants in a multi-species plant community (Law & Dieckmann 2000) where the reproduction through seed dispersal and death of individual plants depend on other individuals in a specified neighbourhood. The model describes the structural dynamics and changes in local neighbourhoods over time and how the local spatial structure influences population dynamics over time. Plant-herbivore interactions were also developed using an Agent-based Model to test the potential interactive effects of explicit space and coevolution on population and community dynamics (Hartvigsen & Levin 1997).

Agent-based Models can also be used to simulate the influence of tree species in rainforest structure and composition. The FORMIND model (Kohler & Huth 1998) is derived from an individual-based model of FORMIX3. In the model, competition between trees for light and space was simulated in 20 x 20 m plots. A carbon balance is calculated using photosynthesis and respiration functions. Tree variables, such as stem diameter, height and crown length are calculated. Falling trees and the canopy gaps are modelled through mortality. Structural characteristics of rainforest stands are analysed to demonstrate the development of layered structures. The model also has the ability to analyse processes and the spatial structure of gap formation in rainforests.

Agent-based Models can also analyse disturbance dynamics and species coexistence under a gradient of lightning strike frequency in a multi-species forest (Savage & Askenazi 2000). The results suggest that 'low levels of disturbance results in highly ordered landscapes which exclude fire and are captured by late succession species'. Savage et al (Savage *et al.* 2000) used an Agent-based Model Arborgames, in which species are used to 'mimic a rational gradient of life history traits from highly opportunistic to late successional forest tree species'.

The main problem for predicting future ecosystem dynamics is the long-term frequent monitoring using experimental field ecology. Schmitz (2000) used an individual-based computational model that predicted long-term community dynamics of herbivores, and found that short-term behavioural responses played a much stronger role in shaping community structure than longer-term processes. Consequently, it was sufficient to predict the long-term dynamic of the population by knowing the short-term responses of herbivores at the evolutionary ecological level.

Agent-based Models show more reliable results than other traditional models in predicting community dynamics. Schwartz *et al.* (2000) investigated 200 individual trees of the endangered species of Florida torreya (*Torreya taxifolia*) from 1988 to 1996 along the eastern side of the Apalachicola River in northern Florida and southern Georgia of the USA. They used an Agent-based Model (TORSIM) and a stage-class transition matrix model (RAMAS) to estimate the likelihood of population persistence over several decades. Both models produced similar results indicating that the extinction of this species in the wild is unavoidable due to the lack of seed resources unless seed production is managed. However, the results showed that the transition matrix model RAMAS was less optimistic than the Agent-based Model on persistence of the population.

Agent-based Models can simulate the whole life span of individual species including inter-specific and intra-specific competition; and the interaction between plants and the environment to produce simulations from the individual level to populations and the community. Models can also explore the dynamics of invasion, establishment, colonisation, and competition of individual species in a changing environment brought about by community changes. Thus, the succession process can be displayed visually.

5.6 Summary

Ecological models can be used to bridge the gap between rehabilitation theory and practice. There are only a few models used in mining rehabilitation due to the lack of long-term transparent and repeatable data. For instance, most conceptual models depend on the general principles of succession but do not take specific mining impacts into account, and are usually not supported by data from field investigations. In addition, the initial and subsequent floristic composition of rehabilitation sites mostly depends on seed stock in the topsoil and seed rain from the neighbouring community, which might indicate rehabilitation processes are site-specific and it is difficult to find a general model to describe the revegetation processes. Many mathematical models have an important role in mining rehabilitation (Wiegleb & Felinks 2001; Rodrigues *et al.* 2004; Hancock *et al.* 2006). The trend in recent years for this kind of model is to extend their analytical functions to include a spatial component. Site-specific goals and post-mining conditions at each mine site suggest that it would be difficult to find a model that can be widely used in rehabilitation practice. Purdie and Slatyer (1976) suggested that the application of the floristic model to vegetation re-establishment after disturbances might only be reliable when environmental stress conditions of rehabilitation sites are similar. Models can be developed to provide a general explanation of ecological principles as a guideline for rehabilitation practice and can also be used to improve ecological knowledge through model validation. Since rehabilitation is a long-term process, models need to predict the development of vegetation to the desired endpoint so it can assist in rehabilitation planning, implementation and management.

Numerous models can be applied to rehabilitation, but most of them are limited by the lack of their spatial and temporal capacity. Agent-based Models with temporal predicting functions overcome the limitation of most traditional models. Such models can be expected to improve the research approach to rehabilitation, and provide predictive patterns for the rehabilitation process and vegetation succession.

CHAPTER 6: DEVELOPMENT OF A VEGETATION COLONISATION MODEL FOR THE BOGGABRI MINE SITE, NSW

6.1 Introduction

Periodic measurements over the last 20 years on vegetation development on different soil materials, preliminary soil-overburden studies, as well as early growth of different species have provided the basic information on initial floristic changes on the study site at Boggabri. However, besides these initial results, the description of plant colonisation and community development in terms of species diversity and changes in community structure and composition over both spatial and temporal scales in the long term are essential for mine site rehabilitation. Such information can be used to develop predictive patterns for vegetation succession, which can then be used to provide decision support for different management strategies. As has been indicated in Chapter 5, an Agent-based Model has potential advantages for this purpose.

This chapter discusses how such a simulation model was developed for vegetation colonisation and succession at Boggabri, NSW. The methods, model rules and parameters will be explained in detail.

6.2 Agent-based Vegetation Succession Model Architecture

The development of the model includes three major components: model initialisation, model establishment and simulation, and model display.

Model initialisation includes the definition of agents, declaration and initialisation of model parameters. Model establishment and simulation determine model functions and modify the logic rules for the agents and the environment in which agents live. It also explains the methods used to simulate the lifespan of agents over time steps. The agents' lifespan, interactions between agents and agents' reaction to environmental objects are governed by a set of logic rules written in the programming language. Model display shows the simulation results in map form and as frequency graphs for different successional states.

The model is built to represent the dynamic interaction between individual plants with different capacities for niche competition on two 'soil' types. Both environmental influences and biotic factors are incorporated into the model to describe vegetation colonisation and community succession. Soil condition is used to modify plant growth conditions. The biotic factors include seed rain and seed bank; seed germination; seedling establishment; plant growth, and plant death along with soil properties.

Six tree species, *E. pilligaensis, E. crebra, E. albens, E. populnea, Callitris glaucophylla,* and *Casuarina cristata,* and three shrub species, *A. deanei, S. nemophila*, and *D. viscosa* are simulated when growing on the soil types of bare overburden and topsoiled overburden.

6.3 Objects and Parameters

6.3.1 Objects Definition

An Agent-based Model is a computational rule-based model. Since the model is programmed by the object-oriented programming language, the definition of objects forms the foundation of the model. The research target and the associated environment can be determined as different objects in the program, and corresponding classes are created. Therefore, the model includes *Space*, *Seeding, Spring*, *Plant*, *Species*, and *Forest* objects, and describes the correlation and interaction of the different objects to simulate the dynamics of different objects. The model is formed by combining the objects into structured networks in a hierarchy.

As discussed in Chapter 5, the entity that has autonomous, reactive, goal-oriented, communicative and temporally continuous properties is designed as an agent, which can be considered as a specific object in the object-oriented program. Individual plants (trees or shrubs) are the basic agents used to describe and develop the dynamics of the vegetation succession. Species diversity or composition at a particular site is based on the contribution of each individual plant. Each individual plant in this model changes over time as a result of germination, growth, adaptation to the environment, competition between individual plants, and mortality. Therefore, *Plant* is the agent in the model. The *Plant* agent has attributes such as plant name, age and height. It also has a range of behaviour which is called 'object's methods' in the program, such as growth processes.

The *Space* is the object to describe the place in which agents live and also contains environmental information (i.e. soil properties). The *Space* object is treated as a series of 2-dimensional lattice cellular models representing the environmental conditions for living plants (see Section 6.4.1).

The *Soil* object contains different soil types that impact on species growth. There are two major soil types in this model, topsoiled overburden and bare overburden. Soil type plays an important role in rehabilitation. Plant species have different germination rates and mortality rates on each soil type, which then impacts on the plant colonisation patterns. For example, shrubs prefer topsoiled areas and only occasionally grow on bare overburden, but trees grow well on bare overburden (see Chapter 4). The *Soil* object is linked to the *Space* object and described in the cellular model, and each cell of the *Space* object will contain soil information.

The *Species* object is a description of the life history for each species and includes species information on seed rain, seedling establishment, mortality and growth rates within the *Space* object. It can capture the similarity of the features of individual plants at the species level.

The *Forest* object is a hierarchical level above the *Plant* and *Species* objects. Its purpose is to display the forest composition visually. The *Forest* object simulates forest changes such as when young plants grow to mature plants over time, old trees die as they reach their life expectancy thereby creating space for new plants to grow and fill the gap. Intra- and inter-specific competition is involved in the *Forest* object and can result in premature death through competition and the creation of additional space for the recruitment of new individuals.

The *Seeding* object simulates how the parent tree drops seeds into neighbouring cells in the *Space* object. The seed tree is set as the central point, and the seed dispersal distance is set as the seeding radius. The cells covered by that radius comprise the seeding area. Seeds are uniformly distributed into those cells.

The *Spring* object dynamically describes the probability of seed germination of each species distributed in the *Space* object.

The *Plant* agent is connected with the *Spring* and *Seeding* objects to form seed production, dispersal and germination.

Models built this way can be viewed as a virtual landscape that can be displayed by computer graphics.

6.3.2 Relationship between Objects

The model is a bottom-up model, and simulates from individual plant growth to the population and community dynamics. The individual life span is described by the interaction of different objects (Fig. 6.1).

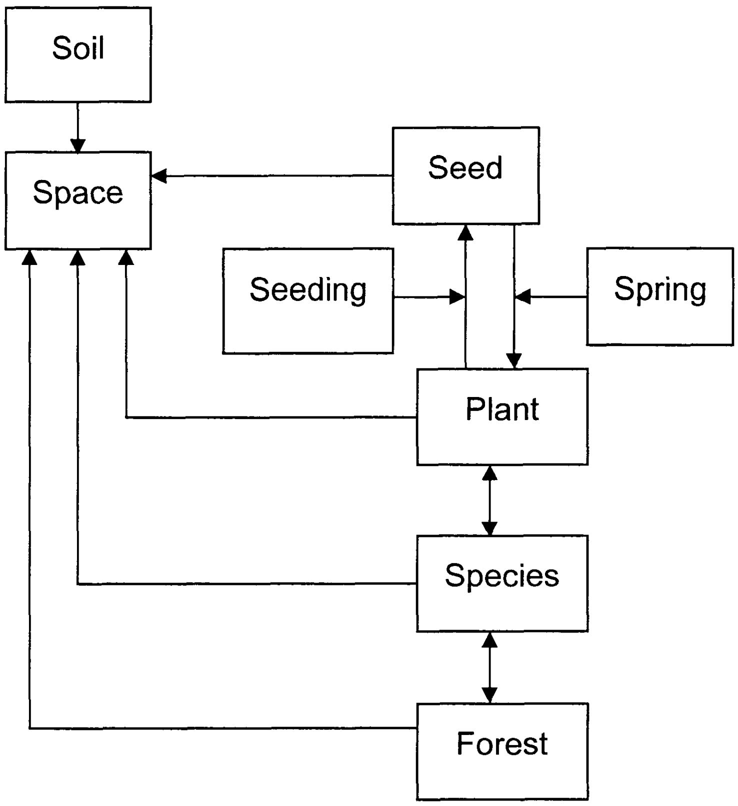

Fig. 6.1 Relationship between different objects.

6.3.3 Data Collection and Parameter Selection

The data used in the model are from two sources: from field observations (which has been discussed in Chapter 4) and from the literature.

Noble and Slatyer (1981) used the 'vital attributes' of key species to explain a successional sequence that is based on the specific life history characteristics in a particular community and pattern of interaction between species over time after a disturbance. Each species in their model was identified as a species type, and the development of replacement sequences in the succession was the result of the various species interaction over time.

The concept of 'vital attributes' is incorporated into Boggabri model to help select parameters. Table 6.1 describes growth, competition, reaction, and adaptation by each agent. This means that they can show the impact of individual plants on the process of vegetation succession. Values for the parameters were derived from research results involving periodic measurements over the past 20 years on vegetation development in different soil materials from soils-overburden studies, as well as germination, survival rate, and early growth studies of each species (Gouvernet, 1980; Duggin, et al., 1982; Grigg, 1987, Denham 1989). These data were then supported where necessary with results presented in the scientific and technical literature (Table 6.1).

Table 6.1 Parameters for each species used in the model

Parameters		Explanation
Seed rain	Seed production	The amount of seed produced by a species in a good seed year (seeds per unit area)
	Viability	The proportion of viable seeds (% viability)
	Viable seed yield	The number of viable seeds produced (production times viability)
	Seeding frequency	The time from one good seed production event to the next (years)
	Dispersal distance	The dispersal distance from parent tree (m)
Seed germination and establishment	Germination rate	Seed germination rate for each soil type (% germination); the soil type is read from soil object.
	Seedling survival	Number of seedlings surviving over the first three years; soil type affects seedling survival.
	Competition mortality	Competitive ability of two plants in a cell; affected by species, height, and age
Species persistence and dominance	Growth	Annual increment in height (m)
	Height	Cumulative height growth; height influences competition
	Age	Increases with each time step (yr)
	Maximum height	Growth terminates when the height of a plant reaches maximum height (m).
	Maximum age	The plant reaches its life span and is then removed from the model (yr).
	Shade tolerance	A criterion for growth and competition (a ranking of relative tolerance)
	Mortality rate	Random mortality applied to mature plants; species dependent

Besides the major parameters described in Table 6.1, the life span of each species is simulated in the model by different stages, and the seed production period is described as:

- Longevity: Each individual plant has a species-specific life span in different life stages: seedling; sapling; young adult; mature adult; and senescent adult. The length of each stage varies by species.

- Seeding periodicity: Trees do not set seeds every year, but have an intermittent periodicity for different species. Seeding periodicity in the model is expressed as an integer which represents the interval of seed production.

- Seed dispersal: Dispersal depends on the capacity of the seeding plant and expressed as the radius of the cells distance from the seeding trees.

6.4 Simulation Methods and Logic Rules for Agent Behaviour

6.4.1 Two-dimensional Cellular Model

The individual plant as an agent has a physical space in which to live. The state and behaviour of each agent is updated in that space over time. The study site is the agent's living space and has been defined as the *Space* object in Section 6.3.

The two-dimensional cellular model of the space object is created as a raster GIS map. The cell size of each grid of the map is 2 x 2 m. Each cell has a row and column number coupled with a location index that relates to the geophysical location in the real world (Fig. 6.2). It forms a two-dimensional cellular model to describe the biophysical information. Soil characteristics and location are contained in the cellular model. The cellular model is also used to track plant growth conditions within the cell.

In this model, each cell is formatted to contain up to one adult plant and one sapling, or two saplings without the adult plant maximally, but many seeds from a range of species. Time-related rules govern individual changes at each time step.

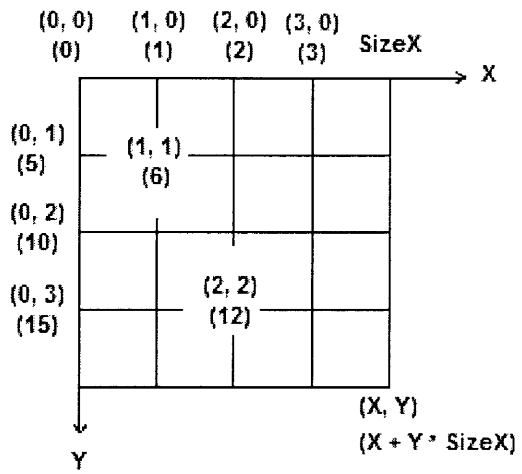

Fig. 6.2 Two-Dimensional Cellular Model applied in the Agent-based Model to contain biophysical information, such as soil. It has a location index. X and Y are column and row numbers that are also referenced with geophysical coordinates; Size X is the number of columns on the X direction; the location index for each cell equals to X + Y * Size X.

6.4.2 Model Simulation Layers

The model is designed such that each grid cell can have one adult tree with one sapling under the tree, or two saplings, or only one dominant adult shrub without any seedling.

The program is designed so that if a tree dominates one cell, it is possible to have a seedling/sapling of a tree or a shrub under the tree; if a shrub dominates the cell, there will be no plants under the shrub; if there is no adult plant dominating in the cell then the cell can have two seedlings/saplings. Each cell can have many seeds. Plants growing in each cell are given a location parameter.

In order to easily track each plant and the seed dynamics in the model, the *Space* object is stated as three major layers. The first layer is called *Seed* Object layer and it is used to track seed germination, while the second is applied to express individual plants growth. In order to track and display each individual plant growth, this layer is sub-divided into two parts: adult plants and saplings. The third layer contains all the plants that dominate in each cell from which the forest is finally formed (Fig. 6.3).

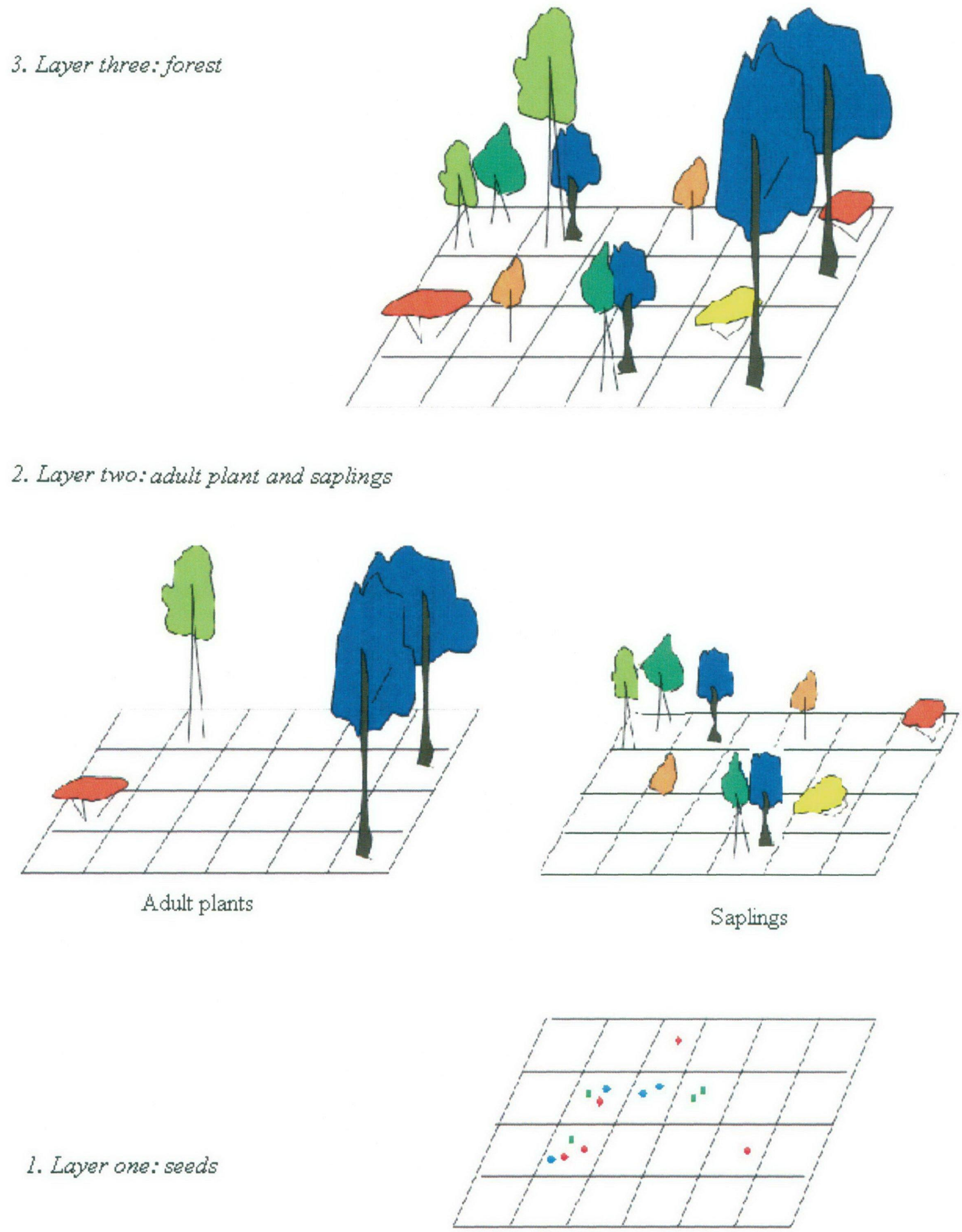

Fig. 6.3 Different layers used to establish the model

The location index and coordinates connect each layer together. In this way it is easy to track a seed as it germinates and grows to a seedling, then to a sapling and an adult plant and then to death. This enables the forest structure to be efficiently displayed. When displaying the forest structure (understorey and overstorey), the different height classes can easily be extracted from the forest and displayed in various graphs (see Chapters 7 and 8).

The individual agent's life history, interactions between the agents, and the reaction of agents to the environment are governed by a set of logic rules over time steps. The rules are expressed by means of the different classes in the agent-based object-oriented program. In addition, how the natural forest disperses seeds into the study site at each time step is also expressed here. Therefore, rules for each agent need to be written based on experimental and theoretical knowledge in order to drive the model.

6.4.3 Logic Rules for Agent Behaviour and Vegetation Colonisation

6.4.3.1 Seed Bank Dynamics

The experimental data showed that the seed bank of the topsoil provides seed for shrubs (Grigg 1987). *Acacia deanei, S. nemophila* and *D. viscosa* are the major shrub seeds. In each experimental plot, the emergent number of shrubs (P) and the location (S) of individual shrubs have been recorded. A colonised rate (Q) for shrubs is calculated for shrubs emerging from the soil seed bank, which is:

$$Q_t = f(P, \mathrm{S});$$

Mature shrubs produce seeds and provide additional seed to the seeds bank.

6.4.3.2 Seed Rain from the Natural Forest

Apart from shrub seeds in the topsoil, tree seeds are also introduced from the surrounding natural forest (Grigg 1987). The individual trees that emerged in the study site were recorded, classified and grouped by ten meter zones to calculate how far seed can be dispersed into the study site from the natural forest (see Chapter 4 Fig. 4.9) with the results used to estimate the dispersal distance of seed rain by species.

6.4.3.3 Life Span of Individual Plants

The simulation of each individual plant occurs was in five growth phases: seed germination; seedling establishment; plant persistence; seed setting; and death. The stages and the factors involved in each stage are described below.

1) Seed Germination

The field germination rates were derived from experimental work for each key species. Different species in different soils have variable germination rates (Chapter 4). In the model, each grid cell contains one or two plants. Only one seed is randomly selected to germinate in each cell if there is a gap for new recruitment.

Seed viability is used in the model. The quantity of viable seeds equals the total number of seeds of one species in a cell multiplied by the germination rate. In this way, all seeds in the cell are assumed to have the ability to germinate.

Moreover, after being buried in the soil for two years or more, most of the seeds will lose viability. Therefore, the model sets up a history to track the time of seeds fall in each cell and removes seeds that have lost viability.

2) Seedling Establishment

- *Survival rate*

The survival rate is determined by counting the number of seedlings surviving one year after germination. Survival rates vary by species and soil type. The data are derived from field investigations (Chapter 4). Survival rate is used in the model, but which seedling survives is randomly determined in the program. This means that the program calculates the total number of the same aged seedlings by species, and then randomly selects those that will survive.

- *Mortality*

Mortality rates for the first, second, fifth and tenth years were derived from field data and are used to describe the establishment of individual saplings. Seedlings of each species destined to die are selected randomly in the program. The program collates all seedlings by species of the same age into a database, and then randomly selects those to die from the database. Dead seedlings are removed from the model.

- *Shade tolerance*

Shade tolerance is used to describe the capacity of a plant to establish and persist under shade. Tolerant species can grow well with little light, such as under the canopy of other plants. Shade tolerance is also a factor in succession. Intolerant trees are usually pioneer species.

3) Growth

Each year (one time step), the *Plant* agent updates the age and height of each surviving individual (The height will be updated by the *Plant Growth Model*).

Plant Growth Model

Plant growth in the model is described as height and age changes with each time step. The height increase each year is simulated by two simple Plant Growth Models.

Shrub height growth is assumed to increase linearly in the model to a maximum height factor for each species. Each species has its own growth functions. When a shrub reaches its maximum height, it is assumed to stop growing. The equation of this simple assumption for the shrubs is as (1):

$$\mathbf{H}_{t+1} = \mathbf{H}_t \cdot (1+ \mathbf{R}); \qquad (1)$$

R = growth rate;

t = time;

H_t = the former height at time t;

H_{t+1} = the current calculated height at time $t+1$;

Tree species height is simulated by Chapman Richards height-age equation (Richards 1959).

$$\mathbf{H} = a * (1-e^{(b \cdot A)})^{c} \qquad (2)$$

Where H is the tree height, A is the tree age, and *a, b, c* are constants.

Based on regular annual measurements of height at the study site, the constants of *a, b* and *c* for each species were determined by non-parametric estimation methods. Figure 6.4 shows tree height growth over 150 years for each species.

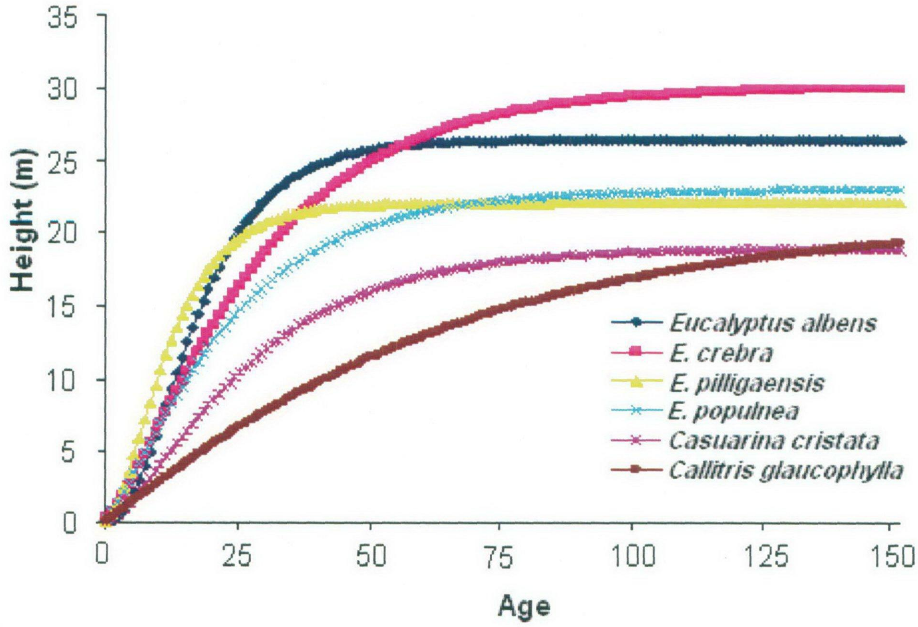

Fig. 6.4 Tree Height/Age simulations using Chapman Richards height-age equation (Richards 1959).

4) Seed Production and Dispersal

Besides the seed bank and seed rain from the surrounding natural forest, established mature plants are able to set seeds in any production year. However, not all plants produce seeds every year. There are significant differences in production between good and poor years. In the model, periodicity is used to express the interval between two good production years. Seed production data are derived from the literature. For each cell, there is a maximum limitation on the number of seeds. The number of seeds distributed into each cell depends on production and dispersal from nearby parent trees. In order to simplify calculations, it is hypothesised that all seeds dropped into one cell have the ability to germinate. Thus the quantity of dispersed seeds from the parent tree equals the 'seed production' multiplied by the 'seed viability rate'. It is assumed that dispersal from the parent tree into neighbouring cells is uniform, provided that cells are within the dispersal distance. Considering the parent tree as a central point and the seed dispersal distance as radius, the numbers of cells covered by seeds and the seeds in the neighbouring cell are represented as follows:

$$Cn = Square\ (2 * (Integer\ ((D + 1)/ 2))); \qquad (3)$$

$$S = (Sp * V) / Cn \qquad (4)$$

Where Cn = number of neighbour cells covered by the seeds, D = dispersal distance, S = seeds that fall into neighbouring cells, Sp = seed production and V = seed viability.

5) End of Life Span:

When a plant grows to its maximum age, it dies and is removed from the model. The vacant space then becomes available for colonisation by a new plant. Thus, another cycle of life starts.

6.4.3.4 Competition

The intra-specific and inter-specific competition for growth is simulated in the model. Height is one factor impacting on the competitive ability of an individual.

Since each grid cell is only 4 m^2 (2 x 2 m), most of the tree crown will cover more than this area. Based on forest structure in surrounding natural forest described by Croft (1979) (Fig. 6.5) and the author's observation in the field, the occupied area of an individual plant is described as follows: all the eucalypts can extend from one to 9 cells (6 x 6 m); *C. cristata* can occupy up to four cells (4 x 4 m) and *C. glaucophylla* can extend to four cells (4 x 4 m). All shrubs occupy one cell (2 x 2 m). Eucalypts dominate the overstorey of the forest while *C. glaucophylla* and *C. cristata* generally occur under the eucalypt canopy. Shrubs occupy the understorey.

Since most trees may occupy more than one cell, competition is modelled and described both within and between cells.

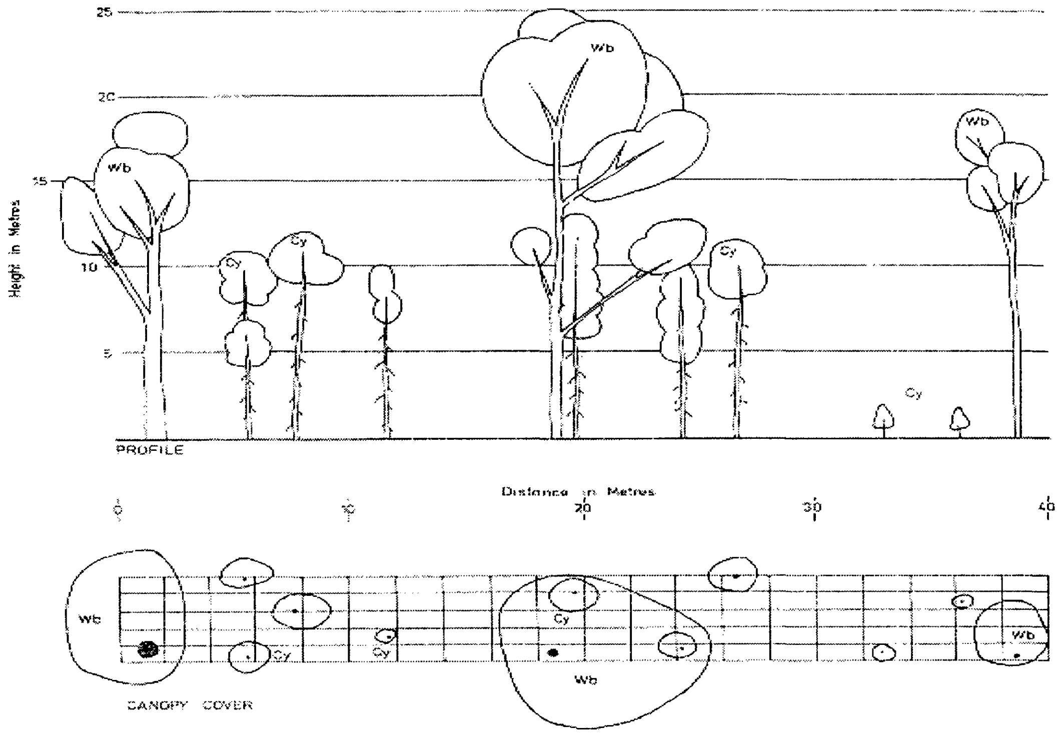

Fig. 6.5 a Natural Forest Structure in Boggabri, NSW. WB: *Eucalyptus albens*, Cy: *Callitris glaucophylla*. Cited from Croft (1979).

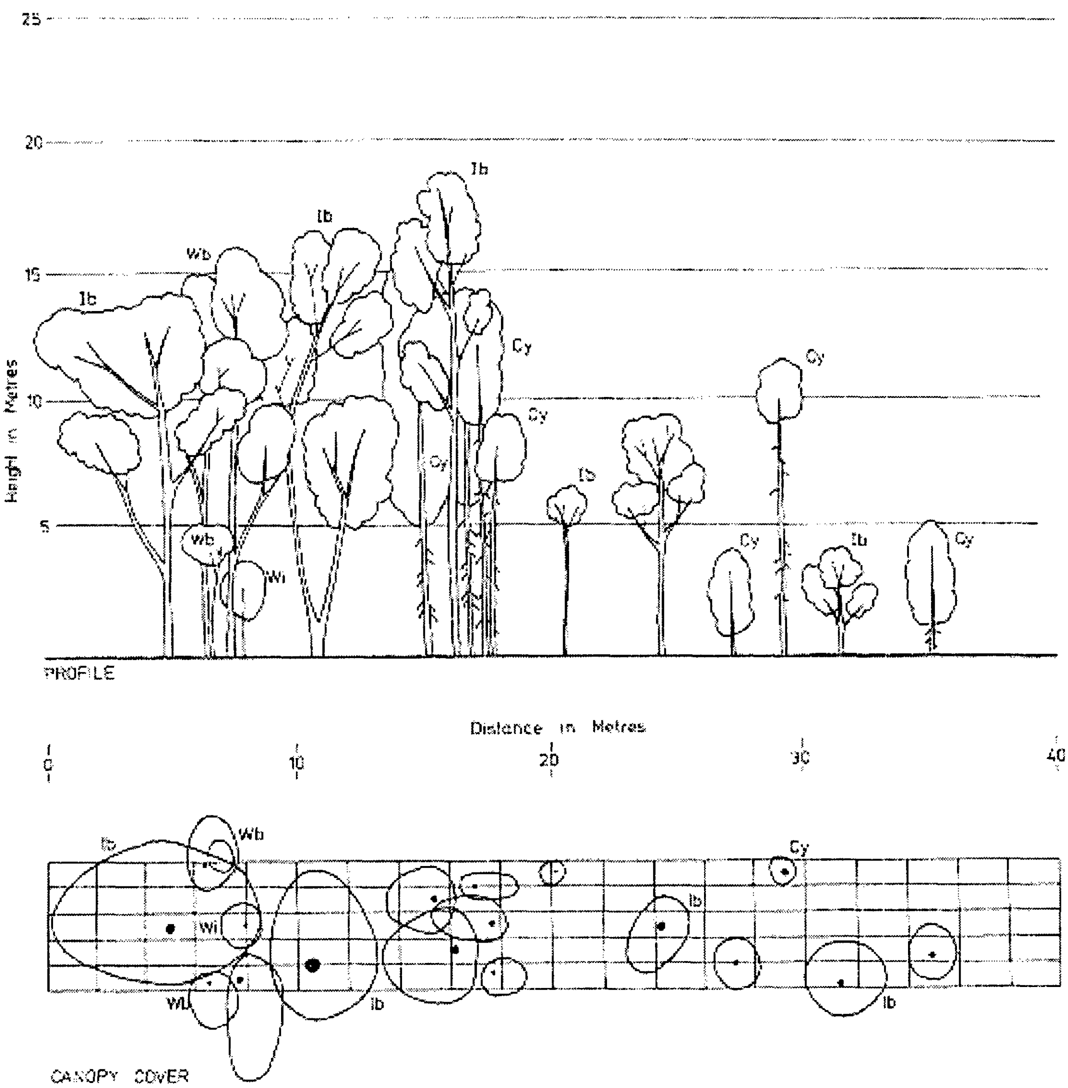

Fig. 6.5 b Natural Forest Structure in Boggabri, NSW. WB: *Eucalyptus albens*; Ib: *E. crebra*; Cy: *Callitris glaucophylla*; Wi = *Geijera parviflora*.

Cited from Croft (1979).

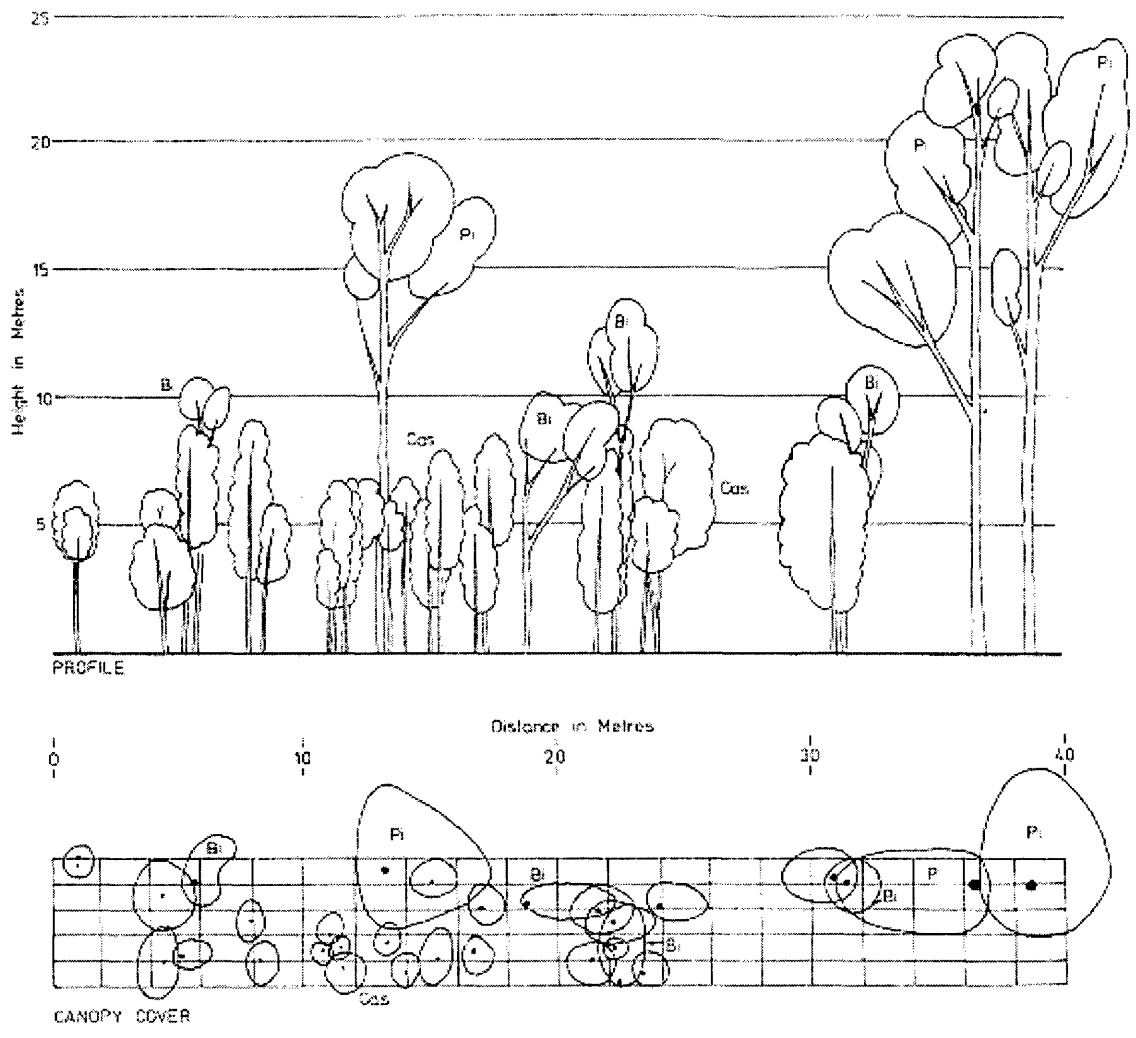

Fig. 6.5 c Natural Forest Structure in Boggabri, NSW. Pi : *Eucalyptus pilligaensis*; Bi : *E. populnea*; Cas: *Casuarina cristata*. Cited from Croft (1979).

Competition within a Cell

When two saplings occur in the one cell, they compete for the growth space, and finally one will survive and have an opportunity to grow to an adult stage. The other may die and be removed from the programme. The different scenarios are discussed below.

- *Two seedlings, both of them are tree species*

Two seedlings can grow together for a few years without competition although seedling mortality functions may apply. The height of each tree is used to determine competition. When the height of one of the seedlings is over 10 m, it will get more of a chance to occupy the cell and the other may be removed by the program if its height reaches two-third the height of the taller one.

- *Two seedlings, one is a shrub and the other a tree*

The shape of shrubs is different from that of trees. There is little space for any plants to grow under a shrub if a shrub dominates the cell. Therefore, the competition between shrub/tree and shrub/shrub will be different from the tree/tree situation.

The comparison of height between a shrub and tree is carried out when the height of the shrub is over 2 m. If the height of a tree is higher than the shrub, these two plants will have no conflict and both can grow in one cell to complete their own life span. This assumes that the shrub should be shade tolerant otherwise the shrub will be removed. On the other hand, if the height of a shrub is greater than the tree, then the tree will be removed from the cell. Generally no tree seedlings or saplings grow under a shrub, unless the shrub dies and leaves a gap for new plant growth.

- *Two seedlings, both of them shrubs*

The height of the two shrubs is compared and when one is over 2 m it is assumed to dominate the cell and the other one will be deleted from the cell.

Competition between Cells

The model determines that only one plant can dominate a cell, but competition between adults in neighbouring cells an occur. This manifests itself in the program as between-cell competition.

One plant crown cannot grow through others. If one tree has dominated the overstorey, it will suppress neighbours growth, and only the plant that can tolerate shade will have a chance to grow well under the canopy.

With increasing height and stem diameter, the tree crown also increases in size. Tree crown will occupy more than one cell and will compete for space with its neighbours. Different species have different reactions to competition, and these are described below.

Eucalypts follow self-thinning rules so that the greater the density the greater the mortality. If there is insufficient space for a eucalypt to grow and occupy 9 cells, its growth will decline and it will finally die and be removed from the model.

Callitris glaucophylla grows to occupy 4 cells if there is sufficient space in neighbouring cells. However, it also can grow under larger eucalypts as an understorey tree because of its level of tolerance. *Casuarina cristata* also grows in the forest as part of the understorey and can occupy 4 cells if given the opportunity. All shrubs are considered to grow in one cell only.

Each plant in one cell will check the eight neighbouring cells around it (Fig. 6.6) to seek potential space for growth, and will also compete for the space with the neighbours.

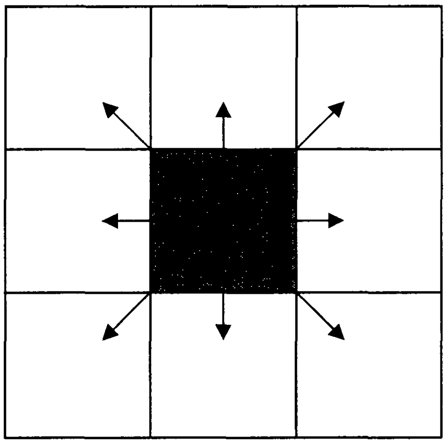

Fig. 6.6 Neighbours check for growth competition between cells.

6.5 Time Step

The program used for modelling (Repast) has a schedule for actions (Chapter 5). According to the determined schedule, the model will update the state of each agent at each time step. A year was selected as the schedule in this model so that each plant will progress according to the rules applying to that species on a yearly basis.

6.6 User Interface and Model Visualisation

The model provides a user interface (Fig. 6.7). Besides a model control bar provided by

Repast, the parameter interface is used to determine model parameters such as the number of years for simulation and how many species are to be modelled. The graph creation function provides linear graphs or column charts. Snapshot and movie making functions can be applied to display the simulation results. It also can display individual plant status when the user highlights the agent during model execution.

The individual plants germinating and emerging in the cells, individual plants dying and being removed from each cell, the species population increase and decrease, and species distribution over spatial and temporal scale can be shown on the computer screen. The instantaneous simulation results can be saved as image files, and the digital results can be saved as text files.

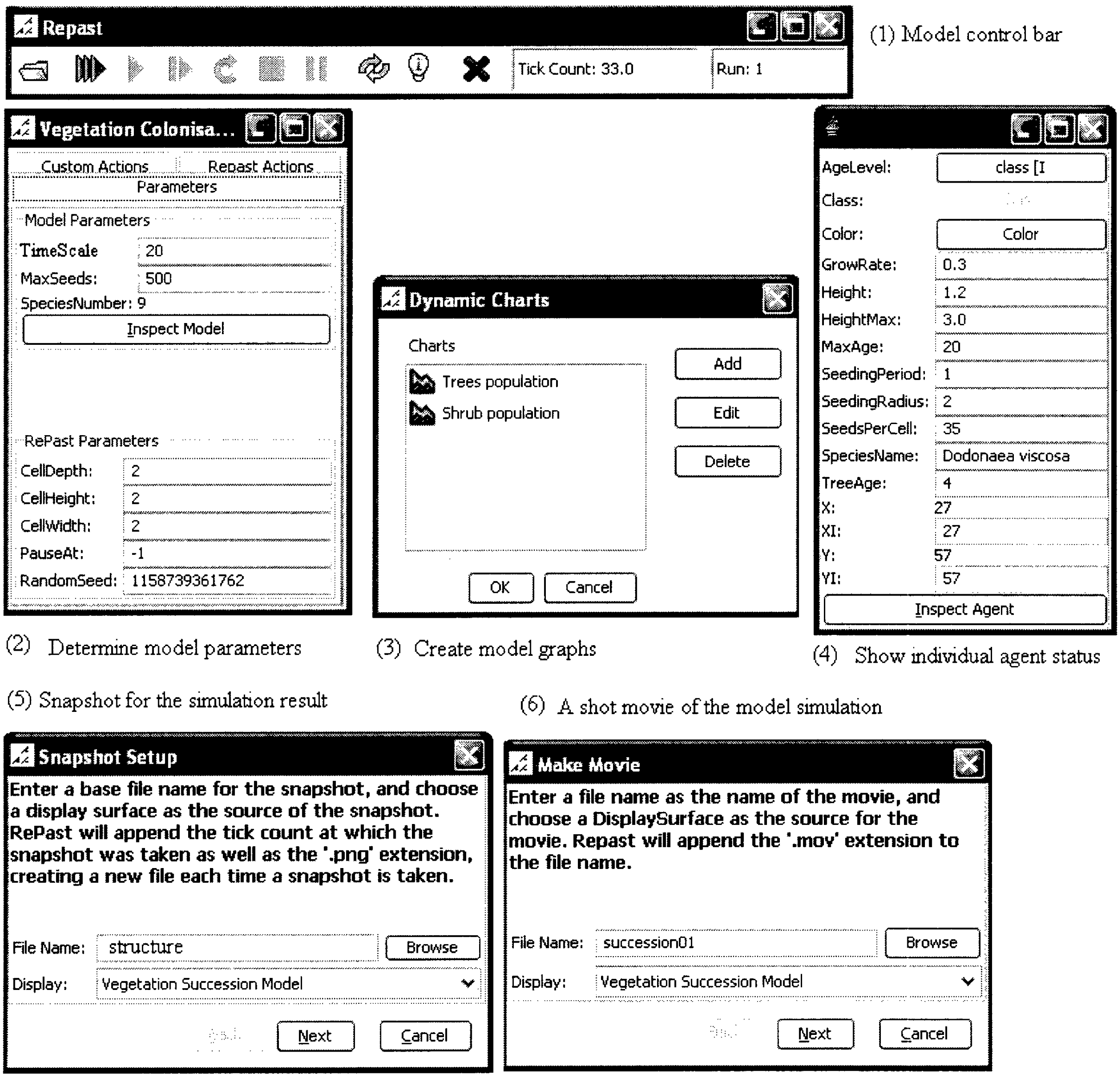

Fig. 6.7 Model user interface

6.7 Summary

This chapter presents the design for this Agent-based Model for mining rehabilitation. The framework and computer programming language used for the model are described and explained. The method used to build the model is described and the model architecture is outlined. Parameter selection and the definition of logic rules are based on ecological and biological principles and influence model development. Survival rate and mortality rate are applied at the earlier growth stage. However, since this research does not study pest/disease, fire or other disturbance, life span will be the only natural mortality process for mature plants except plant competition. The competition between and within cells will be another cause of mortality for mature plants. Random mortality isn't applied as other researchers did (Little 2002; Bravo-Oviedo *et al.* 2006) to reduce the uncertainty of the simulation, since the experimental data of random mortality is unknown. Moreover, height is used as a main factor for competition in this study (Falster & Westoby 2003; Pronk *et al.* 2007). Different species (i.e. shrubs and trees) grow in different layers so shade tolerant is another factor for space competition. This research is simulated on fine scale (2 m x 2 m cells). The selection of the scale size is mostly determined by the purpose of the study and the structure of the studied ecosystem (Schneider 2001; Getzin *et al* 2006; Larson & Franklin 2006; Jenkins *et al.* 2007). Fine scale maintains enough information and is suitable to study the dynamics of growth and competition of individual plants at a small site (3.1 ha). It is possible to miss information if a large scale is applied.

The model simulates individual plants over their life spans and introduces competition based on the ecological, eco-geographical and biological logic rules to provide the final outcomes.