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RADIATA PINE REGENERATION: ECOLOGY AND CONROL

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INTRODUCTION

Pinus radiata D. Don was introduced into New Zealand from California. Its success as a plantation species throughout most of the country illustrates that it is well-adapted to a wide range of environments (Minko and Aeberli, 1986). The ability of *P.radiata* to grow rapidly has led to the development of a successful plantation forest industry. The species has also demonstrated a capacity to regenerate naturally, often profusely, not only under stands or following clearfelling, but also in areas surrounding plantations, including sites occupied by native vegetation (Hunter and Douglas, 1984). This can lead to problems in forestry where the only desirable seedling pines are those which have been grown in nurseries from genetically improved lines, and then transplanted into the field. Pine "wildlings" are an additional source of flammable fuel conducive to the spread of severe crown fires, limit access for wildfire suppression and timber stand improvement operations, and may also compete with the crop for nutrients and moisture (Burrows et al., 1989). Probably most important of all, unwanted regeneration in areas planted with expensive genetically improved stock, can be mistaken for the planted seedlings during control operations, or otherwise displace the crop trees. This natural regeneration in plantations has thus been termed "genetic pollution". With the steady rise in the proportion of second rotation plantings, there has been an equivalent increase in the problem of radiata pine natural regeneration in both Australia and New Zealand (Minko, 1985a,b).

This first part of this paper presents a literature review on methods for radiata pine regeneration control, and summarises current practices in New Zealand. The second part reviews aspects of the seed biology and general population dynamics of radiata pine. Where sufficient information is available, this approach can help to define the nature of the problem and indicate approaches which will assist with the formulation of control measures. Finally, control options and current practices are discussed in the context of the population dynamics of radiata pine.

LITERATURE REVIEW

A review of the literature reveals that although the problem is widespread, there is little published information on control of "wildling" radiata pine regeneration in second rotation plantations. Most of what has been published comes from Australian journals.

Chemical control

Minko (1985b) undertook two trials to evaluate a range of herbicides for the removal of natural radiata pine regeneration in second rotation plantations in Victoria, Australia.

In the first trial, 8 herbicides (Table 1) were tested at various rates. Using a knapsack sprayer, they were applied to run-off to individual trees in spring, summer and winter. All except for oxadiazon, caused either equal or greater mortality when applied in spring, and at the higher rates. Dicamba, paraquat, amitrole+ammonium thiocyanate and glyphosate were also effective when applied in summer or winter, whereas the winter application of fosamine (125 and 250mls/litre) was ineffective.

TABLE 1: Chemicals tested against radiata pine regeneration (Minko, 1985b)

Product	Active chemical	a.i.[1] product (g/litre)	Rate tested (ml product/litre water)
Banvel 200	Dicamba (amine)	200	250 125 63
Brominil	Bromoxynil	200	40
Gramoxone	Paraquat	200	25 12
Krenite	Fosamine ammonium	480	250 125 63
Ronstar	Oxadiazon	250	20 10
Roundup	Glyphosate	360	200 100 50
Velsicol 4092	Dicamba (derivative)	360	250 125 63
Weedazol TL	Amitrole plus ammonium thiocyanate	250 220	100 280 140 70 35

[1] active ingredient.

In the second trial, one intermediate application rate of the three most promising herbicides (dicamba, fosamine and amitrole+ammonium thiocyanate), was applied to 10 m^2 plots containing 1-2 m tall, dense radiata pine regeneration. Application times were spring, summer and winter.

Amitrole+ammonium thiocyanate at 140 ml/litre was the least effective; dicamba was partially effective; and fosamine was relatively slow, but useful, resulting in 86% mortality.

These trials indicate that single trees can be controlled by spraying at the appropriate time with the appropriate quantity of either amitrole+ammonium thiocyanate, fosamine, glyphosate or paraquat. However, fosamine is no longer marketed in New Zealand.

In a separate trial, various herbicides were screened against radiata pine seedling regeneration following a wildfire which destroyed 300 ha of radiata pine in Victoria, Australia (Flinn and Minko 1983). TCA, paraquat+diquat and two formulations of dicamba were each evaluated at two rates. Applications were made using a Dupont spotgun for the liquids and dicamba granules were hand-scattered. Treatments were applied in the spring, and also (to different plots), in the second autumn after the February wildfire.

Although moderate to severe damage occured in all treatments, total control was obtained only with dicamba (liquid) at 4 kg/ha and with paraquat+diquat at 0.5+0.25 kg/ha applied in August (spring) to regeneration (230,000 seedlings/ha), averaging 5 cm tall. One perceived extra advantage of the paraquat+diquat treatment was that it temporarily controlled grasses that recolonised after the fire. The addition of simazine, or other residual herbicides, could be used to maintain weed control after planting, thereby reducing the necessity for any other grass or broadleaved weed releasing. However, with the general move towards oversowing in New Zealand, this would not be desirable.

When the same treatments were applied the following March (one year after the fire) the regeneration was approximately 14 cm tall with 260,000 stems/ha. At this time the treatments, except for the lower dicamba rates, reduced the density , but total control was not achieved. It was concluded that none of the treatments gave adequate control in the second autumn after the fire. However, either dicamba or paraquat/diquat (at rates specified above) would be effective with application in early spring to regeneration less than 5 cm tall.

The trials described above were all ground-applied and the authors did not think that aerial application would give adequate control. Recent New Zealand experience does not support this.

In the above trial, peak germination of natural regeneration occurred between February and August. A further 6.6% germination took place by December, indicating the desirability of ensuring that all germination is complete before spraying. In most cases, however, the planting schedule would dictate that the site should be replanted in the first winter, which would result in a post-plant regeneration problem (Flinn and Minko, 1983).

Although the herbicides used in the above trials are available in New Zealand, it is doubtful whether they would be as effective as the currently favoured metsulfuron/glyphosate mixture or either metsulfuron or glyphosate alone. The other point that must be considered is whether the control operation is primarily targeted against *P. radiata* or whether other woody species must also be controlled. In most cases, the latter situation is probably likely, therefore the chosen chemical must be effective against all species present.

Mechanical and manual control

Mechanical control of natural regeneration before planting has been only partially successful in Australia because stumps from the previous crop restrict ground equipment, and regrowth of slashed stems (Flinn and Minko, 1983). Studies in Australia have compared the productivity of a motorised brushcutter versus hand slashing for thinning 1-6 year-old radiata pine regeneration (Minko, 1985a). Use of the brushcutter was almost twice that of hand slashing which translated into large cost savings.

Prescribed fire

Research in Western Australia has concluded that low intensity prescribed fire is an effective technique for killing wildlings less than about 5 m tall in *P. radiata* stands greater than 15 years of age (Burrows, 1989). No response in crop growth rate was observed as a result of reduction in wildling abundance by fire.

THE REGENERATION PROBLEM AND CONTROL MEASURES IN NEW ZEALAND

It is well known that radiata pine "wildling" regeneration is a major problem on most second rotation sites. A brief survey (Appendix 1) was circulated amongst members of the Site Management Cooperative with the objective to determine what measures were being used to combat the problem. Sixteen responses were recived and the sum of the plantation area covered by the replies represents the vast proportion of the plantation estate in New Zealand.

(a) Extent of the problem

As expected, a high proportion (88%) of respondents agreed that natural regeneration is a problem requiring attention. Very few (12%) regarded it as of little or no concern, and at least some of these responses were from areas where no, or very few, second rotation sites were being planted.

(b) Control measures

(i) Preplant herbicides

Many managers (70%) have used aerial spraying Almost without exception, glyphosate and metsulfuron (Escort) are used, either singly or in mixture (usually with Pulse), with varying success:

- 54% successful
- 15% partially successful
- 8% not successful
- 23% don't know or no comment

Application rates varied enormously:

- Metsulfuron from 20 to 250 g/ha (mainly 100 to 200 g/ha)
- Glyphosate from 3 to 12 litres/ha (mainly 6 to 9 litres/ha).

Mixtures were also very variable, indicating that trial and error played a large part in formulations:

- Roundup 3 litres + Escort 62 g
- Roundup 3 litres + Escort 170 g
- Roundup 6 litres + Escort 50 g
- Roundup 6 litres + Escort 100 g
- Roundup 6 litres + Escort 170 g
- Roundup 9 litres + Escort 100 g

One response indicated the use of Reglone (diquat) at 5 litres/ha, but effectiveness not indicated.

Although costs were not always clearly defined, they appeared to vary considerably from $135 to $265/ha (this appears to be all inclusive).

Note: in some instances spraying was undertaken as part of normal land preparation, not specifically to kill radiata regeneration.

(ii) Post plant herbicides

Only 23% of respondents indicated this approach. Sprays were of course, restricted to spot treatments, and included, Velpar/Escort, Roundup, and Roundup/Escort.

(iii) Oversowing

Only 29% of respondents mentioned this technique. Forty percent of these claimed it was effective, but nobody reported a failure.

(iv) Hand pulling

Out of 47% who adopted this technique, half of them reported it as being effective. Many did not comment.

(v) Other methods

Other methods mentioned were cutting with hand tools (slashers or tree pruners) or chainsaws. These techniques were used for regeneration too large for pulling or spraying, usually at age 3 to 4. Often the operation was combined with a normal thin-to-waste, rather than a specific regeneration control operation.

CONCLUSIONS

Radiata pine natural regeneration is a major problem in second rotation plantation forests. Where a post-plant problem develops the situation is exacerbated by the risk of crop damage if herbicides are used, and in some cases the difficulty in distinguishing between the planted and the wildling pines. The latter situation will likely become more frequent on sites where slash retention makes it more difficult to plant in well-defined lines. Where possible, it is obviously desirable to control regeneration prior to replanting. On sites harvested shortly after the planting season (i.e. in spring), there will be ample opportunity to use pre-plant herbicide applications to control regeneration (and other weeds) which develop through the autumn prior to planting. As reported above, however, germination may continue after this period. An important issue will be the timing of oversowing in relation to harvesting. Would it be preferable to establish the ground cover as early as possible, using species which would allow a herbicide application prior to planting to remove seedlings of woody species? This option would require selection of oversowing species which were tolerant to the herbicide. Alternatively, would it be better to delay herbicide application for as long as possible so that as much regeneration can be killed with the optimum herbicide (mixture) prior to oversowing? The timing of oversowing required to ensure good establishment is obviously another important consideration.

There are plenty of suitable herbicides for pre-plant situations, with a glyphosate+ metsulfuron mixture being preferred. However, the wide range of rates used in these mixtures clearly indicates that the optimum mixture has yet to be defined to everyones' satisfaction.

In post-plant situations, hand-pulling is probably the most cost-effective option with small wildlings. At later stages, cutting with chainsaws or brushcutters is used more frequently, often combined with thinning of the crop trees. As well as being expensive, at this stage it may be too late to offset the intense early competition between planted stock and regeneration (Wilcox and Carson, 1992). With wildlings beyond the hand-pulling stage, it may be worthwhile to investigate alternative control techniques such as the Hypo-hatchet.

RADIATA PINE POPULATION DYNAMICS

Introduction

The development of *P. radiata* populations in second-rotation stands will depend on many factors. In the development of control strategies for weeds of agricultural crops it has often been found useful to construct population models of the species (i.e. the weeds) in question (Sagar, 1982; Sagar and Mortimer, 1976). The model can then be used to identify stages in the life cycle where some form of control measures or management practices will have the largest impact on the population of the species.

There are several important parts to the study of population dynamics (Sagar, 1982):

(a) The determination of the theoretical rate of increase;

(b) The measurements of real rates of increase;

(c) The identification of the factors, resources, or agents which may be responsible for the discrepancy between the theoretical and actual rate of increase.

Although it is not proposed that an attempt should be made to develop a "realistic" model of *P. radiata* population dynamics on a second rotation site, a conceptual model may be useful for two reasons:

1. A conceptual model will identify the major components which contribute to population increase and decrease and will help us to consider how various operational practices may impact the pine population. The goal of these models is not necessarily to precisely predict the expected numbers of population members on a given site, but to test how various management practices may impact the population in a relative sense.

2. The model will provide an illustration of how population models are developed and how they are increasingly being used overseas to help develop weed control strategies.

The components of the life cycle of radiata pine which are relevant to the regeneration problem are discussed below. Much of the information in the review is drawn from a series of studies reported Fielding (1947). These studies were carried out at Mt. Burr in the south-east of South Australia. The climate at Mt. Burr is quite favourable for radiata pine; short dry summers and cold, wet winters.

Seed production

P. radiata, a member of the group *Insignes,* retains its serotinous cones on the tree for a number of years. Repeated periodic opening and closing of the cone scales means that viable seed can be released from a single cone over a number of years (Fielding, 1965b).

Burdon (1992) has recently summarised the reproductive cycle of *P.radiata* in New Zealand. The age of first flowering is normally about 4 - 5 years for male flowers and about 6 - 10 years for female. Large amounts of seed are not generally produced before age 10, although small amounts may be produced betwen the ages of 6 - 9 years. Pollen production is generally from mid-July to mid-October depending strongly on altitude and latitude, and cones take about 27 months to ripen after pollination.

The scale of seed-falls in *P. radiata* depends on the cone crop, and the production of viable seed. These in turn are affected by physiological, biological and environmental factors influencing the initiation and survival of the cone crop. The quantity of seed carried varies with:

- amount of seed produced during the current and previous years;
- weather during past summers;
- season of the year;
- stand age
- site quality
- past silvicultural treatments (Fielding, 1947).

The amount of seed produced by mature stands in any year is extremely variable. Reasons for this variation are not clear, but weather during the time of pollen production may be important.

Radiata pine cones only open and release seed during hot, dry conditions, therefore dissemination varies considerably between seasons and years. Because seeds may remain viable in the cone for 5 or more years Fielding (1965a), the quantity of seed released depends not only on the current, but also the previous years' weather conditions (Table 2). For example, seed dissemination will be greater in a hot, dry summer that follows several cool, wet summers than one which follows several hot, dry summers. More recently, assessments have indicated that seeds in cones on the tree up to three years of age have a typical viability of around 80-90% (Fielding, 1965a).

The amount of viable seed held in cones varies annually from a minimum at the end of the season of dissemination (about April) to a maximum which develops as the new seed crop begines to mature from around August to September (Fielding, 1947). Viable seed is produced from age 6, production increases to a maximum at around 10 to 18 years of age and then slowly declines.

Fielding (1947) compared cone production in high and low quality, unthinned stands of 15 and 27 years of age (Table 3). The classification of high and low quality was on the basis of volume production. At 15 years, where the stands were around the age of maximum seed production, the amount of seeds on the two site types was similar. However, in the older stands, seed production on high quality sites fell more rapidly than on low quality sites. By age 27, the amount of seed produced on low quality sites was much greater. Fielding speculated that thinning may have increased cone production on the high quality site. It is not known how seed production varies by site quality using todays' regimes of low stocking, pruning, and thinning. However, such with a high potential difference in cone production, this is an important issue.

TABLE 2: The quantity of seed carried by cones of different ages on unthinned stands on (a) high and (b) low quality sites (Fielding, 1947)

(a) High quality site, stand age 26:

Year of maturation	Number of seeds/ha	Germination (%)	Viable seeds/ha
1940	4052	81.0	3282
1939	5189	76.0	3944
1938	346	88.0	304
1937	420	4.6	19
1936	-	-	-
pre 1936	198	8.0	16
TOTAL:	10205		7565

(b) Low quality site, stand age 27:

Year of maturation	Number of seeds/ha	Germination (%)	Viable seeds/ha
1940	38176	82.0	31304
1939	21571	77.5	16718
1938	2668	70.5	1881
1937	1210	79.3	960
1936	420	40.0	168
pre 1936	2001	52.0	1049
TOTAL:	66046		52080

TABLE 3: Cone production in high and low quality, unthinned stands of 15 and 27 years of age (Fielding, 1947).

Stand age (years)	Number of cones per hectare	
	Low quality	High quality
15	3212	3459
27	504	30

Dispersal

Dispersal of radiata pine seeds can take place from cones on branches of standing trees or from cones on the ground. Dispersal from cones within trees leads to an even distribution of seed, and the seed will be able to germinate as soon as conditions are suitable (Fielding, 1947). The light, winged seeds (samaras) of *P. radiata* are well adapted for long-range dispersal by wind (Richardson and Brown, 1986). Samara wing-loading (weight per 100 mm^2 samara area) is considered to be a good predictor of dispersability (Green, 1980). Out of three species tested (also *P. pinaster* and *P. pinea*), *P. radiata* had the lowest wing-loading, an indication of its relatively high invasive potential (Cremer, 1975; Wilgen and Siegfried 1986). Interestingly, it has been calculated that *P. contorta* has twice the wind dispersal potential of *P. radiata* (Cremer, 1975).

Minko and Aeberli (1986) cited Stabb (1974) who had studied the spread of *P. radiata* and *P. nigra* (Corsican pine) in Australia. Pine regeneration was denser on the southern side of these plantations, and its density declined with distance from the plantation. Spread appeared to be related to topography of the plantation boundary and its exposure to the prevailing winds. Seedlings spread further towards the south and east than towards the north and west, indicating the influence of summer northerlies and westerlies.

Fielding (1947) measured annual seed dissemination from a good quality stands over a period from stand age 11 - 13 years. Seed dissemination per year was approximately 363,000, 133,000, and 526,000 seeds per hectare. As with seed production, dissemination varies greatly between years because of variation in the current and previous weather conditions.

There is also variation in the distribution of seed fall throughout the year. In general, however, peak seed fall is during summer with relatively small amounts through the rest of the year. When harvesting occurs around August to November, prior to the peak dissemination period, the cones which end up on the ground are likely to contain the maximum amount of seed. With a high proportion of the total viable seed on the site contained within cones on the ground, the density of radiata pine regeneration is likely to be at a minimum. For established seedlings to develop from these cones, conditions must first be suitable for cone-opening, followed by a different set of conditions for germination. Because seeds from cones on the ground are released in clumps, it may make them more susceptible to predation (Fielding, 1947).

Fire is known to stimulate the opening of *P. radiata* cones and this can lead to dense regeneration (Richardson and Brown, 1986). It has been stated that *P. radiata* is unusual among the serotinous pines of California because fires that produce optimum reproduction are generally surface fires in which the parent trees survive; more typically among this group of species, a severe stand-replacing fire is required for optimum regeneration (Richardson and Brown, 1986; Vogl et al., 1977).

Germination and mortality

Weather conditions are probably the major factor influencing seed germination. Fielding (1947) assessed the numbers of viable seeds under a 33 year old radiata pine plantation throughout the year. Peak germination was in autumn with a large drop in the number of viable seeds from autumn to winter and a smaller drop from winter spring. By spring, only rleatively few viable seeds remain ungerminated.

Germination of pine seeds is also affected by sowing depth and soil type. Results from a nursery trial in North-eastern Victoria, Australia, using a washed granitic sand, showed that a seed cover of 1 cm of sand resulted in the best seedling emergence (79% of sown seeds) (Minko, 1986). Below a sowing depth of 1.25 cm, seedling emergence decreased, and subsequent mortality increased with depth.

Scott (1960) stated that the average germination of *P.radiata* seed is about 70 or 80%, but it is not clear whether this information was based on field studies. Germination and growth is usually best on a moist mineral soil, but seedlings are also found growing on pine litter (Scott, 1960). Page and Spiers (1969) presented data which confirmed this; percentage seed germination was 59, 36, and 28% in seedbeds containing more than 75% soil, 25-75% soil, or less than 25% soil respectively. Possible reasons suggested for these findings were:

- lower minimum temperatures over litter than mineral soil;
- nitrogen starvation;
- drying of seedling roots since debris rapidly loses its moisture during dry periods.

In contrast to these findings, however, Fielding (1947) showed that a high proportion of seeds germinated whether they were on top of, or buried within needle litter.

Excess quantities of slash, heavy weed growth, and compaction by machinery, were all reported to inhibit *P. radiata* regeneration (Chavasse, 1969). Sub-terranean slash (where machinery has forced it into the soil) was thought to be particularly detrimental. However, Olsen (1969) concluded that a loose, well-distributed, light slash cover is probably not a major impediment to regeneration. Fielding (1947) compared radiata pine regeneration on sites either with slash or cleared of slash (Table 4). Germination was reduced by more than 50% on slash covered sites. Thus, on balance, it would seem likely that the practice of slash retention will significantly reduce *P. radiata* seed germination, although the precise explanation for this is not clear.

TABLE 4: Number of germinating seedlings on sites with slash or cleared of slash (Fielding, 1947)

Year	Mean percentage germination		Reduction with slash (%)
	Slash	Cleared	
1938-1939	19.7	44.5	55.7
1939-1940	8.5	19.3	56.0

Although mature crop trees may shed much seed each year onto the plantation floor, in heavily stocked stands with a dense canopy, seedlings rarely develop (Burrows, 1989). It is not clear whether this is because germination is not stimulated at low-light levels or because young seedlings die from competition for light. Following thinning operations, however, the amount of light reaching the forest floor increases and germination and growth of seedling pines is stimulated (Burrows, 1989).

The development and growth of pine populations in areas where seed is present is limited by environmental and biological factors which prevent germination and which cause mortality of the seeds or young seedlings. Thus, the absence of pines in a given location does not necessarily mean that conditions are not suited to germination. It could also result from high levels of mortality of the seedling pines following germination. Losses of *P.radiata* regeneration have been attributed to shade from slash, slash and duff preventing seedling roots from reaching the mineral soil, frost heave, *Hylastes ater* attack, weed growth (particularly grasses and gorse), and soil compaction (Chavasse, 1969; Page and Spiers, 1969). Humid, still-air conditions produced by slash or a vegetation canopy may also increase the likelihood of attack by fungal pathogens (Fielding, 1947).

It has been stated that natural regeneration in New Zealand is unreliable on sites at higher altitudes or subject to too much frost, on bare exposed areas, steep southerly slopes or with competition from scrub hardwoods (Scott 1960). However, it is not clear whether this is through low seed production, low germination, high seedling mortality, or (most likely) a combination of these factors.

There is little information on seed predation in plantations (as opposed to nurseries), but it is known that birds (particularly finches), rodents and insects can significantly impact seed numbers (Scott, 1960; Hedderwick 1969, 1981a,). In nurseries, a variety of rodents and birds have been reported as being severe predators of pine seed and seedlings (Hedderwick, 1981a,b). However, no quantitative data were presented. Rabbits were shown to reduce seedling survival by up to 60% in areas with moderate rabbit populations and by up to 97% where there were high numbers of rabbits (Fielding, 1947).

As stated earlier, regeneration may be inhibited to a certain extent by the presence of a dense overstorey and competition from herbaceous species. However, there is no quantitative information on the competitive interactions among radiata pine and herbaceous species. This is an important issue because of the interest in oversowing forest sites. The presence of herbaceous vegetation has numerous effects. It may alter the environmental conditions (temperature, soil pH, soil bulk density etc.), have an influence on insect and animal populations, and it will influence the availability of resources (water, light, and nutrients). These factors may either reduce germination, increase mortality, or cause both of these effects.

The model

A conceptual model for *P. radiata* population dynamics is shown in Figure 1, the details of which are explained below. It is assumed that the starting point for this model is immediately after harvesting. The time scale for the model is unspecified at present. One likely scenario would be to run through one complete cycle each season i.e. all of the numbers would have to be representative of the seasonal total. It would, however, be equally possible to have a monthly, weekly, or even a daily time scale if the numbers were available and if a high degree of resolution was required.

Starting at the top of Figure 1, within each time interval the number of seeds which come into the clearcut site from surrounding areas, In, will depend on:

- the proximity of mature stands;
- prior conditions for cone production;
- weather conditions relating to cone opening and seed dispersal.

Conditions leading to high values of In are discussed in the above review. Apart from wind dispersal, it is unlikely that there are any other major mechanisms by which *P. radiata* seeds invade a newly clearcut site. A certain proportion, probably about 10%, of these seeds will be non-viable (m1). The remaining proportion of seeds will land within the site on litter/slash, on bare mineral soil, or they may be buried in the soil. The latter case is unlikely unless the incoming seed coincided with some form of disturbance such as mechanical site preparation operations. Thus, in general, the seed will be partitioned between the soil and the litter/slash fractions in a proportion related to the amount of bare ground. The proportion of bare ground is likely to decrease over time, particularly with the trend to oversowing.

Invading seed will be added to the quantity of seed already stored in the litter/slash, soil surface, and buried soil components (Sa, Sb, and Sc, respectively). If conditions are suitable, seeds stored in cones also resident in any of these components (Ca, Cb, Cc) may also be released according to the proportions c1, c2, c3. Seeds stored in these various components will be subject to losses (m2, m3, m4) from the following sources:

- seed predation (birds, rodents, insects etc.);
- fungal decay;
- loss of viability through ageing; because it has been estimated that pine seeds will not remain viable in the soil for longer than 12 months (J. Miller per comm.), it is important to keep track of the age of each component of the seed population.

Within each time interval, a proportion of the surviving seeds stored within each component will germinate and be added to the number of seedlings present (Sn). These proportions (s1, s2, s3) will depend mainly upon environmental conditions (temperature, moisture, burial depth, soil bulk density). Before seedlings make the transition to established plants, another set of losses (m5) must be accounted for. These are likely to result from:

- environmental conditions (extremes of high or low temperatures, moisture levels);
- competition for water, light, or nutrients;
- seedling damage or consumption by birds, rodents, and insects;
- pathogens.

The proportion of seedlings which survive this stage (sn1) will make the transition, and be added to the pool of established plants. Although there will also be losses from the established plants, m6, the greatest opportunities for impacting the pine population as a whole are likely to come from earlier in the life cycle.

To apply the model shown in Figure 1 to the problem of how best to manage radiata pine regeneration, the next stage would be to enter actual numbers for all of the stages. The model could then be used to determine how various management practices impacted the pine population. Unfortunately, as the above review indicated, the type of quantitative data relevant to New Zealand conditions required to run this model are not available. The value of obtaining these data in this instance is doubtful, due to the scale of the problem. However, it may be useful to consider this approach for species such as buddleia and pampas that appear to be increasing in their distribution and importance.

Today, most of radiata pine management is focussed on the last stage of the scheme, that is control of established plants. It is, however, worthwhile to consider how other site preparation practices may impact the population before the established-plant phase is reached.

After clearcutting, there will normally be a large reservoir of seed and cones partitioned between the various components. As discussed ealier, the relative proportions will be strongly influenced by the timing of cutting. Stands harvested in spring, with a maturing seed crop but prior to dissemination, are likely to result in minimum regeneration. Germination will probably be greatest on sites with minimal slash levels, perhaps following a light burn, and with exposed mineral soil. The current trend, however, is towards slash retention on the site. On balance, it would seem that this practice will help to inhibit germination and enhance seedling mortality. A high percentage cover of slash (i.e. a low percentage of exposed mineral soil) would help to ensure that few invading seeds make a succesful transition to the seedling stage).

Radiata pine seed germination and survival decreases with burial depth. However, the degree of disturbance required to bury pine seed makes consideration of this factor unrealsitic.

The practice of oversowing probably offers the greatest possibility of severely impacting the pine population for the following reasons:

- a cover of vegetation will help to prevent invading seeds from reaching exposed mineral soil;
- a cover of vegetation or slash will lead to increased severity of out-of-season frosts which will increase mortality of vulnerable newly germinated seedlings;
- a cover of vegetation may encourage bird and rodent populations which in turn may impact the pine seed and small seedling population;
- herbaceous species will provide severe competition for water, light, and nutrients.

For these reasons, it is likely that oversowing in conjunction with slash retention would minimise seed germination and maximise seedling mortality. However, to use this strategy to the maximum advantage it would be critical to establish the oversown species as soon as possible. Early establishment would ensure the rapid development of a competitve ground cover. In reality, the timing of oversowing will depend on the season for optimum establishment of the oversowing species in relation to the time of harvesting. Further work is required to weigh up the advantages (or otherwise) of delaying oversowing to apply pre-plant kill sprays versus immediate oversowing and later applying a herbicide which will not harm the oversown species.

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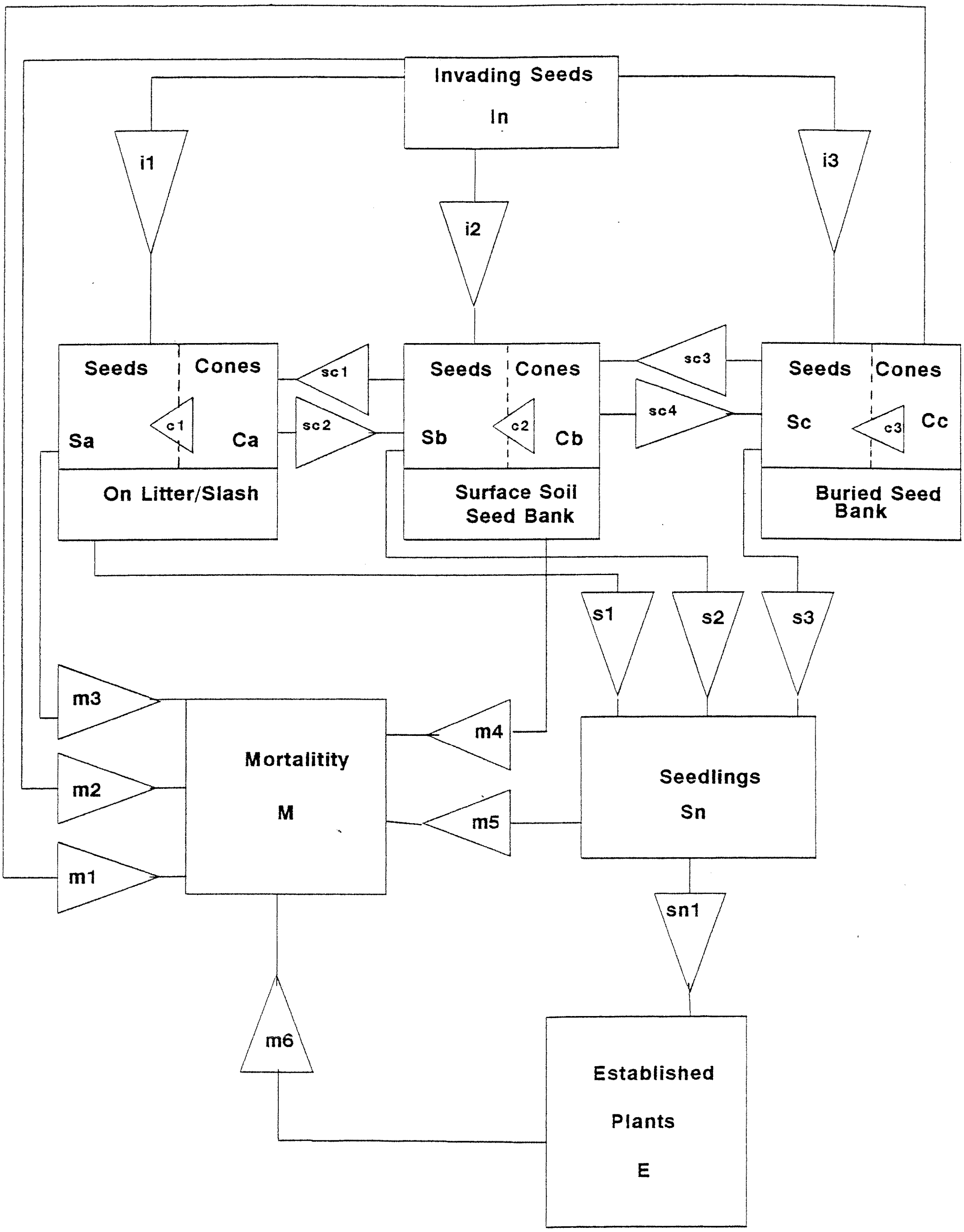

Figure 1: Conceptual diagram of the population dynamics of radiata pine natural regeneration after clearcutting. See text for a full explanation.

APPENDIX 1

RADIATA PINE NATURAL REGENERATION SURVEY

		Yes	No
1.	Do you have a problem with radiata regeneration?	☐	☐
2.	(a) Is it severe enough to need controlling?	☐	☐
	(b) Area involved:		

3. How are you controlling it?

(a) After planting

Herbicides used:

(i) rates
(ii) application method
(iii) water rate
(iv) costs

Has it been effective? ☐ ☐

Comments:

____

____

Other techniques used (e.g. handpulling, oversowing)

____

____

Cost of these techniques.

(i) chemical:
(ii) other

(b) Before planting

Herbicides used:

(i) rates
(ii) application method
(iii) water rate
(iv) costs

Has it been effective? ☐ ☐

Comments:

____

____

Other techniques used (e.g. handpulling, oversowing)

____

____

Cost of these techniques.

(i) chemical:
(ii) other