CHAPTER 7   SIMULATION OF NATURAL RECOVERY

7.1 Introduction

Colonisation and community succession are components of vegetation recovery in response to external changes and disturbances (McCook 1994). Disturbed sites can recover naturally or artificially through human intervention. In this thesis natural vegetation recovery refers to regrowth from natural processes after disturbance, initiated by seed banks, seed fall or re-sprouting. There is no doubt that successful rehabilitation can be achieved by natural processes, therefore, understanding the dynamics of natural vegetation colonisation and succession provides a basis for predicting the likely outcome. However, natural recovery of an ecosystem following disturbance takes considerable time (Cremer 1965) with uncertainty as to the likely end point. Human intervention may be required to accelerate the processes or direct them to the desirable endpoint. Simulation models provide the opportunity to predict outcomes that may take many decades to achieve.

In this chapter, the Agent-based Model designed in Chapter 6 is used to simulate natural colonisation at Boggabri. Species changes, colonisation patterns, forest structure patterns, and predictive spatial and temporal patterns of different successional states are displayed and described by the model over time.

The potential applications for this model will be discussed in Chapter 8 which will describe its application to mine sites rehabilitation to achieve particular goals.

7.2 Methods

7.2.1 Model Parameters and the Presentation of Simulation Results

The parameters used in this Agent-based model have been described in Chapter 6, and their values were derived from Chapter 4, but the major parameters and their values used in this chapter and Chapter 8 are listed in Table 7.1. The model includes two types of soil which were bare overburden and topsoiled overburden (see Chapter 3). The topsoil and the nearby natural forest provide seed sources (Chapters 4 and 6).

The simulation commenced in 1980 and was run over 200 years in one year time steps. Simulation results are presented in 20, 50, 100 and 200 year time-spans respectively by different species using graphs, tables and linear figures. The first 20 years simulation is compared with the field observation results for validating the model.

Table 7.1 Parameter values used in the Agent-based Model developed for Boggabri. (NBO: northern bare overburden, SBO: southern bare overburden)

Parameters		Species Name								
		E. populne	*E. pilligaensis*	*E. crebra*	*E. albens*	*Callitris glaucophylla*	*Casuarina cristata*	*Acacia deanei*	*Senna nemophila*	*Dodonaea viscosa*
Maximum Height (m)		30	20	20	25	20	18	5	3	5
Maximum Age (year)		300 (Jacob 1955)	300 (Jacob 1955)	300 (Jacob 1955)	300 (Jacob 1955)	250 (Bowman & Panton 1993)	20	20 (Hall 1972)	10	20
Height Growth Rate (cm per year) (Data Source: Grigg 1987)		45	60.5	43	31	37	44	50	30	30
Seeding Period (years)		2	2	2	2	3	1	1	1	1
Seeding year (years)		20	20	20	20	12	10	8	3	3
Dispersal distance (m)		= Height	= Height	= Height	= Height	10	Under the tree	< 5	< 5	< 5
Germination (%)	Topsoil	40	40	49 (Grigg 1987)	40	72 (Denham 1989)	37 (Grigg 1987)	37 (Grigg 1987)	30	30
	NBO	76	76	76 (Grigg 1987)	76	74 (Denham 1989)	39 (Grigg 1987)	45 (Grigg 1987)	15	15
	SBO	35	35	35	35	70	24 (Grigg 1987)	15 (Grigg 1987)	15	15
Mortality at year 1 (%) (Data Source: Grigg 1987)		13	9	7	26	7	10	27	44	28
Mortality at year 2 (%) (Data Source: Grigg 1987)		8	4	13	21	9	7	13	4	5
Mortality at year 3 (%) (Data Source: Grigg 1987)		13	14	0	6	11	13	17	4	9
Mortality at year 10 (%)		50	54	55	67	65	85	94	100	95

7.2.2 Statistical Analysis

The total number of plants by species for the simulation results were recorded in text files over years and compared with the observed data. Shrub and tree colonisation patterns were drawn by the model and compared with GIS patterns observed from the study site at each measurement year.

ANOVA analysis was used to test for the significant difference between the simulation results and the field observations, and number of plants of each species is used. The null hypothesis is that the model and observed results have the same probability distribution and if the hypothesis is true then there is no significant difference between these two distributions, indicating that the model simulates community development appropriately. Finally, the regression coefficient (R^2) is used to express the similarity between the model and the observed results in the study site.

7.3 Comparison between the Simulation and Field Observations

The model was run for 20 years and the population of each species, community composition and structure was presented graphically. In order to check whether simulation represents past succession, total number plants by species are compared with the observed results at measurement years (Figs. 7.1 and 7.2). Simulation results were similar to the measured results. The spatial maps of trees and shrubs for the 20 year simulation also show a similar pattern to the observed results from the study site (Fig. 7.3).
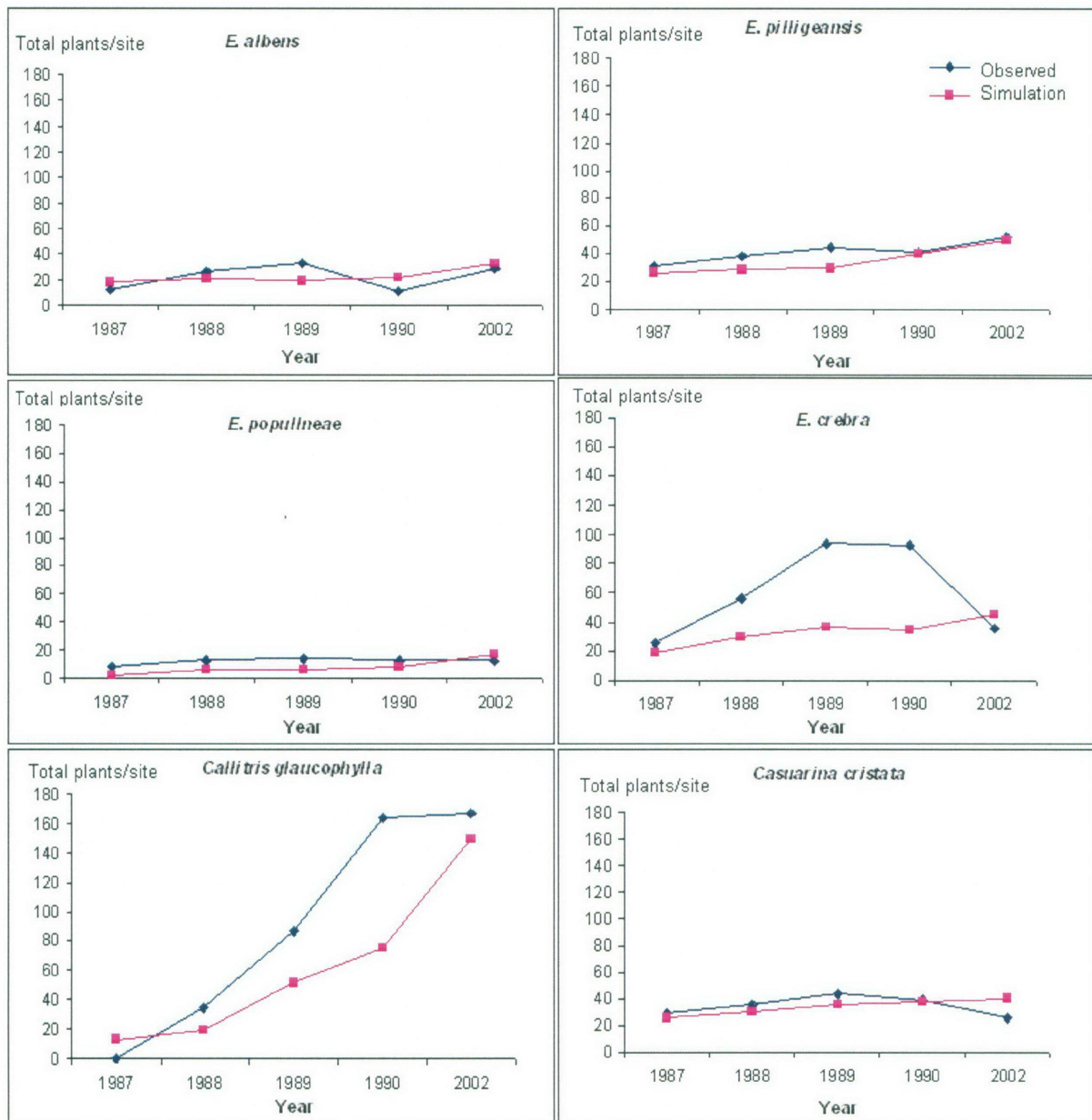
Fig. 7.1 Comparison of the total number of plants by tree species for the measured and simulation results
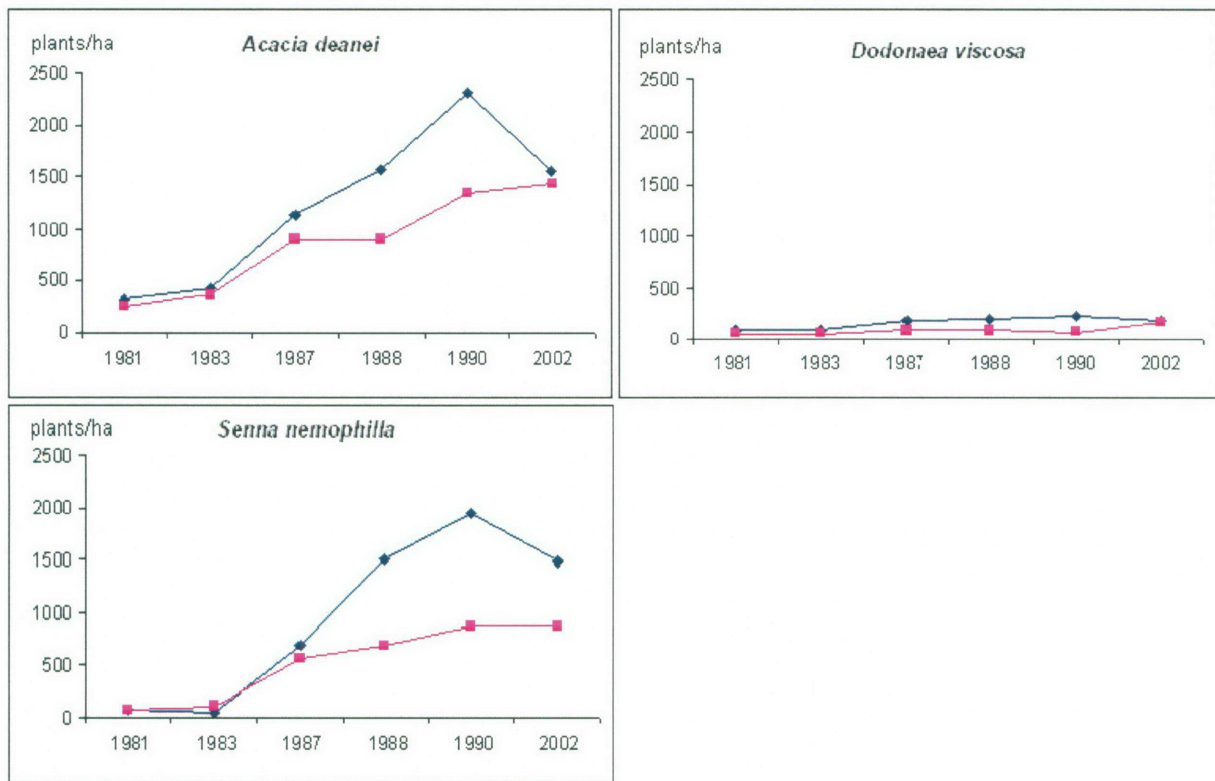
Fig. 7.2 Comparison of shrub density for the measured and simulation results

The comparison showed that trees colonised the study site from the edge, and presented similar patterns to those observed in the field. The simulation results for shrubs indicated that *S. nemophila* only occurred in southern topsoiled site, but *A. deanei* and *D. viscose* were widely distributed across the study site. *Acacia deanei* dominated most parts of the topsoiled areas and the composition and structure was similar to the field observed pattern (Fig. 7.3).
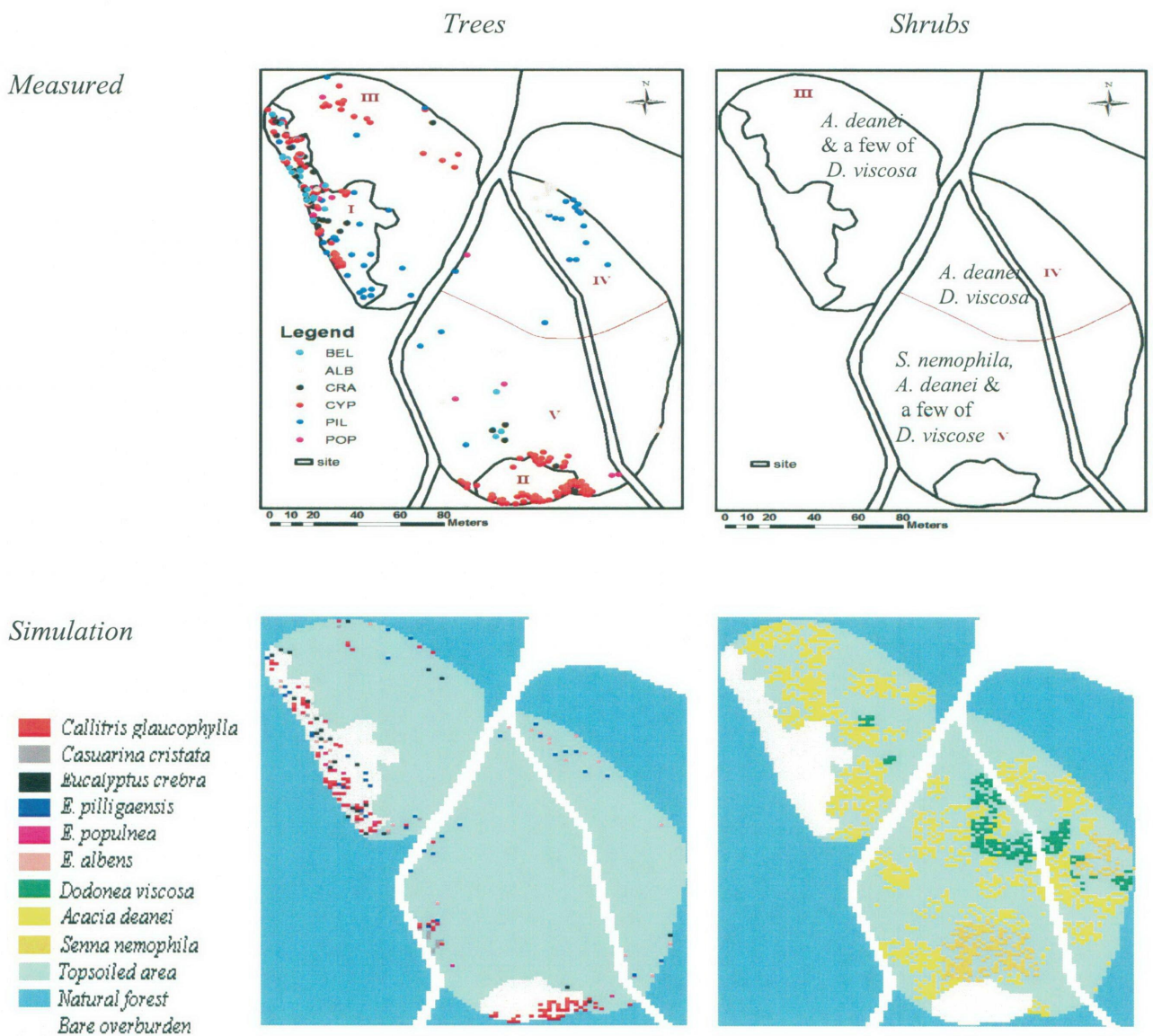
Fig. 7.3 Comparison of natural succession simulation results for colonisation of trees and shrubs over 20 years with field patterns observed in 2002

Model Validation

Although the simulation results presented similar patterns to the measurement results (Figs. 7.1 and 7.2), statistical analysis is required to test whether there is a significant difference between these two results. The hypothesis is that the simulation results (number of plants) and observed values come from the same probability distribution and there is no significant difference between them. The ANOVA demonstrated that the F value (2.02471) < F critical (4.009868), indicating there is no significant difference between the simulation and observed results, and the hypothesis of no difference can not be rejected (Table 7.2). In another words, the simulation represents the past vegetation succession. The regression analysis indicated that the model can explain about 72% variance of observed data ($R^2 = 0.72$, Fig. 7.4).

Overall, the model simulates and represents the vegetation succession appropriately.

Table 7.2 ANOVA analysis between simulation results and observation data

Source of Variation	SS	df	MS	F	P-value	F critical
Between Observation and Simulation	2367.594	1	2367.594	2.02471	0.160209	4.009868

Number of plants (Simulation)
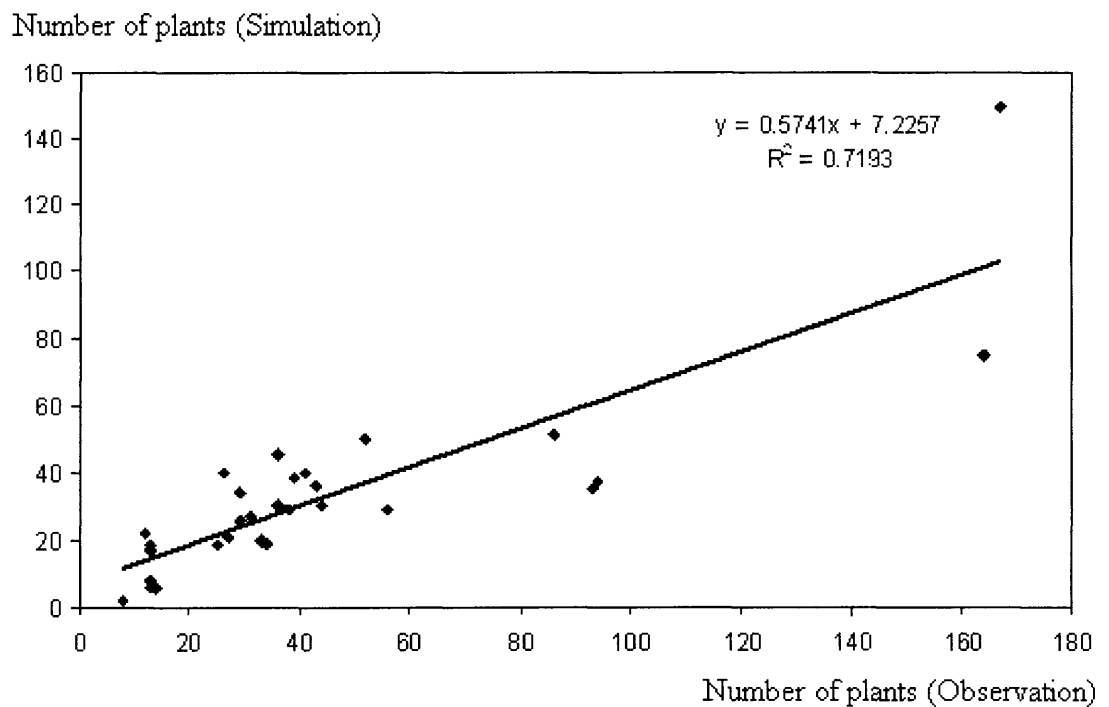

Number of plants (Observation)

Fig. 7.4 Regression between simulation and field observed results for number of plants of tree species at 20 years.

7.4 Prediction of Succession

7.4.1 Population Changes by Species

The total tree population (all species combined) increased regularly throughout the 200 year simulation (Fig. 7.5). *Callitris glaucophylla* and *Eucalyptus* species combined were the major species together with *C. cristata*. *Callitris glaucophylla* increased to about 1,600 plants after 200 years. *Eucalyptus crebra, E. albens* and *E. pilligaensis* showed a steady increasing trend, but *E. populnea* rose steadily in the first 50 years and then stabilised. *Eucalyptus populnea* had the smallest population because there were only a few individuals in the surrounding
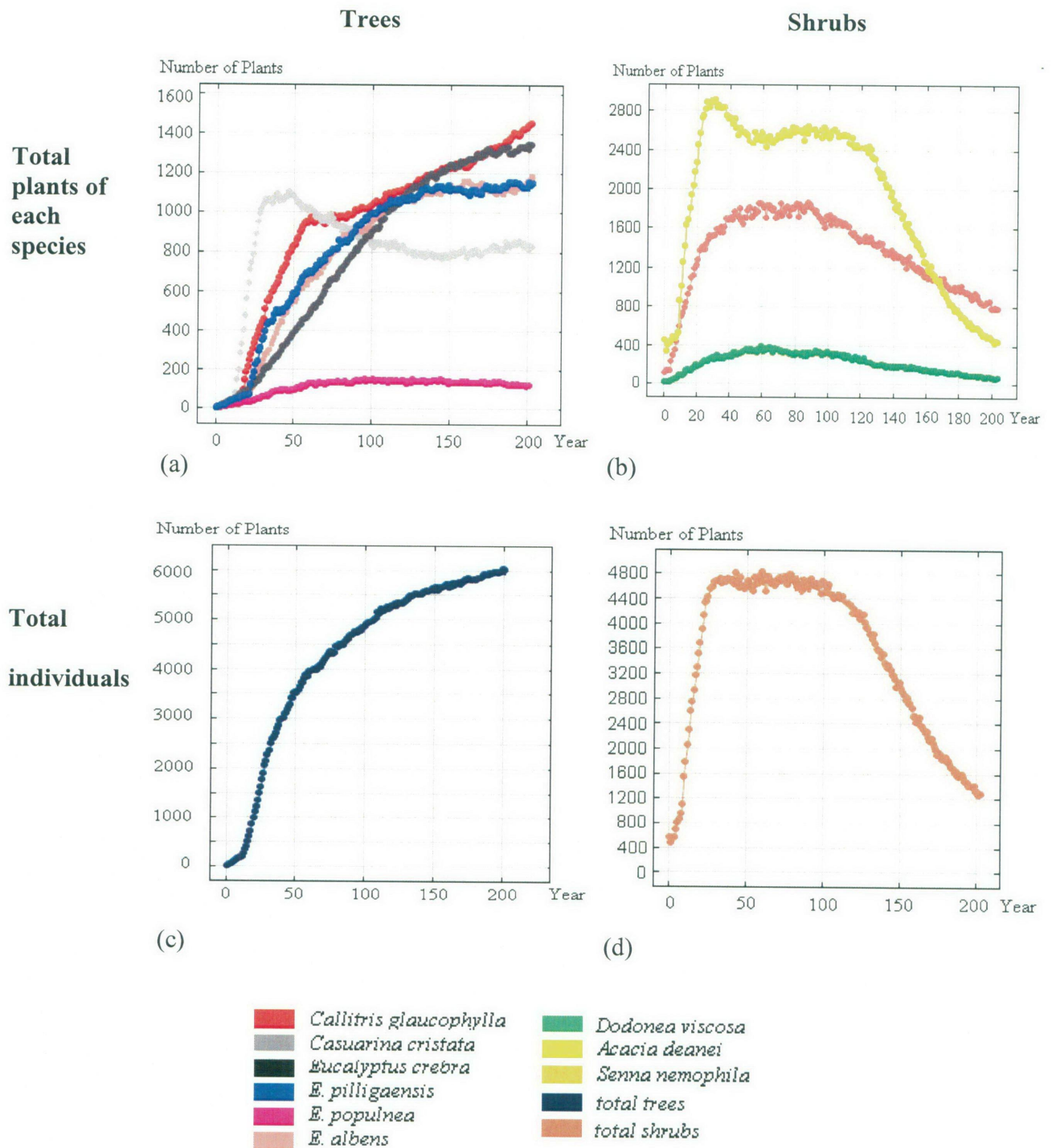
Trees

Shrubs

Total plants of each species

Number of Plants

Number of Plants

(a)

(b)

Total

individuals

Number of Plants

Number of Plants

(c)

(d)

■ *Callitris glaucophylla*	■ *Dodonea viscosa*	
■ *Casuarina cristata*	■ *Acacia deanei*	
■ *Eucalyptus crebra*	■ *Senna nemophila*	
■ *E. pilligaensis*	■ *total trees*	
■ *E. populnea*	■ *total shrubs*	
■ *E. albens*		

Fig. 7.5 Community composition changes: changes in number of plants for (a) tree species and (b) shrubs; and changes in total individuals for (c) trees and (d) shrubs over a 200 year simulation.

natural forest (Chapter 4) that provided a seed source. However, *C. cristata* increased rapidly and began to decline after 50 years.

The simulation results for shrubs shows a rapid increase during the first 100 years thereafter declining through the loss of *A. deanei* while total tree numbers continue to rise over 200 years (Fig. 7.5). In particular, the *A. deanei* population declined by 83% from over 2860 plants to 460 plants after 200 years of simulation (Fig. 7.5).

7.4.2 Community Composition and Structural Changes

The overburden heaps effectively changed from a grassland (Chapter 4) to a woodland structure along with tree development over time. *Callitris glaucophylla* steadily increased over time and occupied the southern bare overburden site and invaded the northern side from the edge, where it formed pure stands (Figs. 7.6 a and c, Figs. 7.7 a and c).

The results at 50 years of simulation showed that the topsoiled area was mostly dominated by shrubs (Figs. 7.6 b and c), particularly on the southern side with smaller patches of grassland on topsoiled area (dynamics of herbaceous species are excluded from the simulation, but if the topsoiled area was neither dominated by trees nor shrubs, it is covered as grassland). *Acacia deanei* was distributed throughout the study area, while *S. nemophila* and *D. viscosa* were restricted in their distribution and dominated patches on the southern topsoiled areas.

After 50 years of simulation, trees occupied the bare overburden area and dominated the northern side of overburden heaps. *Callitris glaucophylla* invaded the study site from the western to eastern side. This is because the community composition in the natural forest close
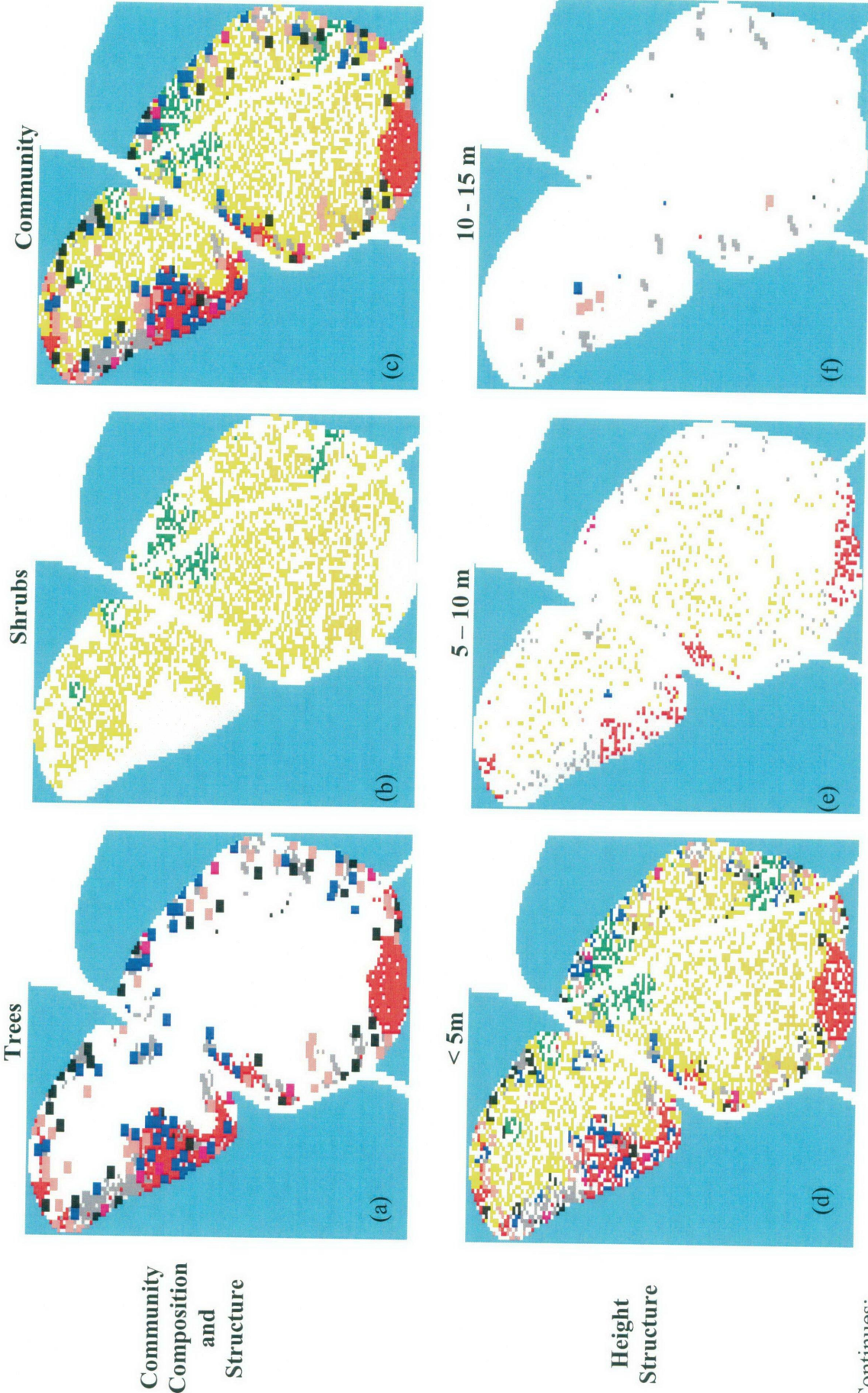
to the eastern study site was different from that to the western site, where eucalypts dominated with a few *C. glaucophylla* but at a distance from the edge. *Callitris glaucophylla* increased in dominancy over time (Fig. 7.6).

The community height structure was expressed in height classes of < 5 m, 5 - 10 m, 10 - 15 m, 15 - 20 m, and over 20 m to show the changes in height structure over time.

The results of the simulation showed that after 50 years there were only some eucalypts higher than 20 m (Fig. 7.6 h), and they were all located along the edge of the study site close to the natural forest. *Casuarina cristata, C. glaucophylla* and eucalypt saplings formed the middle layer (Fig. 7.6 f), and under them, shrubs and small tree saplings formed the understorey (Figs. 7.6 d and e).

Due to competition between trees and shrubs on the southern site, the 100 year simulation showed a trend of tree domination (Figs. 7.6 a and c, and Figs. 7.7 a and c). The numbers of trees higher than 20 m had increased (Figs. 7.6 h and 7.7 h). *Callitris glaucophylla* had moved from class of 5 – 10 m in height (Fig. 7.6 e) to class of 15 – 20 m, and had a large population in the understorey. The area of forest increased (Figs. 7.6 a and 7.7 a) at the expense of a declining shrubland (Figs. 7.6 b and 7.7 b).
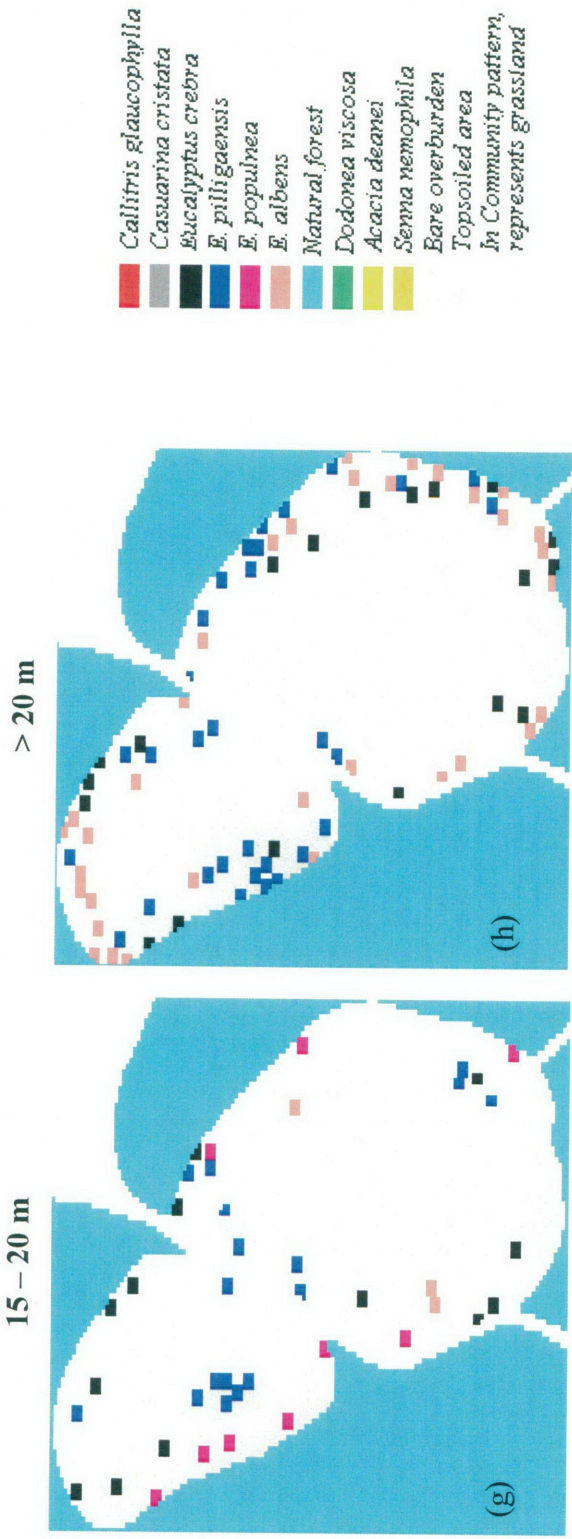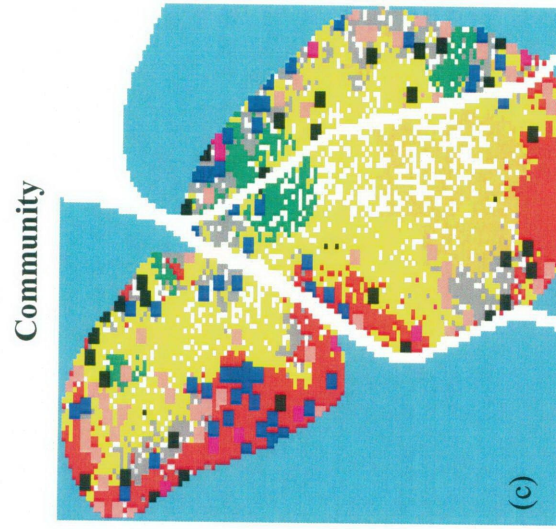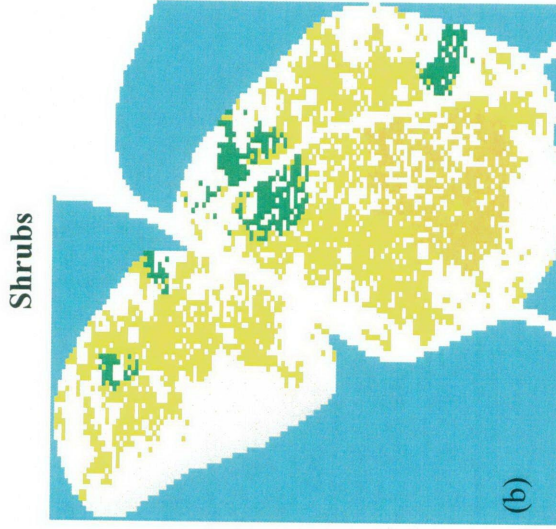
A 50 Year Simulation

Community Composition and Structure

Trees

Shrubs

Community

(a)

(b)

(c)

Height Structure

< 5m

5 – 10 m

10 – 15 m

(d)

(e)

(f)

Continues:

Callitris glaucophylla
Casuarina cristata
Eucalyptus crebra
E. pilligaensis
E. populnea
E. albens
Natural forest
Dodonea viscosa
Acacia deanei
Senna nemophila
Bare overburden
Topsoiled area
In Community pattern,
represents grassland
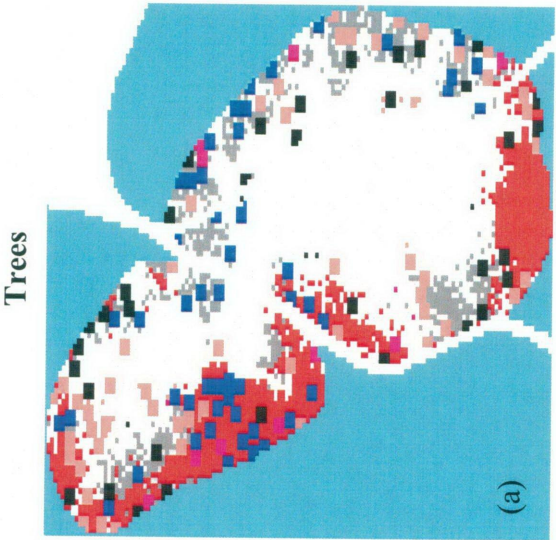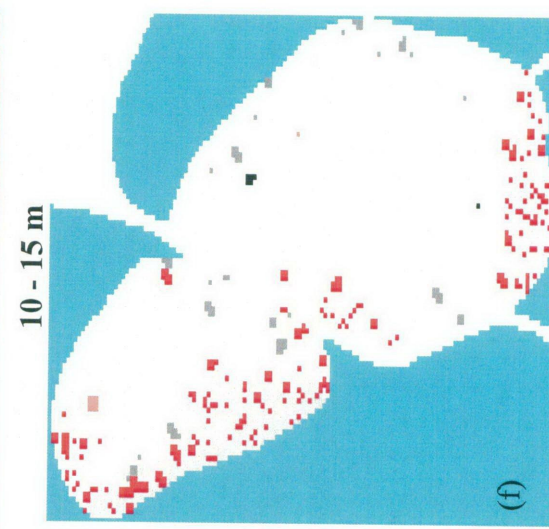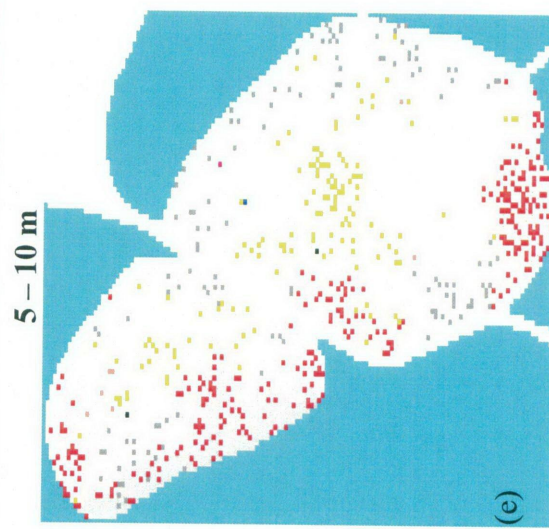
> 20 m

(h)

15 – 20 m

(g)

Fig. 7.6 Initial colonisation of a 50 year simulation: (a) trees colonisation, (b) shrubs colonisation, (c) community structural and composition, and (d – h) height structure changes for the community.

A 100 Year Simulation

Community
Composition
and
Structure

Trees
(a)

Shrubs
(b)

Community
(c)

Height
Structure

<5m
(d)

5 – 10 m
(e)

10 – 15 m
(f)

Continues:

Callitris glaucophylla
Casuarina cristata
Eucalyptus crebra
E. pilligaensis
E. populnea
E. albens
Natural forest
Dodonea viscosa
Acacia deanei
Senna nemophila
Bare overburden
Topsoiled area
In Community pattern,
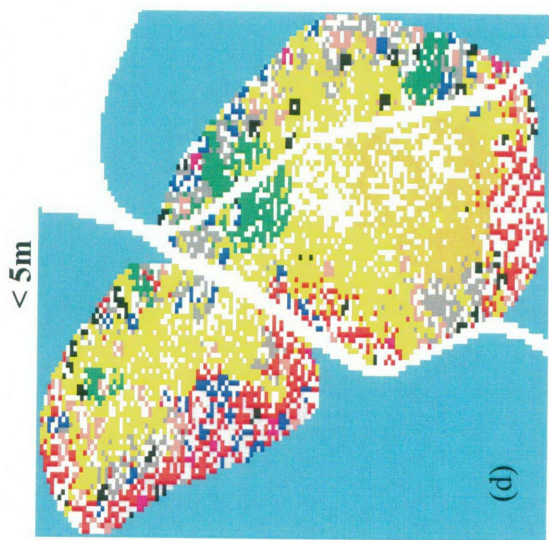represents grassland
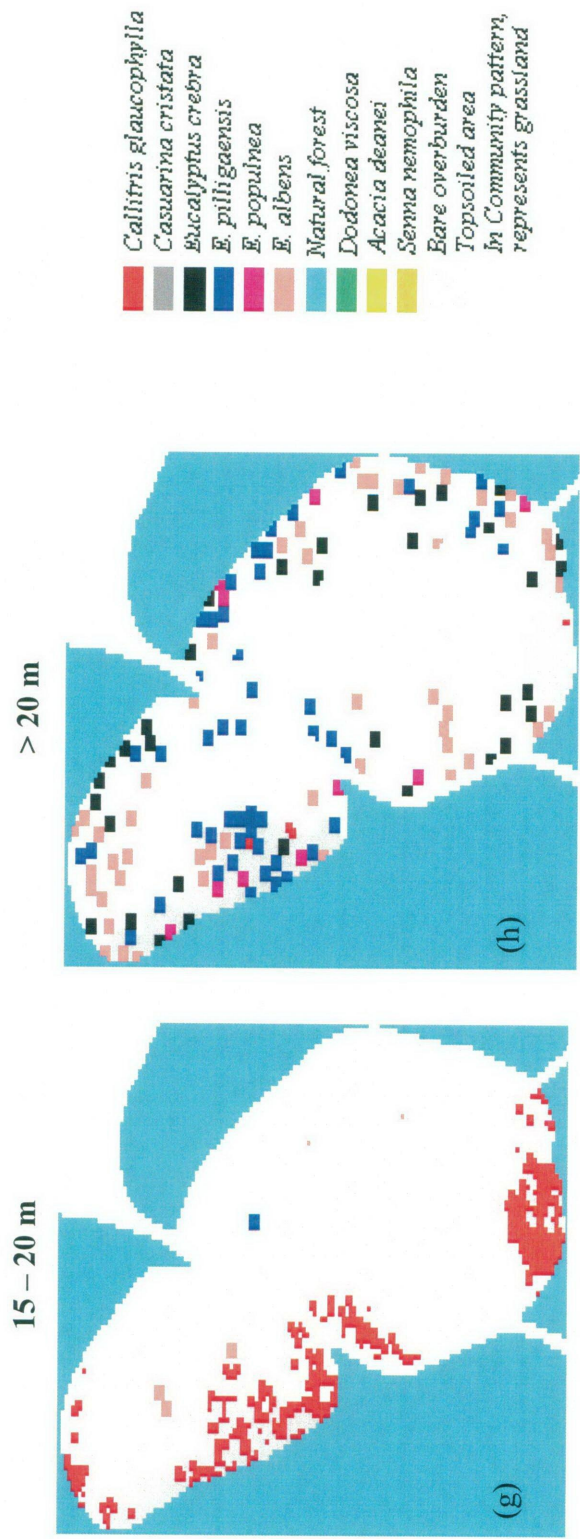
> 20 m

(h)

15 – 20 m

(g)

Fig. 7.7 Initial colonisation of a 100 year simulation: (a) trees colonisation, (b) shrubs colonisation, (c) community structural and composition, and (d – h) height structure changes for the community.

Simulation predicted a slow encroachment of tree species into the area from the edge over time (Figs. 7.6 a, 7.7 a and 7.8 a), as observed in the field for the first 20 years (Chapter 4). After 200 years of simulation, the shrubs still dominate some of the southern area (Figs. 7.8 b and c). Tree species dominated the northern part of the study site with the structure changing from a woodland to a forest mostly within 200 years but with a small patch of woodland. Significant changes in structure were evident between 100 and 200 years of simulation on northern site but not on southern site although the population of *C. glaucophylla* increased while that of *C. cristata* decreased.
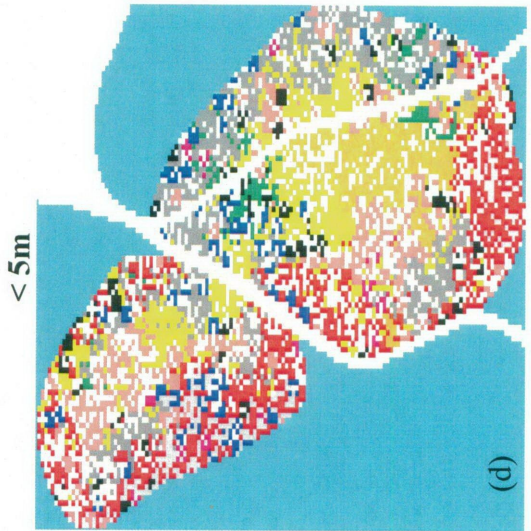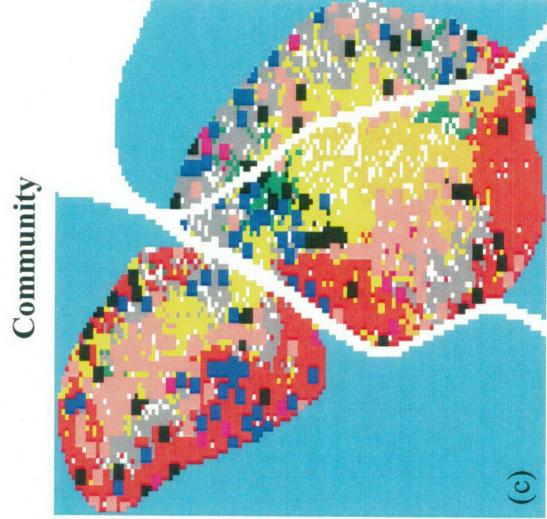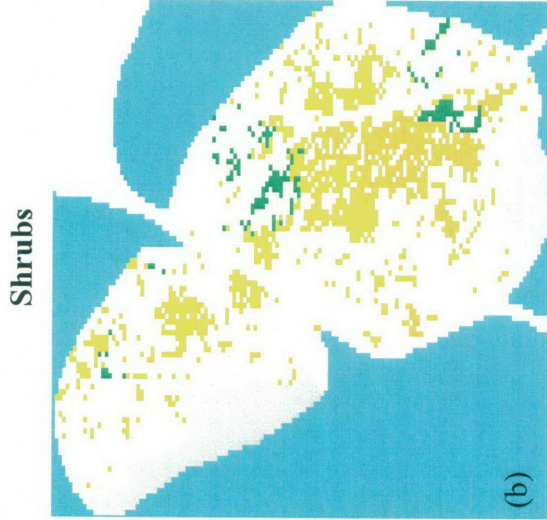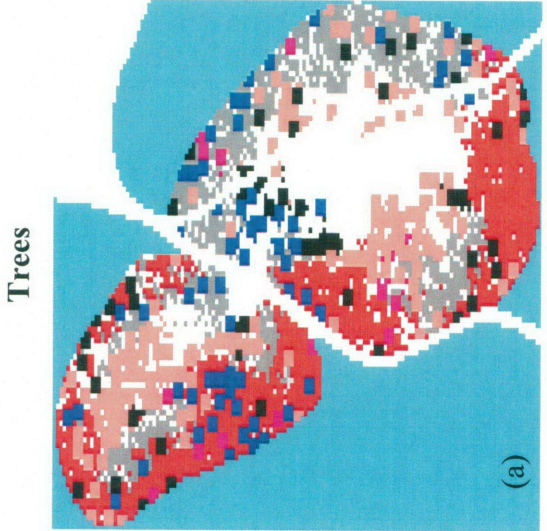
After 200 years of simulation (Figs. 7.6 - 7.8), the study site had formed a forest structure with the overstorey dominated by *E. albens, E. pilligaensis, E. crebra* and *E. populnea* (Fig. 7.8 e).

Callitris glaucophylla grew strongly and over time moved up from the lowest layer (0 - 5 m) (Fig. 7.6 a) to the middle layer (10 – 15 m) (Fig. 7.7 c) and finally dominated the secondary overstorey layer (15 - 20 m) (Fig. 7.8 d) after 200 years. The abundance of trees less than five metres in height indicates that regeneration occurred over time during the simulation. However, tree saplings were not evident in areas dominated by shrubs, which indicated that competition between shrubs and trees precluded their invasion.

The densities and relative abundances of *E. crebra and C. glaucophylla* in simulation ecosystem (50 years simulation) showed similar trend to that in natural forest, so was the total density (see Table 7.3). Most of the trees colonised along the edge of spoil heaps (Fig. 7.6), which indicated that the surrounding forest impacted on the community composition in study site.

A 200 Year Simulation

Community Composition and Structure

| Trees | Shrubs | Community |

(a)

(b)

(c)

Height Structure

| <5 m | 5 – 10 m | 10 - 15 m |

(d)

(e)

(f)

Continues:

Callitris glaucophylla
Casuarina cristata
Eucalyptus crebra
E. pilligaensis
E. populnea
E. albens
Natural forest
Dodonea viscosa
Acacia deanei
Senna nemophila
Bare overburden
Topsoiled area
In Community pattern,
represents grassland

15 – 20 m

> 20 m

(g)

(h)
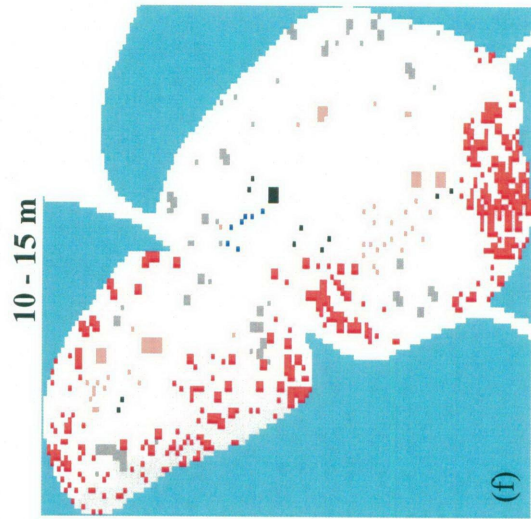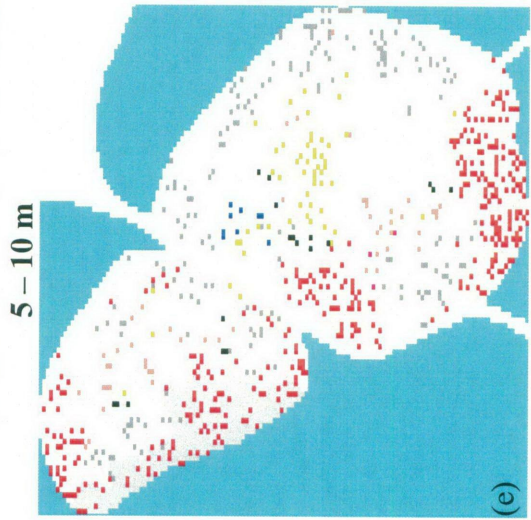
Fig. 7.8 Initial colonisation of a 200 year simulation: (a) trees colonisation, (b) shrubs colonisation, (c) community structural and composition, and (d – h) height structure changes for the community.

Table 7.3 Comparison of major tree species densities and relative abundances between the simulation ecosystem (after 50 years) and natural forest

Species Name	Simulation		Natural Forest	
	Density (plants /ha)	Relative abundance (%)	Density (plants /ha)	Relative abundance (%)
E. albens	202	16.5	100	7.5
E. crebra	134	11.0	149	11.2
E. pilligaensis	205	16.8	20	1.5
E. populnea	32	2.6	0	0
Callitris glaucophylla	289	23.6	296	22.3
Casuarina cristata	360	29.4	764	57.5
Total	1223		1329	

7.5 Sensitivity Analysis

Sensitivity analysis were carried out to determine how the model responded to variation of parameters or parameter values to assess which parameters might be important in succession. The simulation results are also used to compare results with other published work to validate

model reliability in response to changes in the main parameters. The following sensitivity analyses were performed:

- The distance between the natural forest and the study site was increased by 20 m from the original distance (0 – 2 m), to assess whether seed rain is a critical parameter.

- The seed bank in the topsoil was set to nil, to see if it is a major factor in rehabilitation and assess how long it will take for the site to transit from a grassland to a woodland.

- Since the recovery of the study site relied on a seed source from the surrounding natural forest, the composition and structure of that forest was changed from two different communities to one community to assess the impact of these changes in the model simulation.

- The original soil condition in the simulation was changed to 100% topsoil and then to 100% bare overburden to assess how soil type affected regeneration.

The model was run for 200 years, and results of tree colonisation and community structure and composition were recorded and compared with revegetation patterns presented in Section 7.3.

7.5.1 Seed Source Distance

The natural forest provides seed rain to the disturbed area. Chapter 4 (Figs. 4.9 & 10) indicated the significant difference of distribution between the different species on the two

spoil heaps by 10 m intervals. Trees recolonised from the edge of the rehabilitated area to the centre with a decline in density. When the distance from the natural forest to the study site was increased by 20 m (the original condition of edge distance from the natural forest to the spoil heaps was changed from 1m to 21 m), the simulation showed that after 50 years the number of trees present in the disturbed area was significantly reduced (Figs. 7.9 a and c compared with Figs. 7.5 a and c, Table 7.3), but shrubs presented in a large population (Fig. 7.9 c compared with Fig. 7.5 c). Trees did not totally occupy the northern bare overburden (Fig. 7.10 a). After 100 years of simulation, forests developed on the northern and southern bare overburden sites, but shrubs still dominated the topsoiled area (Fig. 7.10 b). Although there was no significant change in community structure between 50 and 100 years simulation (Figs. 7.10 c and f), the population of tree species had increased (Figs. 7.9 a and c). After 200 years of simulation, trees finally dominated most northern topsoiled area, and finally formed a forest on the western side (Figs. 7.10 c and i).

According to the comparison of the population changes for each tree species between the original succession and the simulation of seed source distance, the increment of seed source distance slows down initial colonisation but once trees established and begin reproducing seed community development progresses more quickly to be similar by 200 years (Table 7.3).

Trees   **Shrubs**

Total

plants of

each

species

Number of Plants

(a)   (b)

Total

individuals

Number of Plants

(c)   (d)

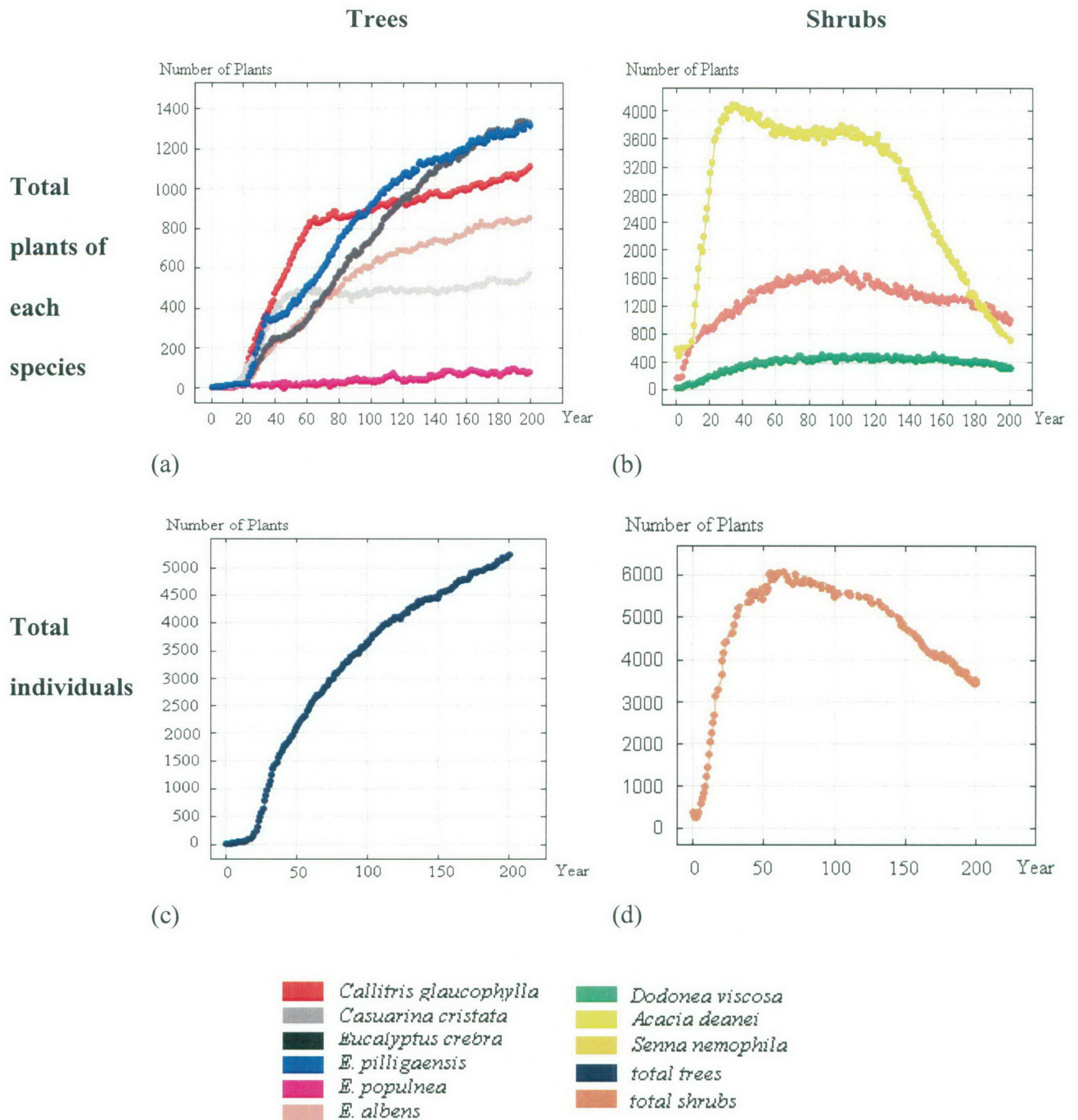|	Callitris glaucophylla		Dodonea viscosa
	Casuarina cristata		Acacia deanei
	Eucalyptus crebra		Senna nemophila
	E. pilligaensis		total trees
	E. populnea		total shrubs
	E. albens		

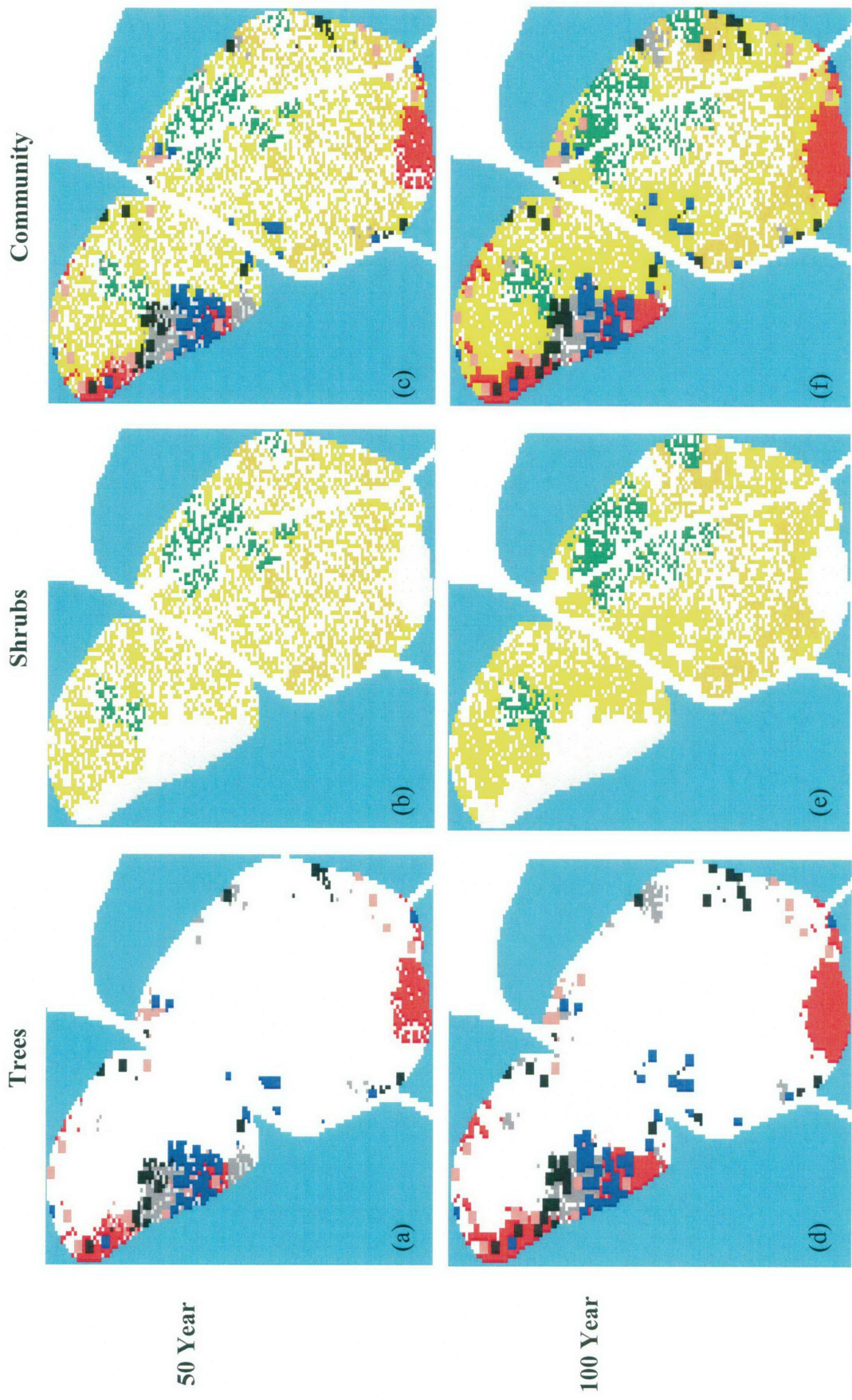**Fig. 7.9** Sensitivity analysis of community composition change after the seed source distance was increased by 20 m: changes in number of plants for (a) tree species and (b) shrubs; and changes in total individuals for (c) trees and (d) shrubs over 200 years simulation.

Sensitivity analysis: seed source distance

Trees

Shrubs

Community

(a)   (b)   (c)

(d)   (e)   (f)

50 Year

100 Year

200 year

Trees (g)

Shrubs (h)

Community (i)

Callitris glaucophylla	*E. pilligaensis*	*Dodonea viscosa*
Casuarina cristata	*E. populnea*	*Acacia deanei*
Eucalyptus crebra	*E. albens*	*Senna nemophila*

Natural forest

Bare overburden

Topsoiled area
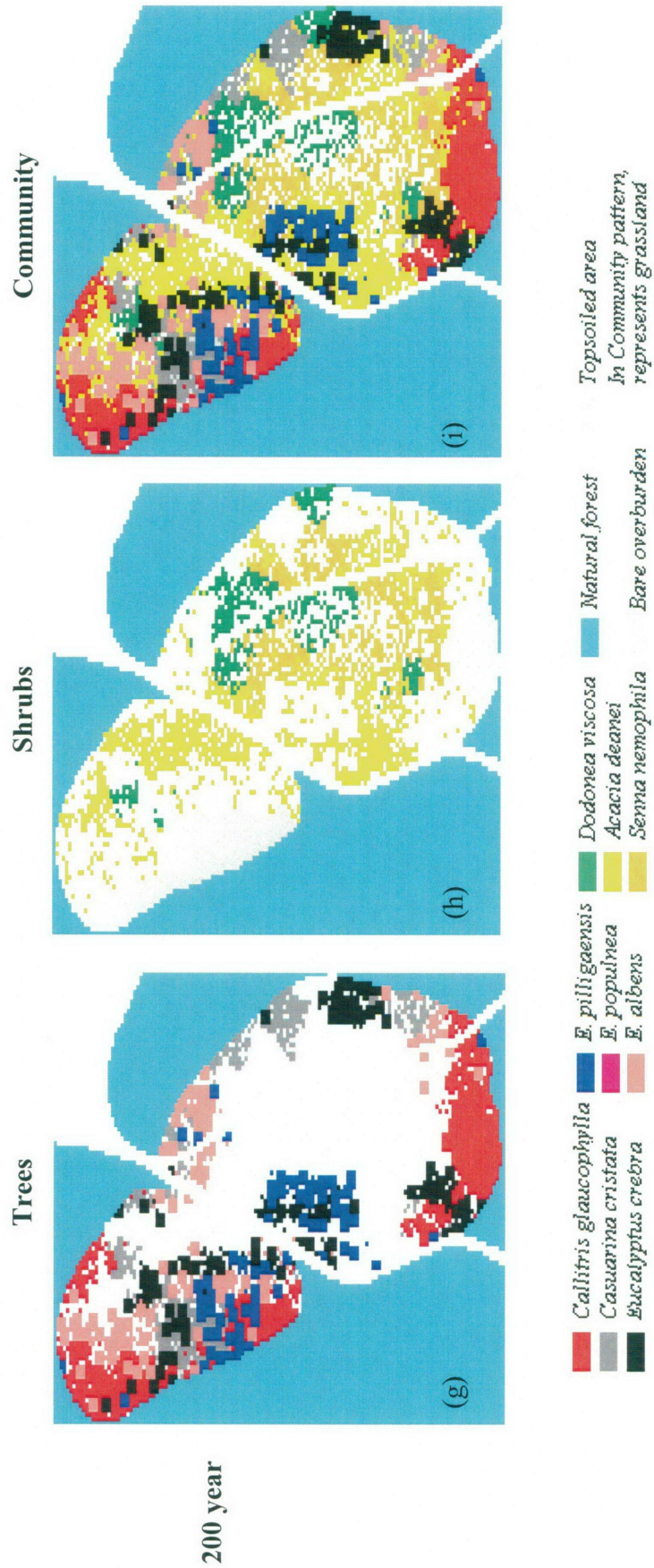*In Community pattern,*
represents grassland

Fig. 7.10 Sensitivity analysis of composition and structural changes after the distance from natural forest to spoil heaps was increased from the original distance (1 m) to 20 m: (a - c) a 50 year simulation, (c - f) a 100 year simulation, and (g - i) a 200 year simulation.

Table 7.4 Comparison of species population changes of simulation over 200 years when the distance from natural forest to the study site was increased by 20 m.

Species Name	50 Years Simulation (plants/ha)		100 Years Simulation (plants/ha)		200 Years Simulation (plants/ha)	
	Original distance (1 m)	+ 20 m	Original distance (1 m)	+ 20 m	Original distance (1 m)	+ 20 m
E. pilligeansis	205	134	359	304	397	435
E. crebra	134	70	297	241	447	439
E. albens	202	70	336	201	376	293
E. populnea	32	2	59	12	54	30
C. glaucophylla	289	210	350	300	456	367
C. cristata	360	166	293	156	281	196
Total	1223	652	1694	1214	2011	1761

7.5.2 Seed Banks in the Topsoil

Seed banks in the topsoil are another factor that impacts on natural succession and influence establishment, successional patterns of shrubs and ultimately the level of competition between trees and shrubs. In order to test the effect of this parameter on the model output, all seeds were removed from the topsoil so that the natural forest is the only seed source for rehabilitation.

Total number of trees increased significantly up to 70 years and then remined steady, whereas

C. cristata dominated up to about 70 years and then declined significantly while *C.*

glaucophylla, E. crebra, E. albens, and *E. pilligaensis* steadily increased in number. Shrubs

had a much reducer population with the succession of original condition (Table 7.4), but total

numbers of trees were larger than that of initial colonisation (Fig. 7.11).   Intra-specific

competition between trees is likely to be a reason for *C. cristata* declined.

Table 7.5 Comparison of plant density (plants/ha) over 200 years of simulation when the seed bank was removed from the topsoil.

Total individuals	50 years		100 years		200 years	
	Initial colonisation	Topsoil seed bank removed	Initial colonisation	Topsoil seed bank removed	Initial colonisation	Topsoil seed bank removed
Trees	1223	1703	1694	2084	2011	2135
Shrubs	1583	133	1507	107	433	43

Plants (trees and shrubs) colonised the spoil heaps from the edge, and formed a forest along

the edge (Fig. 7.12). The northern overburden was densely covered by trees in 50 year

simulation (Figs. 7.12 a and c). However, a patch of grassland is evident in the middle of

southern site (Figs. 7.12 b and c) whereas it developed into a shrubland if the topsoil seed

bank was available (see Figs. 7.6 b and c). Shrubs established along the edge (Figs. 7.12 b and

c) in small populations (Figs. 7.11b and d) and declined after 40 years (Fig. 7.11 d). By 100

years, the site was totally covered by forest thereby accelerating the initial colonisation (Fig.

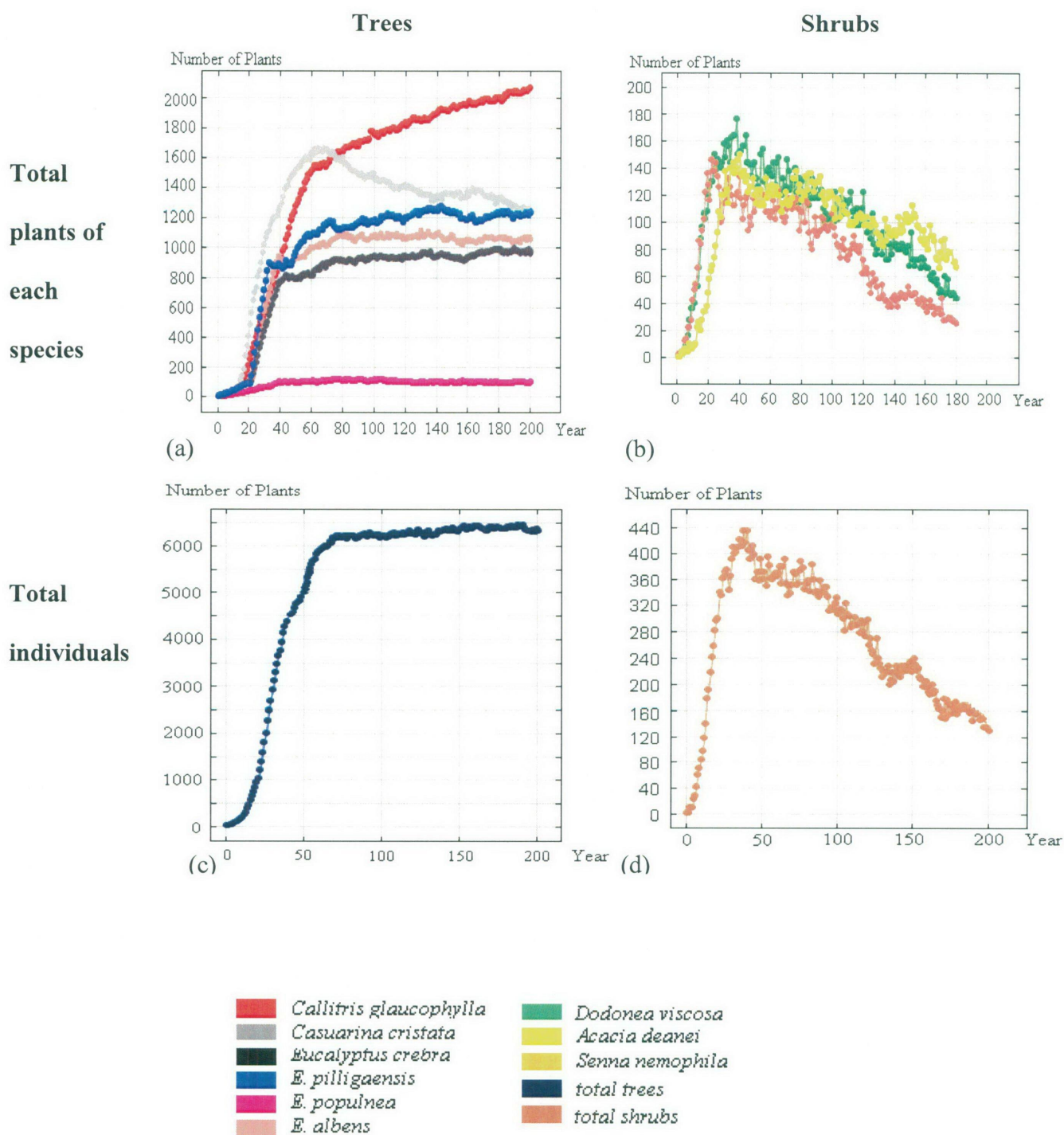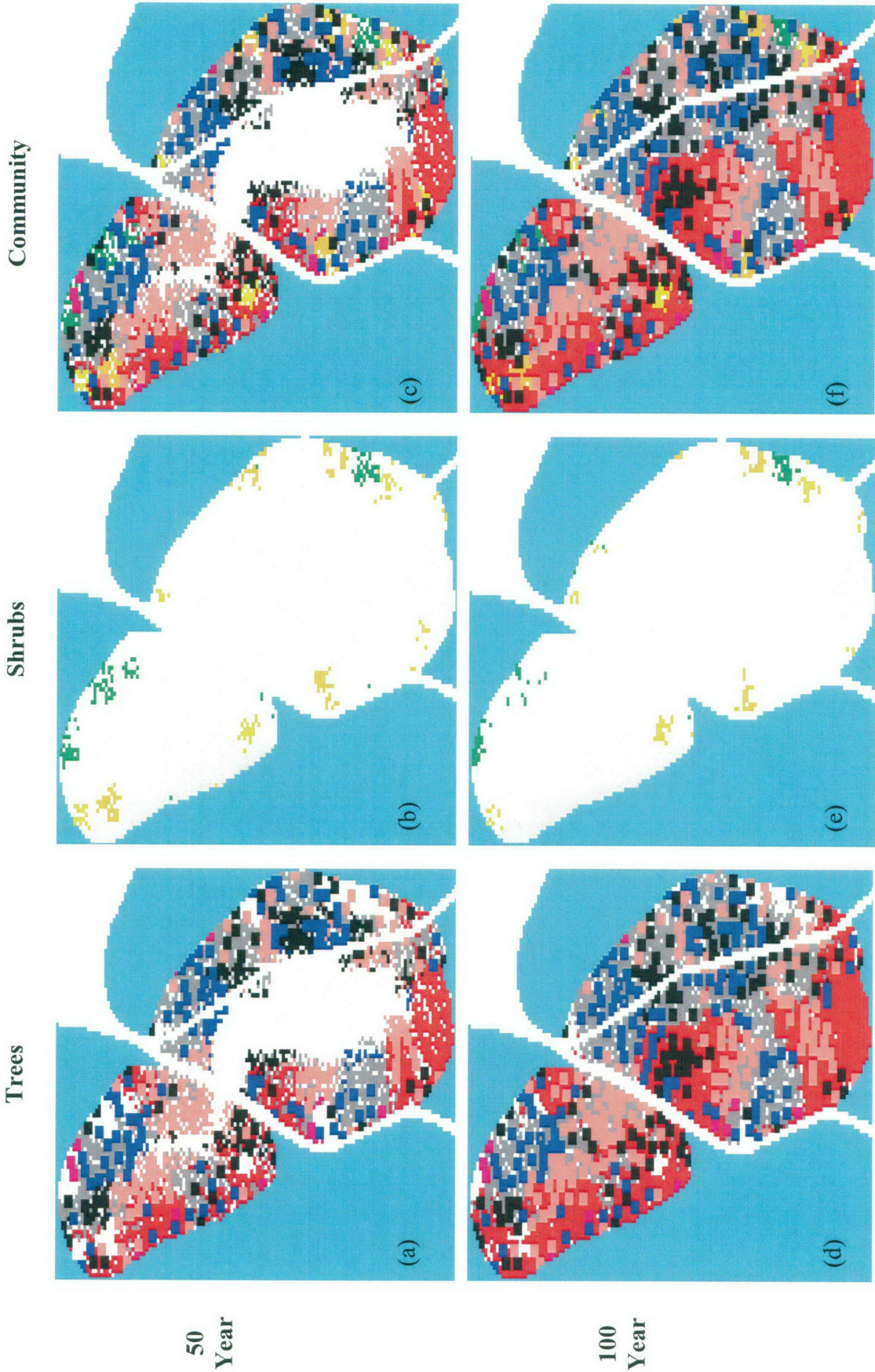7.7) from a grassland to a forest principally by removing competition between shrubs and trees.

Trees   **Shrubs**

Total

plants of

each

species

(a)   (b)

Total

individuals

(c)   (d)

🟥 *Callitris glaucophylla*	🟩 *Dodonea viscosa*
⬜ *Casuarina cristata*	🟨 *Acacia deanei*
⬛ *Eucalyptus crebra*	🟨 *Senna nemophila*
🟦 *E. pilligaensis*	🟦 *total trees*
🟥 *E. populnea*	🟧 *total shrubs*
🟧 *E. albens*	

Fig. 7.11 Sensitivity analysis of community composition changes when the seed source in the topsoil was removed: changes in number of plants for (a) trees and (b) shrubs; and changes in total individuals for (c) trees and (d) shrubs over 200 years simulation.

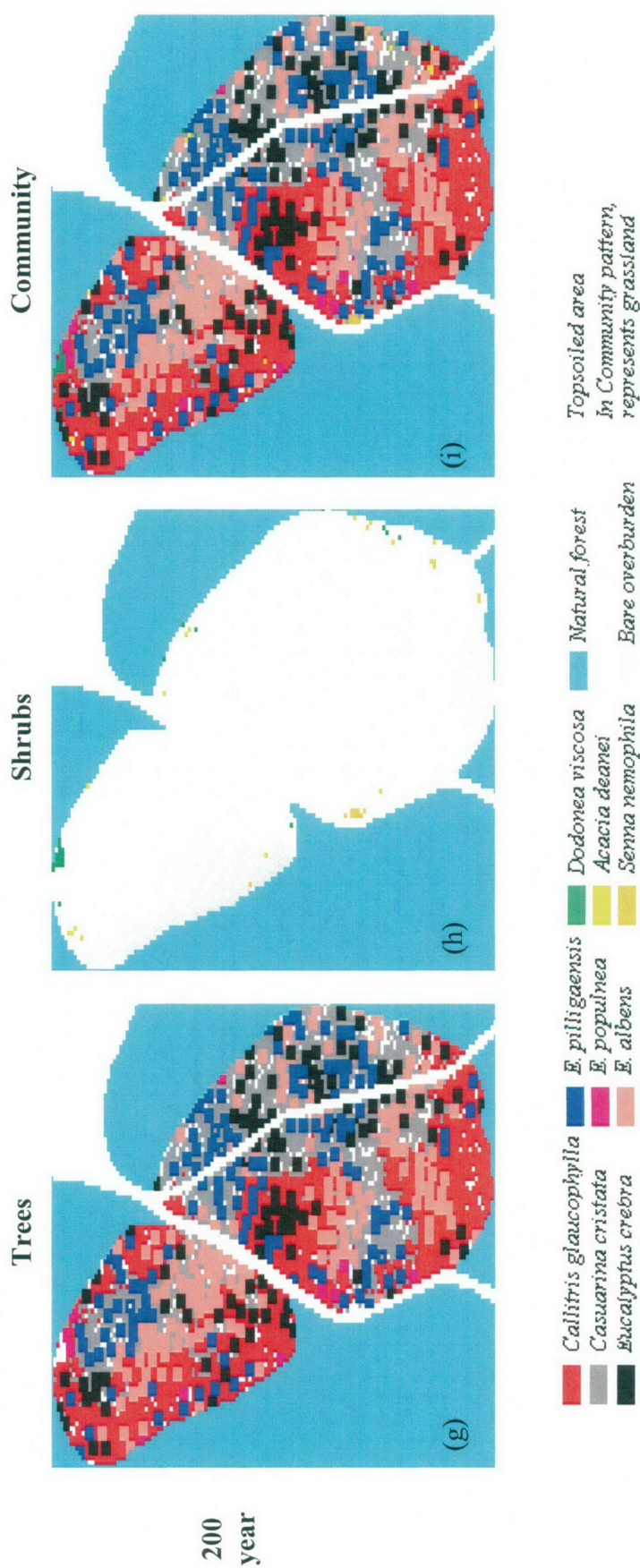**Sensitivity analysis: seed source in the topsoil was removed**

Trees   Shrubs   Community

50 Year

100 Year

Continues:

Trees

Shrubs

Community

(g)   (h)   (i)

200 year

	Calitris glaucophylla		E. pilligaensis		Dodonea viscosa		Natural forest		Topsoiled area
	Casuarina cristata		E. populnea		Acacia deanei				In Community pattern,
	Eucalyptus crebra		E. albens		Senna nemophila		Bare overburden		represents grassland

Fig. 7.12 Sensitivity analysis of community composition and structural changes when the seed source in the topsoil was removed: (a – c) a 50 year simulation, (c – f) a 100 year simulation, and (g – i) a 200 year simulation.

7.5.3 Changes in Community Composition and Spatial Structure in the Surrounding Forest

Since recovery of the study site relied on seed sources from the surrounding natural forest, the community composition of the natural forest was also varied to understand its influence in rehabilitation.

Under the original condition, *C. glaucophylla* did not occur in the southeast part of the site (Fig. 7.6) due to the difference in community composition in the surrounding natural forest. However, when the vegetation in the surrounding forest on the south eastern site was assumed similar to that on the northern site, then the population of *C. glaucophylla* increased (Fig. 7.13) and *C. glaucophylla* was also present along the eastern edge (Fig. 7.14). The changes of composition in the surrounding forest resulted in population changes of other tree species, for instance, *C. cristata* and *E. pilligaensis* reduced. These results indicate that the community composition of the natural vegetation surrounding the recovery site had an impact on the succession pattern.
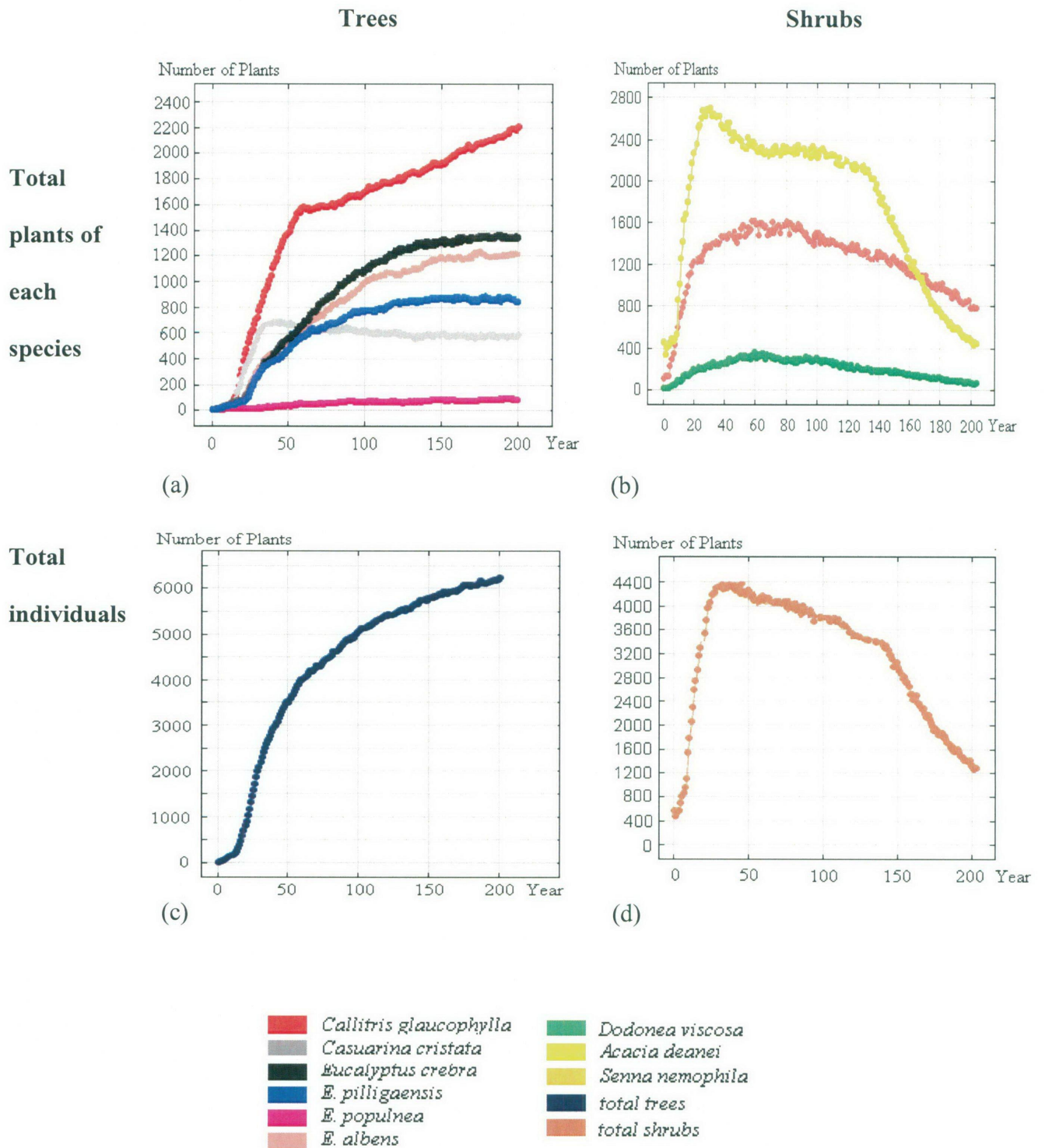
Trees

Shrubs

Total plants of each species

(a)

(b)

Total individuals

(c)

(d)

�	*Callitris glaucophylla*	�	*Dodonea viscosa*
▯	*Casuarina cristata*	▯	*Acacia deanei*
▮	*Eucalyptus crebra*	▯	*Senna nemophila*
▮	*E. pilligaensis*	▮	*total trees*
▮	*E. populnea*	▮	*total shrubs*
▮	*E. albens*		

Fig. 7.13 Sensitivity analysis of community composition changes when *C. glaucophylla* was added to the eastern community in the surrounding natural forest: changes in number of plants for (a) tree species and (b) shrubs; and changes in total individuals for (c) trees and (d) shrubs over 200 years simulation.

Sensitivity analysis: community composition changes in the surrounding forest

Trees

Shrubs

Community

50 Year

100 Year
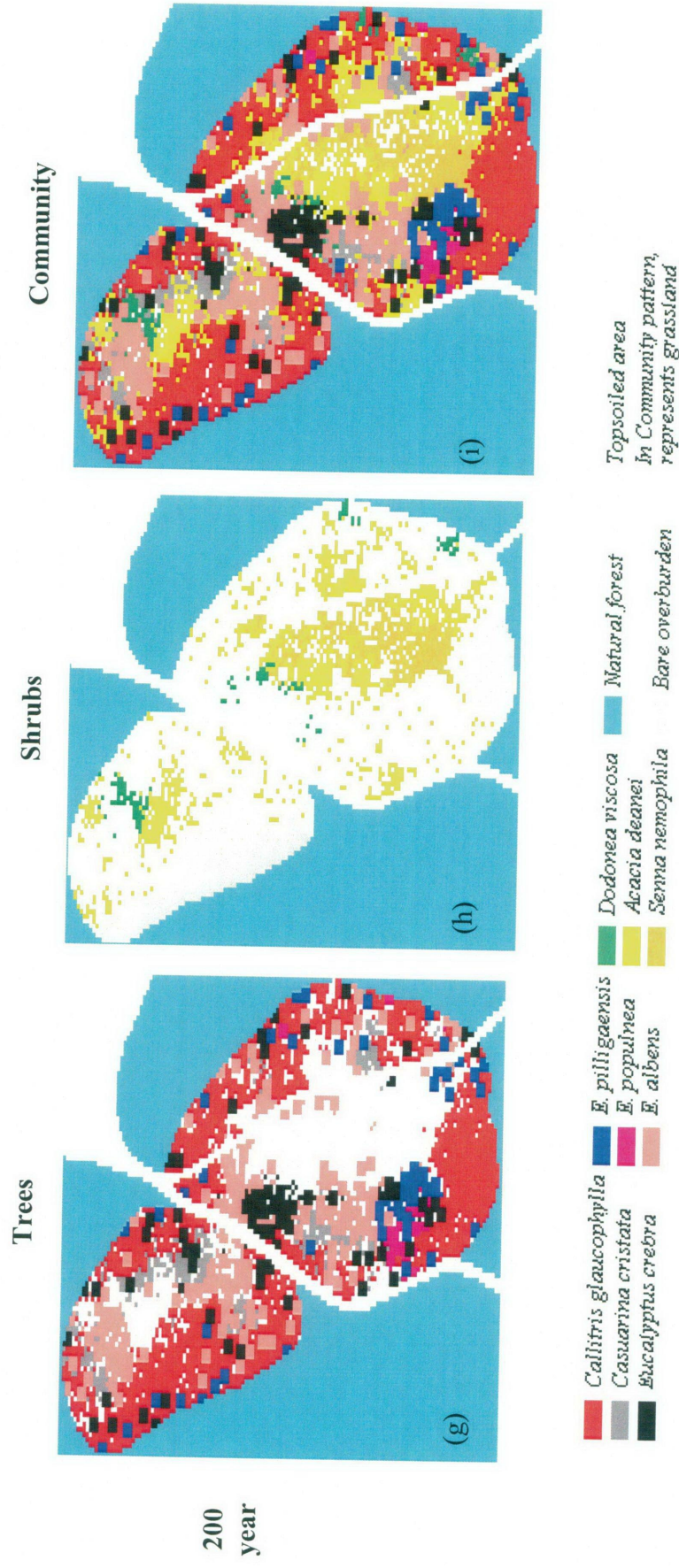
(a)

(b)

(c)

(d)

(e)

(f)
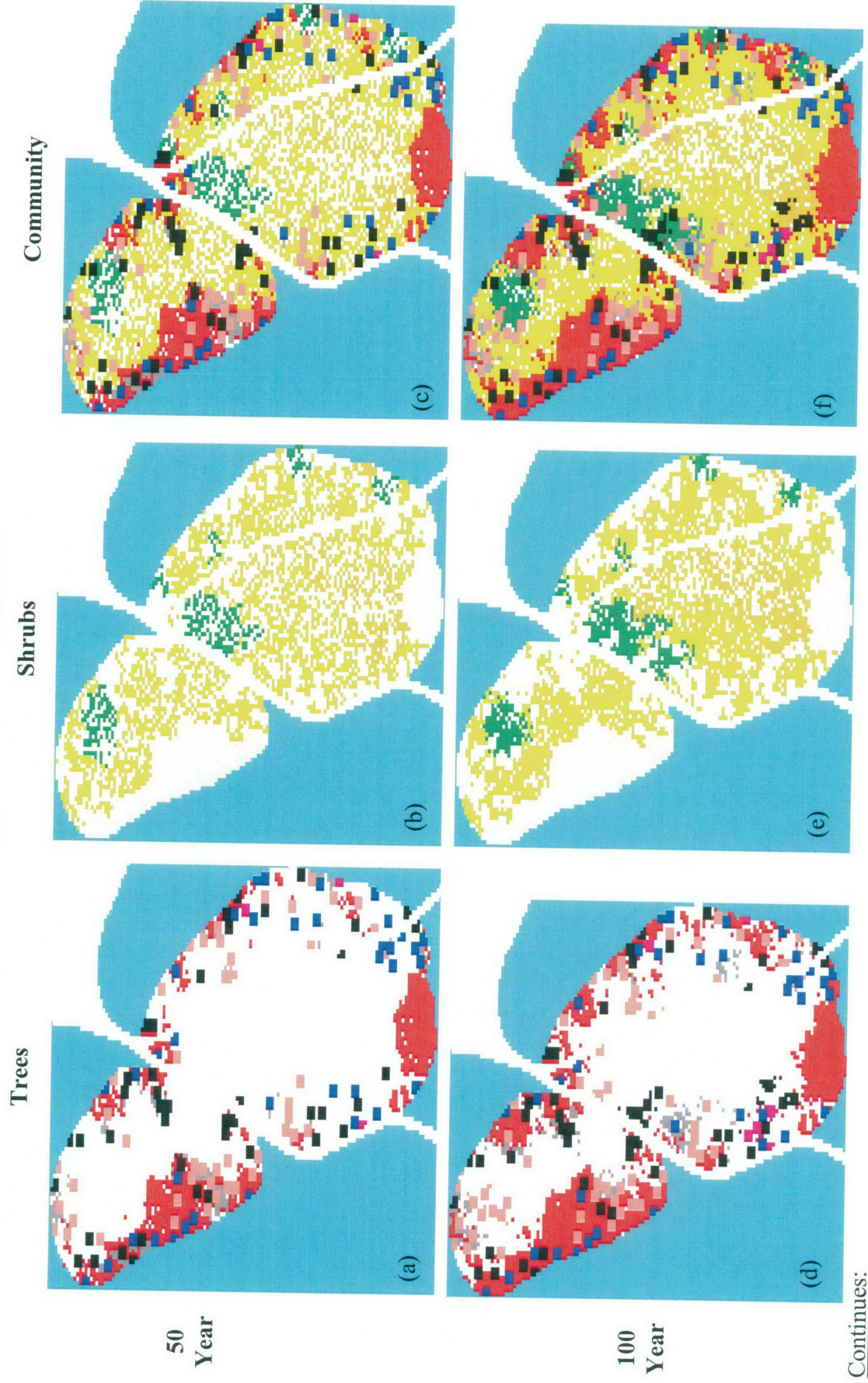
Continues:

Fig. 7.14 Sensitivity Simulation of community composition and structural changes when *C. glaucophylla* was added to the eastern community in the surrounding natural forest: (a - c) a 50 year simulation, (c - f) a 100 year simulation, and (g - i) a 200 year simulation.

7.5.4 Soil Type

Soil type plays an important role in rehabilitation. At the study site two kinds of materials were present, namely overburden covered with topsoil and bare overburden (Chapter 3). The topsoil introduced a seed bank dominated by shrubs (Chapter 5) as well as providing a good growth medium for plants. Varying the soil type influences vegetation succession through the available seed source as well as affecting germination, mortality and growth of both trees and shrubs. Species have different germination and mortality rates in the two different soil types (Chapter 4), and this affects colonisation patterns.

When the soil type was changed to 100% topsoil, shrubs were abundant (Fig. 7.15) with up to 6000 plants around 60 years, and then declined with a concomittant increase in individual trees. However, shrubs were present in very low populations when the soil type was bare overburden (Fig. 7.16). Total individual trees increased to 6500 plants in around 70 years of simulation with bare overburden compared to 5800 in 200 years with topsoil (Figs. 7.15 c and 7.16 c).

When the study site was totally covered by topsoil, the site was quickly covered by shrubs and trees (Fig. 7.17). However, even after 100 years of simulation, the succession pattern showed that shrubs persisted and dominated most part of southern study site and formed a shrubland (Fig. 7.17). This indicates that competitive exclusion of the tree species was occurring.

When the soil type was changed to bare overburden, the seed bank was eliminated so the natural forest was the only seed source for rehabilitation. Even some shrub seeds dispersed

into the study site from the natural forest to the bare overburden soil but at a much lower rate. Trees had more chance to colonise without competition from shrubs and after 100 years, the study site was covered by a forest (Fig. 7.17). However, after 50 years of regeneration on bare overburden, the middle part of the study site remained as bare overburden without vegetation cover (Fig. 7.17). A few shrubs were present over the site after 200 years, because the surrounding natural forest provided a regular seed source (it is assumed that the community composition of surrounding forest does not change) and suitable environmental conditions were available for shrub colonisation (Figs. 7.16 and 7.17).

The soil type provides different environment for growth of shrubs and trees, and results in different colonisation patterns of community.
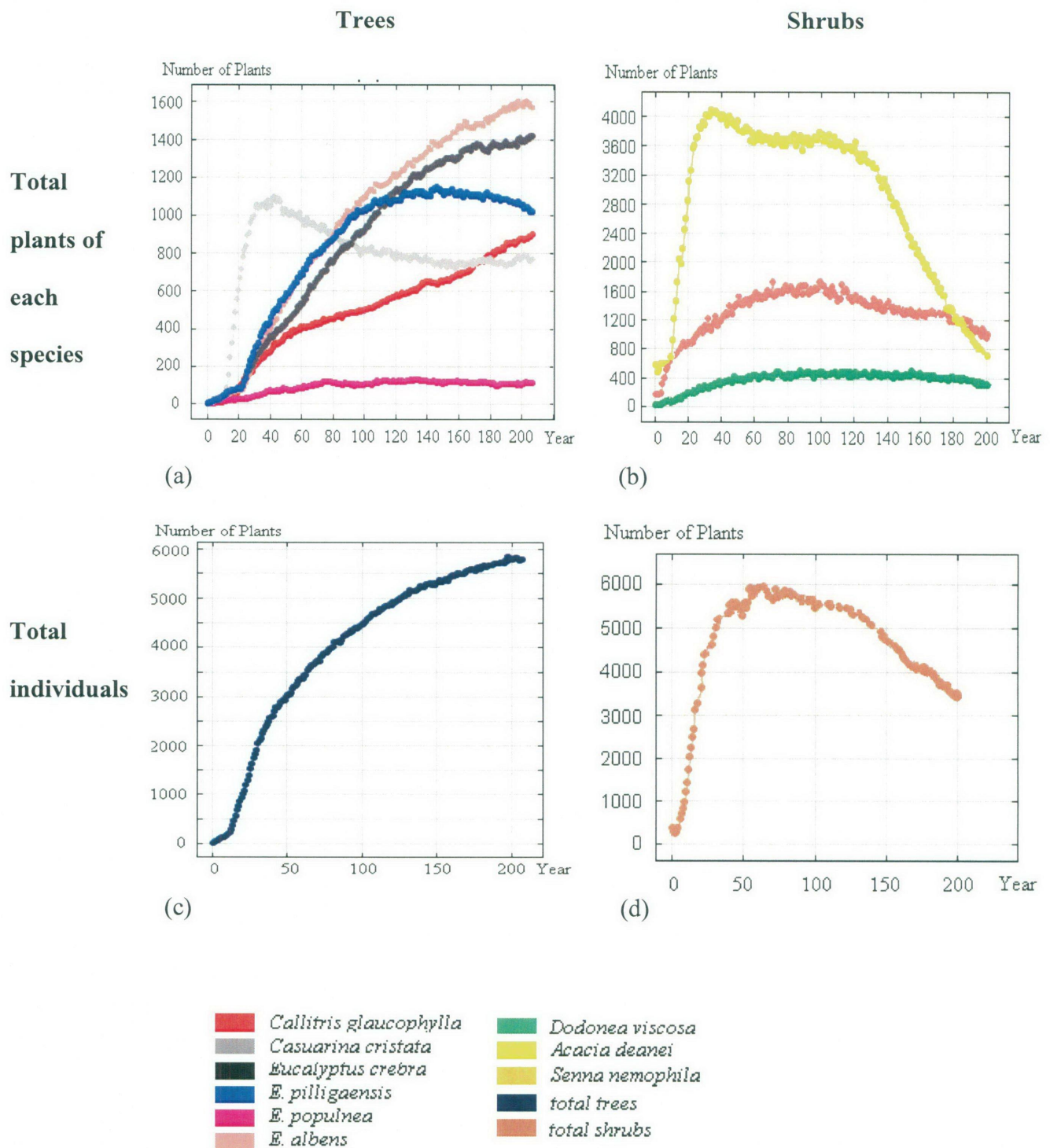
Trees   **Shrubs**

Total

plants of

each

species

(a)   (b)

Total

individuals

(c)   (d)

	Callitris glaucophylla		*Dodonea viscosa*
	Casuarina cristata		*Acacia deanei*
	Eucalyptus crebra		*Senna nemophila*
	E. pilligaensis		*total trees*
	E. populnea		*total shrubs*
	E. albens		

Fig. 7.15 Sensitivity analysis of community composition changes when soil type of study site was topsoil: changes in number of plants for (a) tree species and (b) shrubs; and changes in total individuals for (c) trees and (d) shrubs over a 200 year simulation.
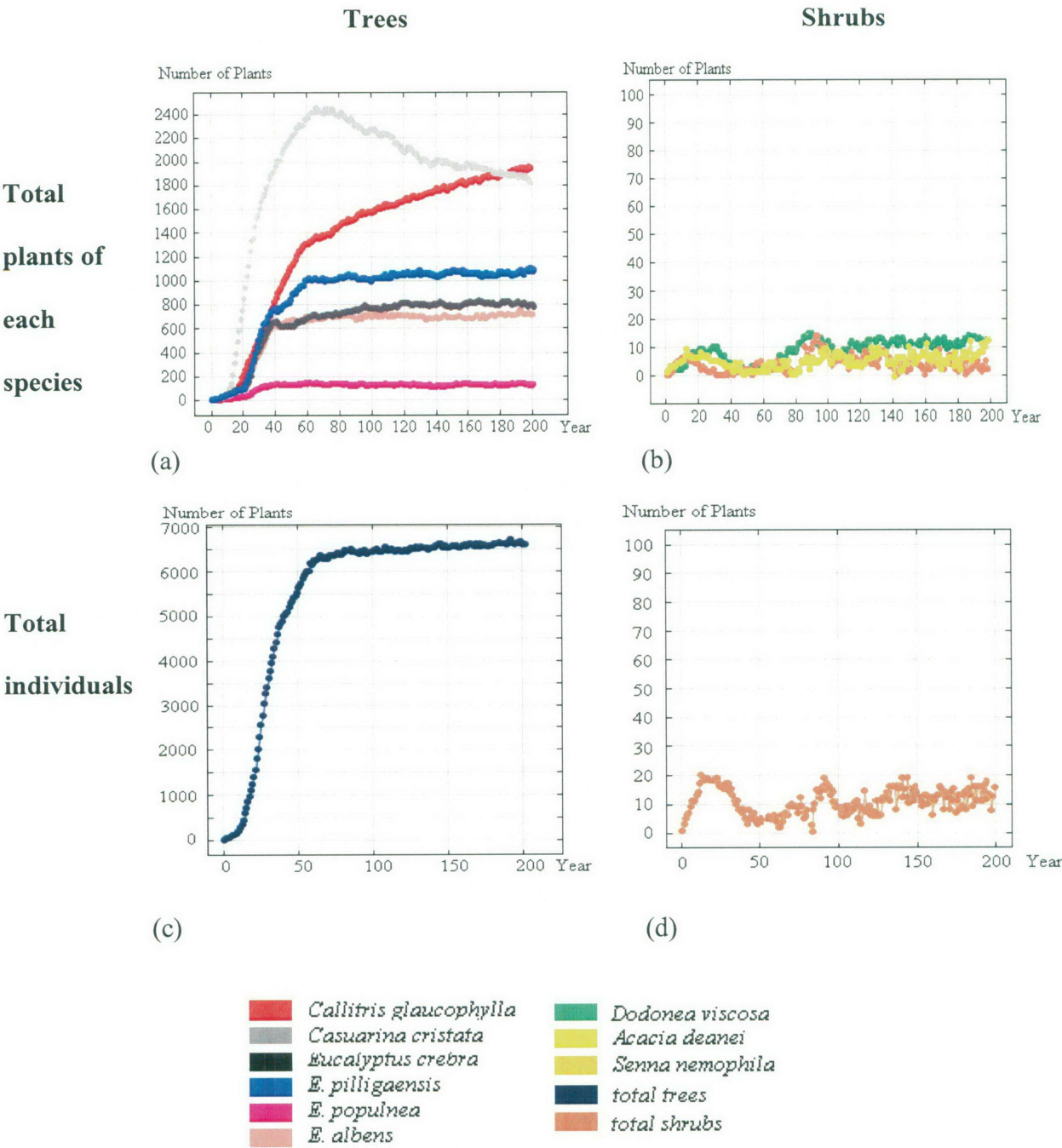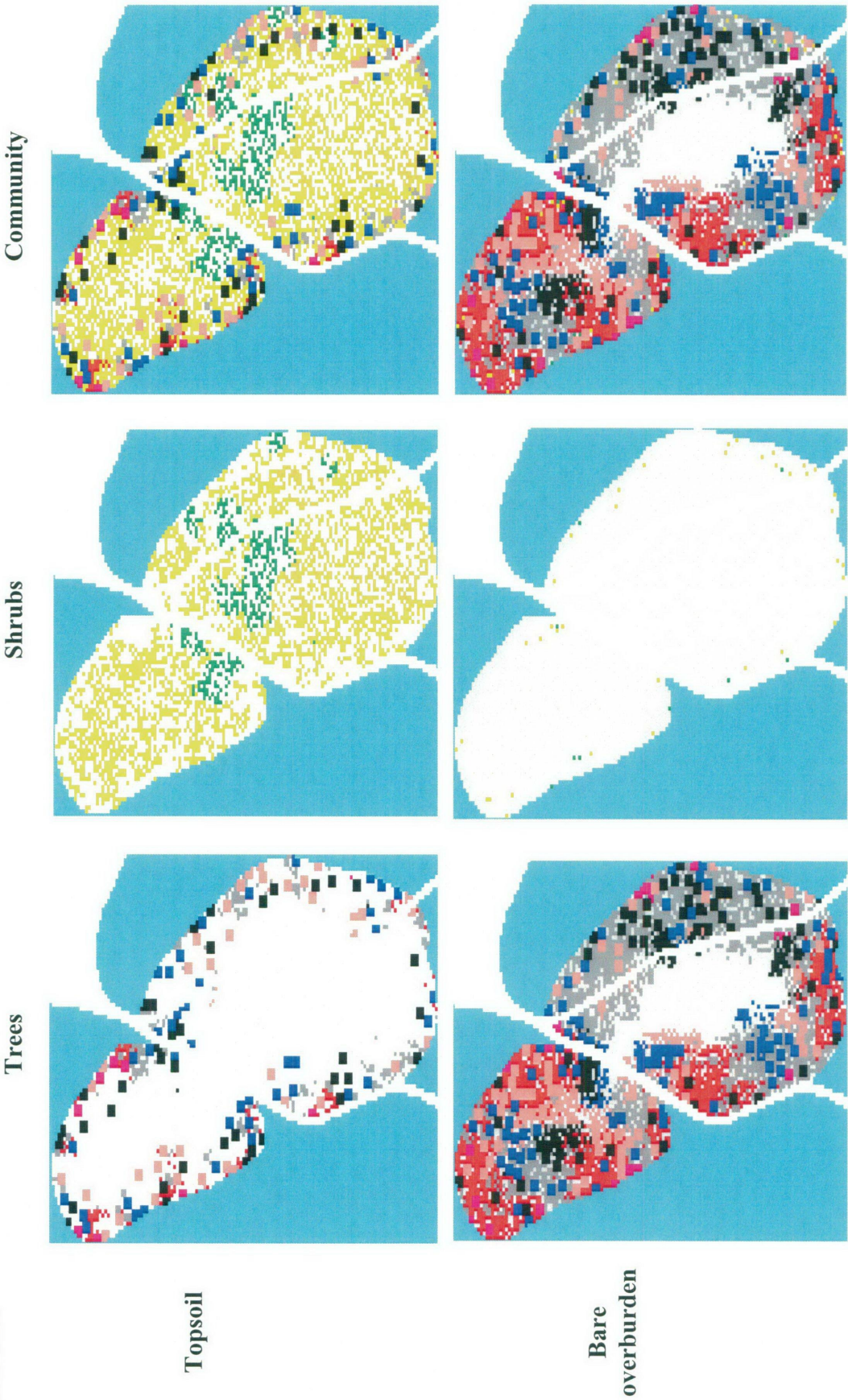
Trees   **Shrubs**

Total

plants of

each

species

(a)   (b)

Total

individuals

(c)   (d)

■ *Callitris glaucophylla*	■ *Dodonea viscosa*
■ *Casuarina cristata*	■ *Acacia deanei*
■ *Eucalyptus crebra*	■ *Senna nemophila*
■ *E. pilligaensis*	■ *total trees*
■ *E. populnea*	■ *total shrubs*
■ *E. albens*	

Fig. 7.16 Sensitivity analysis of community composition changes when soil type of study site was bare overburden: changes of number plants of tree species and shrubs, and changes of total individuals of trees and shrubs over a 200 year simulation.
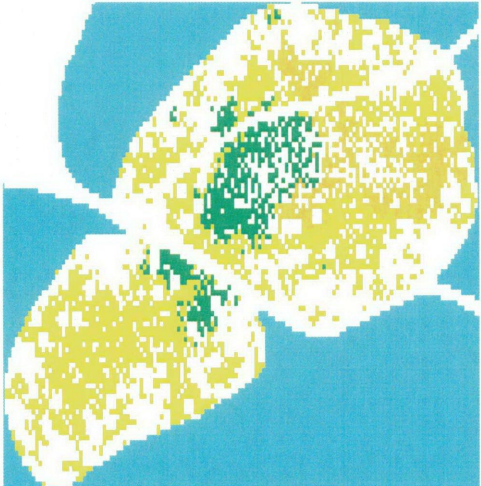
162

Sensitivity analysis: soil type

50 Year

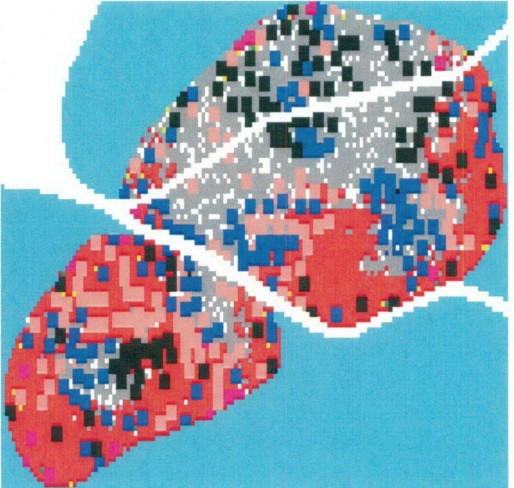Trees   Shrubs   Community
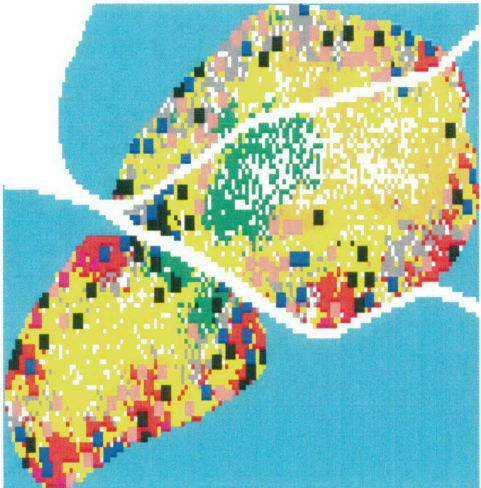
Topsoil
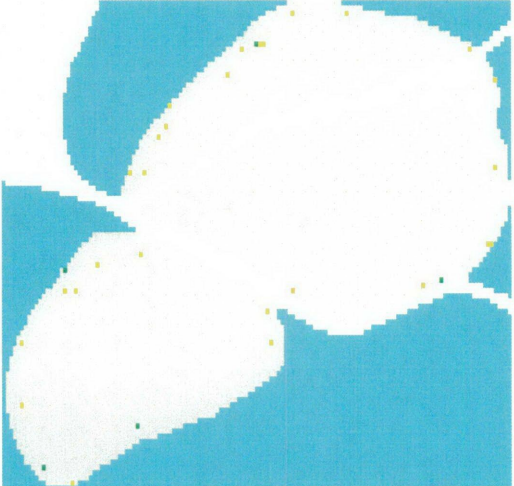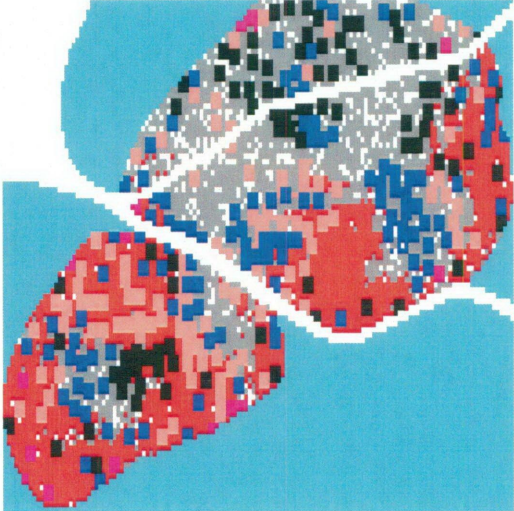
Bare
overburden

Continues:

Trees

Shrubs

Community

100 Year

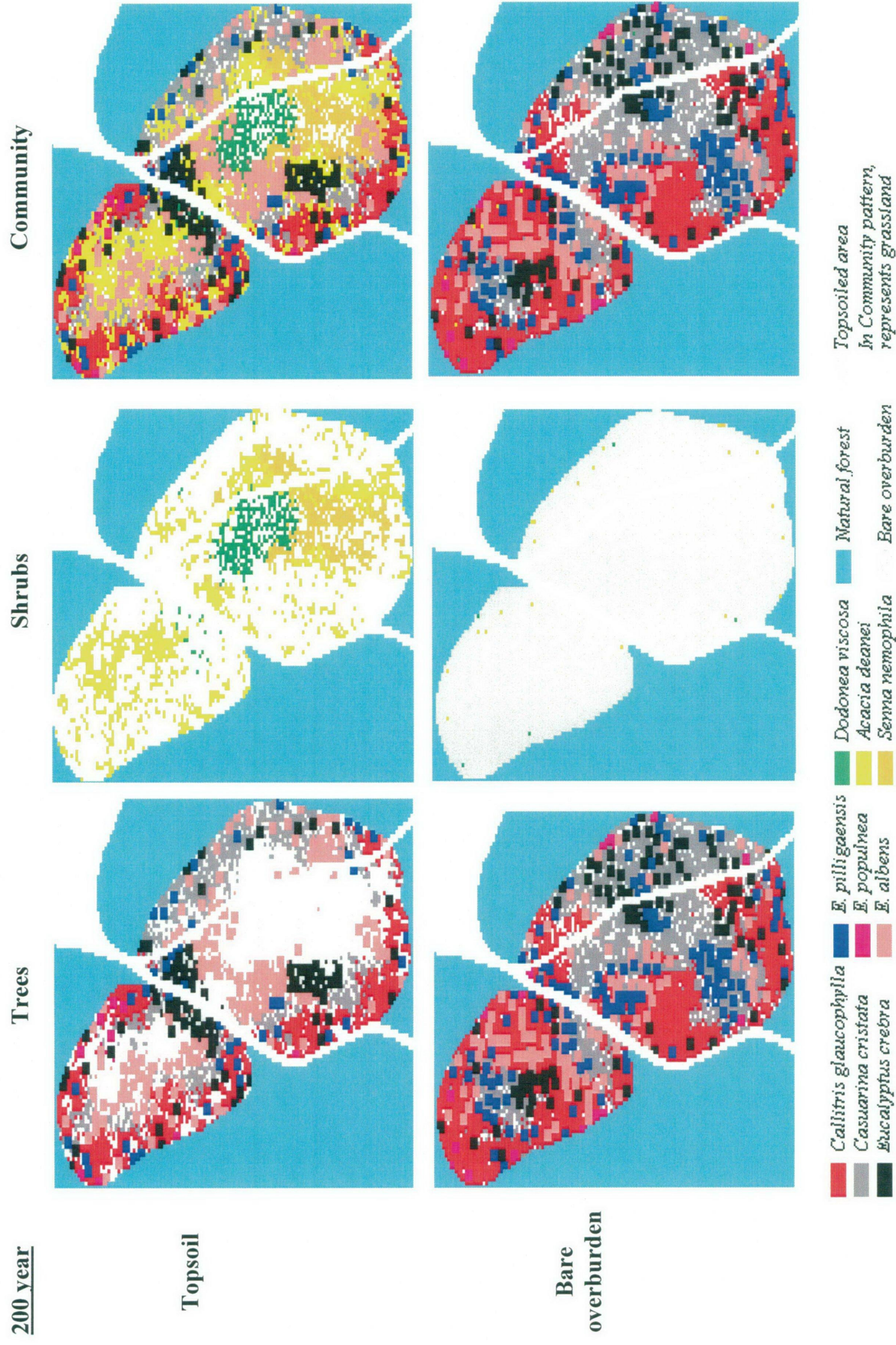**Topsoil**

Bare overburden

Fig. 7.17 Sensitivity analysis of community composition and structural changes when soil type of study site was changed as topsoil or bare overburden only.

7.6 Discussion and Conclusions

The results presented in this chapter show that the Agent-based Model developed was able to reliably simulate natural succession after disturbance. After 20 years of succession the species distribution predicted by the model was similar to that observed and measured in the field. As the model was able to simulate the first 20 years of succession it was considered likely that it would also be able to simulate succession beyond 20 years. However, since field monitoring does not go beyond 20 years, it is difficult to validate the model appropriately.

The results of the simulation showed that natural succession on spoil heaps was mainly controlled by seed source, seed dispersal distance, and the species composition of the surrounding vegetation. Soil type influences plant growth and soil seed banks and results in different community composition and structure. Vegetation development was soil type specific. Depending on the soil type the communities were dominated by either shrubs or trees. Trees took much longer to colonise the topsoil area where shrub communities developed well and the shrubs tended to persist for a considerable time. The importance of soil type was recognised by the sensitivity analyses. When the soil cover was changed to total overburden type, the tree species dominated and the site became a closed canopy forest within 100 years. However, before the entire area was colonised by trees large parts remained without vegetation cover for a considerable time (i.e. at leat 50 years). Such a delay in vegetation development meant that the risk of soil erosion increased (Chaulya *et al.* 1999; Hancock & Turley 2006).

The success of rehabilitation relies on seed supply. The topsoil provided a seed bank for natural rehabilitation (Koch & Ward 1994). The sensitivity analysis showed that if seed viability is reduced in the topsoil, the re-colonisation by shrubs would take longer thereby providing a better chance for trees to colonise topsoil.

The sensitivity analysis of the major parameters affecting natural re-vegetation indicated that composition and structure of tree communities in restored sites also depends on seed rain and its composition. If the species composition in the surrounding forest was varied the composition of the revegetation was also different. The distance between the seed source and spoil heaps was a major factor influencing rehabilitation. To accelerate species colonisation the use of fresh topsoil or supplementing seed sources is suggested. This management option is likely to hasten rehabilitation towards the desired state.

The initial floristic composition following disturbance is determined by propagules, which can be from the seed bank or seed rain (Noble & Slatyer 1981) or by vegetative growth from plant fragments. The results presented here confirm this conclusion.

Research on mining rehabilitation has progressed since the 1970s (Bell 2001; Cairns 1995; Lubke 1999). Conceptual and mathematical models have been developed for predicting future community structure and composition using the state and transition model (Grant 2006). However, no suitable simulation model has been developed to use in mining practices and improve rehabilitation outcomes. This study developed an Agent-based Model for simulating vegetation colonisation and succession that will help users predict vegetation development patterns on the basis of different rehabilitation strategies. The model was developed using

observed and measured data. A statistical analysis showed that the model can represent vegetation development over the first 20 years. The sensitivity analysis on the main parameters used in the model also indicate that the model can react to parameter changes, and provide similar conclusions as to what other researchers have found. Thus, the model is considered reliable and can be used in simulating vegetation succession for rehabilitation application. For instance, the model can be applied to simulate the different soil applications on the basis of a rehabilitation plan (Noble 1981), can predict patterns for proposed rehabilitation designs, and can help managers adjust management strategies to reach the desirable rehabilitation state. Essentially this model has the potential to improve rehabilitation of mining sites.

This study assumed that the forest was only disturbed by mining activity, with no further natural or human disturbance later in the succession. Any other disturbance, such as fire or disease, has not been considered. This simulation model needs to be validated by further field measurements and other case study site.