CHAPTER 1

General Introduction

Commercial plantation forestry competes with agricultural crops for the limited arable land in South Africa (Vlok & Van der Merwe 1999), especially since the lapse of its expansion phase. Over the past decade, most of the land that is available for new afforestation was in low productivity sites (Burley *et al.* 1989). The tree species selected for planting were often not suited to these sites because of incomplete site-species interaction studies (Darrow 1994) or the tree species were susceptible to insect pest and disease attacks. To maximize yields in a limited area, there has also been a corresponding shift from extensive to intensive silviculture of seedlings (Schönau 1990). This increase in plantation productivity is, however, dependent on the initial stocking of trees within compartments. It therefore became important to ensure the protection and survival of seedlings during the establishment and regeneration of sites, which created a renewed emphasis on plantation establishment.

Problem statement

During the initiation of this study, a variable value of up to about 42% failure of various species of forestry seedlings to establish in South Africa was recorded (Rusk *et al.* 1992, 1993, 1994). The causes of this mortality were vaguely known and the impact of soil invertebrate pests and diseases were poorly understood. Various silvicultural attempts to address this problem focussed on the use of improved genetic material, site preparation and cultivation, weed management, nutrition responses, and site-species matching studies. Although these inputs considerably improved the growth of seedlings, they did not always ensure the survival of seedlings. Entomological research on the problems of establishment was a low priority because of the reliance on the corrective use of insecticides. The probability of soil invertebrate pests attacking different species of seedlings was based on previous experience with wattle seedlings (Sherry 1971). Knowledge of the effects of different plantation residue management regimes on the incidence of soil invertebrate pests was also lacking. High-risk areas could not be accurately identified, which precluded strategic planning and budgeting for control measures in the planting programmes. Foresters often replanted dead seedlings with no corrective action, until they experienced repeated failure of seedlings to establish. In some plantation areas of South Africa, the preventative use of insecticides at planting as an insurance against soil invertebrate pest damage was adopted. Besides being financially wasteful and environmentally hazardous, many certified forests were in contravention of certification guidelines.

Study objectives

1. To present a case for the revival of Forest Entomology research in South Africa and to prioritise the entomological research needs of the forestry industry.
2. To assess the status, and to quantify the impact of soil invertebrate pests and any other mortality factors that were responsible for the loss of establishment of regenerated wattle, eucalypt and pine seedlings.
3. To determine the effects of plantation residue management practices on the incidence of soil invertebrate pests.
4. To provide an overview and to consolidate previous research on soil invertebrate pests, some of which appeared in miscellaneous reports.
5. To evaluate current management strategies for forestry pests against the principles and criteria of the Forest Stewardship Council.

Selection of trial sites

Plantation forestry occurs in 13 different geographical zones in South Africa (Department of Water Affairs and Forestry, 1991) (Figure 1). Zones one to four are in the Transvaal and Free State regions, while zones five to nine are in the KwaZulu-Natal regions, and all these zones collectively make up the summer rainfall region of South Africa. Zones 10 to 13 are in the Cape and represent the winter and all year rainfall regions. Experimental trials were conducted only in the summer rainfall region for logistical reasons.

Trial sites and the species of trees that were included in the trial series were selected according to the percentage distribution of commercial plantation areas and tree species within the different zones. Those plantation areas and associated tree species in these zones that had a distribution of about 10% or more of the total distribution of commercial plantation area or tree species (numbers in bold in Table 1), were initially selected for the placement of

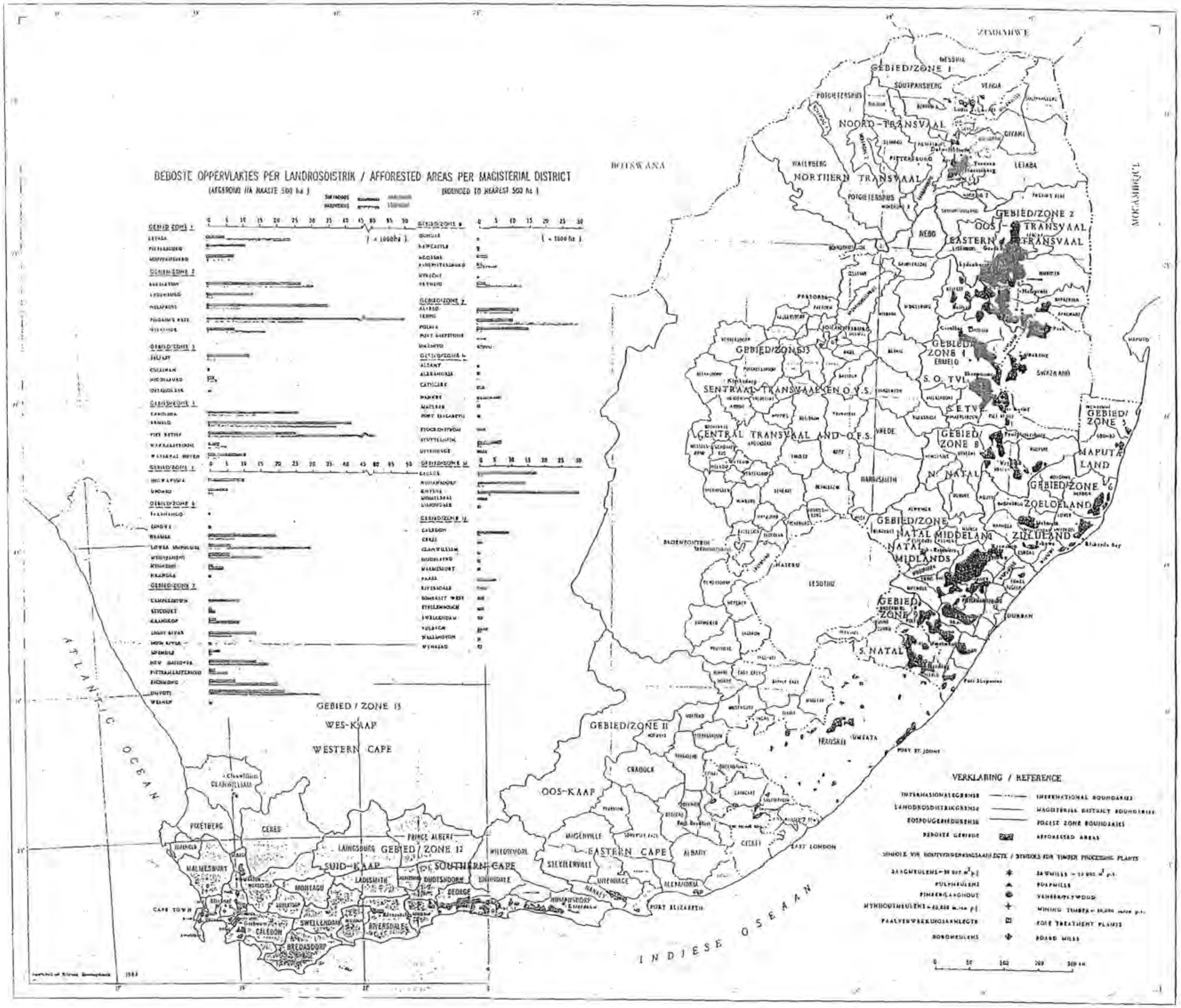

Figure 1. Economic map and regional zones of commercial forestry in South Africa.

Table 1. A comparison of the percentage distribution of commercial forestry plantation species according to economic zones in South Africa over two growing seasons (1995/96 and 1998/99) (extracted from Department of Water Affairs and Forestry 1997, 2000). Predominant areas and species are in bold.

ZONES	Percentage distribution of commercial plantation areas and tree species							
	All plantation tree species		Pines		Eucalypts		Wattle	
	1995/96	1998/99	1995/96	1998/99	1995/96	1998/99	1995/96	1998/99
Summer rainfall areas								
Zone 1 Northern Province	4.2	4.4	3.7	3.9	5.5	5.7	0.1	0.1
Zone 2 Mpumalanga North	**19.5**	**17.6**	**23.5**	**22.0**	**17.6**	**15.5**	0.2	0.0
Zone 3 Central Districts	0.9	1.4	1.2	2.2	0.8	0.6	0.1	0.1
Zone 4 Mpumalanga South	**20.9**	**20.7**	**17.1**	**17.8**	**25.2**	**24.7**	**25.8**	**19.6**
Subtotal	*45.5*	*44.1*	*45.5*	*46.0*	*49.1*	*46.6*	*26.2*	*19.8*
Zone 5 Maputaland	1.2	1.5	1.4	1.3	1.3	1.9	0	0
Zone 6 Zululand	**9.2**	**9.9**	5.4	4.3	**15**	**17.9**	4.1	5.6
Zone 7 Natal Midlands	**14.2**	**13.4**	**11.4**	**9.9**	**13.2**	**12.0**	**40.8**	**42.6**
Zone 8 Northern KZN	5.5	5.8	1.9	2.3	8.3	7.6	**17**	**20.2**
Zone 9 Southern KZN	7.4	8.2	6.1	6.5	8.9	10.2	9.3	9.2
Subtotal	*37.5*	*38.8*	*26.2*	*24.5*	*46.7*	*49.5*	*71.2*	*77.7*
Zone 10	has become invalid							
Zone 11 Eastern Cape	9.9	9.8	15.7	16.2	3.2	3.1	2.4	2.3
All year rainfall areas								
Zone 12 Southern Cape	5.3	5.3	9.3	9.7	0.8	0.6	0.2	0.2
Winter rainfall areas								
Zone 13 Western Cape	1.8	2.0	3.3	3.7	0.2	0.2	0.0	0.0
Subtotal	*17.0*	*17.1*	*28.3*	*29.6*	*4.2*	*3.9*	*2.6*	*2.5*
TOTAL	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

trials. The selection of trial sites was then further refined according to site availability because of the cyclic nature of plantation forestry, previous crop and type of plantation residue management regime. Low versus high productivity plantation area was also screened for the placement of trials to ensure representation.

The percentage distribution of the commercial plantation area per zone and tree species per zone in South Africa were found to be more or less constant when compared during the second (1995/96) and third (1998/99) stages of the trial series (Table 1). This reduced the possibility of deviation from the long-term study objectives or any significant variation in site selection during the study. Zones one to four, five to nine (KwaZulu-Natal) and 11 to 13 (Cape) constituted about 45%, 38% and 17% of the total South African forestry area, respectively (Department of Water Affairs and Forestry 1991). Zones two (Mpumalanga North), four (Mpumalanga South), six (Zululand), seven (Natal Midlands) and eight (Northern KwaZulu-Natal) were therefore selected for the planting of trials. Although the initial study included many tree species in each trial (to test the effects of tree species conversions), only trial sites re-established to the same tree species were considered in this study.

Research Methodology

The trials were conducted in three stages:

1. Ten trials that simultaneously investigated the chemical control of whitegrubs and cutworms (Govender 1995) and the mortality factors influencing the establishment of commercial eucalypt and wattle seedlings, were planted over three growing seasons (1990/91 to 1992/93). The trials were planted in ex-wattle sites, some with different plantation residue management regimes, predominantly in the Natal Midlands (zone 7) and Mpumalanga South (zone 4), these regions representing about 41% and 26% of all the wattle plantations in South Africa respectively (Table 2). These trials were either a complete randomised block design or latin square design with five or six replicates. Seedlings were planted in split plots of treated and untreated seedlings, surrounded by untreated guard row seedlings. During the first year of growth, trials were assessed at monthly intervals after planting. Stressed, dead or dying seedlings were dug and the roots and surrounding soil were examined to determine the cause of death. A description of the

Table 2. Details of site characteristics, species of seedlings planted, and plantation residue management of the three trial series in the study. (MAT: mean annual temperature, MAP: mean annual precipitation).

Trial code	Month planted	Region	Previous species	Zone	Plantation residue management	Latitude	Longitude	MAT (^oC)	Altitude (m)	MAP (mm)	Plantation seedling species planted				
WG1	October-90	Seven Oaks	wattle	Z 7	windrow, burnt	29° 12' S	30° 38' E	16.9	1110	837	wattle	*E. grandis*			
WG2	December-90	Umvoti	wattle	Z 7	windrow, burnt, ripped	29° 11' S	30° 27' E	15.8	820	774	wattle	*E. grandis*			
WG3	December-90	Melmoth	wattle	Z 6	windrow, burnt, close spacing	28° 31' S	31° 17' E	17.0	1050	972	wattle	*E. grandis*			
WG4	January-91	Pietermaritzburg	wattle	Z 7	windrow, burnt	29° 32' S	30° 27' E	17.0	930	875	wattle	*E. grandis*			
WG5	February-91	Richmond	wattle	Z 7	fallow, mowed	29° 49' S	30° 17' E	17.0	1020	1019	wattle	*E. grandis*			
WG6	March-91	Hilton	wattle	Z 7	fallow, manually weeded	29° 34' S	30° 16' E	16.0	1165	1111	wattle	*E. grandis*			
WG7	December-91	Seven Oaks	wattle	Z 7	windrow, burnt, close spacing	29° 11' S	30° 40' E	17.1	1110	754	wattle	*E. grandis*			
WG8	January-92	Pietermaritzburg	wattle	Z 7	windrow, burnt	29° 33' S	30° 27' E	17.6	840	990	wattle	*E. grandis*			
WG9	October-92	Pietermaritzburg	wattle	Z 7	windrow, burnt	29° 33' S	30° 27' E	17.6	900	990	wattle	*E. grandis*			
WG10	October-92	Seven Oaks	wattle	Z 7	windrow, burnt	29° 10' S	30° 39' E	18.6	1020	708	wattle	*E. grandis*			
ESPD1	November-95	Bulwer	pine	Z 7	completely burnt	29° 36' S	30° 08' E	15.2	1440	918	wattle	*E. grandis*	*E. mac*	*P. patula*	*P. elliottii*
ESPD2	December-95	Pietermaritzburg	eucalypts	Z 7	windrow, burnt	29° 32' S	30° 27' E	17.9	866	889	wattle	*E. grandis*	*E. dunnii*	*P. patula*	*P. elliottii*
ESPD3	February-96	Pietermaritzburg	wattle	Z 7	windrow, burnt	29° 32' S	30° 28' E	17.9	850	897	wattle	*E. grandis*	*E. dunnii*	*P. patula*	*P. elliottii*
ESPD4	November-96	Howick	eucalypts	Z 7	windrow, no burn	29° 27' S	30° 13' E	16.8	1100	961	wattle	*E. grandis*	*E. mac*	*P. patula*	*P. elliottii*
ESPD5	February-97	Iswepe	wattle	Z 4	broadcast, herbicide	26° 48' S	30° 37' E	16.1	1470	800	wattle	*E. grandis*	*E. mac*	*P. patula*	*P. elliottii*
ESPD6	February-97	Iswepe	wattle	Z 4	windrow, burnt	26° 48' S	30° 37' E	16.1	1470	800	wattle	*E. grandis*	*E. mac*	*P. patula*	*P. elliottii*
ESPD7	March-97	Sabie	pine - fallow	Z 2	fallow, herbicide	25° 06' S	30° 46' E	17.3	1140	1222	wattle	*E. grandis*	GU	*P. patula*	*P. elliottii*
ESPD8	September-97	KwaMbonambi	eucalypts	Z 6	broadcast	28° 36' S	30° 06' E	21.6	50	1065	GU170	*E. grandis*	ZG40	TAG53	GC747
ESPD9	October-97	Elandsdrift	pine	Z 2	broadcast, chopper rolled	25° 12' S	30° 48' E	16.8	1320	1290	*Grandis* CSO	*E. grandis*	*P. gregii*	*P. patula*	*P. elliottii*
ESPD10	July-98	Nylalazi	eucalypts	Z 6	broadcast	28° 03' S	32° 24' E	21.9	37	852	GU7	*E. grandis*	GC SZ14	GC SZ17	GC SZ11
ESPD11	April-00	Wakkerstroom	wattle	Z 4	windrow, burnt	27° 21' S	30° 38' E	17.8	1197	897	wattle	*E. grandis*	*E. dunnii*	*E. mac*	GXN121
ESPD12	April-00	Piet Retief	pine	Z 4	windrow, burnt	26° 56' S	30° 33' E	16.2	1433	882	GPVM	*E. mac*	*E. dunnii*	*P. patula*	*P. elliottii*

symptomatic damage was also recorded. These trials were observational and were backed by responses or a lack thereof to insecticidal treatments. Mortality of the untreated seedlings was expressed as a percentage loss of establishment.

2. Seven trials were planted over two seasons (1995/96 to 1996/97) to determine the mortality factors influencing the establishment of commercial pine, eucalypt and wattle seedlings (Table 2). These trials were planted in both low and high productivity, ex-wattle, ex-eucalypt and ex-pine sites with different plantation residue management regimes. Zones two, four and seven were targeted as representative of the major areas of forestry. Trials were a complete randomised block design with five treatments (seedling species) per replicate (four). There were no insecticide treatments and the treatment plots were large (100 seedlings per plot). Causes of seedling mortality were assessed at monthly intervals after planting, and the cause of death was determined in a similar manner (observational and symptomatic) as the stage one trials.

3. Five trials over three seasons (1997/98 to 1999/00) were planted to cover the remaining representative sites, tree species and plantation residue management regimes (Table 2). The trial design was expanded to a five by five latin square, with five species of trees but each plot comprised 120 trees. Each plot was divided into five subplots of 24 trees. Each subplot was treated with either an insecticide, a fungicide, or a mixture of this insecticide and fungicide and two subplots were untreated. The response of these treatments compared to untreated plots was used to test the accuracy of the observational method above and shed light on the cause of death in cases where a diagnosis could not be made. Surveys and evaluations were conducted in a similar manner as before.

Thesis structure

There has been much erosion of Forest Entomology capacity in South Africa and a case to revive this important discipline is presented in Chapter 2. The need for research on soil invertebrate pests that affect the establishment of seedlings/saplings of all three exotic plantation species is also highlighted. Chapter 3 assesses the impact and status of soil invertebrate pests that affect the regeneration of wattle seedlings and presents an overview of previous research on the biology of these pests. The effect of deviations from the commonly practiced windrow and burn regime of plantation residue management on soil invertebrate pests of wattle regeneration is discussed in Chapter 4. Although all the major eucalypt production areas in South Africa were not surveyed, soil invertebrate pests affecting eucalypt regeneration in both low and high productivity areas of zones six and seven are presented in Chapter 5. The management of pine plantation residue varies in the different pine production zones of South Africa and its effect on soil invertebrate pests and diseases of pine regeneration is investigated in Chapter 6. Chemical control is the first line of defense against many pests that attack plantation forestry in South Africa. However, the majority of commercial growers have opted to certify their plantations according to the Forest Stewardship Council (FSC) guidelines, and the implications of FSC principles and criteria on the management of these pests is assessed in Chapter 7. For the sake of completeness, an overview of entomological research in the winter rainfall region is presented in Chapter 8.

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CHAPTER 2

Forest Entomology in South Africa: current status and future prospects

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ABSTRACT

Insect pests impart significant losses to the South African forestry industry. Together with pathogens, they pose one of the greatest threats to its long-term sustainability. South African forestry has previously gained advantage from the use of an exotic planting stock that was, as a result, initially free from its natural enemies. This situation is changing with the gradual appearance of accidentally introduced new and damaging pests. This trend is likely to continue with the increasing movement of people and products around the world. South African forestry also faces the prospect of the introduction of pests and pathogens for the biological control of those plantation species that have become invasive. Forest entomology services and research in South Africa have become fragmented and depleted and capacity in this field has dwindled in recent years. Yet there is a need for research in areas such as biological, and other, pest control measures; contingency plans against incursions; the biology and bioeconomics of new pests and insect-pathogen interactions. A concerted effort is, therefore, required to create capacity and revitalise this important field of science in South Africa.

INTRODUCTION

The total forest area in South Africa is estimated to be about 2,19 million hectares (Fairbanks *et al.*, 2000), of which the area occupied by commercial forestry plantations is about 1,43 million hectares (Department of Water Affairs and Forestry, 1996). Only one eighth of South Africa is considered arable (Vlok and Van der Merwe, 1999) and about 12,2 % is cultivated (Fairbanks *et al.*, 2000). Commercial forestry plantations occupy about 1,2 % of the total land area of South

Africa (122,3 million ha) (Department of Water Affairs and Forestry, 1996), and there is little room for expansion. It is thus essential to ensure maximum productivity of plantations.

Since their first establishment in South Africa, plantations of pine, eucalypts and wattle have been severely damaged by insect pests. Early in the history of plantation development, beginning with wattle in 1884 (Hepburn 1973), native insects such as defoliating Lepidoptera [*Chaliopsis junodi* (wattle bagworm) (Hardenberg, 1919; Hepburn, 1973; Naude *et al.*, 1939; Ossowski, 1956, 1958; Ripley *et al.*, 1934, 1936; Sherry and Ossowski, 1967), *Imbrasia cytherea* (pine emperor moth) (Tooke, 1935a; Tooke and Hubbard, 1941), *Euproctis terminalis* (pine brown tail moth) (Grobler, 1956; Tooke, 1935b, 1938) and *Pachypasa capensis* (pine lappet moth) (Du Toit, 1975a; Tooke, 1943; Van Dyk, 1969)] imparted significant loss and necessitated extensive and costly insecticidal applications.

Fortunately, only a few of the potential pests of locally grown exotic trees have been accidentally introduced into South Africa. None the less, many of these have resulted in serious damage. For example, the early arrival of the Eucalypt snout beetle (*Gonipterus scutellatus*) caused sufficiently serious damage to prompt the initiation of one of the earliest programmes for biological control of a forest pest (Mally, 1924; Tooke, 1942, 1955) (Table1). Many other introduced pests, such as the black pine aphid (*Cinara cronartii*) (Van Rensburg, 1979, 1981), the pine wooly aphid (*Pineus boerneri*) (Barnes *et al.*, 1976), the root feeding bark beetle (*Hylastes angustatus*) (Bevan and Jones, 1971; Du Toit, 1975b; Tribe, 1990), the eucalypt borers (*Phorocantha semipunctata, Phoracantha recurva*) (Tooke, 1928, 1935c) and the very recently introduced pine wood wasp (*Sirex noctilio*) (Tribe, 1995) have a serious impact on South African forestry. They are likely to continue to do so in the future.

THE CURRENT STATUS OF FOREST ENTOMOLOGY

Exotic pests

A large number of herbivore insects that are able to cause severe damage, occur on pine, eucalypts and wattle in their areas of origin (Cibrián-Tovar *et al.*, 1995; CSIRO, 1970; Davidson and Prentice, 1967; Syme, 1990). It would be naïve to believe that many of these pests can be prevented from entering South Africa in the future. There is good evidence to show that there has been a gradually increase in new forest pests and pathogens entering South Africa (Table 1), despite considerable quarantine efforts to prevent accidental introductions.

Quarantine measures

Even in countries such as New Zealand, Great Britain and the United States of America, with enviable quarantine services, introduced pests and diseases of pine and eucalypts are being discovered (Evans, 1997; Haack and Cavey, 1997; Haack *et al*., 1997; Potter, 1997). There has been increased movement of people and products into South Africa because of the lifting of trade sanctions and the promotion of tourism in recent years. Other countries in Africa, particularly those south of the Sahara, have less efficient quarantine systems than those in South Africa. This weakens most quarantine measures that will be effected or that are in place in South Africa. These factors increase the risk of quarantine failures in the future.

The recent accidental introduction of two of the most serious pests of plantation and urban ornamental trees into countries, despite their outstanding quarantine, illustrates the fact that even the best quarantine measures can fail. One of these pests, the Asian longhorn beetle (*Anoplophora glabripennis*) appeared in North America for the first time in 1996 on urban maple (*Acer*), poplar (*Populus*) and willow (*Salix*) trees. The costs and impact associated with this introduction are already huge (Haack *et al*., 1997). Likewise, the appearance of one of the most serious pests, the insect-vectored pine wood nematode (*Bursaphelenchus xylophilus*) in Portugal during the latter part of 1999, is already raising significant concerns for the future of native pines throughout Europe (Sousa *et al*., 2001). Strategies to contain this introduction are being implemented, but based on past experience (Dwinell and Nickle, 1989; Kinn, 1986; Kobayashi, 1981), there is little hope that this species will be eradicated.

Table 1. Approximate dates of discovery of important insect pests on plantation trees species in South Africa.

Introduced Pest	**Year**	**Reference**
Phoracantha semipunctata (phoracantha beetles) (Coleoptera: Cerambycidae)	1906	(Tooke 1928)
Gonipterus scutellatus (eucalypt snout beetle) (Coleoptera: Curculionidae)	1916	(Mally 1924)
Hylastes angustatus (pine bark beetle) (Coleoptera: Scolytidae)	1930	(Bevan & Jones 1971)
Hylotrupes bajulus (pine longhorn beetle) (Coleoptera: Cerambycidae)	1935	(Tooke & Scott 1944)
Pissodes nemorensis (pine weevil) (Coleoptera: Curculionidae)	1942	(Van V. Webb 1974)
Orthotomicus erosus (European bark beetle) (Coleoptera: Scolytidae)	1968	(Geertsema 1979)
Cinara cronartii (black pine aphid) (Hemiptera: Aphididae)	1974	(Van Rensburg 1979)
Pineus boerneri (pine woolly aphid) (Hemiptera: Adelgidae)	1978	(Barnes *et al.* 1976)
Eulachnus rileyi (pine needle aphid) (Hemiptera: Aphididae)	1980	(Katerere 1984)
Trachymela tincticolis (eucalypt tortoise beetle) (Coleoptera: Chrysomelidae)	1982	(Tribe & Cillie 1997)
Cinara cupressi (cypress aphid) (Hemiptera: Aphididae)	1992	
Sirex noctilio (pine wood wasp) (Hymenoptera: Siricidae)	1993	(Taylor 1962; Tribe 1995)

Every effort must be made to exclude forest pests and pathogens from entering South Africa. There has also been an increase in indigenous insects adopting exotic plantation species as hosts over time. A total of 329 species of invertebrates, especially insects, spiders and mites, have been recorded as being associated with wattle trees in South Africa (Hepburn, 1966), 221 species of which are listed as being phytophagous on wattle (Swain and Prinsloo, 1986). Strategies to minimise losses once introductions or infestations have occurred, must also be a critically important component of the long-term security of the local forestry industry. Failure to recognise this will unquestionably lead to lack of future sustainability.

Biological control of plantation trees that have become weeds

Some species of *Pinus*, *Eucalyptus* and *Acacia* disperse from plantations, seedlings establish on roadsides and in other areas of disturbed as well as natural habitats. There are various examples of this happening in South Africa (Henderson, 1999). As part of the Working for Water Programme, *Acacia mearnsii* was estimated to have become invasive in about 2,5 million hectares (widespread, except in arid areas) and *Pinus* species in about 3 million hectares of various biomes (mountain catchments, forest fringes, grasslands and fynbos). This represents 38% of the area invaded by weeds in South Africa (unpublished Working for Water brochure, 1999). The invasive weeds label of plantation forestry species, the liability and responsibility for its eradication when it becomes an invasive weed outside forestry areas, and the new Water Act (Act 36 of 1998), which only recognises plantation forestry, as a "streamflow reduction activity" is a controversial issue between the forest industry, government and environmental groups. The resolution of these issues requires a multidisciplinary research focus.

One of the perceived solutions to the invasive weed problem is to introduce pests and pathogens as biological control agents that would potentially reduce the reproductive capacity of problematic plantation tree species (Zimmerman and Neser, 1999). A recent example is the seed-feeding weevil, *Melanterius maculatus*, that was released for the biological control of *A. mearnsii* (Dennill *et al.*, 1999; Donnelly, 1995; Donnelly *et al.*, 1992). While the South African forestry industry supports environmental preservation, it must remain concerned about any strategy that might threaten its existence (M.B.P. Edwards, personal communication, 2001).

Plant health risk assessment studies are, therefore, necessary before the release of any biological control agents for commercial forestry species. This is currently limited to host specificity studies in quarantine laboratories, which is often restricted by the choice of tree species and the lack of interaction of other biotic factors, for example, pathogens.

Research capacity

In the past, South Africa had a reasonably robust research programme in Forest Entomology. However, in recent years, forest entomology research and services in South Africa have become fragmented and substantially eroded. Capacity since 1990 has seriously dwindled, when approximately 10 people conducted research in this field.

A review of forestry research in South Africa in 1995 identified various threats to forestry research and development. Some of these factors have also contributed to the present lack of Forest Entomology research capacity. One such factor was scientist movement out of forestry research into research management, education, other fields or overseas. Another was the lack of planning for the succession of personnel and transfer of experience, partly because of the fragmented structure in most organisations. Uncertain research funding appears to have had a destabilizing effect on scientists and their associated research institutes (unpublished Bill Dyck report, 1995).

Key forest industry role players have recognized that an appropriate long-term strategy should include the view that forest entomology and forest pathology are closely disciplines. These fields require interchangeable skills that would best reside together in a combined research facility. Sustainable Forest Entomology and capacity building requires a "critical mass" of active participants. This is consistent with recommendations emerging from various reviews of forestry research in South Africa (unpublished Bill Dyck report, 1995). A further view was that it should be possible to establish a sound base of forest entomology, alongside pathology, and that significant synergy would emerge from having these disciplines combined.

FUTURE PROSPECTS

Survey of research needs

During 2000, the Forest Owners Association undertook to launch a survey of the Forest Entomology research needs of various industry participants. Participants identified all their entomological needs and listed the four most important needs in order of priority. These were further classified as a current or potential problem and the severity and financial loss associated therewith was estimated. The actions that participants currently use to address these problems were identified (diagnosis, monitoring, remedial). Participants also rated the importance of services (monitoring, diagnosis, extension, and research) required for each prioritised need. These responses were evaluated to develop a broad series of priority research areas.

Some trends emerged from the results of the survey (Table 2). Responses on specific insects were condensed into categories (damage, control measures, research action required) to accommodate the variable nature of the responses to questions posed.

Research focus areas

Pests that cause poor establishment of pine, wattle and eucalypt seedlings were identified as an important research focus area. Insects included members of the soil pest complex, for example, whitegrubs, cutworms, termites, *Hylastes angustatus* (bark beetles), millipedes, as well as above ground pests such as grasshoppers. Most respondents required research on impact assessment and alternative non-chemical methods to control these pests.

Insects that defoliate established pine, wattle and eucalypts constituted another key area of concern. This revolved around current and potential problems with wattle bagworm and wattle mirid, for example, determination of economic injury levels and impact assessment studies. The control of *Gonipterus* (Eucalypt snout beetle) attacking cold tolerant *Eucalyptus* species and to a lesser extent research on *Euproctis* (Pine brown tail moth) that defoliates pines, was also required.

Table 2. A breakdown of priority entomology research focal areas required by all South African commercial forestry industry participants.

COMPANY	PRIORITY RESEARCH FOCAL AREAS			
	1	2	3	4
A	Defoliating insects	Defoliating insects	Defoliating insects	-
B	Insects affecting seedling/sapling establishment	Insects affecting seedling/sapling establishment	Insects affecting seedling/sapling establishment	Insect/pathogen interactions
C	*Sirex* wood wasp	Biocontrol of all pests	Human resource development	Insects affecting seedling/sapling establishment
D	*Phoracantha*	New pests and incursions	Insects affecting seedling/sapling establishment	-
E	Insect/pathogen interactions	-	-	-
F	Monitoring + diagnosis	Monitoring + diagnosis	Research	Human resource development
G	Insects affecting seedling/sapling establishment	Insects affecting seedling/sapling establishment Defoliating insects	Defoliating insects Insects affecting seedling/sapling establishment	Defoliating insects
H	Insects affecting seedling/sapling establishment	*Sirex* wood wasp	Insect/pathogen interactions	Defoliating insects

* This information is a synthesis of responses to a questionnaire on Forest Entomology research needs conducted by the Forest Owners Association

Monitoring of the spread and augmentation of biocontrol of the *Sirex* wood wasp on pines in the Western Cape was considered important. However, the fact that the pest needs to be contained in the Cape and prevented from spreading northwards was not reflected in the results of the survey.

There were both general and specific requests for studies on insect-pathogen interactions. Research to determine the vectors of *Ceratocystis* wilt of wattle was considered a priority. Furthermore, the possible association of *Hylastes angustatus* with pathogens that infect pine seedlings was highlighted.

All respondents noted a significant need for extension, monitoring and diagnostic services. Failure to monitor the forest resource for new introductions of insects and diseases can have significant economic implications. Greater effort to reduce risks was required with surveillance (including quarantine) and strategies to minimise losses once introductions have occurred. Resistance breeding and the implementation of biological control were also identified as important. Human resource development, both of forestry personnel and postgraduate students was also highlighted amongst key requirements.

CONCLUSION

South Africa had an active Forest Entomology research programme in the past, which is renown for its many successful biological control initiatives. Existing insect pests, new incursions and quarantine failures, however, continue to threaten the health of plantation trees, and capacity to address these problems is lacking.

There is a need for long term (process) research to ensure that results can to be modelled and extrapolated beyond the immediate but necessary, short term applied (empirical) research. This type of strategic focus would also allow the use of molecular techniques to understand population genetic variability and to resolve taxonomic questions regarding important pests. Biological control programmes, for example, can then be designed to be more host-specific and matched to site and abiotic factors. There is also a need to determine the origin and history of spread of exotic pests to develop strategic control strategies.

The research directions to ensure that insect pests do not destroy South African forestry are clear. The forestry industry has identified pests of establishment and defoliators of wattle, pine and eucalypts; insect-pathogen interactions; new incursions; biological control and *Sirex* wood wasp as crucial research focus areas. Monitoring, extension and diagnostic services plus the creation of research capacity are also recognized as essential. A research programme in Forest Entomology needs to be revived, and it can draw synergy and derive impetus from a related programme in pathology (Tree Pathology Co-operative Programme), which is linked to student training, basic services and sustainable research.

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CHAPTER 3

Status of soil invertebrate pests of *Acacia mearnsii* regeneration in South Africa

ABSTRACT

Acacia mearnsii (wattle) plantations in South Africa comprises about 106 687 hectares. Wattle was previously grown mainly for the commercial potential of its bark (tannin extract) but it is now also managed on a short rotation for pulpwood. Clearfelled sites are continually being regenerated. Although, considerable research has been done on the post establishment insect pests of wattle, little is known about the incidence and status of soil invertebrate pests. Fourteen trials were planted, on previous wattle sites, over six growing seasons from 1990/91 to 1999/00. Seedlings were evaluated monthly after planting, for a period of six months. Stressed, damaged and dead seedlings were uprooted and inspected to determine the cause of death. Seedlings that failed to establish during wattle regeneration ranged from 8.95% to 50.84%, and the incidence of damage by soil invertebrate pests ranged from 2.15% to 30.21%. In sites where the plantation residue was windrowed and burnt, the average total incidence of soil invertebrate pests was 20.34%, and the average total failure of wattle seedlings to establish was 34.42%. Whitegrubs were the dominant and most economically important soil invertebrate pests (average incidence of 12.52%), followed by cutworms (average incidence of 3.97%) and grasshoppers (average incidence of 2.12%). Other soil invertebrate pests included termites, tipulid larvae, false wireworms, crickets, millipedes, ants and nematodes. Nematodes were sporadically important (11.58%) in old arable wattle sites. Although the prophylactic and corrective application of insecticides was widely used to control these pests at planting, their routine use in certified plantations contravenes the Forest Stewardship Council guidelines.

Keywords: seedling mortality, soil invertebrate pests, wattle, establishment

INTRODUCTION

Acacia mearnsii De Wild. was first introduced into South Africa from Australia in approximately 1864 (Hepburn 1973). It was primarily imported as a shade tree for livestock, for windbreaks and as a source of fuel wood on farms. It was only in 1884 that the commercial potential of wattle bark (tannin extract) was exploited (Hepburn 1973). Commercial wattle plantations have since expanded to their current holdings of 106 687 hectares despite a gradual decrease in the area under wattle of 1.3% per year during the last 20 years (Department of Water Affairs and Forestry 1980 - 2001). Wattle plantations are now grown and managed for pulpwood, mining timber, poles, bark extracts, charcoal, firewood and to a lesser extent for sawlogs.

A total of 329 species of invertebrates, especially insects, spiders and mites, have been recorded as being associated with wattle trees in South Africa (Hepburn 1966). Swain and Prinsloo (1986) listed 221 species of these invertebrates as being phytophagous on wattle. These phytophagous invertebrates represent various feeding guilds (leaf eaters, leaf miners, gallers, sap suckers, flower and bud feeders, seed insects, wood borers, shoot borers, bark feeders and root feeders) and belong to the orders Coleoptera (46.1%), Lepidoptera (35.7%), Hemiptera (11.8%), Isoptera (3.6%), Psocoptera (1.4%), Orthoptera (0.9%) and Thysanoptera (0.5%). All the insect pests that damage wattle in South Africa are indigenous. Most of them had low pest status prior to them colonising and exploiting the resource rich, exotic commercial wattle plantations. Besides a few attempts to control the wattle bagworm with natural biological agents (Hepburn & Borthwick 1968; Hepburn 1969a; Ossowski 1960), there has been a reluctance to use biological control as a tactic to manage wattle pests in the past because of the view (Atkinson 1997) that these indigenous pests already have their complement of natural enemies and are therefore best controlled with the preventative or corrective use of insecticides.

There is a limited availability of land and water to agriculture in South Africa (Vlok & Van der Merwe 1999) and commercial forestry is often in intense competition with other agricultural crops for these valuable resources. To maximize yields in a limited area, there has been a corresponding shift from extensive to intensive silviculture of wattle (Schönau 1990), hence a renewed interest in the management of wattle pests, especially soil invertebrate pests that affect the establishment of new transplants. Although a failure of wattle seedlings to establish (variable value from 16.6% to 31.0%) has been recorded (Rusk *et al.* 1992, 1993, 1994), the causes of this mortality were vaguely known. Annotated checklists of wattle pests have been compiled (Hepburn 1966; Ossowski & Wortmann 1960; Sherry 1971; Swain & Prinsloo 1986), which reported the general incidence of damage and associated pest species. However, the pest status and impact of most soil invertebrate pests are poorly understood and in many cases unknown. High risk areas and the reasons for soil invertebrate pest outbreaks have only recently been identified (Chapter 4) which precluded any strategic planning in planting programmes and silvicultural budgeting in the past. Foresters often replant dead seedlings when a mortality threshold of greater than 10% is observed, with no corrective or preventative action because of a lack of understanding of the causes of mortality. Alternatively, a general recommendation of the preventative use of a pesticide at planting is financially wasteful, short sighted in terms of strategic planning, and environmentally hazardous. This practice is also prohibited by the Forest Stewardship Council (FSC) certification guidelines (Chapter 7) (Qualifor 2002).

MATERIALS AND METHODS

Fourteen trials were planted on previous wattle sites, over six growing seasons (1990/91 to 1999/00) to determine the mortality factors affecting the regeneration of wattle. Sites were selected in representative regions of the wattle production area where the plantation residue management varied according to the practice of the region. Trial 1 (Seven Oaks: 29° 12′ S, 30° 38′ E), trial 2 (Umvoti: 29° 11′ S, 30° 27′ E), and trial 3 (Melmoth: 28° 31′ S, 31° 17′ E) were a randomised complete block design with 12 plots/replicate (20 trees/plot), and replicated six times. Trial 4 (Pietermaritzburg: 29° 32′ S, 30° 27′ E), trial 5 (Richmond: 29° 49′ S, 30° 17′ E) and trial 6 (Hilton: 29° 34′ S, 30° 16′ E) were a randomised complete block design with eight plots/replicate (20 trees/plot), and replicated six times. Trial 7 (Seven Oaks: 29° 11′ S, 30° 40′ E) was a randomised complete block design with five plots/replicate (20 trees/plot), and replicated 10 times. Trial 8 (Pietermaritzburg: 29° 33′ S, 30° 27′ E), trial 9 (Pietermaritzburg: 29° 33′ S, 30° 27′ E) and trial 10 (Seven Oaks: 29° 10′ S, 30° 39′ E) were two adjacent 5 plot x 5 plot latin square designs (20 trees/plot), and replicated 10 times. Trial 11 (Pietermaritzburg: 29° 32′ S, 30° 28′ E), trial 12 (Iswepe: 26° 48′ S, 30° 37′ E) and trial 13 (Iswepe: 26° 48′ S, 30° 37′ E) were a randomised complete block design of five tree species per replicate (total four) with 100 trees/plot. Only one of the five tree species in each trial was wattle (Chapter 1). Trial 14 (Wakkerstroom: 27° 21′ S, 30° 38′ E) was a 5 plot x 5 plot latin square design of five 5 tree species (plot) per replicate with 120 trees/plot, and only one of the five tree species was wattle (Chapter 1). Large trials with many trees per plot were planted because of the aggregate nature of soil invertebrate distributions (Allsopp & Bull 1989; Edwards 1991).

Sites where the plantation residue was windrowed and burnt and weeded (manual or post emergent herbicide spray) was the most common practice for wattle regeneration, and therefore mainly used to evaluate the status of soil invertebrate pests. Although the effect of the different plantation residue management practices [windrowed-burnt-weeded, windrowed-burnt-ripped, fallow (mowed, manual weed), windrowed-burnt-closer spacing, windrowed-'broadcast'-herbicide] on the incidence of soil invertebrate pests was evaluated in Chapter 4, the change in status of soil invertebrate pests during these differing plantation residue management practices was also evaluated.

All seedlings and subsequent surviving seedlings were evaluated monthly for a period of six months after planting. During each survey all stressed, damaged and dead seedlings were systematically dug together with approximately 0.012 m^3 of the surrounding soil to determine the cause of death. With practice it became easier to recognise the damage caused by the various soil invertebrate pests and these mortality factors were confirmed in most instances by the presence of the pest. Mortality was expressed as a percentage loss of establishment (number of stressed, damaged and dead seedlings per mortality category versus the total number of seedlings planted), where damage by soil invertebrate pests is equivalent to percentage infestation. Although all mortality factors were determined, including an unknown category, only soil invertebrate pest infestations were evaluated in this paper because most other mortality factors can be overcome with a more careful application of existing silvicultural and nursery practices. It was not possible to determine the incidence of pathogens because most seedlings dried out during the monthly survey interval and the isolation for pathogens only showed saprophytes.

A pest database of extension visits and reported incidences of seedling damage (Pest & Diseases DataBase) was initiated at the start of these experiments. This was used to supplement the evaluation of the status of soil invertebrate pests and include a discussion on pests that were not observed in the trial series.

Table 1: Percent incidence of soil invertebrate pests during the regeneration of wattle seedlings in South Africa. (Clustered according to the similarity of the plantation residue management regime). (WBW: windrowed-burnt-weeded, WBH: windrowed-broadcast-herbicide, WBR: windrowed-burnt-ripped, FMO: fallow-mowed, FMW: fallow-manual weed, WBS: windrowed-burnt-closer spacing, WBA: windrowed-burnt-old arable land). (T 1 to T 14: trials 1 to 14).

Soil invertebrate pest	**Clustered plantation residue management regimes**																
	windrowed-burnt-weeded; broadcast									**fallow; ripped**				**espacement**			**arable**
	WBW	WBW	WBW	WBW	WBW	WBH	WBW	WBW	**avg**	WBR	FMO	FMW	**avg**	WBS	WBS	**avg**	WBA
	T 1	T 4	T 8	T 9	T 11	T 12	T 13	T 14		T 2	T 5	T 6		T 3	T 7		T 10
whitegrubs	10.70	18.85	10.62	12.89	13.67	9.17	9.17	15.07	**12.52**	0.94	0.88	0.28	**0.70**	4.73	5.39	**5.06**	**2.37**
cutworms	0.53	0.75	2.97	1.77	11.08	7.00	6.29	1.39	**3.97**	1.96	0.57	1.79	**1.44**	2.52	1.33	**1.93**	**1.76**
termites	0.00	0.14	0.00	0.08	0.25	0.00	0.00	0.00	**0.06**	0.04	0.00	0.00	**0.01**	0.00	0.17	**0.09**	**0.00**
tipulid larvae	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.28	**0.04**	0.00	0.00	0.00	**0.00**	0.00	0.00	**0.00**	**0.00**
millipedes	0.59	3.32	1.78	0.55	0.00	3.75	1.54	0.00	**1.44**	0.11	0.17	0.00	**0.09**	0.88	0.00	**0.44**	**0.33**
nematodes	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**	0.00	0.00	0.00	**0.00**	0.38	0.00	**0.19**	**11.58**
wireworms	0.00	0.21	0.00	0.29	0.00	0.00	0.13	0.00	**0.08**	0.00	0.00	0.00	**0.00**	0.00	0.00	**0.00**	**0.66**
crickets	0.00	0.00	0.00	0.16	0.00	0.00	0.00	0.76	**0.12**	0.00	0.00	0.00	**0.00**	0.00	0.00	**0.00**	**0.00**
grasshoppers	0.00	0.00	0.00	0.67	2.63	10.29	2.00	1.39	**2.12**	0.00	0.14	0.08	**0.07**	0.00	0.17	**0.09**	**0.74**
ants	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**	0.11	0.00	0.00	**0.04**	0.00	0.00	**0.00**	**0.00**
Total soil invertebrate pest incidence	11.82	23.27	15.37	16.41	27.63	30.21	19.13	18.89	**20.34**	3.16	1.76	2.15	**2.36**	8.51	7.06	**7.79**	**17.44**
Total loss of seedling establishment (all mortality factors)	33.94	33.86	23.15	27.31	40.75	36.50	29.00	50.84	**34.42**	8.95	12.65	41.03	**20.88**	30.03	11.83	**20.93**	**23.00**

RESULTS AND DISCUSSION

The incidence of soil invertebrate pest damage during the regeneration of wattle seedlings in South Africa was clustered according to the similarity of the plantation residue management regime (Chapter 4), and was presented in Table 1. This data was used to evaluate the status of these soil invertebrate pests and to describe their damage. The biology and control of these pests was overviewed in the light of knowledge gained while conducting this study and to collate information from numerous unpublished reports.

WHITEGRUBS

Status

Whitegrubs were the dominant and most important pests that affected the regeneration of wattle seedlings. An average of 12.52% of wattle seedlings failed to establish because of whitegrub damage in sites where the plantation residue was windrowed and burnt, and this mortality ranged from 9.17% to 18.85%. The incidence of whitegrub damage was significantly reduced when the plantation residue was windrowed, burnt and ripped or the site left fallow (average 0.70%) or when the seedlings were planted closer together (average 5.06%) (Table 1) (Chapter 4).

Biology

Whitegrub is the common name of the larvae of several species of leaf chafer beetles (Coleoptera: Scarabaeidae: Rutelinae, Melolonthinae) (Scholtz & Holm 1985). The adults of some species often defoliate pine and wattle trees. Whitegrubs are C-shaped, have three pairs of well-developed thoracic legs, a sclerotized head and are whitish with a blue tinge where the gut shows through the distended abdominal body wall. Size varies from 2.6 to 36.0 mm long, according to age and species of larva (Borthwick 1975). A particularly damaging species in the Natal Midlands is the large wattle chafer, *Hypopholis sommeri* Burm., where both the adult and larval lifestages are pests. Several species of whitegrubs have been recorded as either or both root feeders and defoliators of wattle while many species remain undescribed. Hepburn (1966) recorded about 26 species and Swain & Prinsloo (1986) recorded a further five species of scarabaeids that attack wattle. Some of the common genera are *Anomala*, *Adoretus*, *Hypopholis*, *Maladera*, *Schizonycha*, *Trochalus* and *Monochelus*.

Scarabaeid larvae are mostly found in soils with a high organic content because the early instars initially feed on organic matter in the soil and switch to root feeding during their second and third instars (Annecke & Moran 1982; Govender 1995). Whitegrubs are common during and after wattle rotations in the Natal Midlands (Carnegie 1974).

Eggs are laid in moist soil beneath the host plants, mainly during October to March. The eggs hatch after two to three weeks (Borthwick 1975). There are three larval stages before pupation in the soil. In some species, for example *Adoterus ictericus* Burm., there is one generation per year (Prins 1965) but in other species, for example *H. sommeri* and *Schizonycha affinis* Boheman, the life cycle may take up to two years (Annecke & Moran 1982). The consequent overlapping of generations results in waves of infestation (Sherry 1971), which further adds to the economic importance of whitegrubs in the regeneration of wattle.

Damage

Whitegrubs eat the roots and sometimes ringbark young seedlings up to the root collar region. This causes a reduction in growth and frequently the death of newly emerged or planted wattle seedlings when the root plug is devoured. Older saplings that develop sufficient lateral roots prior to whitegrub infestation are less affected and able to withstand subsequent whitegrub attack. Seedlings that are not killed by whitegrub attack often have stunted growth, which makes them more susceptible to frost damage during winter. Whitegrub damage of seedlings in the summer rainfall region begins soon after planting (October to April) and follows a bell shaped curve, peaking in February, and tails off towards winter. Transplants were most susceptible to whitegrub damage from December to April (Govender 1995). Although numerous whitegrub larvae were present during winter they were often deeper in the soil because of their vertical movement in response to soil moisture and temperature (Edwards 1991; Fleming 1972) and hence outside the root range of seedlings.

Control

Extensive trials have been conducted to evaluate the efficacy, formulations and method of application of various insecticides to control both whitegrubs and cutworms at planting (Govender 1993, 1995; Govender & Atkinson 1992, 1993). Three insecticidal treatments were subsequently registered for use against whitegrubs in forestry (Nel *et al.* 1999). These include deltamethrin 5% SC applied as a drench at a rate of 0.025 g active ingredient (a.i.)/seedling at planting in 1 to 2 litres of water), gamma BHC 0.6% DP applied around the root plug at a rate of 0.06 g a.i./seedling in the planting pit and carbosulfan 10% CRG applied around the root plug at a rate of 1.00 g a.i./seedling in the planting pit. Another insecticide that was also effective in these experiments was chlorpyrifos 10% CRG applied around the root plug at planting at a rate of 1.0 g a.i./seedling (Govender 1995). This treatment has not been registered for use against whitegrubs in forestry. In line-sown wattle, Borthwick (1975) proposed that gamma BHC 0.6% DP be sprinkled into the furrow at the rate of at least 11 kg per hectare and that nursery beds or sleeves be dusted at the rate of 30 g/m^2 to achieve whitegrub control. The use of gamma BHC, an organochlorine insecticide, is however, prohibited in terms of FSC regulations (Qualifor 2002, Chapter 7).

CUTWORMS

Status

Cutworms were the second most frequent and important soil pest (but with about a threefold lower status than whitegrubs) that affected the regeneration of wattle seedlings. Cutworm infestations in sites where the plantation residue was windrowed and burnt caused an average of 3.97% (range from 0.53% to 11.08%) damage to wattle seedlings. They assumed a twofold (1.44%) higher status than whitegrubs (0.70) in sites that were left fallow or ripped after being windrowed and burnt because of the greater presence of weeds that could support a larger population of cutworms. However, the average incidence of cutworm damage on the latter sites was still lower than on sites that were windrowed and burnt (Table 1).

Biology

Cutworms are the caterpillars of numerous species of *Agrotis* moths (Lepidoptera: Noctuidae). *Agrotis segetum* Schiff. and *A. longidentifera* Hmpsn. have been observed to damage wattle seedlings (Sherry 1971). The mature caterpillars are about 35 mm in length, dull-greyish or brown in colour, lack secondary setae (hairless, waxy appearance), and curl up into a tight ring when disturbed. The moths have nondescript greyish or brownish forewings and whitish hindwings, are strong nocturnal fliers, and attracted to light (Annecke & Moran 1982).

Eggs are laid singly or in clusters on the soil or host plants and hatch after 3 to 15 days. An adult female can lay between 1000 and 2000 eggs. There are six larval instars lasting from 20 to 128 days and the pupal stage takes 9 to 45 days, depending on the species and climatic conditions (Annecke & Moran 1982). They can have many generations during summer and seedlings are susceptible throughout the planting season. The insects tend to over-winter in the larval stage.

Damage

Soon after planting, cutworms sever the stems of seedlings at their bases at ground level, which are dragged underground before the leaves are eaten. They tend to move from one plant to another along the row. Seedlings either die, become vulnerable to frost damage during winter or growth is set back for some time while coppicing. Older seedlings, where the bark on the stem has hardened, may often be ringbarked at the root collar. Callous tissue develops around the wound in actively growing seedlings and forms strongly elbowed stems that later break; hence cutworm damage impacts beyond the establishment phase. Some damaged seedlings are out-competed by weeds and die or break off in the wind. Young cutworm larvae can climb the stems and sever the tender branches of older seedlings. Older larvae tend to feed nocturnally at the root collar, and during the day they seek refuge in the soil or beneath debris around the bases of seedlings.

Cutworm damage is very common in sites where the plantation residue has been windrowed and burnt prior to wattle regeneration. Fire breaks the dormancy of wattle seed and results in a flush of wattle seedlings, which is selected by adult moths for oviposition. Poor weed control also aggravates cutworm damage because weeds support a larger cutworm population, which feed aerially in the earlier instars before becoming subterranean (Annecke & Moran 1982). Cutworm damage occurs throughout summer into autumn. The younger the seedlings, the more prone they are to cutworm damage.

Control

The same trials that were conducted to evaluate the efficacy, formulations and method of application of various insecticides for the control of whitegrubs, were also tested for control against cutworms at planting (Govender 1993, 1995; Govender & Atkinson 1992, 1993). Deltamethrin 5% SC applied as a drench at a rate of 0.025 g a.i./seedling in 1 to 2 litres of water at planting was subsequently registered for use against both whitegrubs and cutworms in forestry. Several other insecticides are also registered for use against cutworms of other crops, for example, alpha-cypermethrin, beta-cyfluthrin, chlorpyrifos, cyfluthrin, cypermethrin, cypermethrin-high cis, deltamethrin, endosulfan, esfenvalerate, fenvalerate, lambda-cyhalothrin, permethrin, quinalphos, sodium fluosilicate, tau-fluvalinate, tralomethrin and trichlorfon (Nel *et al.* 1999). The different methods of applying these insecticides depend on their formulation and include pre and post-emergence spraying, row application, aerial application and pre-emergence bait application at specified dosages. Spray treatments should preferably be applied when the top three to five centimetres of soil is moist. The traditional practice of sprinkling gamma BHC dusting powder around the seedling (Sherry 1971) was ineffective against cutworms (Govender 1995).

TERMITES

Status

Very rarely does one encounter termite damage (average 0.06%) during the regeneration of wattle plantations (Table 1). Termites are infrequent pests of wattle. However, when present, especially during first conversion from grassland to forestry, can cause extensive damage to seedlings (Sherry 1971).

Biology

Termites (Isoptera: Hodotermitidae, Termitidae) are social insects with four different castes. Fungus-growing termites viz. *Macrotermes natalensis* Haviland, *Macrotermes falciger* Gerstäcker and *Macrotermes mossambicus* Hagen cause most damage. Termites appear to be associated with deep, well drained soils in warmer (north of 30^0S latitude, below about 1300 m altitude) and drier areas (less than about 900 mm mean annual rainfall) (Atkinson *et al.* 1991). *Macrotermes natalensis* is by far the most common species and their hard conical mounds are characteristic of the drier areas of KwaZulu-Natal and Mpumalanga. *Odontotermes* sp. was occasionally involved in damage along the south coast of KwaZulu-Natal, very rarely *Microtermes* (Sherry 1971). *Hodotermes mossambicus* Hagen was also reported to cause damage to wattle in the eastern Cape, KwaZulu-Natal and south-eastern Mpumalanga (Hepburn 1966; Ossowski & Wortmann 1960; Sherry 1971). Adult workers of the fungus grower termites gather plant fibre and this digested vegetable matter, which is produced as faecal pellets forms the basis of a fungus garden that is constructed within the nest and tended by workers.

Damage

Termites eat the roots, root collar and bark of living plantation trees. Trees are ring-barked and the wood is whittled away so that the damaged tap and lateral roots have a tapered and roughly sand papered appearance. Seedlings are killed and young trees are attacked throughout the year for up to two years in wattle. Trees consequently cannot be firmly anchored in the soil, which leads to windthrow and a resultant reduction in stocking (Sherry 1971). Damage usually ceases when the canopy closes (Atkinson 1991), and although nests may survive canopy formation damage to subsequent rotations is rare. Termite damage to wattle can be extensive when the trees are planted in ex-grassland sites (Sherry 1971). Termite activity can be detected before land preparation, not only by the presence of visible nests but also by the soil sheeting constructed over stumps, twigs, dry grass stems and dry cattle dung.

Control

Carbosulfan 10% CRG applied around the root plug in the planting pit at a rate of 1.00 g a.i./seedling is the only treatment registered for use against termites in forestry (Nel *et al.* 1999). The exorbitant cost of carbosulfan and its unavailability in South Africa are two important constraints to this recommendation. Chlordane 60% EC was previously registered for use in forestry, but has subsequently been withdrawn (Nel *et al.* 1999) and being a chlorinated hydrocarbon insecticide, is prohibited in terms of FSC regulations (Qualifor 2002). The traditional practice of nest fumigation during or before land preparation (Sherry 1971) is not recommended because not all nests are visible above ground as mounds and this practice also has a negative environmental impact in that termites also serve a useful function in nutrient recycling. The seedlings themselves should rather be protected with insecticide until canopy closure when the trees are no longer attacked.

GRASSHOPPERS

Status

Grasshoppers were regularly recorded as a low occurrence (2.12%) pest of wattle seedlings. Although a maximum of 10.29% incidence of grasshopper infestation was recorded in the site where the plantation residue was 'broadcast', this is an overestimation. The plantation residue was windrowed and only broadcast prior to planting, allowing grass and weeds to accumulate on the site. This allowed a build up of grasshoppers and also the migration of grasshoppers from an adjacent site that was windrowed and burnt (Table 1). Grasshoppers usually increase in numbers in fallow areas, and when these areas are treated with herbicide prior to planting the resident orthopteran population concentrates its feeding on the wattle seedlings. A more appropriate average incidence of grasshopper damage would be about 0.96%, when the result from the 'broadcast' site was excluded (Table 1).

Biology

Numerous species of phytophagous short-horned grasshoppers, for example *Duronia chloronota* Stål. (Orthoptera: Acrididae), attack wattle seedlings but a common pest is the elegant grasshopper, *Zonocerus elegans* Thunb. (Orthoptera: Pyrgomorphidae) (Hepburn 1966). *Zonocerus elegans* is very common in sparse vegetation and often occurs on bare soil. Most are aposematically coloured in red, yellow, green or blue and produce repugnatorial secretions. Young grasshopper nymphs generally feed on monocotyledons (grasses) whereas the later instars prefer dicotyledons (Scholtz & Holm 1985).

Each female (*Z. elegans*) can lay about three egg packets (between 30 and 100 eggs per packet) in loose soil during late summer (March to April). These eggs overwinter and hatch when the temperature increases and after the first spring rains (Annecke & Moran 1982). Nymphs and adults are present for about six months, which coincides with the planting season in the summer rainfall area. Therefore the blanket treatment of competing vegetation and weeds with herbicides prior to planting accentuates grasshopper damage of wattle seedlings.

Damage

Grasshoppers sever the young stems and branches of seedlings. In instances where the stem has been partly damaged, the stems often snap off at these weak spots. Late detection of this type of damage can be confused with cutworm or duiker browsing damage.

Control

Although no insecticides are registered for use against grasshoppers in forestry, several insecticides are registered for use against these pests affecting other crops (Nel *et al.* 1999). Various formulations of carbaryl, for example, carbaryl 85% WP (wettable powder) at a rate of 127.5 g a.i./100 *l* water, sprayed from a knapsack applicator, can be used against the elegant grasshopper. Deltamethrin 5% SC at a rate of 0.15 g a.i./100 *l* water is used to control short-horned grasshoppers. It has been reported that the tannins present in wattle leaves and stems have a toxic effect and exert control on *Schistocerca gregaria* Forsk. in Morocco (Sherry 1971).

MILLIPEDES

Status

Millipedes were a recurrent but low status pest of wattle seedlings. The average millipede damage was 1.44% in sites where the plantation residue was windrowed and burnt. The highest incidence of millipede damage was recorded in the site where the plantation residue was broadcast (3.75%) (Table 1). One can expect their status as pests to increase with the move towards the broadcasting of plantation residue because such practices favour the breeding of millipedes.

Biology

Millipedes (Diplopoda: Juliformia) are usually found in soil, debris, under stones or bark and often accumulate under brush piles in forestry. They are active after summer rains. Eggs are laid in small nests made of hard earth, over which the female keeps guard. Several species may be involved, but only the identity of *Orthoporoides pyrrocephalus* Krabb., which is widely distributed in localised areas of South Africa, has been recorded (Lawrence 1984). *Orthoporoides pyrrocephalus* is reported to show little discrimination in its choice of food. However, Lawrence (1984) states that millipedes should not be regarded as pests of primary importance and that in general they prefer already damaged (by other soil invertebrate pests) and decaying plant tissue (by soil pathogens) as food. Millipede attack should therefore be construed as a symptom rather than a cause of damage.

Damage

There is still some uncertainty about the exact nature of the damage that millipedes cause. The roots of seedlings may be damaged or destroyed, either mechanically by burrowing into the root plug or by feeding. Where damage has already begun by other soil invertebrate pests, millipedes may be present in sufficient numbers to aggravate the injury. There have been reports that millipedes emerge from brush piles in summer and move along the rows of seedlings, chewing the stems at or above soil level (Atkinson 1997). The stems may be severed, or broken at the calloused wound or the seedling may be ringbarked (similar to cutworm damage). In Western Nigeria, *Odontopyge* species has been reported as a pest in nursery beds of *Gmelina arborea* Roxburgh (yemane trees) and *Tectona grandis* Linnaeus (teak trees) in the high forest zone, where it destroys young seedlings by eating through the stems (Browne 1968).

Control

Although no insecticides are registered for use against millipedes in forestry, a bait is registered for use against this pest in other crops (Nel *et al.* 1999). Methiocarb 80% WP can be prepared as a soft porridge bait at a rate of 200.0 g a.i./bait mixture (with 10 kg bran and 15 litres of water). This bait is strategically distributed in the field during the late afternoon when the pests become active.

NEMATODES

Status

Nematodes were sporadic pests of wattle but when present in large numbers, especially on old arable land, caused extensive damage (11.58%) (Table 1). An accurate estimation of the status of nematodes was difficult because wattle seedlings were seldom killed but showed stunted growth with sparse and chlorotic foliage, which could also be attributed to other silvicultural causes.

Biology

The plant parasitic nematodes (Nematoda), commonly called eelworms, are microscopic, slender, transparent worms living in the soil. Most are free-living and feed on the roots of plants, while others are parasitic in the roots. *Meloidogyne javanica* Treub. (Heteroderidae), causes root knots in which the females are obligate parasites (Sherry 1971). *Paratrichodorus* (Trichodoridae) is another debilitating ectoparasitic nematode that accumulates at and feeds on the growing tips of roots, resulting in root necrosis and terminal thickening of the roots. Other genera found attacking wattle seedlings included *Pratylenchus*, *Helicotylenchus* and *Xiphinema* (Govender 1993).

Damage

Plant parasitic nematodes seldom kill the plant but debilitate it, and fungal pathogens may gain access through the lesions they cause. Nematodes damage the roots of seedlings, which interferes with the normal functioning of the root system and this causes stunted growth. Damage by *M. javanica* results in the formation of small nodules, galls or knots that are different to the nitrogen fixing rhizobium nodules, which have distinct stalks.

Control

Although no nematicides are registered for use in forestry, aldicarb 15% GR applied at the rate of 0,75 g a.i./m^2, is registered for use against this pest affecting other crops (Nel *et al.* 1999). Aldicarb, like most systemic nematicides is normally phytotoxic, so caution needs to be exercised in trying to adapt this recommendation for use in forestry. Carbosulfan 10% CRG at 1 g a.i./seedling, although not registered against nematodes in forestry, effectively controlled nematodes under experimental conditions (Govender 1993). Nematode damage is more prevalent in sandy soils with a low organic content but when the humic content of the soil has been built up by the broadcasting of plantation residue, wattle seedlings are seldom affected by nematodes (Sherry 1971). Decomposition of organic matter promotes the build up of nematophagous fungi and predatory nematodes that can suppress parasitic nematode populations (Kleynhans *et al.* 1996).

TIPULID LARVAE

Status

Tipulids are infrequent, low status pests of wattle seedlings. In only one trial was tipulid larval damage (actual infestation of 0.28%, average 0.04%) recorded during the regeneration of wattle plantations (Table 1).

Biology

Tipulid or cranefly larvae (Diptera: Tipulidae), commonly called 'leather jackets' are seldom encountered as pests. However, the larvae of some soil-inhabiting species can be destructive feeders on subterranean parts of plants (Scholtz & Holm 1985). *Nephrotoma* spp. has been recorded in association with wattle in South Africa (Hepburn 1966). *Nephrotoma sodalis* Loew strips the bark from the roots of *Pinus strobus* Linnaeus seedlings and is recorded as a pest in North America and Canada (Browne 1968). *Tipula paludosa* Meigen is an introduced pest that attacks white spruce seedlings in the coastal areas of British Columbia (Sutherland & Van Eerden 1980).

Damage

Tipulid larvae girdle the stem above and below the soil line, thereby affecting water transport to the shoots. They may also consume some of the upper roots.

Control

No control measures have been developed for tipulid larvae in South Africa. In British Columbia tipulid larvae have been observed to survive in fallow moist soil by feeding on decaying seedling roots and weed roots. Larvae are therefore susceptible to desiccation (Sutherland & Van Eerden 1980), and discing or shallow ripping of the soil and keeping a site weed free would reduce tipulid larvae infestations.

WIREWORMS

Status

Wireworms were low status, occasional pests of wattle seedlings, especially in sites where the plantation residue was windrowed and burnt. The average incidence of wireworm damage was 0.08% with a maximum of 0.66% in an old arable site (Table 1).

Biology

Four species of wireworms (Coleoptera: Elateridae) are listed as being associated with wattle, but only the larvae of *Agriotes* spp. is listed as a pest of wattle seedlings (Hepburn 1966). The larvae of some species of *Agriotes* are major agricultural pests in Europe and the United States of America but only occasionally attack the roots of wheat and tubers of potatoes in South Africa (Scholtz & Holm 1985). False wireworm larvae (Coleoptera: Tenebrionidae) are pests on the roots of various cultivated crops in South Africa (Scholtz & Holm 1985). The larvae of *Somaticus varicollis varicollis* Koch and adults and larvae of *Gonocephalum simplex* Fabricus are recorded as pests of maize in KwaZulu Natal (Drinkwater 1989). *Gonocephalum simplex* is also recorded on a wide spectrum of field crops in Zimbabwe (Mlambo 1983). Larvae of *Somaticus angulatus* Fahraeus are regarded as one of the most economically important pests of maize and groundnuts in South Africa (Drinkwater & Giliomee 1991; Van Eeden *et al.* 1994a, 1994b). Whilst the wireworm and false wireworm species attacking new afforestation in ex-arable lands are known, many of the species found in forestry soils require identification.

Damage

Adults tenebrionids chew the bark off stems and sometimes wattle seedlings are ringbarked at ground level. while the larvae damage the subterranean parts of seedlings. especially the roots.

Control

No insecticides are registered for use in forestry. However. gamma BHC 0.6% DP applied at a rate of 40 kg/ha for wireworm and false wireworm larvae and quinalphos 0.5% RB applied at a rate of 5-10 kg/ha for adult tenebrionids. is registered for use against these pests in other crops (Nel *et al.* 1999).

CRICKETS

Status

Crickets were occasional pests of wattle seedlings. The incidence of damage averaged about 0.12% with a maximum of 0.76% in sites that were windrowed and burnt (Table 1). Crickets usually became resident in areas that had been left to weeds and were problematic on wattle seedlings especially during dry conditions when these areas were treated with broad-spectrum herbicides prior to planting.

Biology

Crickets (Orthoptera: Gryllidae) are widespread. nocturnal insects which live in and on the ground. under stones or logs or amongst fallen leaves by day. emerging at night to feed on seedlings of cultivated crops (Scholtz & Holm 1985). The shiny black cricket. *Gryllus bimaculatus* Degeer is about 25 mm long and usually has a conspicuous yellowish mark on either side at the base of the forewing. *Brachytrypes membranaceus* Drury has also been identified as damaging to wattle plantations (Hepburn 1966).

Damage

Crickets strip the bark off the stems of seedlings at ground level and feed on the underlying tissue. Late detection diagnosis presents as a dried frayed and ringbarked stem.

Control

Although no insecticides are registered for use against crickets in forestry, mercaptothion 50% EC at a rate of 12.5 g a.i./10 *l* water, as a full cover spray, is registered for use in ornamental plants, flowers and lawns against crickets (Nel *et al*. 1999).

ANTS

Status

In only one trial have ants been implicated in the mortality of regenerated wattle seedlings, with an infestation of 0.11% (Table 1).

Biology

Although *Anoplolepis custodiens* Sm. is usually associated with honeydew secreting scale insects on wattle (Hepburn 1966), these ants were also observed to mine soil from the planting pits of wattle seedlings (Pest & Diseases Database).

Damage

Ants were observed to mine the soil from seedling planting pits, thereby creating air pockets around the rootplug.

Control

No control measures are warranted.

OTHER WATTLE ESTABLISHMENT PESTS

Several other pests that were recorded over a fourteen-year period from extension visits and samples submitted for diagnosis or identification (Pest & Diseases DataBase), affect the establishment of wattle seedlings, but were not encountered in this study. Adults of various leaf beetles (Coleoptera: Chrysomelidae), for example *Peploptera curvilinae* Jac., *Colasposoma semihursutum* Jac., and several closely related species defoliate wattle seedlings, whilst their larvae feed on the roots. Curculionid adults of *Ellimenistes laesicollis* Fhs., *Catamonus melancholicus* Boh. and *Protostrophus lugubris* Mshl. defoliate and chew the bark of wattle seedlings causing the stems to break. The brown wattle mirid, *Lygidolon laevigatum* Reut. (Hemiptera: Miridae) causes serious defoliation of wattle seedlings.

Damage by soil invertebrate pests creates wounds, which permit the entry of fungal pathogens, for example, *Fusarium* spp., *Phytophthora* spp. and *Cylindrocladium* spp. (Pest & Diseases DataBase) or seedlings become stressed and secondary pathogen invasion cause their death. Factors that impede rapid growth such as poor site quality, drought, frost and weed competition also tend to increase exposure to and delay the recovery from insect pests and diseases (Stone *et al.* 1997). The current insecticide recommendations for soil invertebrate pests of wattle seedlings are, however, in contravention of the Forest Stewardship Council guidelines, and are evaluated in Chapter 7.

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CHAPTER 4

Effects of plantation residue management on wattle regeneration pests in South Africa

ABSTRACT

The limited availability of land for the expansion of wattle plantations in South Africa has resulted in a shift from extensive to intensive silviculture. One way to increase productivity in a given area is to ensure the survival of seedlings during regeneration, thereby increasing the stocking of compartments. Soil invertebrate pests constitute one of the important causes of seedling mortality. The effect of different plantation residue management practices on the incidence of these pests is unknown. Fourteen trials were planted on previous wattle sites, over six growing seasons. Six different plantation residue management regimes [windrowed-burnt-weeded, windrowed-burnt-ripped, fallow (mowed, manual weed), windrowed-burnt-closer spacing, windrowed-'broadcast'-herbicide] were tested. Seedlings were evaluated monthly after planting, for a period of six months. Stressed, damaged and dead seedlings were uprooted and inspected to determine the cause of death. Members of the soil invertebrate pest complex included whitegrubs and cutworms that generally had a higher pest status than the millipedes, nematodes, grasshoppers, ants, false wireworms, termites and crickets. A higher incidence of cutworm damage was observed in the windrowed-burnt-ripped and fallow sites. There was a greater infestation of soil invertebrate pests on sites where the plantation residue was windrowed-burnt-weeded or 'broadcast' (20.34%) than in the other treatments [windrowed-burnt-ripped or fallow (mowed, manually weeded) 2.36%]. The addition of a rip treatment to a depth of above 50 cm in the windrow and burn regime significantly reduced the infestation of soil invertebrate pests, especially whitegrubs. Seedlings that were planted at a closer spacing in windrowed and burnt sites also had a lower incidence of soil invertebrate pest damage (7.79%). Regeneration of an old arable site had a sporadically high incidence of nematodes (11.58%) in the total 17.44% incidence of damage by soil invertebrate pests. This has important management

implications because windrow and burn are standard plantation residue management practices in wattle silviculture. Pursuit of the sustainable silviculture of wattle warrants a move away from the burning of windrows (hot burns) to cool burns or the broadcasting of plantation residue. Planting is facilitated by the use of a tractor operated 'coulter ripper', which consists of a hydraulic cutting wheel and ripping tine on terrain with slopes of up to 40%. Insecticide application is the alternative option although its use is restricted by Forest Stewardship Council guidelines.

Keywords: slash management, seedling mortality, soil invertebrate pests, *Acacia mearnsii*

INTRODUCTION

The regeneration of wattle (*Acacia mearnsii* Wild.) plantations in South Africa has shifted over the years from extensive to intensive silvicultural management (Schönau 1990). The limited availability of arable land (Vlok and Van Der Merwe 1999) and the need for planting permits to expand these plantations (Department of Water Affairs and Forestry 1998) have largely necessitated this. Over the past 20 years, the area planted to wattle plantations in South Africa has decreased by 1.3% per year from 139 381 ha in the 1979/80 growing season to 106 687 ha in 1999/00 (Department of Water Affairs and Forestry 1981-2001).

One way to increase plantation productivity in a limited area is to ensure the survival of seedlings during regeneration, thereby increasing the stocking of trees within compartments. Numerous silvicultural parameters, for example, genetic improvement (Dunlop & Hagedorn 1998; Nixon 1977; Sherry 1971), site preparation (Boden 1984; Norris 1993, 1995; Sherry 1971), planting practices (Roberts & Kunz 1995; Sherry 1971; Sherry & Schönau 1966), fertilization (Beard 1952; Du Toit 1995; Herbert 1984; Schönau 1971), vegetation management (Little 2000; Sherry 1971), espacement and mensuration (Schönau 1982; Sherry 1971), soil type (Osborn 1931) and site-species matching (Donkin 1994; Herbert 1993; Schönau 1975) have been addressed to increase wattle productivity in South Africa. Another important aspect in the regeneration of wattle plantations is the management of harvesting residue from the previous rotation. Previous research has focussed on the effect of plantation residue management on the survival and growth of various species of seedlings from a weed management (Schumann *et al.* 1995; Little *et al.* 1996, 2000a, 2000b), fertilisation (Davis *et al.* 1996), harvesting impact (Smith 1998; Smith 2000), and site preparation (Allan 1998; Allan & Higgs 2000; Allan *et al.* 2000; Norris 1993, 1995; Lockett 1998; Schumann *et al.* 1994; Smith *et al.* 2000a, 2000b) perspective.

Soil invertebrate pests are some of the important factors that were often overlooked as a cause of seedling mortality in plantation residue management studies. Indigenous cultivators of slash-and-burn agriculture in the tropics practice burning to also control pests and diseases (Bandy *et al.* 1993). Some traditional plantation growers believe that the burning of plantation residue clears an area of pests prior to regeneration. Recently a view has been expressed that prescribed fire decreases the incidence of pests and diseases in established stands (Brennan & Hermann 1994). This dogma, which is cheap and easy to implement, together with the need to reduce fire hazard because of harvest residue fuel buildup and for ease of silvicultural operations during regeneration of wattle plantations, has resulted in the standard practice of windrowing and burning of plantation residue. The windrow and burn management of plantation residue has been recommended when wattle brush piles become large and unmanageable or there is a danger of frost damage to seedlings (MacLennan & Jarmain 1990). However, the promotion of sustainable management of wattle plantations (Norris 1993; Norris 1995; Sherry 1952) and adherence to Forest Stewardship Council guidelines (Qualifor 2002) prescribes a policy of not burning the plantation residue. The incidence of soil invertebrate pests and their status during the regeneration of wattle as a result of these different plantation residue management practices are unknown.

MATERIALS AND METHODS

Fourteen trials were planted on previous wattle sites, over six growing seasons (1990/91 to 1999/00). Sites were selected in representative regions of the wattle production area according to the plantation residue management practices and their frequency of application. Different plantation residue management practices [windrowed-burnt-weeded, windrowed-burnt-ripped, fallow (mowed, manual weed), windrowed-burnt-closer spacing, windrowed-'broadcast'-herbicide] were tested. Seedlings were evaluated monthly for a period of six months after planting. Stressed, damaged and dead seedlings were dug to determine the cause of death, which was expressed as a percentage loss of establishment. Only the mortality that was caused by soil invertebrate pests was evaluated in this paper.

Multivariate analyses of the soil invertebrate pest component of the mortality factors were performed using PRIMER 5 for Windows v5.1.2 2000 (Plymouth Routines in Multivariate Ecological Research), developed by the Plymouth Marine Laboratory, United Kingdom. Similarity matrices were calculated using Bray-Curtis coefficients for the percentage loss of establishment of seedlings by soil invertebrate pest species between localities. This similarity coefficient is considered to be one of the most robust coefficients because it is insensitive to joint species absences and is widely used in ecology (Clarke and Warwick 1994). From this similarity matrix a cluster analysis, using hierarchical agglomerative clustering and group-average linking, was performed and a dendrogram produced. Non-metric multidimensional scaling (MDS) was used to map the sample inter-relationships in an ordination of a specified number of dimensions. The dimensionality of the MDS ordinations plotted was chosen according to the acceptability of their associated stress values.

The differences in pest species structure were tested using ANOSIM (analysis of similarity) on the similarity matrix of each trial. This is a non-parametric permutation procedure applied to the rank similarity matrix underlying the ordination of samples. The Global R in ANOSIM is a test statistic indicating the degree of discrimination between groups or clusters and falls between 0 and 1. R equals 1 if all samples within a cluster are more similar to each other than any samples between clusters, and R approximates 0 when similarities between and within samples are similar on average.

RESULTS

The analysis of the similarity test produced a Global R sample statistic of 0.918, which showed that there are highly significant differences ($p = 0.001$) between clusters within the similarity matrix (Figure 1). These hierarchical clusters were arbitrarily named A, B, C and D according to the collective plantation residue management practice within each cluster. Cluster A had eight trials where the plantation residue was windrowed, burnt and weeded (7 trials) or broadcast (after initially being windrowed) with a herbicide application (1 trial). Cluster B had three trials where the plantation residue was windrowed, burnt and ripped (1 trial) or the site was left fallow for several seasons after harvesting and the weeds mowed prior to planting (1 trial) or the site was left fallow for a season and manually weeded prior to planting (1 trial). The plantation residue in the two trials within cluster C was windrowed and burnt but the seedlings were planted closer within the rows (either at 3m x 1.5m or 2m x 2m) rather than the standard spacing of 3m x 2m. The plantation residue in the single trial in cluster D was also windrowed and burnt but this was an old arable site adjacent to a sugarcane plantation.

In pairwise test comparisons of the clusters produced by ANOSIM, A and B ($R = 1$, $p = 0.006$) were significantly well separated and clusters A and C ($R = 0.728$, $p = 0.022$) overlapped slightly although they were significantly different. Clusters A and D ($R = 1$, $p = 0.111$), B and C ($R = 0.917$, $p = 0.100$), B and D ($R = 1$, $p = 0.250$) and C and D ($R = 1$, $p = 0.333$) were well separated despite their significance levels, which were low because of the few replicates in each cluster. In guidelines given by Clarke and Gorley (2000) these clusters are still considered different because the pairwise R values give an absolute measure of the separation of the clusters on a scale of zero (indistinguishable) to one.

The consistency of the results was checked with a non-metric multi-dimensional scaling (MDS) ordination (Figure 2). Clarke and Warwick (1994) recommended that even for strongly grouped samples, cluster analysis should be used in conjunction with ordination. The dimensionality (3-d and 2-d) of the MDS ordinations produced associated stress values of 0.03 and 0.06 respectively, giving confidence that the plot is an accurate representation of the sample relationships. A stress value of less than 0.1 gives a good ordination with little risk of misinterpretation (Clarke and Warwick 1994).

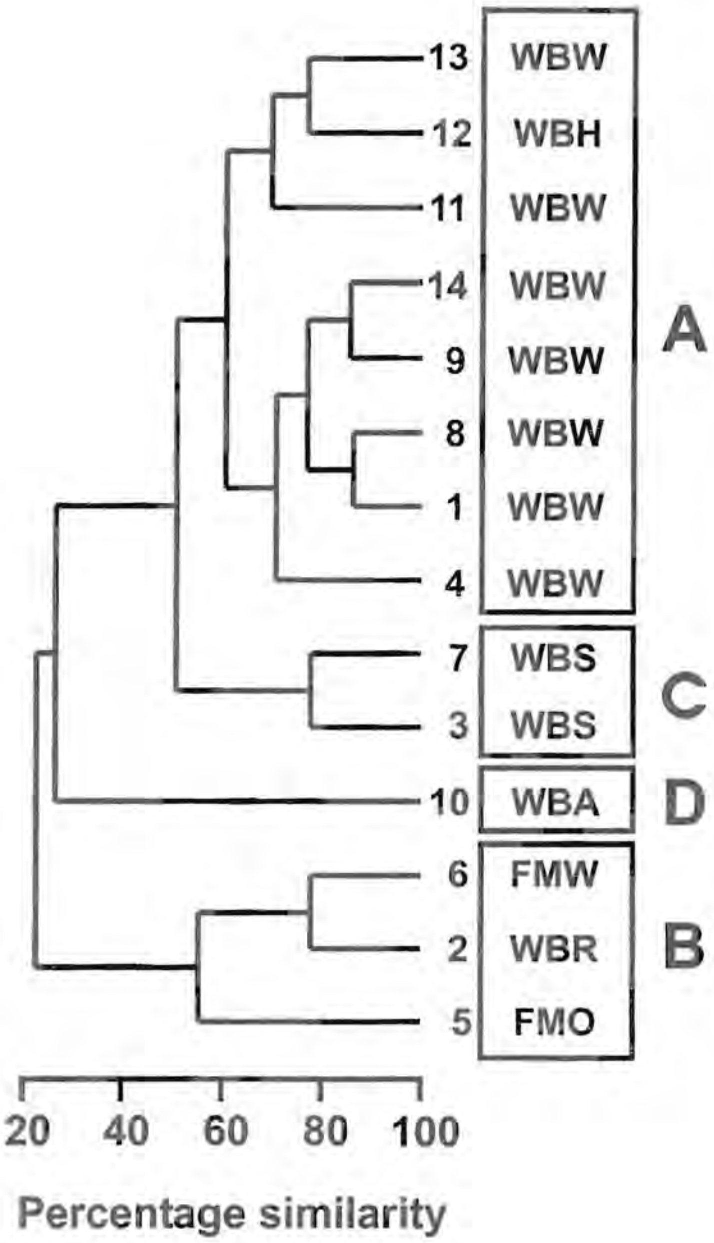

Figure 1. Dendrogram of Bray-Curtis percentage similariti es between fourteen wattle regeneration trials with varying plantation residue management regimes. (WBH, windrow-broadcast herbicide; WBW, windrow-burn-weeded; WBS, windrow-burn-closer spacing; WBA, windrow-burn-old arable; FMW, fallow-manual weed; WBR, windrow-burn-rip, FMO, fallow-mow).

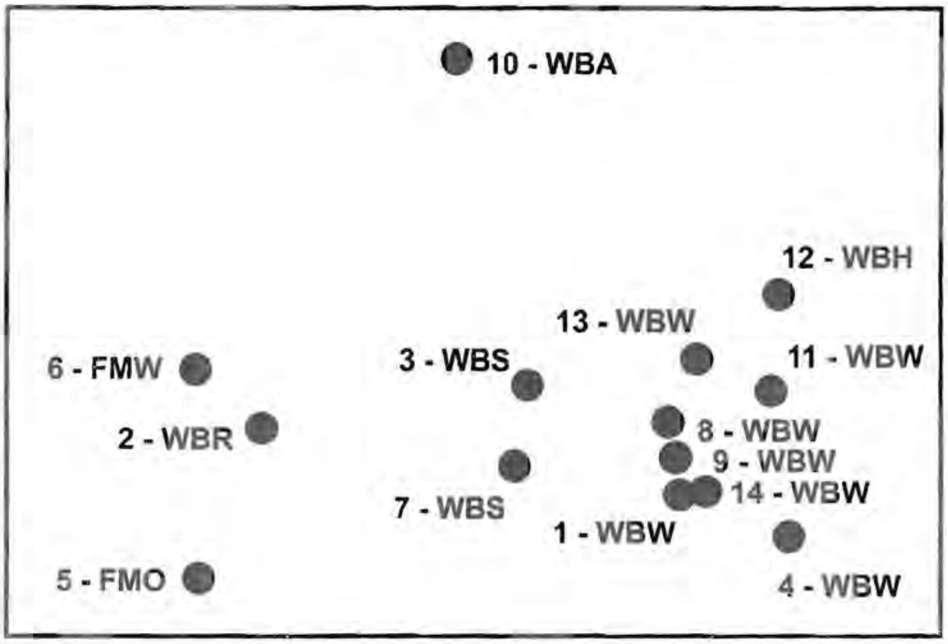

Figure 2. Ordination of fourteen wattle regeneration trials based on non-metric Multi-Dimensional Scaling of the soil invertebrate pest community structure (stress = 0.06) (scaled axes of these plots are unnecessary as the absolute distance between every pair of points on the ordination is a relative measure of their similarity).

Table 1. Incidence of soil invertebrate pests during the regeneration of wattle in different plantation residue management regimes (clustered according to analyses of similarity).

PEST MORTALITY FACTOR	PEST INCIDENCE (%) ACCORDING TO PLANTATION RESIDUE MANAGEMENT REGIME			
	Windrow - burn, Broadcast	**Windrow - burn - rip, Fallow**	**Windrow - burn, Espacement**	**Windrow - burn, 'Old arable land'**
	Cluster A (average)	Cluster B (average)	Cluster C (average)	Cluster D (average)
Whitegrubs	12.52	0.70	5.06	2.37
Cutworms	3.97	1.44	1.93	1.76
Termites	0.06	0.01	0.09	0.00
Tipulids	0.04	0.00	0.00	0.00
Millipedes	1.44	0.09	0.44	0.33
Nematodes	0.00	0.00	0.19	11.58
Wireworms	0.08	0.00	0.00	0.66
Crickets	0.12	0.00	0.00	0.00
Grasshoppers	2.12	0.07	0.09	0.74
Ants	0.00	0.04	0.00	0.00
% soil pest infestation	**20.34**	**2.36**	**7.79**	**17.44**
% total loss of establishment	34.42	20.88	20.93	23.00

The incidence of soil invertebrate pests from the various trials was averaged according to their cluster groupings in Figures 1 and 2 and presented in Table 1. The highest infestation (20.34%) by soil invertebrate pests was in trials where the plantation residue was windrowed and burnt or 'broadcast' (cluster A). Soil invertebrate pest infestations were progressively lower in the old arable site trial where the plantation residue was also windrowed and burnt (17.44%) (cluster D), followed by the trials where the plantation residue was windrowed and burnt and the seedlings planted at a closer spacing (7.79%) (cluster C) and by the trials where the plantation residue was either windrowed and burnt with the addition of a rip treatment or left fallow (2.36%) (cluster B). Soil invertebrate pests were responsible for 59.09%, 11.30%, 37.22% and 75.83% of the total trial mortality observed in clusters A, B, C and D respectively. These clusters usually had high pest species richness with low evenness but high dominance of a few pest species.

Indigenous soil invertebrate pests that caused the mortality of wattle seedlings included numerous species of whitegrubs (Coleoptera: Scarabaeidae), cutworms (Lepidoptera: Noctuidae), termites (Isoptera: Termitidae), tipulid larvae (Diptera: Tipulidae), millipedes (Diplopoda: Juliformia), various species of nematodes (Nematoda: Heteroderidae), false wireworms (Coleoptera: Tenebrionidae), grasshoppers (Orthoptera: Pyrgomorphidae, Acrididae), crickets (Orthoptera: Gryllidae) and ants (Hymenoptera: Formicidae) (Table 1). Whitegrubs and cutworms generally had higher pest status than the termites, tipulid larvae, millipedes, wireworms, grasshoppers and crickets. Although nematode damage was recorded, it was sporadic, but high (11.58%), in the trial that occurred in the old arable site. An unusually greater incidence of cutworm than whitegrub damage was observed in cluster B. In many of the trials though, whitegrubs were the most important and frequent soil invertebrate pest, followed by cutworms. The high incidence of soil invertebrate pest damage in the windrow and burn plantation residue management regime has important management implications because this is standard practice in commercial wattle silviculture in South Africa. However, leaving the site fallow or planting at a closer spacing, and especially the addition of a soil rip treatment with a single tine to a depth above 50 cm in the windrow and burn option, significantly reduced the infestation of soil invertebrate pests, especially whitegrubs.

DISCUSSION

The harvest residue of clear-felled wattle plantations is commonly piled along the rows of stumps (windrowed) and burnt prior to the regeneration of stands in most wattle growing regions of South Africa (Norris 1993; Norris 1995). This is a modification of the previous practice of burning the broadcast harvest residue to break the dormancy of wattle seeds, achieve even germination, destroy grass tufts and hence reduce weed control costs (O'Connor & Craib 1929). These advantages of burning in the previous era of extensive regeneration of wattle plantations are outweighed by numerous disadvantages. Burning of the plantation residue results in additional weeding costs during the control of natural wattle regeneration and delays in planting operations because of the need to burn under suitable weather conditions (MacLennan & Jarmain 1990). Cool burns, which are equivalent to prescribed fires (McRae 1994), are preferred if burning is necessary (Norris, 1995). During hot burns, carbon (Robertson 1998), nitrogen and sulphur may volatilise as gases. Increased rainfall reaching the soil may result in further loss of nutrients through leaching and surface movement. Furthermore, the exposed soil surface is exposed to wind and water erosion, and a breakdown of soil structure occurs because of the destruction of soil organic matter. Lastly, fire induces additional water repellency of the topsoil (Norris 1995). Although several insecticides have been successfully tested for their efficacy against whitegrubs (Govender 1995; Nel *et al.* 2002), burning of the plantation residue causes a buildup of carbon residue that becomes incorporated into the topsoil, which can absorb insecticides, thereby reducing their activity (Kamm & Montgomery 1990). This is further exacerbated by an increased incidence of soil invertebrate pests, especially whitegrubs, in sites where the plantation residue was windrowed and burnt.

The inclusion of a rip treatment to this plantation residue management regime and leaving the site fallow resulted in a significant fivefold reduction in the incidence of soil invertebrate pests. The effectiveness of the rip treatment is commensurate with about an eighteen-fold decrease in the incidence of the dominant whitegrub pests. Ripping the topsoil has the same effect as the cultural practice of ploughing and discing, which was traditionally used in agriculture to control whitegrub pests and prevent oviposition in the soil by adults (Veeresh 1977). Ripping also exposes the various lifestages of soil invertebrate pests to desiccation and further enhances predation by their natural enemies (Prins 1965).

Sites often remain fallow for several months before the next planting season. Some sites remain unplanted and unproductive for a few years, although it is uncommon in commercial operations. The grass and weed cover that develops is manually weeded, mowed if it is not too dense or a blanket herbicide treatment is applied prior to planting. During mechanical mowing or manual line cleaning there is still an abundance of grass and weed roots for the polyphagous whitegrubs to feed. The presence of vegetation in the interrow averts the migration of many native soil invertebrate pests (termites, tipulid larvae, millipedes, wireworms, crickets, and grasshoppers) onto newly transplanted wattle seedlings. Mowing and weeding operations results in mulch cover which conserves water and provides refuges for soil invertebrate pests that would otherwise be attracted to the moist planting pits of seedlings. An exception to this trend in windrow-burn-rip or fallow sites is the higher pest status of cutworm rather than whitegrub, unlike the case in all other plantation residue management regimes. It has been observed that the longer a site remains fallow, the lower the incidence of whitegrub damage because emerging beetles leave the site in search of their wattle hosts. A high density of weeds can support a larger population of early instar cutworm larvae, which feed above ground before switching to a subterranean feeding habit in their later instars (Annecke & Moran 1982). They actively search for tender stems, like those of young transplants, which are severed at ground level and dragged underground before the leaves are eaten.

Broad spectrum, systemic herbicides, for example glyphosate, are generally applied as a post-emergent spray (Grober *et al.* 2000) prior to the planting of wattle in most windrow and burn or late broadcast plantation residue management regimes. These herbicides kill both the aerial portions and roots of all potentially competing vegetation. Resident soil invertebrate pests divert their feeding onto the only remaining vegetation (young transplants), hence the higher incidence of soil invertebrate pest damage in these management regimes.

In the trial where the plantation residue was broadcast, the residue was first windrowed after harvesting and only broadcast a few weeks prior to planting. Effective broadcasting of the plantation residue is supposed to suppress the growth of weeds, and one can therefore expect a decreased incidence of damage by cutworms, grasshoppers, crickets, tipulid larvae and wireworms. Whitegrub distribution, however, is dependent on the feeding habit of adult beetles that oviposit in close proximity to these feeding sites (Fleming 1972). Hence one can still expect a high incidence of whitegrub damage in ex-wattle sites where the plantation residue is broadcast because some species of adult scarabaeids also defoliate wattle trees. Millipedes breed and seek harborage under decomposing brush piles and an increased incidence of damage can also be expected in sites where the plantation residue is broadcast.

Wattle seedlings are normally planted 1.5 m apart in rows, which are 3 m apart with an initial stocking of 2 222 trees per hectare. This is thinned to 2 000 trees per hectare after the first year and finally 1 500 stems per hectare after the second year of growth (MacLennan & Jarmain 1990). Although the soil invertebrate pest species richness remained similar to other windrowed and burnt sites that were planted at a wider spacing, there was about a two and a half fold decrease in the incidence of soil invertebrate pest damage when seedlings were planted at a closer row spacing. The role of spacing and plant density in insect control depends on the crop, the types of insects and other factors that are not clearly understood (Kumar 1984). Generally though, an increase in plant density appears to reduce pest numbers, especially pests that are early colonizers of disturbed ground or patchy vegetation (Dent 1991). Although the yields of short rotation crops are negatively affected by an increase in plant density (Dent 1991), wattle is thinned at one and two years after planting, which would negate any yield loss during its ten year rotation cycle. Closer row spacing results in earlier canopy closure and hence a reduction of weeding operations. This also permits a greater degree of selection during thinning operations (Sherry 1952).

The old arable land site, that was adjacent to a sugarcane field, had an unusually large incidence of nematode damage. Both sugarcane and wattle are hosts to similar parasitic nematode species that gradually increase in population numbers to damaging levels when these crops are grown repeatedly on the same sites (Kleynhans *et al.* 1996). Nematodes inhibit root growth; some species cause root galls while other species cause root lesions, root necrosis and terminal thickening of the roots (Govender 1993). The damage and decrease in the fine root mass (on which whitegrubs feed) of nematode damaged wattle seedlings could probably explain the lower incidence of whitegrub damage in this windrow and burn plantation residue management regime.

Existing recommendations for the management of harvest residue in wattle plantations therefore needs to be reexamined with a view to decreasing the incidence of soil invertebrate pest damage. There should be a shift away from burning, especially the intense fires associated with the burning of windrows (Norris 1995) and a retention of the practice of minimal tillage (pitting, shallow ripping or ploughing) in regeneration sites (Hendrick 1979; van Goor 1985). Broadcasting of the plantation residue at clearfelling overcomes most of the disadvantages associated with burning. Compaction caused by heavy harvesting machinery is reduced when machines travel over plantation residue (Smith 2000; Smith *et al.* 2000a). The mulch layers reduces the germination of weeds, soil water runoff, direct evaporation from the soil surface, soil erosion and improves water infiltration (Norris 1995). The reduction in weeds because of not burning and broadcasting of the plantation residue has been shown to reduce most soil invertebrate pests except whitegrubs, nematodes and, to a limited extent, millipedes. However, the inclusion of shallow ripping decreased the numbers of whitegrubs and millipedes. An implement (coulter ripper), which consists of a hydraulically driven cutting wheel in front of a ripping tine, has been successfully used to manage broadcast plantation residue (Norris 1995). During tillage, harvest residues are also cut and incorporated into the soil. Decomposition of organic matter promotes the build up of nematophagous fungi and predatory nematodes that can suppress parasitic nematode populations (Kleynhans *et al.* 1996).

Coulter ripping should preferably be done along the contour and would depend on the terrain (Norris 1995). It is possible to perform this operation on a maximum slope of 11 degrees (13% to 20%), but with a crawler tractor one can attempt slopes of up to 40%. Average terrain would take about 1 hour/ha with a 60 kW tractor and although one is restricted to interrow planting this does not appear to be a problem in wattle because stumps decompose before the next rotation (Craig Norris, personal communication). The total cost of coulter ripping which includes diesel, tractor, ripping equipment, running costs, labour, depreciation of equipment, marking and loosening of the soil is about R110/hr (Craig Norris, 2001, personal communication). If sites outside of the coulter ripper range are regenerated to wattle, one has the option of preventatively treating seedlings with an insecticide during planting. Deltamethrin 5% SC at a rate of 0.025 g a.i./seedling (equivalent to 55.55 g a.i./ha for wattle at 2222 stems/ha) is registered for use against both whitegrubs and cutworms in forestry (Govender 1995; Nel *et al.* 2001). This costs about R236/ha (excluding labour) (Farmers Agricare, 2001, personal communication). The preventative use of insecticides, however, contravenes the Forest Stewardship Council guidelines and should be avoided (Govender, 2002).

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