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Effects of management techniques on the establishment of eucalypt seedlings on farmland: a review

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Abstract Research into the effects of seven management techniques on survival and growth of eucalypt seedlings planted on farmland is reviewed. The techniques include: pre- and post-planting weed control; soil cultivation; fertiliser; mulch; tree guards/shelters; and irrigation. The initial and ongoing effects of each technique are discussed—including the effects of timing, type and quantity. Consideration is given to site, species and climatic influences. A statistical analysis of the published survival rates is then presented, to provide information on the relative importance of, and interactions between, practices. The analysis shows that maximum survival may be achieved by using one or two management techniques. Combining this result with the insights gained from the review suggests that the use of soil cultivation and post-planting weed control are likely to achieve the greatest improvements in early eucalypt survival and growth.

Keywords Site preparation · Survival · Growth · Eucalypt · Seedling · Revegetation

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Introduction

Internationally, there has been a significant increase in the amount of private and public investment in tree planting over the last four decades (Potter and Lee 1998; Bureau of Rural Sciences 2007). This increase in investment has been associated with a move away from large-scale, commercial operations, towards smaller-scale plantings (Arnold and Townson 1998; Bureau of Rural Sciences 2007). In particular, there has been a proliferation of small-scale operations established for plantation production (where timber and pulp are the primary products), multiple purpose farm forestry (where there may be a range of commercial products and environmental benefits), as well as purely environmental plantings (some of which may have commercial products in the form of paid environmental services) (Potter and Lee 1998; Keipi 1999). Investment in smaller scale tree planting is likely to increase in the coming years in response to forest scarcity, increased demand for forest products, globalising markets and increased environmental and social concerns (Scherr et al. 2003).

Many planting operations invest in site preparation and management techniques to maximise the success of plantings. In particular, large-scale industrial forestry has existed for over a century (Mather 1993) and has developed a standard set of practices to increase the productivity of plantings. These practices include pre- and post-planting weed control, soil cultivation, and the application of fertiliser (Gladstone and Ledig 1990). Practices in smaller-scale operations (e.g. farm forestry) are often borrowed from existing commercial forestry and cropping practices, as well as some more labour intensive practices such as the use of mulch, tree guards and irrigation (Close and Davidson 2003; Graham 2006). These site preparation and management techniques are used on the assumption that they will improve the survival and growth of plantings. Revegetation guidelines for smaller-scale operations frequently indicate that the use of a suite of techniques is necessary for successful establishment, and that the benefits of employing a range of techniques are cumulative (Stelling 1998; Corr 2003).

Since site preparation and management are labour and resource intensive (and hence expensive), the aim of this work is to review the existing scientific literature on seven key management practices employed in small-scale operations (i.e. pre- and post-planting weed control, soil cultivation, fertilisation, mulch application, tree guards and irrigation), to assess the individual and collective merits of each practice. The focus of the review is on eucalypts, because eucalypts are important commercial species globally (Zobel et al. 1987; Keipi 1999; Merino et al. 2003), as well as being key species in environmental plantings in Australia.

Review approach

Forty-four studies which directly or indirectly examined the effects of management practices on eucalypt seedling survival and/or growth were reviewed (Table 1). The main focus of this review was on published, peer-reviewed studies. Studies published in non-peer reviewed conference proceedings and journals, such as "Land and Water Research News" and "Agroforestry News", were only included if they reported the results of experimental work and included a statistical analysis, i.e. they were perceived to be scientifically rigorous.

Studies which directly examined the effects of various management practices on establishment fell into two broad categories. The first compared the effects of different management practices, when used either in isolation or in combination. The second compared differences within a particular technique such as timing, quantity or concentration. Studies that indirectly examined the effects of management practices on establishment included species and provenance trials, since detailed information on the management techniques used was provided as well as survival and growth data. Although these studies did not analyse treatment effects, their data complement those of other management studies. We first review the results of the studies which directly examine the

Table 1 Number of studies based in Australia (Aust) and internationally (Int'l), which investigated the effects of management techniques on eucalypt survival and/or growth

Management technique	Survival only		Growth only		Survival and growth		Total	
	Aust	Int'l	Aust	Int'l	Aust	Int'l	Aust	Int'l
Pre-planting weed control	0	0	1	2	3[a]	0	4	2
Post-planting weed control	0	0	2	1	2	0	4	1
Soil cultivation	0	0	2	1	6	1	8	2
Fertiliser	0	0	1	1	7	2	8	3
Mulch	1	0	0	0	5	1	6	1
Guards	0	0	1	0	3	0	4	0
Irrigation	0	0	1	0	2	0	3	0
Other	0	0	1	1	11[b]	5	12	6
Total	1	0	9	6	39	9	49	15

Some studies dealt with more than one management technique resulting in higher totals than studies reviewed

[a] One study (George and Brennan 2002), which examined the effects of weed control, initiated the treatments prior to planting and continued the treatments post planting. For simplicity, this study has been counted and reviewed as a pre-planting weed control study

[b] One Australian study (Burgess 1988) had three study sites one of which was located in Zimbabwe

effects of management techniques (Table 2). We then analyse the documented survival data from all the studies to assess the individual and interaction effects of each of the management techniques on survival.

Results from the following types of studies were not included in the review: (1) pot trials, as soil cultivation techniques cannot be tested in pots, and plants in pot trials display significantly different responses to those in field-based trials (McGinness et al. 2008); (2) trials where plants were established from seeds rather than seedlings, as the requirements and responses of germinants are not equivalent to planted seedlings; and (3) where only mature trees were considered.

Numerous measures of growth were reported in the studies reviewed. These included, but were not limited to: height (43); diameter at breast height (11); basal stem diameter (10); diameter at a non-standard height (12); crown volume (5); and biomass (3). Numbers in brackets indicate the number of studies in which each type of measurement was reported. The only measurement which was always recorded was height, therefore only the effects of management techniques on height (as a measurement of growth) will be discussed in this paper.

The distinction between pre-planting weed control, soil cultivation and site preparation in both the literature and in the field is often ambiguous. For example, some pre-planting weed control methods involve soil disturbance, while site preparation is taken to be synonymous with either one (Ellis 1990) or both of the other practices (Adams et al. 2003; Corr 2003). For the purposes of this review, soil cultivation refers to any mechanical method of soil disturbance, conducted prior to or at planting, regardless of its intended purpose (i.e. removal of vegetation, encouraging accumulation of soil moisture and/or facilitating root growth). Pre-planting weed control refers only to techniques that are used to remove weeds and other existing vegetation prior to planting, which do not involve significant soil disturbance. This includes the application of herbicides and manual removal of weeds. The term site preparation is used to refer to a combination of both pre-planting weed control and soil cultivation.

For each article, a distinction was made between: (1) the control techniques, i.e. the management practices which were used across all treatments, including the control; and (2) the treatment techniques, i.e. the management practices which were varied to assess the effects of management techniques, and were not applied to the control. This distinction was made because significant variation existed in the control techniques used in each article (Table 2), limiting the extent to which comparisons could be made between studies about the effects of the treatment variables.

Individual management techniques

Pre-planting weed control

Six studies directly examined the effects of pre-planting weed control on eucalypt establishment. Of these studies, three examined growth and three examined survival and growth (Table 1). Seven species were covered by the six studies (Table 4).

Growth

Five of the six studies indicated that variability exists in the effects of pre-planting weed control on growth. It was reported that the effects of pre-planting weed control on growth were dependent on: (1) the type of weed control used—such as manual versus chemical weed control (Ellis et al. 1985) or manual versus cover crops or slashing (George and Brennan 2002); (2) the types of herbicides used (Fagg 1988); (3) the application rates (Fagg 1988; Ellis 1990); and (4) the extent of weed control (Chingaipe 1985). The remaining article used only one type of herbicide (Schönau et al. 1981). Generally, pre-emergent/post-emergent herbicide mixes (Fagg 1988; Ellis 1990; George and Brennan 2002), post-emergent herbicides used alone (Schönau et al. 1981; Ellis et al. 1985) and manual weeding (Ellis et al. 1985; George and Brennan 2002) were found to improve growth rates, while cover crops and slashing did not (George and Brennan 2002).

Only one study (Ellis 1990) tested the effects of herbicide at different sites; however, site descriptions were not provided, and it appears that different herbicide regimes were applied at each site, making it difficult to interpret whether there were site effects. The only study that considered more than one species found similar responses (George and Brennan 2002).

Table 2 Comparison of treatment and control techniques used within and across studies

Variable/s being examined	Article	Treatment variables							Control variables						
		Pre-planting weed control	Post-planting weed control	Soil cultivation	Fertiliser	Mulch	Guard	Irrigation	Pre-planting weed control	Post-planting weed control	Soil cultivation	Fertiliser	Mulch	Guard	Irrigation
Pre-planting weed control	Ellis (1990)	x													
	Ellis et al. (1985)	x													
	Chingaipe (1985)	x													
	Fagg (1988)	x							x		x	x			
	Fagg (1988)	x									x	x			
Post-planting weed control	Ball et al. (2002)		x												
	Dalton (1992)		x								x				
	Fagg (1988)		x								x	x			
	Fagg (1988)		x						x		x	x			
	Little and van den Berg (1999)		x												
Soil cultivation	Ellis (1990)			x											
	McKimm and Flinn (1979)			x								x			
	Measki et al. (1998)			x											
	Lacey et al. (2001)			x					?	?		x			
	Pettit and Ritson (1990)			x											
	Ritson and Pettit (1992)			x											
	Shaw and Underdown (1998)			x					x						

Table 2 continued

Variable/s being examined	Article	Treatment variables							Control variables						
		Pre-planting weed control	Post-planting weed control	Soil cultivation	Fertiliser	Mulch	Guard	Irrigation	Pre-planting weed control	Post-planting weed control	Soil cultivation	Fertiliser	Mulch	Guard	Irrigation
Fertiliser	Ellis (1990)				x						x				
	Ellis (1990)				x					x					
	McKimm and Flinn (1979)				x						x				
	Mercuri et al. (2005)				x				x						
	Ritson and Pettit (1990)				x				x						
	Ritson et al. (1991)				x				x		x				
Mulch	Close et al. (2005)					x			x		x				
	Dalton (1992)					x					x				
	George and Brennan (2002)					x					x	x			
	Ritson and Pettit (1989)					x					x				
	Sun et al. (1994)					x					x				
Guard	Beetson et al. (1991)						x		x	x	x	x	x		
	Close et al. (2005)						x		x		x				
	Ritson and Pettit (1989)						x				x				
	Sun et al. (1994)						x				x				
Irrigation	Dalton (1992)							x			x				
	Mercuri et al. (2005)							x	x						

Table 2 continued

Variable/s being examined	Article	Treatment variables							Control variables						
		Pre-planting weed control	Post-planting weed control	Soil cultivation	Fertiliser	Mulch	Guard	Irrigation	Pre-planting weed control	Post-planting weed control	Soil cultivation	Fertiliser	Mulch	Guard	Irrigation
Interaction variables	George and Brennan (2002)	x	x								x	x			
	Schönau et al. (1981)	x			x					x					
	Schönau et al. (1981)	x		x	x					x					
	Adams et al. (2003)		x		x			x	x			x			
	Dalton (1992)		x			x					x				
	Dalton (1992)		x					x			x				
	Schönau et al. (1981)			x	x					x					
	Bird et al. (2000)			x	x				x	x					
	Chamshama and Hall (1987)			x	x				x	x					
	Gupta (1991)				x	x					x				
	Marcar et al. (2000)				x	x			x		x				x
	Marcar et al. (2000)				x	x	x				x				x
	Marcar et al. (2000)				x	x	x			x	x				
	Mercuri et al. (2005)				x			x	x						
	Dalton (1992)					x		x			x				

The symbol '?' denotes uncertainty regarding whether a particular variable was used

Table 3 Description of soil cultivation techniques

Technique	Description
Cultivate	To break up (land or soil) with a cultivator or hoe (Main Collins Dictionary 2004)
Cultivator	A farm implement equipped with shovels, blades, etc., used to break up soil and remove weeds (Main Collins Dictionary 2004)
Disc	A cultivation system that only affects the surface soil (<0.3 m deep) (Harper et al. 2008)
Furrow	A narrow trench made in the ground, especially by a plough (The Macquarie Dictionary 1990)
Harrow	A heavy frame with iron teeth dragged over ploughed land to break up clods, remove weeds, cover seed, etc. (The Concise Oxford Dictionary of Current English 1990)
Mound[a]	Any surface cultivation operation that piles up surface soil for seedling beds (Harper et al. 2008). Ritson and Pettit (1992) refer to three types of mounds:
	1. Standard: 15–20 cm above the level of the original land surface with a 15 cm deep and 10 cm wide trough in the top of the mound
	2. Single-ridge: 25–100 cm above the level of the original land surface
	3. Double-ridge: 25–100 cm above the level of the original land surface with a trough in the top between 10–70 cm deep and 50–90 cm wide
Pit	Schönau et al. (1981) use four different types of pits. Garden pits (1 m), small pits (0.5 m), pits (0.4 m) prepared with a motorised crumbler bit and pits (0.1 m) prepared with a tubular planting tool
Plough	An agricultural implement with sharp blades used for cutting or turning over the earth (Main Collins Dictionary 2004)
Rip	Deep tillage operation which aims to affect the regolith to depths below 0.3 m (Harper et al. 2008)
Scalp	Displacement of surface soil and vegetation using a near-horizontal blade (Harper et al. 2008)

[a] Mounding was referred to as bedding in Chamshama and Hall (1987)

Survival

The effects of pre-planting weed control on survival were found to be inconsistent, both within and between studies. George and Brennan (2002) found that five pre-planting weed control treatments (hand weeding, slashing, two cover crops and a pre-emergent/post-emergent mix), had no significant effects on survival. However, the application of herbicide resulted in significantly higher survival than the slashed treatment. Ellis (1990) found that using a pre-emergent/post-emergent herbicide mix increased survival while Fagg (1988) found that survival could be better or worse than the control depending on the treatment.[1]

The studies reviewed here indicate that pre-planting weed control has the potential to considerably increase the growth of eucalypts, depending on the type of weed control used and the amount applied. Pre-planting weed control has not been shown to have any significant positive effects on survival.

[1] Neither Fagg (1988) nor Ellis (1990) provided a statistical analysis of the effects of pre-planting weed control on survival.

Post-planting weed control

Five studies examined the effects of post-planting weed control. Three studies examined growth and two examined survival and growth (Table 1). Six species were covered by the five studies (Table 4).

Growth

The effect of post-planting weed control on growth was determined by the type (Fagg 1988; Little and van den Berg 1999), extent (Dalton 1992; Little and van den Berg 1999) and duration (Adams et al. 2003) of weed control. The results indicate that post-planting weed control provides the greatest benefits to growth when it is applied manually (Fagg 1988; Little and van den Berg 1999; Ball et al. 2002), or, in the case of herbicides, when a pre-emergent/post-emergent mix is used (Fagg (1988)[2]; Dalton 1992),

[2] Three of the four treatments that Fagg (1988) found to have significant positive effects on growth included propyzamide. Although Fagg (1988) considered this chemical to be a pre-emergent herbicide, other, more recent, studies consider this chemical to display post-emergent properties (e.g. Dear et al. 2006; British Columbia Ministry of Agriculture and Lands 2008).

Table 4 Species included in studies that directly examined the effects of management practices

Species name	Article	Management practice						
		Pre-planting weed control	Post-planting weed control	Soil cultivation	Fertiliser	Mulch	Guard	Irrigation
E. botyoides	Ritson and Pettit (1989)[a]					x		
E. botryoides Sm.	Mercuri et al. (2005)				x			x
E. camaldulensis	Chingaipe (1985)[b]	x						
	Ritson and Pettit (1989)[a]					x		
	Ritson and Pettit (1990), Ritson et al. (1991)				x			
	Sun et al. (1994)					x	x	
E. camaldulensis Dehnh. (Lake Albacutya, VIC)	Pettit and Ritson (1990), Ritson and Pettit (1992)			x				
E. camaldulensis Dehnh. (Uni of Melb. and Lake Albacutya, VIC and Silverton, NSW)	Marcar et al. (2000)				x	x	x	
E. cloeziana F. Muell	Beetson et al. (1991)[b]						x	
E. cornuta	Pettit and Ritson (1990)			x				
	Ritson et al. (1991)				x			
E. cypellocarpa (Nth of Erica, VIC)	Measki et al. (1998)[b]			x				
E. delegatensis	McKimm and Flinn (1979)			x	x			
E. delengatensis R. T. Baker	Ellis et al. (1985)[b]	x						
E. dunnii	George and Brennan (2002)	x				x		
	Little and van den Berg (1999)[b]		x					
E. globulus	Shaw and Underdown (1998)			x				
E. globulus (Jerralang, VIC)	Adams et al. (2003)[b]		x		x			
E. globulus ssp. *bicostata*	McKimm and Flinn (1979)			x				
E. globulus ssp. *globulus*	Ellis (1990)	x		x	x			
	Ritson et al. (1991)				x			
E. globulus ssp. *globulus* (Yeodene Seed Orchard and Otway Ranges, VIC)	Bird et al. (2000)[b]			x	x			
E. grandis	Schönau et al. (1981)[b]	x		x				
E. largiflorens F.Muell (Lake Albacutya, VIC)	Ritson and Pettit (1992)			x				
E. melliodora	Ritson et al. (1991)				x			
E. microcarpa	Ritson et al. (1991)				x			
E. nitens	McKimm and Flinn (1979)			x	x			

Table 4 continued

Species name	Article	Management practice						
		Pre-planting weed control	Post-planting weed control	Soil cultivation	Fertiliser	Mulch	Guard	Irrigation
E. nitens (Rubicon, NSW)	Close et al. (2005)					x	x	
E. occidentalis Endl.	Mercuri et al. (2005)				x			x
E. pauciflora (Midlands Tasmania)	Close et al. (2005)					x	x	
E. pauciflora Sieb. ex Spreng. (Orroral Valley, ACT)	Ball et al. (2002)[b]		x					
E. pilularis	Lacey et al. (2001)			x				
E. regnans	Fagg (1988)	x	x					
	McKimm and Flinn (1979)			x				
E. saligna	George and Brennan (2002)	x				x		
E. saligna (Termeil and Armidale, NSW)	Measki et al. (1998)[b]			x				
E. sideroxlyon	Ritson et al. (1991)				x			
E. socialis	Dalton (1992)		x			x		x
E. tereticornis Sm.	Chamshama and Hall (1987)			x	x			
	Mercuri et al. (2005)				x			x
E. transcontinentalis	Dalton (1992)		x			x		x
E. viminalis (Sth of Braidwood, NSW)	Measki et al. (1998)[b]			x				
E. woollsiana	Ritson et al. (1991)				x			

Provenances, where known, are provided in brackets. All provenances are Australian in origin

[a,b] Studies that measured survival only (d) or growth only (e) the remaining studies measured both

when it is applied over a large area (Dalton 1992; Little and van den Berg 1999) and when it is applied soon after planting (Adams et al. 2003). Only one study (Dalton 1992) examined more than one species and found that both species responded in the same way. Each article only examined the effects of post-planting weed control at one site. This means that it is unknown whether there are interactions between site and post-planting weed control.

Survival

Neither Fagg (1988) nor Dalton (1992) provided a statistical analysis of the effects of post-planting weed control on survival. Fagg (1988) found that weed control treatments could increase or decrease survival relative to the control depending on the rates of herbicide applied and the effectiveness of the method used to shield seedlings. Dalton (1992) found that the effect of herbicides on survival depended on the extent of application and the types of herbicide applied.

The studies indicate that post-planting weed control, whether manual or chemical, has the potential to increase the growth of eucalypts. Whether post-planting weed control provides significant benefits for eucalypt survival is yet to be proven.

Soil cultivation

Studies which examined the effects of soil cultivation on eucalypt establishment were the second most common. The soil cultivation techniques examined by the studies were mounding (7), ripping (6), discing (3), furrowing (1), scalping (1) and digging pits (1). Table 3 provides a description of each technique. Of the ten studies reviewed, three examined growth only and seven examined survival and growth (Table 1). Fourteen species were covered by the ten studies (Table 4).

When considering soil cultivation treatments it is important to recognise that soil cultivation is strongly linked to site characteristics, such as soil properties, landscape position and rainfall zone. The most appropriate soil cultivation technique for a particular site depends on these three factors. For example, the soil characteristics will determine whether ripping is necessary, with ripping likely to have less effect on sandy as opposed to clay soils. Similarly, mounding is more suited to low-lying or salt affected sites.

Growth

There was general agreement across studies that that the effects of mounding, ripping and full cultivation on eucalypt growth were moderated by site characteristics, such as the soil profile (McKimm and Flinn 1979; Measki et al. 1998; Shaw and Underdown 1998; Lacey et al. 2001) and soil moisture (McKimm and Flinn 1979; Shaw and Underdown 1998). There was less agreement about whether soil cultivation results in a persistent improvement in growth across time and across techniques.

Ritson and Pettit (1992) and Bird et al. (2000) found that the positive effects of some soil cultivation treatments diminished over time while and McKimm and Flinn (1979) found a persistent positive effect of soil cultivation for 5 years on a high rainfall site. With respect to soil cultivation techniques, two studies reported persistent, significant differences between techniques (Schönau et al. 1981; Ellis 1990) while two other studies did not find any growth differences between techniques (Chamshama and Hall 1987; Lacey et al. 2001). However, it is important to note that no two studies compared the same soil cultivation techniques, which may explain the different time and technique effects observed.

Four studies explored the effects of soil cultivation on two or more eucalypt species and found similar responses (McKimm and Flinn 1979; Pettit and Ritson 1990; Ritson and Pettit 1992; Measki et al. 1998).

Survival

All seven studies that examined the effects of soil cultivation on survival found positive effects that were moderated by site and some technique differences. McKimm and Flinn (1979) and Shaw and Underdown (1998) found that soil cultivation only significantly affected survival on the drier, more exposed sites. Chamshama and Hall (1987) and Lacey et al. (2001) found that use of any soil cultivation treatment significantly improved survival but that there were no significant differences between various techniques. Ellis (1990), Pettit and Ritson (1990) and Ritson and Pettit (1992) did not include control plots. However, they all found significant differences between soil cultivation techniques. Generally, they found that mounding performed better than scalping (Ellis 1990) and that freshly formed (Pettit and Ritson 1990), taller and double ridged mounds (Ritson and Pettit 1992) resulted in greater survival on saline sites.

In contrast to growth, species and length of time after planting did not interact with soil cultivation techniques with respect to survival. Four studies considered the effects of soil cultivation on survival of more than one species (Table 4); however, no species by soil cultivation interactions were reported. Also there may not have been a length of time interaction, as seedling deaths mainly occur soon after planting, with mortality declining after that (McKimm and Flinn 1979; Ritson and Pettit 1992).

The studies reviewed here indicate that site characteristics determine whether soil cultivation has a positive effect on growth and the strength and persistence of the effect. Survival improved with the use of mounding, particularly on saline sites or sites with low soil moisture.

Fertiliser

Studies examining the effects of fertiliser application on eucalypt establishment were the most numerous. Schönau and Herbert (1989) conducted a review of the effects of fertiliser on eucalypt growth, citing more than 100 references. Due to the comprehensiveness of that review, this paper will aim to build on their discussion by only considering studies which: (1) were published since 1989 and have investigated the effects of fertiliser on growth; or (2) any studies which have considered the effects of fertiliser on survival, as survival was not covered by Schönau and Herbert (1989). Thirteen species were covered by the nine studies, which met either criterion (Table 4).

Growth

Schönau and Herbert (1989) asserted that there is overwhelming evidence of a universally sustained growth response of short-rotation eucalypts to fertiliser application. In particular, the review suggests that phosphorus (P) is needed by eucalypts in early stages of tree development. Later application of fertiliser requires careful consideration of the existing balance between nitrogen (N) and P at the site and the effect that site preparation has on this balance through N mineralisation. In this review, two studies reported no effect of fertiliser on growth, regardless of the amount applied (Ritson and Pettit 1990; Bird et al. 2000). Furthermore, Ritson et al. (1991) found that only two of six species responded to N and/or P. All these experiments were conducted on farms which had a history of nutrient applications. This indicates that there may not be an additional benefit of providing fertiliser to eucalypts on high nutrient sites, an issue not discussed by Schönau and Herbert (1989).

In addition to site differences, Schönau and Herbert (1989) discussed how the effects of fertiliser on growth were moderated by species, time of application, method of application and length of time since planting. Only some of these effects were confirmed by subsequent studies. Ritson et al. (1991) and Mercuri et al. (2005) found few differences in species responses to various fertiliser applications. While Ellis (1990) found that time of application affected growth of *E. globulus* ssp. *globulus*, with trees fertilised at time of planting being taller than those fertilised after 3 months.

Schönau and Herbert (1989) cited five studies to suggest that initial responses of eucalypts to fertilising are maintained through time, especially if the experiments are designed satisfactorily. Subsequent studies have shown varying responses to fertiliser over time. Mercuri et al. (2005) found that *E. botryoides*, *E. occidentalis* and *E. tereticornis* showed a persistent response for 24 months to an initial application of fertiliser, biosolids, compost or topsoil. Adams et al. (2003) found that *E. globulus* responded to biannual N application after 24 months but not at 12 months (Adams et al. 2003). Marcar et al. (2000) found that fertiliser significantly increased the growth of *E. camaldulensis* up to 20 months but not at 35 months at one site and decreased growth to 10 months but not 69 months on a different experiment at the same site. Chamshama and Hall (1987) found that N positively affected height at 2–3 months after planting, during the rainy season, but did not persist after this period to an age of 2 years. Ritson et al. (1991) reported a persistent effect after 3 years for two species on one site. The results of Ritson et al. (1991) provide the greatest evidence that experimental design is unlikely to explain a sustained response to fertiliser, as the same experimental design was applied to six species over two sites. This, combined with the other studies presented here, suggest that site and species are likely to determine whether there is a response to fertiliser and whether the effect persists.

Survival

With one exception, the results from six studies indicate that N and P have no effect, or significantly reduce survival of eucalypts.

Both McKimm and Flinn (1979) and Ritson and Pettit (1990) found that a range of fertilisers had no effect on survival at three and five sites, respectively. Ritson et al. (1991), Marcar et al. (2000) and Mercuri et al. (2005) found that fertiliser had no effect or a negative effect on survival depending on the form of fertiliser used (Ritson et al. 1991; Mercuri et al. 2005), site characteristics (Ritson et al. 1991), species (Ritson et al. 1991), and the use of pre-planting weed control (Marcar et al. 2000). The only study which found a positive effect of fertiliser on survival was Chamshama and Hall (1987). After 12 months N (9 g) significantly increased the survival of *E. tereticornis* but P (31 g) did not.

The studies reviewed here indicate that existing site nutrient levels and species determine whether fertiliser has a positive effect on growth. On sites where there has been a history of fertiliser application fertiliser is unlikely to be beneficial. With one exception, fertiliser was found to have no effect, or a negative effect on survival.

Mulch

Of six studies which examined the effects of mulch on eucalypt establishment, one dealt with survival and five with survival and growth (Table 1). Eight species were covered by the six studies (Table 4).

Growth

Two studies showed that the effects of mulch on growth differed by site (Marcar et al. 2000; George and Brennan 2002), mulch type (George and Brennan 2002) and length of time after planting (Marcar et al. 2000; George and Brennan 2002). Generally, oaten hay and meadow hay improved growth on saline sites (Marcar et al. 2000) and jute and sawdust mulch (but not woodchips) enhanced growth on a high rainfall site (George and Brennan 2002). The remaining three studies found no effects on growth of organic mulch (Dalton 1992; Sun et al. 1994), plastic mulch (Sun et al. 1994) or native litter (Close et al. 2005). No species related differences were reported (Dalton 1992; George and Brennan 2002; Close et al. 2005).

Survival

Three of the six studies found that the type of mulch type determined whether there was a response in survival to mulch, while two studies found no effect of mulch on survival. Ritson and Pettit (1989) and Marcar et al. (2000) found that oaten straw significantly improved survival on saline sites and Sun et al. (1994) found that organic mulch (rice husks) significantly improved survival on the high salinity site only. Sawdust (Ritson and Pettit 1989; George and Brennan 2002), plastic mulch (Sun et al. 1994), meadow hay (Marcar et al. 2000), native litter (Close et al. 2005), jute and woodchips (George and Brennan 2002) did not have a significant effect on survival.

Dalton (1992) did not conduct a statistical analysis on the effects of mulch on survival; however, it appears that there may be a species effect.

Only two of five studies have shown a significant positive growth response to mulch. Only two types of mulch have been found to improve survival of eucalypts on saline sites. No significant benefits of mulch have been found for survival on non-saline sites.

Guards

Two studies examined the effects of tree 'shelters' on growth (Beetson et al. 1991) and survival and growth (Sun et al. 1994), and two studies examined the effects of tree 'guards' on survival and growth (Marcar et al. 2000; Close et al. 2005). Tree shelters are taller than guards, often at least 1.2 m in height, and are a silvicultural aid particularly designed for enhancing growth and to a lesser extent survival (Evans and Potter 1985; Costello et al. 1996). Four species were covered by the four studies (Table 4).

Growth

Beetson et al. (1991) tested the effects of three Growtube® tree shelter lengths on two soil types. Growtubes significantly increased growth 1 year after planting, with taller shelters resulting in taller trees. Sun et al. (1994) found that Growtubes did not produce significantly taller trees on either the low or high salinity sites.

Marcar et al. (2000) found that guards significantly improved growth at the drier, more saline site. Close et al. (2005) found that both standard tree guards and water guards (guards with fillable sleeves that drip water) significantly improved the growth at two sites. There was no significant difference between the two types of guards.

Survival

Sun et al. (1994) found that there was an interaction between soil type and Growtubes with regards to survival, as Growtubes significantly improved survival on the high salinity site only.

Marcar et al. (2000) found that tree guards improved survival and growth at the higher salinity site. At the other site survival was only enhanced after 5 months. Close et al. (2005) found that tree guards resulted in high survival at both (non-saline) sites (94 and 99%), however, no statistical analysis was provided as to whether tree guards resulted in significantly higher survival than the controls.

Tree shelters and guards resulted in improved growth on non-saline sites. On saline sites, guards improved growth on a drier site. Tree shelters improved survival of one eucalypt species on a saline site. It is uncertain whether tree guards would improve survival on non-saline sites.

Irrigation

In conducting this review only two studies (Dalton 1992; Mercuri et al. 2005) were found which directly examined the effects of irrigation on field planted eucalypt seedling survival or growth. Five species were covered by the two studies (Table 4).

Growth

Dalton (1992) found that watering seedlings at fortnightly intervals after planting on an arid site (mean annual rainfall 257 mm) significantly improved growth compared with watering every 2 months. In contrast, Mercuri et al. (2005) found no significant differences between heights of rain-fed and irrigated treatments up to 24 months after planting, on a site with 645 mm mean annual rainfall.

Only one other article, studying the effects of post-planting weed control on growth, documented the application of low and high irrigation rates on a site with 512 mm mean annual rainfall; however, no significant response was found during the first 12 months (Adams et al. 2003).

Survival

Mercuri et al. (2005) found that irrigated treatments significantly increased the survival of all species compared to rain-fed treatments, resulting in 89.8 and 78.6% survival, respectively. This trend was also apparent in Dalton (1992), where fortnightly watering resulted in higher survival (significance not tested) for both species than watering every 2 months and no watering, with the latter resulting in no survival.

The results indicate that irrigation has the potential to provide benefits for survival. The benefits of irrigation for growth have only been shown for an arid site.

Review of interactions between and relative importance of management techniques

In practice, management techniques are rarely used in isolation. Consequently, there is considerable value in studying their combined effects on eucalypt establishment. Such research can be used to show whether there are positive or negative interactions between techniques and their relative importance. Where funds are limited this can facilitate prioritisation of techniques. In spite of the importance of studying more than one technique, only nine of the studies, which directly examined the effects of management practices on seedling establishment, dealt with a combination of techniques (Table 2). Only three of these studies (Chamshama and Hall 1987; Marcar et al. 2000; Mercuri et al. 2005) directly tested for interaction effects. In addition, Ellis (1990) commented on the results of multi-factor experiments but did not provide details of where or how the experiments were carried out. The aim of this section is to synthesise the results of these papers, so as to identify where the greatest benefits are likely to be obtained from using a combination of management techniques.

Eight of the nine studies included fertiliser as one of the interacting variables. Three studies considered the effects of soil cultivation and fertiliser. Chamshama and Hall (1987) were the only authors who directly tested for an interaction effect and reported none of significance. Bird et al. (2000) applied a range of fertilisers to four soil cultivation treatments, but interactions were not considered. Schönau et al. (1981) found that fertilising caused a narrowing of the distribution of heights across the soil cultivation (and pre-planting weed control) treatments. In addition, the effect of fertiliser on the full cultivation treatment only persisted for 1 year, whereas the effect persisted for 3 years in the remaining 10 treatments. This was probably because there was insufficient P in the fertiliser to compensate for the enriched N available from mineralisation of the original vegetation. Tree height achieved under full cultivation in isolation far surpassed that in any of the other treatments used in combination with fertiliser, indicating that fertiliser cannot compensate for poor site preparation (Schönau et al. 1981; Schönau and Herbert 1989).

Two studies (Gupta 1991; Marcar et al. 2000) examined the combined effects of mulch and fertiliser, with Marcar et al. (2000) examining the effects of guards in addition to these two factors. Unfortunately, Gupta (1991) did not have a complete factorial experiment, and only considered a combined fertiliser (superphosphate and urea) and mulch (coirpith—a waste from coconut factories) treatment. This treatment significantly increased survival and growth of *E. camaldulensis* by 132 and 86%, respectively. However, due to the design of the experiment it is not possible to determine the independent effects of mulch and fertiliser or whether there was an interaction effect. In contrast, Marcar et al. (2000) considered all factors independently and in combination. In two trials trees treated with mulch + fertiliser, and mulch + fertiliser + guards, were significantly taller than the control but were not significantly different from those treated with the techniques separately. There were no treatment effects in the other two, wetter trials. While differences between the treatments were not significant, the combined treatments did produce taller trees. Where mulch and fertiliser improved survival and growth the explanation given was that the increased moisture provided by the mulch may have facilitated the uptake of nutrients provided by the fertiliser. This may also explain why there was no effect in the other trials, as these trials had greater soil moisture, which could have mitigated the effect of the mulch.

Mercuri et al. (2005) examined the combined effects of fertiliser and irrigation. There was a significant interaction between irrigation and application of fertiliser on survival. Rain-fed trees that had been fertilised had significantly lower survival than rain-fed trees that had not been fertilised or irrigated trees that had been fertilised. No significant interaction between fertiliser and irrigation was reported for growth.

Adams et al. (2003) was the only article that examined the combined effects of post-planting weed control, fertiliser and irrigation. Although not directly tested, it appears that there was a negative interaction between weed control and fertiliser in the second year, as treatment with high N reduced tree growth (both height and diameter) in the weed control treatments and facilitated tree growth in treatments without weed control. The effects of irrigation on weed control and N were unclear and poorly presented. Over the first 2 years, treatment with low irrigation and no fertiliser resulted in the greatest growth when weeds were controlled and the smallest growth when weeds were not controlled. Although not discussed in the paper, other combinations of irrigation and N may have resulted in intermediate growth rates and some interaction may have occurred.

Dalton (1992) was the only article which examined the combined effects of using two-way combinations of post-planting weed control, mulch and irrigation. This study provides evidence that the benefits of conducting a range of techniques may not be additive and that there are species differences in responses to combined treatments. For *E. transcontinentalis* application of organic mulch as well as a pre-emergent/post-emergent herbicide mixture, applied to a circle of diameter 3 m, resulted in the greatest growth. However, this was not significantly different from the use of the herbicide mixture alone, or the application of fortnightly watering. For *E. socialis* the greatest growth was achieved by using fortnightly watering in combination with the herbicide mixture applied to a circle of diameter 1 m. However, this was not significantly different from fortnightly watering used alone or in combination with mulch. One weakness of this study was that there were only seven seedlings per treatment, which may have reduced the strength of the statistical analysis. Also, there was no treatment which included a combination of fortnightly watering and the herbicide mix applied to a diameter of 3 m, the two treatments which, when used alone, resulted in the greatest improvements in growth. Nevertheless, this study indicates that in arid areas the use of a combined herbicide mixture applied to a 3 m diameter circle around each seedling can give results comparable to those achieved with fortnightly watering.

Ellis (1990) briefly discussed the key findings of several multi-factor experiments; however, methods and results were not presented. These experiments indicated that the most important management factor in establishing eucalypts on ex-pasture sites is soil cultivation in conjunction with weed control, followed by fertiliser. It was also found that fertiliser had marginal benefits relative to weed control, supporting the conclusions of Schönau et al. (1981). There were no significant interactions between the factors, with the benefits of each appearing to be additive. While the lack of interactions between factors is consistent with the other eight studies presented here there is little evidence in the remaining studies that the benefits are additive. Rather, it appears that there may be some maximum improvement in survival and growth that can be achieved by using management techniques. By using a combination of techniques it may be possible to reach this maximum, with use of further techniques having minimal effect. This is most notable in the work of Dalton (1992), Marcar et al. (2000) and Schönau et al. (1981). Dalton (1992) and Marcar et al. (2000) found that the combined treatments provided no significant benefit over using treatments in isolation, and Schönau et al. (1981) found that adding fertiliser to site preparation treatments that did not use full cultivation did not compensate for conducting full cultivation.

Consistency in application of management techniques

While an attempt has been made in this review to compare results across studies, it is important to note that there were considerable differences in the control techniques used, i.e. those techniques used across all treatments in a trial, including the control (Table 2). This issue was also raised by Schönau and Herbert (1989). They found that much confusion had arisen in the literature on fertilising due to poor experimental techniques. They highlighted the importance of uniformity in site preparation and silviculture to maximise true treatment response. Our current review indicates the weaknesses identified by Schönau and Herbert (1989) persist to the present day. This not only evident in the research on fertilising is but also for the other six management practices.

There were two components to variability in the control techniques. Firstly, there was variability within and across the studies as to whether a particular control technique was used. Secondly, there was variability within each control technique as to the methods used and the timing at which they were applied.

An example of both forms of variability is provided by the studies which examined the effects of post-planting weed control. Of five studies, two did not apply any control techniques and one used soil cultivation alone (Dalton 1992). The remaining two studies both used pre-planting weed control and fertiliser and one used soil cultivation as well (Table 2). The types of pre-planting weed control and fertiliser used across the two studies differed. While Adams et al. (2003) applied a post-emergent herbicide and light cultivation, Fagg (1988) used only scalping. Similarly, while Adams et al. (2003) applied two treatments of urea fertiliser per year, providing a total of 900 kg/ha of N over the 2 years, Fagg (1988) only applied one 10 g slow-release fertiliser tablet at the time of planting.

Analogous inconsistencies in the application of control techniques could be found for each management variable reviewed here (Table 5). These inconsistencies clearly limit the extent to which the effects of individual management techniques can be isolated. The value of future research could be significantly enhanced by matching new experimental designs with those of past studies, with regards to both the control and treatment management techniques. This would facilitate the determination of optimum thresholds for the amount and timing of particular management practices, rather than just broad positive or negative effects.

Table 5 Details of the control treatments used across 59 trials in 26 studies

Experimental controls	Details of control treatments
Spacing	2 m × 2 m (7); 1.2 m × 1.2 m (5); 3 m × 4 m (5); 3 m × 3 m (3); 1.6 m × 1.6 m (2); 2.5 m × 2.5 m (2); 2 m × 3 m (2); 2.6 m × 2.6 m (1); 4 m × 2.5 m (1); 4 m × 4 m (1) 5 m × 5 m (1); 2 m along mounds (1)
Frequency of measurement	Irregular intervals (15); once at 12 months (7); annually (6); monthly (2); once at 7.5 years (2); once at 7 months (2); 6-weekly (1); 3 monthly (1); biannually (1); once at 4 years (1); once at 29 months; once at 2 years (1); once at 10 months (1); once at 101 days (1)
Pre-planting weed control	
Type	Pre-emergent herbicide only (6); Post-emergent herbicide only (4); Pre- and post-emergent herbicide (3); Scalping (2); Slashing (2); Cultivation (1); Chopping (1)
Time of application (before planting)	1 month (4); 7 and 2 months (1); 1.5 months (1); 1 day (1)
Post-planting weed control	
Class	Pre-emergent herbicide only (4); Pre-emergent herbicide and grazing (1); manual weeding (1); clean-hoe (1)
Time of application (after planting)	4 months (1) 9 months (1); at 8, 9 and 11 months (1); at 6 and 18 months (1); 3-monthly intervals for 2 years (1)
Soil cultivation	
Class	Rip and mound (6); rip only (5); mound only (4); plough and harrow (2); pit only (2); plough only (1); rip and harrow (1); rip (1); cultivate, mound and harrow (1); cultivate, mound and rip (1); rotary hoe and mound (1)
Mound height	50 cm (4); 100 cm (2); 40 cm (2); 60 cm (1); 18 cm (1)
Ripping depth	65 cm (3); 30 cm (3); 60 cm (2); 40 cm (2)
Time of application (before planting)	At planting (17); 2 months (9); 4 months (3); 1 month (3); 5 months (2)
Fertiliser	
NPK ratio	20:4:4 (4); 17:7:9 (3); 13:4:4 (2)
Amount applied	10 g/seedling (4); 50 g/seedling (2); 85 g/seedling (3); 167 kg/ha (1)
Time of application	At planting (7); at planting and 1 year after planting (3); 2 months after planting (1); autumn and spring for 2 years (1)
Irrigation	
Amount	2 l/seedling (2); 6 l/seedling (1)
Time of application	At planting (1); end of first weed (1); first 2 weeks (1)

Numbers in brackets refer to the number of trials in which a particular method was used as a control treatment. For each method there was at least one trial for which the details of the method were not provided

Analysis examining interactions and relative importance of techniques

Initially, studies considered in this review were those that directly examined the effects of management practices on eucalypt establishment. However, given the limited number of studies (27) which were found, and the considerable variation in results, the review was extended. Seventeen other studies, which dealt with the effects of non-management related variables on eucalypt establishment and documented management practices (Table 6), were included. The data from these additional studies were used to further develop an understanding of the effects of various management practices on eucalypt survival.

Table 6 provides a summary of the management techniques employed by the additional 17 studies. None of these studies used tree guards.

Of the 44 studies reviewed, 21 documented survival rates for control treatments and clearly explained the control techniques. This covered 48 species over 49 sites, providing 152 data points. The data from these studies were analysed to determine the interactions between, and relative importance of,

Table 6 Use of management techniques by studies not testing for differences between such techniques

Article	Non-management variables							Management techniques						
	Species	Provenance	Site characteristics	Container type	Nursery care	Browsing	Salinity	Pre-planting weed control	Post-planting weed control	Soil cultivation	Fertiliser	Mulch	Guard	Irrigation
Burgess (1975)	x	x	x											
Burgess (1988)	x	x	x					x		x				
Burgess (1988)	x	x	x					x						
Chamshama and Hall (1984)					x				x	x				
Chamshama and Hall (1999)		x						x	x	x				x
Chaturvedi et al. (1989)		x	x											
Cotterill et al. (1985)	x	x							x	x	x			
Darrow (1983)		x	x											
Dubois et al. (2000)		x	x											
Ellis (1990)[a]				x										
Griffin et al. (1982)		x	x		x			x			x			
Marcar et al. (2003)							x	x	x	x	x			x
Marcar et al. (2003)							x	x		x	x	x		x
Matheson and Mullin (1987)		x	x											
McArthur and Appleton (2004)				x		x		x			x			
Neilsen and Pataczek (1991)						x		x		x	x			

Table 6 continued

Article	Non-management variables							Management techniques						
	Species	Provenance	Site characteristics	Container type	Nursery care	Browsing	Salinity	Pre-planting weed control	Post-planting weed control	Soil cultivation	Fertiliser	Mulch	Guard	Irrigation
Sun and Dickinson (1995)							x		x	x	x	x		
Tibbits (1986)	x									x	x			
Turnbull et al. (1993)	x		x					x	x	x	x			
Wilkinson and Neilsen (1990)				x				x		x	x			

[a] Although Ellis (1990) was one of the studies included in the original review, one experiment dealt with a non-management technique (container type)

management techniques on survival. As survival proportions are constrained to lie between 0 and 1, the proportions were transformed by the empirical logit (i.e. Ln{(survival rate + 0.5)/(1−survival rate + 0.5)}). A generalised linear model (McCullagh and Nelder 1989) was then fitted to the logit transformed survival rates.

The explanatory variables used were years since planting and then each of the six management techniques (i.e. pre- and post-planting weed control, soil cultivation, fertiliser, mulch and irrigation) as binary factors to indicate whether they were or were not used. Guards were not included, as there were no studies in which guards were used in the control treatment (Tables 2, 6). Species and site were not used as explanatory variables, as there were only one or two published survival rates for most sites and species. However, sufficient information existed to include mean annual rainfall and altitude in the analysis, as continuous variables.

The analysis indicated that the only management techniques which had a significant correlation with survival in isolation ($F = 0.05$) were post-planting weed control, soil cultivation and fertiliser (Table 7), which were all associated with higher survival. Of these three variables, only soil cultivation was consistently found to have a positive influence on survival in the literature. This indicates the value of including the data from the studies examining non-management variables. Years since planting also significantly affected survival, with increasing time equating to lower survival. However, when 12 values with high leverage were removed (i.e. ages of 9 years and above) this trend was no longer significant. Mean annual rainfall and altitude were both negatively correlated with survival. Altitude had four values with high leverage. When these values were removed (i.e. mean altitude above 1,100 m) and the model refitted, the trend was still significant. This refitted relationship is presented in Fig. 1.

Interactions between single variables were also investigated. This analysis (Table 7) showed that there were few significant two-factor interactions. These occurred between: pre- and post-planting weed control; pre-planting weed control and soil cultivation; pre-planting weed control and mulch; post-planting weed control and irrigation; and fertiliser and soil cultivation. There was only one significant interaction between post-planting weed control, soil

Table 7 Coefficients of the one-factor models for control survival proportions

	One factor model	*df*, *n*	Variance ratio[a]	Probability	Parameter estimate	Standard error	Increase in odds ratio
Continuous	Altitude—high leverage values	1,136	11.662	<0.001	−0.000886	0.00012	0.999
	Altitude	1,140	7.070	<0.001	−0.000601	0.00011	0.999
	Annual rainfall	1,100	7.640	<0.001	−0.000643	0.00011	0.999
	Time after planting	1,146	1.226	0.036	−0.034300	0.01620	0.966
	Time after planting—high leverage values	1,134	0.034	0.722	0.009000	0.02530	1.009
Binary	Post-planting weed control	1,150	7.137	<0.001	0.436400	0.07890	1.547
	Soil cultivation	1,150	6.686	<0.001	0.459400	0.08640	1.583
	Fertiliser	1,150	2.049	0.006	0.279000	0.10100	1.322
	Pre-planting weed control	1,150	0.471	0.195	0.114200	0.08770	1.121
	Irrigation	1,150	0.373	0.249	−0.146000	0.12700	0.864
	Mulch	1,150	0.046	0.685	0.057000	0.14000	1.059

[a] We assume that the variance ratio is distributed as an '*F*' statistic

cultivation and fertiliser, the three management techniques that were significantly correlated with survival in isolation (Table 7). There was a significant interaction between fertiliser and soil cultivation but no significant interactions between soil cultivation or fertiliser and post-planting weed control. Each of the significant interactions will be briefly discussed.

Post-planting weed control, soil cultivation and mulch resulted in higher survival when used individually than when used in combination with pre-planting weed control, or when pre-planting weed control was used alone. This supports the notion that there may be a maximum benefit that can be achieved by using management techniques and beyond this point there may be no additional benefit, or even a disbenefit, to using additional approaches.

When used in isolation soil cultivation and fertiliser resulted in better survival than pre-planting weed control, however, the best effect was achieved by using both techniques, as they had a significant positive interaction. There may be two explanations for this. Firstly, soil cultivation, such as ripping, may provide seedlings with greater access to water resources, which in turn allows them to take greater advantage of the nutrients provided by the fertiliser. Alternatively, soil cultivation may act in a similar way to the fertiliser by increasing N mineralisation, thereby amplifying the effects of the fertiliser.

Post-planting weed control results in much higher survival in the absence of irrigation. This may be because irrigation reduces the effectiveness of post-planting weed control by encouraging weed competition, which reduces survival. This analysis revealed that no eucalypt survival studies exist which used mulching in isolation of soil cultivation or fertiliser, and no studies exist of irrigation in isolation of soil cultivation.

Conclusions

Tree planting for environmental benefit is receiving increasing attention worldwide, and is likely to increase in response to concerns regarding climate change. With so much depending on the success of environmental plantings it is important to ensure that financial costs are minimised and that the environmental benefits are maximised. One way to achieve this is by employing management techniques which optimise survival and growth. Applying management techniques is resource and labour intensive and therefore clear advice is needed to inform tree planters of the most effective ways of maximising the success of environmental plantings.

The review indicates that the survival and growth of eucalypts can be maximised through application of one or two management techniques, with use of additional techniques providing little benefit. Reviewing and comparing individual studies showed that: (1) pre-planting weed control, soil cultivation and post-planting weed control generally provide benefits for early eucalypt growth; and (2) soil

Table 8 Sums of squares for two-factor models with significant interactions between management techniques on control survival proportions

Two factor model	*df*	s.s	*F*-ratio	Probability
Post-planting weed control	1	7.137	34.07	<0.001
Pre-planting weed control	1	0.471	2.25	0.136
Pre-planting weed control × post-planting weed control	1	3.509	16.75	<0.001
Residual	148	31.001		
Post-planting weed control	1	7.137	31.04	<0.001
Irrigation	1	0.045	0.200	0.657
Post-planting weed control × irrigation	1	0.904	3.930	0.49
Residual	148	34.033	0.230	
Soil cultivation	1	6.686	29.81	<0.001
Pre-planting weed control	1	0.074	0.33	0.567
Soil cultivation × pre-planting weed control	1	2.159	9.63	0.002
Residual	148	33.200	0.224	
Soil cultivation	1	6.686	30.41	<0.001
Fertiliser	1	0.160	0.395	0.395
Soil cultivation × fertiliser	1	2.737	12.45	<0.001
Residual	148	32.536	0.220	
Pre-planting weed control	1	0.471	1.72	0.192
Mulch	1	0.002	0.01	0.937
Pre-planting weed control × mulch	1	1.151	4.21	0.042
Residual	148	40.495	0.274	

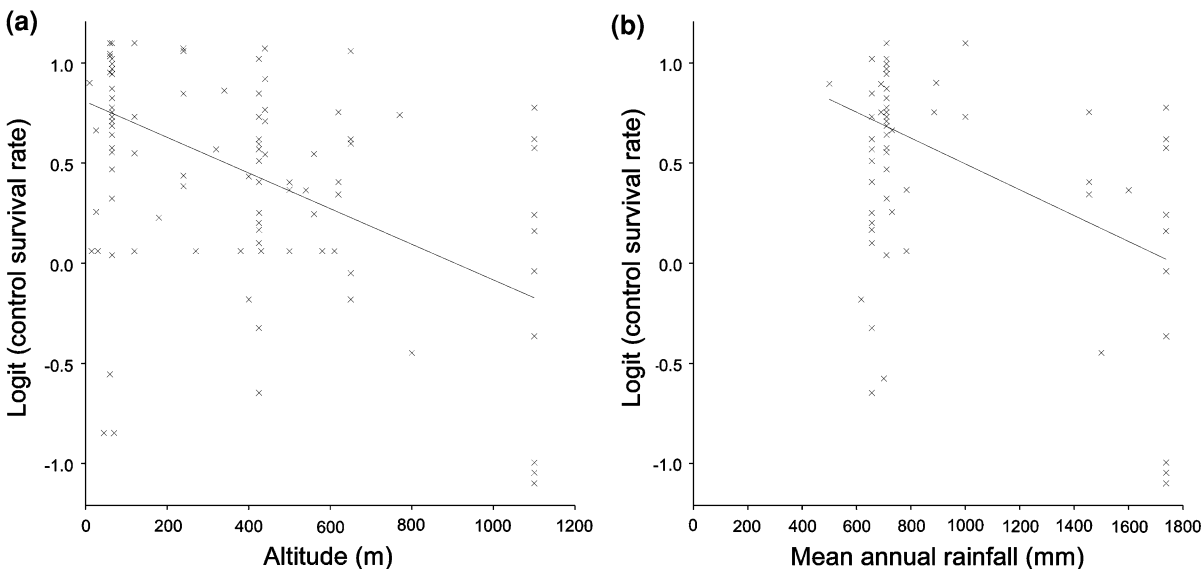

Fig. 1 Relationships between the logit of the control survival rates and: **a** altitude, without high leverage values; and **b** mean annual rainfall

cultivation and irrigation can provide benefits for survival. The statistical analysis showed that soil cultivation, post-planting weed control and fertiliser can significantly improve the survival of eucalypts across a range of sites and species. The two practices that had a positive effect in both the review and the statistical analysis were soil cultivation and post-planting weed control. This suggests that the greatest improvements in environmental planting outcomes are likely to be achieved by using these two techniques.

There are two major limitations to the existing studies that examine the effects of management techniques on survival and growth of eucalypts. Firstly, many studies do not have complete factorial designs. This makes it difficult to interpret the relative benefits of different techniques or test for possible interactions. Secondly, there is a lack of consistency in the application of control and treatment management techniques across studies. It is recommended that future studies replicate past studies, while ensuring complete factorial design, so as to maximise the extent to which comparisons can be drawn over space and time.

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