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EFFECTS OF NON-CROP VEGETATION ON GROWTH AND PRODUCTIVITY OF YOUNG RADIATA PINE.

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SYMBOLS AND COMPETITION INDEX NOTATION

The following notation was used in constructing competition equations from the assessed non-crop variables:

Hpc = herbaceous or low-stature weeds percent cover;

ca = crown area {pi*(mean crown diameter/2)^2};

wht = weed height;

cd = crown density (percent crown foliage cover);

dist = proximity of woody weed from the target crop tree;

k = distance weighting factor (**1-dist/nr**). It weights weeds closer to the crop tree more than those farther away, **nr** = neighbourhood radius;

H = crop tree height (cm);

Rcd = root collar diameter (mm);

BA = basal area at ground level (square mm);

f = function of;

% = percentage;

α, β, and δ = coefficients estimated from regression models, they are real numbers.

ABSTRACT

A study of the effect of weeds on diameter and height growth of young plantation-grown radiata pine was undertaken in Rolleston Forest (Selwyn District) in the Christchurch region of the South Island of New Zealand. The objectives of the study were to identify practical and easily measurable indices of competition and to provide a method of quantifying inter-specific competition from non-crop vegetation in young plantations by deriving indices of competition using neighbourhood predictors.

A randomised block design with 4 replications was used. Each block had 8 treatments based on manipulation of percentage weed ground cover. Measurements of weed abundances and their proximities to and dispersion around individual crop trees in 2 neighbourhoods (1 m and 2 m) were assessed together with crop tree height and diameter.

Mathematical expressions of the competition indices (CI) were developed based on the hypothesis that tree vigour is a function of size and competition intensity (CI). The competition indices were estimated using measures of vegetation abundance, distance from crop tree, and neighbourhood radius using expressions of the general form:

$$CI = f(a_i, dist_i, wht_j, nr)$$

where;

CI = competition index,

a_i = measure of vegetation abundance or number of species or individual plants of non-crop vegetation,

$dist_i$ = distance from crop tree,

wht_j = non-crop woody vegetation height, and

nr = neighbourhood radius.

Scatter diagrams of competition formulations versus tree crop growth (height,

root collar diameter and basal area at ground level) were plotted, the trends of which were used to indicate the type of models which would best describe the relationships between tree crop growth and the competition indices. Regression analyses were employed to regress height, root collar diameter and basal area of the crop trees on the competition indices. Mean Square Residuals (MSQR) and the distributions of residuals were the main test criteria used.

The results from the study showed that percent herbaceous cover (for low-stature vegetation), woody weed crown foliage density*height/tree height, i.e. (**∑(cd*wht/H)** and **∑(cd*wht*k/H)**, where k is distance weighting factor (1-distance/neighbourhood size) were good indicators of competition intensity. Estimating competition from neighbourhood predictors around each tree gave better relationships than measures of site occupancy at a plot level. Grouping the competitors by species did not further improve the indices. Moreover, incorporating crop tree height into the woody indices (division by H) made them more realistic as they became sensitive to weeds taller than target crop plants. These results are similar to those from studies elsewhere (Wagner and Radosevich 1991a, Wagner *et al.* 1989, DeLong 1991 and Brand 1986). Crown area (on its own) of woody weeds was not useful in expressing inter-specific competition effects in this study.

The results also indicated that conventional weed control regimes as commonly used by forest managers in the region (1 m band spraying along the planting rows) resulted in individual crop trees still experiencing high levels of inter-specific competition. Even in plots where control had been undertaken, most trees still experienced considerable interference effects from non-crop neighbours of shrub and herbaceous species. Forest managers in the region may need, therefore, to redefine their non-crop vegetation reduction standards. In addition, managers need to set different priorities for controlling herbaceous and woody weeds so as to use available resources more efficiently. The implications of these findings on present and future vegetation management regimes in the area and a brief mention of the economic implications are also presented.

CHAPTER 1

INTRODUCTION

1.1 GENERAL INTRODUCTION

Weeding in forest plantations has been quoted in many sources as an important and, in some cases, a mandatory exercise for viable plantation ventures (Evans 1982, Zabkiewicz and Richardson 1990, Nambiar and Sands 1993, Lowery *et al.* 1993, Markin and Gardner 1993). Many studies have reported a general increase in tree crop growth and productivity with weed control (Walstad and Kuch 1987, Stewart 1987, Gjerstad and Barber 1987, Newton *et al.* 1987, Mason 1992, Richardson 1993, Nambiar and Sands 1993, Lowery *et al.* 1993, Tesch *et al.* 1993, Wagner and Radosevich 1991a, Shainsky *et al.* 1992). Crop growth is usually reduced with increasing weed infestation in a site, irrespective of the management practices (Perry *et al.* 1993, Pallardy 1986).

Weeds exert their interference effects by directly competing for resources (water, nutrients and light) or by using resources meant to improve growth and productivity of crop trees: for example, nutrients in fertilizers (Squire 1977, Cellier and Stephens 1980, Will 1985, Mason 1992, Nambiar and Sands 1993). In moderately low-quality sites any inter-specific competition can induce severe deficiencies in one or more growth-limiting resources, especially water and/or nutrients. Alternatively, on high-quality sites with plentiful water and nutrients, lack of light can severely limit radiata pine growth. Non-crop vegetation also responds to the plentiful resources. Shrub and tree competitors can sometimes rapidly establish dominant canopies with the result that light quality and quantity available to young seedlings is reduced. The result can be a dramatic reduction in pine growth and productivity (Stewart 1987, Gjerstad and Barber 1987, Ross *et al.* 1990, Comeau *et al.* 1993, Nambiar and Sands 1993, Richardson 1993, Morris and Forslund 1991). Weeds can also have similar effects to those of poor sites, for example making crops take longer to close canopy which could result in increased tending costs, poor stem form, delayed maturity and harvests (Balneaves 1981), and consequently increased exposure to both biotic and abiotic risk agents (Morris and Forslund 1991). Moreover, as a result of competing for limited resources, non-crop vegetation may increase crop mortality (Walstad and Kuch 1987, Stewart 1987, Nambiar and Sands 1993, Richardson 1993, Morris and Forslund 1991, Auld *et al.* 1987)

Crop tolerance to weeds varies with species, the control frequency, growth rates and weed morphology (Nambiar and Zed 1980), while site factors, especially fertility, previous land use and rainfall or pests, can exacerbate the detrimental effects on the crops (Wagner and Radosevich 1991b, Lowery *et al.* 1993). Understanding weed biology and the mechanisms of weed and crop competition are, therefore, important prerequisites to any successful weed control program (Richardson 1993, Lowery *et al.* 1993). Good weed management also requires knowledge of effects of the physical and biological environment including location, climate, rainfall, main vegetation types, soil fertility and other factors limiting to growth (McDonald and Fiddler 1993, Harrington and Tappeiner 1991).

The main drive behind the forest industry's concern for more efficient weed control methods is improved growth and health of the crops. The primary aim of vegetation management should, therefore, be to suppress the influence of non-crop vegetation to levels where it does not interfere with the growth of tree crops (Walstad and Kuch 1987), but at an affordable cost (Zabkiewicz and Richardson 1990, Nambiar and Sands 1993, Wagner *et al.* 1989). Sound vegetation management should also aim to derive maximum efficiency and crop health by employing silvicultural practices which appropriately modify weed and crop interactions (Berkowitz 1988, Britt *et al.* 1991, Wagner *et al.* 1989, Tappeiner II and Wagner 1987).

Non-crop vegetation is not necessarily bad. There are many references in the literature describing beneficial effects of weeds, for example, protecting the soil against erosion, forage for livestock and wildlife and ameliorating poor sites (especially legume species), (Auld *et al.* 1987, Wagner *et al.* 1989, Walstad and Kuch 1987, West and Dean 1992). Resource complementarity between different species can also be used to advantage leading to minimal weeding (Liebman 1988). The relationship between crop yield and non-crop vegetation density assumes the form of a hyperbolic curve (Auld *et al.* 1987, Cousens 1987, Radosevich and Oysteryoung 1987, Wagner *et al.* 1989) and this has helped show that competitive effects from weeds are significant only when they occupy the site with certain densities. Consequently, managers can leave some non-crop vegetation below a certain density (threshold level) to grow with the desired crop trees without risking significant losses in growth and final yields (Cousens 1987, Wagner *et al.* 1989, Brodie *et al.* 1987, Morris and Forslund 1991, Brand 1986, Radosevich 1988). Thus, in some situations the control frequency and/or the volumes of herbicides used may be greatly reduced leading to greater efficiency and minimising possible negative ecological impacts.

The amount of non-crop vegetation which can be left to grow together with the desired crop trees both in space and time without incurring significant losses in growth and final yields (Wagner *et al.* 1989, Walstad and Kuch 1987, Morris and Forslund 1991, Brand 1986), has to be determined for each site, crop and crop age. Lack of adequate quantitative criteria for determining and differentiating "significant" from "insignificant" losses in the forest industry has been discussed in many fora (Walstad and Kuch 1987, Radosevich 1988, Wagner *et al.* 1989, Richardson 1993).

Competition studies have made significant advances over a range of experimental designs to tackle various factors of interest (Radosevich and Holt 1984, Walstad and Kuch 1987, Radosevich 1988, Cousens 1995). Qualitative approaches which use subjective measures of non-crop vegetation density or size to evaluate control needs (for example, control can be undertaken only after the non-crop vegetation has overtopped the crop trees) have been shown to result in less than optimal management (Auld *et al.* 1987, Gjerstad and Barber 1987, Wagner *et al.* 1989, Wagner and Radosevich 1991a). As competition is a dynamic process, subjective methods may not be very reliable as tools for silvicultural decision-making regarding control needs (Morris and Forslund 1991, Brand 1986, Wagner *et al.* 1989, Wagner and Radosevich 1991a).

Quantitative methods fall broadly into two major groups; whole stand and neighbourhood approaches. In whole stand approach mean measures of non-crop vegetation are used to estimate yield of an average tree or the whole stand. Using a neighbourhood approach, neighbourhood predictors are used to estimate yield of individual crop trees (Radosevich 1988, Wagner and Radosevich 1991a). Various techniques of assessing competition effects quantitatively have led to development of models relating tree growth reductions to levels of competition (Radosevich and Holt 1984, Walstad and Kuch 1987, Radosevich 1988). These inter-specific competition models, when soundly developed, may be integrated into frameworks for silvicultural decision-making (Radosevich *et al.* 1990). Competition indices may help forest managers not only to understand inter-specific competition effects and therefore the need for control, but may also be useful in evaluating the effectiveness of weed control treatments (Auld *et al.* 1987, Wagner *et al* 1989). However, no such models have been developed for New Zealand radiata pine plantation crops (Richardson 1993).

The study described here, therefore, aimed to develop simple practical techniques for determining and interpreting inter-specific competition in young plantations of radiata pine by evaluating specific neighbourhood factors affecting height and stem diameter growth of crop trees.

1.2 STUDY OBJECTIVES

The specific objectives of the study were to:

1) identify practical and easily measurable indices of competition;

2) provide a method of quantifying competition from non-crop vegetation in young radiata pine plantations; and

3) derive an index of competition from neighbourhood predictors to estimate inter-specific competition.

CHAPTER 2

REVIEW OF PERTINENT LITERATURE

2.1 IMPORTANCE OF NON-CROP VEGETATION MANAGEMENT IN YOUNG PLANTATIONS

The concept of weed control has undergone a revolution with the realization that some non-crop vegetation (weeds) can offer beneficial effects to the crops and site (Walstad and Kuch 1987, Berkowitz 1988, Nambiar and Sands 1993, Comeau *et al.* 1993, Lowery *et al.* 1993). Weeds can also increase the total productivity of some systems, especially agro-forestry systems (Auld *et al.* 1987, Boyall 1983, Liebman 1988, Nambiar and Sands 1993). Thus while **weed control** was formerly synonymous with attempts to completely remove "undesirable" species from the site, **vegetation management** as it is called today, implies the **reduction of competition to biologically, environmentally, ecologically and economically acceptable levels** (Walstad and Kuch 1987, Comeau *et al.* 1993). Vegetation management decisions are therefore, more strategic than its predecessor (weed control), which relied mainly on tactical decisions (Walstad and Kuch 1987). Also, managers have come to realise that bare ground provides an opportunity for weeds to establish. Therefore, in some sites non-crop vegetation which is easy to control after planting is deliberately established, a process called oversowing (West and Dean 1992, van Rossen and West 1993). Liebman (1988) names the use of "smother crops" or "living mulch" as a successful approach for suppressing weeds in some mixed cropping systems.

2.1.1 Definitions

2.1.1.1 Weeds. Weeds have been defined by Auld *et al.* (1987) and Walstad and Kuch (1987) as any plant species growing in places where they are not wanted. But the "unwanted" status of a plant species is both time - and location - specific. Numerous examples exist of introduced ornamentals, medicinal plants or fodder crops which later became weeds. Meanwhile the persistence of a crop species in the following crop rotation may also give it weed status, as is obvious to many potato (*Ipomea batatas*) farmers (Auld *et al.* 1987).

Weeds can therefore be defined broadly in the light of the above facts as "**non-crop**" plants of a **different species** or the **same species** (as in the case of naturally regenerated seedlings or wildings in forestry), whose presence may interfere with the growth and productivity (final yields) of the desired crop trees through competition for site resources. Weeds can be aesthetically displeasing, can hinder access to a site and can be poisonous to both humans and livestock (Evans 1982, Auld *et al.* 1987, Walstad and Kuch 1987, Comeau *et al.* 1993).

The above definition makes it clear that weeds can be of the same species as the crop trees, and therefore it is more appropriate to call them **non-crop vegetation**, a term that will be used throughout the remaining part of this text. The definition also highlights the economic importance of non-crop vegetation. Non-crop vegetation can increase production costs, for example tending and establishment cost of forest plantations (Balneaves 1981). By reducing final crop tree yields (volumes or biomass) or the quality of the final products, non-crop vegetation can also decrease final profit margins (Auld *et al.* 1987, Boyall 1983).

2.1.1.2 Weed control and vegetation management. Weed control is the reduction of negative effects on the desired crop trees arising from the presence of "unwanted" or undesirable plants. Formerly it implied the complete removal of the competing vegetation from the site (Walstad and Kuch 1987). **Vegetation management** deploys physical, mechanical and chemical technologies rationally and combines these appropriately with relevant cultural practices and "good husbandry" to achieve effective control of non-crop vegetation (Walstad and Kuch 1987, Fryer 1987). The result is that non-crop vegetation is suppressed only to the extent that they interfere significantly with the useful crop plants or other desired land uses. Further, Walstad *et al.* (1987) report vegetation management to enhance wildlife habitats, stabilize soil and maintain rights-of-way facilitating recreational use. Moreover, it can also result in major positive changes in plant community structure with time, and ensure dominance of the desirable species.

2.1.2 Attributes of non-crop vegetation

Non-crop vegetation can be advantageous and disadvantageous to both the desired crop trees and the site. Despite historical antagonism to all weeds present among the desired crops due to their deleterious effects on tree growth (Nambiar and Sands 1993, Comeau *et al.* 1993, Horsley 1993, Perry *et al.* 1993, Wagner *et al.* 1989, Walstad and Kuch 1987, Gjerstad and Barber 1987, Newton *et al.* 1987), some non-crop vegetation species are now used in agro-forestry (Liebman 1988) and in young forest plantations for oversowing (West and Dean 1992, van Rossen and West 1993).

2.1.2.1 Beneficial characteristics of non-crop vegetation. Non-crop vegetation growing in plantations can protect soil against erosion by enhancing its physical and chemical properties (Comeau *et al.* 1993). Following harvesting most soils are left bare and easily erodible, oversowing with easy to control non-crop vegetation may give protection against erosion (West and Dean 1992). Weeds can also reduce some types of pest damage, for example increased pine moth attack incidence was reported with increase in weed control (Comeau *et al.* 1993, Ross *et al.* 1990). Moreover, they can provide forage for livestock and wildlife (West and Dean 1992, Comeau *et al.* 1993). Nitrogen fixing species growing in poor sites release carbon and fixed nitrogen to the site upon their death and decomposition thereby ameliorating the sites. This may benefit tree crops (West and Dean 1992, Richardson 1993, van Rossen and West 1993).

Weeds have also been reported to lower evaporative demands as a result of reduced wind velocity and low vapour pressure deficits plus reduced solar radiation reaching the ground. This can be especially beneficial in areas where moisture is limiting (Lanini and Radosevich 1986). However, there are trade-offs of the benefits gained from reduced evaporative demands against lower soil moisture availability that will inevitably occur in the presence of weeds. Menzies *et al.* (1981) report removing of weeds to lead to reduced albedo and thus decrease the likelihood of out-of-season frosts. Moreover, some species can increase the total productivity of some systems in agro-forestry, especially when weeds and crops are mixed in appropriate temporal sequence (Auld *et al.* 1987, Liebman 1988, van Rossen and West 1993, Nambiar and Sands 1993). Non-crop vegetation can also reduce high wind velocities which could damage the root collar of young crop trees leading to juvenile instability (Mason 1992, Lanini and Radosevich 1986). In an ongoing experiment at Dalethorpe (Canterbury, South Island of New Zealand) seedlings that were established in a weed-infested plot were observed to have been protected from abrasive effects caused by high-velocity debris-laden winds. Meanwhile seedlings in an adjacent weed-free plot, were observed to have suffered severe cambium abrasion damage especially on the windward facing side.

2.1.2.2 Undesirable characteristics of non-crop vegetation. Having non-crop vegetation on a site also has disadvantages that define the need for vegetation control in plantations. High densities, cover and size can interfere with crop growth through competition for limited site resources, especially nutrients (as in gorse or broom understorey which compete particularly for boron and phosphorous in some districts of New Zealand), (Balneaves 1981), water (Nambiar and Zed 1980, Carter *et al.* 1984, Sands and Nambiar 1984, Nambiar and Sands 1993) and light (Berkowitz 1988, Comeau *et al.* 1993). Fast growing weeds may reduce crop quality especially under extreme overtopping (Comeau *et al.* 1993, Ross *et al.* 1990), making forest crops to be spindly and leading as a result to loss of volume (Balneaves and Clinton 1992) and value especially of ornamental or fruit trees in agro-forestry systems (Boyall 1983).

The presence of extensive non-crop vegetation in a site can also slow down or hinder routine management operations for example tending (thinning and/or pruning), (Balneaves and Zabkiewicz 1981, Markin and Gardner 1993), or lower the quality of some operations such as planting, tending, or harvesting (Boyall 1983). In poor sites weeds can also compete aggressively for added nutrients in fertilizers (Squire 1977, Will 1985, Balneaves and Clinton 1992), leading to poor survival and reduced growth of the crop trees (Cellier and Stephens 1980). Consequently they can render such management interventions, which are meant to improve tree growth, futile. Weeds especially thorny or spiny species, can cause physical damage to crops. For example gorse, or pampas grass can smother crop trees due to their spiny nature (Maclaren 1993, Richardson

1993), while some species can cause abrasion due to physical e.g. thorns or spines (Boyall 1983, Comeau *et al.* 1993). Moreover, some species are poisonous to humans and livestock e.g. *Pteridium*, bracken or ragweed (Evans 1982, Walstad and Kuch 1987, Auld *et al.* 1987). Others are thought to produce chemicals that inhibit the growth of any neighbouring species (Auld *et al.* 1987, Berkowitz 1988).

Balneaves and Zabkiewicz (1981) report non-crop vegetation to be an economic liability as it raises operational costs of some management systems e.g. establishment and tending costs of forest plantations, or blocking of irrigation systems (Auld *et al.* 1987, Comeau *et al.* 1993, Ross *et al.* 1990). Some aquatic "weeds", for example *Salvinia auriculata* in some tropical and subtropical regions may impede the smooth flow of streams. Such species can interfere with ecological systems such as lakes, streams and aquariums (Boyall 1983). Furthermore, the danger of fire from highly inflammable species like gorse (Balneaves 1981, Markin and Gardner 1993) can not be ignored. In some sites, high densities and size have been reported to offer haven for damaging agents especially rodents and insect pests, which can devastate crops (Comeau *et al.* 1993, Markin and Gardner 1993, Boyall 1983, Newton *et al.* 1987).

2.1.2.3 Biological and ecological characteristics of non-crop vegetation. Non-crop vegetation sometimes has biological and ecological attributes which enable it not only to thrive luxuriantly and to spread rapidly but also to compete successfully with the desired crop plants. For example, seedlings grow very rapidly and colonize empty or bare sites. They can also flower and fruit quickly thereafter (Holt 1988). Some species have prolific reproduction rates which enable spread and reinvasion of old sites quickly, meanwhile vegetative fragments can also reshoot forth (Gjerstad and Barber 1987). Both reproduction methods are thought to be survival techniques against eradication. High dispersal rates of specialized "seeds" or diaspores have also been reported. Physical adaptations such as being light, or having hooks or fluffs to attach to animals, birds and/or machines ensure effective spread over wide areas. Other species have long-lived propagules (diaspores or underground structures as in nut grass species), which can survive long unfavourable environmental conditions.

In many weeds, flowering and germination periodicity vary with wide resilience and tolerance levels to harsh environmental conditions. Specific temperatures, photoperiod or vernalization may be necessary in some cases to trigger germination and/or flowering, however. Moreover, chemical compounds thought not to be directly involved in plant metabolism and which could inhibit growth of other plant species growing in the vicinity through allelopathy have been reported in some species (Berkowitz 1988). Auld *et al.* (1987) report that these chemicals may serve also to protect some weeds against herbivory.

All the foregoing factors have important implications for the choice and timing of control procedures in order to achieve success.

2.1.3 Summary: non-crop vegetation management practices today and in the future

Weed control involves the reduction of the negative effects arising from the presence on the site of "unwanted" or undesirable plants. It used to mean complete removal of the competing vegetation from the site (Walstad and Kuch 1987). However, some species of non-crop vegetation have positive contributions to the site and sometimes to the benefit of the crop plants. Furthermore, numerous studies have shown a general curvilinear relationship between weed density and crop yield (Auld *et al.* 1987, Radosevich and Oysteryoung 1987, Wagner *et al.* 1989, Cousens 1987). This implies that competition is critical only at certain densities of weeds. However, the general negative hyperbolic model of competition (some competition models have different shapes see page 70 figure 4.6) indicates that even small amounts of non-crop vegetation can cause large reductions in crop growth. Consequently, the implication as to what level of competition is "critical" depends on the criteria used, for example considering economic, competition or statistical threshold levels (Cousens 1987).

Weed control methods which advocated complete removal of undesirable species and which, therefore, implied a "**yes**" or "**no**" decision to control or not to control, were suboptimal, often employing more control than necessary. Given that a site can produce a finite amount of biomass in a given time (Walstad and Kuch 1987, Auld *et al.* 1987), the management goal should be to improve the yield of the desirable crops. Decisions relating to weed control should be "**how much**" leading to a "**which**" decision among alternatives as justified by costs, physical and biological aspects (terrain, weed characteristics), and environmental constraints (weather, proximity to ecologically sensitive habitats) (Radosevich *et al.* 1990, Zabkiewicz and Richardson 1990, Auld *et al.* 1987). This search among alternatives to come up with sound non-crop vegetation control technologies given costs, physical aspects and environmental constraints is the theme of vegetation management (Walstad and Kuch 1987).

A comprehensive discourse on weed ecology and biology was beyond the scope of this study. However, it may suffice to point out that future control strategies should involve studies in the fields of weed ecology and biology in order to come up with effective and environmentally acceptable control methods. Auld *et al.* (1987) reiterated the importance of adequate knowledge of important characteristics of weeds like their broad range of germination temperatures, continued germination even during the growth of the crop plants, fast maturation, well adapted seeds for dispersal and high dormancies as being crucial in developing sound control technologies.

2.2 NON-CROP VEGETATION MANAGEMENT IN PLANTATIONS: AIMS AND METHODS OF NON-CROP VEGETATION MANAGEMENT

2.2.1 Competition from non-crop vegetation in plantations

The growth and survival of seedlings to maturity depend on their ability to extract and use resources from the environment efficiently. Resources important for growth are limited in most environments mainly because of inadequate supply (e.g. in impoverished sites), unavailability (e.g. in barren sites), or use by neighbours as in competition (Evans 1982, Squire 1977, Will 1985, Balneaves 1981, Radosevich and Oysteryoung 1987, Berkowitz 1988). In situations where resources are limited, the presence of neighbours even of the same species, in the same micro-site can aggravate deficiencies.

Negative interaction between plants of the same species (intra-specific competition) can be very severe because the individuals are closely related, and hence exhibit same growth patterns and therefore have the same needs. In most natural systems a high degree of species diversity results from the different species within the community trying to use different parts of the environment, so as to minimise competition. This is called niche separation. However, with reference to plant species only it is also true that many natural systems tend towards monoculture (or relatively low plant diversity). For example D. fir or lodgepole pine forests in Western U.S.A., or Mountain beech forests in New Zealand (Richardson pers comm.). Therefore, even in communities of systems where a high degree of biodiversity is encountered and a degree of "niche separation" is expected, often there will be strong competition within each niche.

In forest monocultures, the success of the crop species is of utmost importance and management procedures normally aim to direct the available resources to the crop trees. Competition in plantations is a dynamic process with both the crop plants and the unwanted species trying to optimise growth by maximising use of the available resources present at the site (Berkowitz 1988, Cannell and Grace 1993). Thus understanding the interference mechanisms between the crop plants and the undesirable species is an important pre-requisite to developing successful non-crop vegetation control technologies (Radosevich and Oysteryoung 1987).

2.2.2 Aims and methods of non-crop vegetation management

2.2.2.1 Aims of non-crop vegetation management. Non-crop vegetation control aims to improve the desired tree crop species' growth by reducing the interference effects of unwanted species to levels where further expenditure on control would not be justified. The actual control method chosen may be constrained by physical and financial resources, environmental factors or other activities on a farm (Auld *et al.* 1987). In agriculture, classical control methods took the form of:

i) quarantine, where total exclusion of the unwanted species was observed;

ii) containment, where the unwanted species was confined to a localized area and its dispersion hampered; and

iii) eradication, where the whole population was eliminated or reduced to zero.

The control methods used frequently included:

i) physical methods for example, manual and mechanical weeding, burning, mulching, and flooding;

ii) biological methods, including the classical use of insects or fungi (also known as mycoherbicides);

iii) chemical methods employing the use of herbicides, either contact or systemic, to kill the weeds; and

iv) integrated approaches which combined the above technologies appropriately with the nett effect being a group of non-conflicting control strategies (Auld *et al.* 1987, Walstad *et al.* 1987).

2.2.2.2 Summary of common methods of non-crop vegetation control in plantation forestry. Lowery *et al.* (1993) report weeding to be a critical factor in tropical forest plantations. Competition from weeds is the most common cause of mortality and growth loss, especially from grasses. Moreover, in these regions, it is feasible to reduce rotation lengths considerably, if weeds can be controlled in a timely fashion. Evans (1982) names ground weeding until the crop achieves dominance in the site and thereafter cleaning and releasing operations, (for example climber cutting), during the rotation whenever needed as the two main control methods in many parts of the tropics.

The bulk of control methods fall under cultural, mechanical and chemical groups (Evans 1982, Lowery *et al.* 1993, McDonald and Fiddler 1993, Richardson 1993). Classical biological control methods, where introduced weeds are targeted by importing their native enemies, need to be used cautiously especially where introduced weeds are similar to native species. These methods may also be inappropriate where target plants have other beneficial uses like grazing of livestock (West and Dean 1992), while the risk of attacking non-target plants can not be ruled out (Markin and Gardner 1993). However, there increasing evidence of the potential of biocontrol methods particularly where introduced weeds are dissimilar to native genera and/or where other control methods have had little success (Lawton 1990, Jessep 1990, Johnston 1990). For example in New Zealand alone grazing (Hansen 1988, Breach 1988, **Dale** 1990, West and Dean 1990, Radcliffe 1990), insects (Sutherland and Hill 1990, Jessep 1990, Hill and Gourlay 1990, Harman and Syrett 1990, Kay and Smale 1990, Lawton 1990, Markin and Gardner 1993), and Fungi i.e. mycoherbicides, (Auld 1990, Johnston 1990, McElwee *et al.* 1990, Popay and Cheah 1990). Studies on the biological control of gorse by a weevil that feeds on the seeds are underway; a joint venture by researchers from Hawaii and New Zealand (Markin and Gardner 1993).

In most parts of the tropics manual methods are preferred to mechanical and chemical methods mainly because of availability of cheap manual labour and easily available hand tools for cutting or hoeing which demand little or no operational expertise. Common methods include inter-row-, strip-, and spot-hoeing, or complete weeding. These approaches have various success rates and adoption mainly depends on the region and the political inclinations of the government of the day. Many governments in these areas view forest plantations as employment generators for rural people. Thus, there is a possibility that less labour intensive weed control methods, even when very successful and cheap, may generally not be favoured. Furthermore, many forest plantations are sited near natural ecosystems and extensive use of machinery or chemicals could result in a public outcry (Walstad *et al.* 1987).

Richardson (1993), reports that mechanical and chemical methods are the main control tools used in Australia and New Zealand. Mechanical methods remove weeds and may also improve soil physical properties (e.g. aeration and bulk density), root growth, and root access to soil moisture and nutrients. Mounding and ripping techniques have also been reported to enhance plant growth in poorly drained sites or in heavy and compacted sites respectively (Mason 1992, Richardson 1993).

In forestry the following methods have been used widely to control non-crop vegetation in plantations.

(1) Cultural practices and physical methods. Physical techniques mainly involve the use of manual and mechanized methods. Manual weeding methods are generally

labour intensive and demand high control frequencies. They are the main control modes in places where labour is still relatively cheap. These methods are especially effective for low-stature weeds or for within-row weeding where other methods may not be very successful. However, high labour requirements may limit the total area under production (Walstad *et al.* 1987).

Mechanical methods are energy intensive involving removal or disturbance of large volumes of soil. They are mainly used during site preparation. They may however, break up vegetative propagules especially rhizomatous weeds and spread them (also seeds for example broom), stimulating their growth and reinvasion. They may also increase the risk of wind and water erosion and can create hard pans in fragile ecosystems. Other modifications for example mowing and slashing can prevent flowering and seeding and thereby reduce underground storage reserves. But they may not be very effective for well established perennial weed populations for example Bracken or *Pteridium* species. They have an added advantage in that large production areas can be treated within a short time and at low cost.

Cultural practices like site preparation methods (Newton *et al.* 1987, Mason 1992), harvesting techniques and release treatments also reduce weed infestation levels on the site thereby encouraging establishment of new seedlings (Walstad *et al.* 1987). Economic and environmental constraints should however govern the decisions taken.

(a) Harvesting practices. Most harvesting practices have a nett effect of reducing biomass on the site depending on the:

i) type and abundance of the vegetation species before the operation;

ii) frequency and intensity of disturbance; and

iii) presence of soil seed banks, neighbouring seed sources or residual plants capable of colonizing the unoccupied site (Walstad *et al.* 1987).

(b) Site preparation methods. Most site preparation methods, when effectively undertaken will lead to:

i) even distribution of logging slash across the entire site (slash retention), sometimes high densities of slash are reduced to reduced fire danger;

ii) increased access to the site and micro-site for operations like planting, seeding or tending;

iii) easy conversion of the site to preferred species following the removal of most unwanted species; and

iv) newly planted stock getting a head start over potential colonizers or other non-crop vegetation.

Site preparation methods therefore, form an important part of non-crop vegetation management in many commercial forestry ventures. Numerous studies of the silvicultural and management benefits resulting from site preparation have identified opportunities to enhance future tree crop growth (Newton *et al.* 1987, Walstad *et al.* 1987, Mason 1992).

(2) Chemical control methods. Chemical compounds which kill the undesirable species or arrest their growth are often used. Systemic compounds are advantageous as they kill underground structures. Auld *et al.* (1987) cite chemical methods as being quite a recent phenomenon in forestry but that they have been used for over a century in agriculture where copper based compounds were used to control broadleaved non-crop vegetation. Wide adoption initially was favoured by low labour requirements and the success in controlling a broad range of weed species (Walstad *et al.* 1987, Auld *et al.* 1987).

Chemicals can be classified in various ways for instance by their mode of action or by the time of application. For example using the time of application the following groups are used:

i) pre-sowing chemicals are incorporated into the soil or applied to non-crop vegetation before sowing crops;

ii) pre-emergent chemicals are applied to soil surfaces before emergence of the crops; and

iii) post-emergent chemicals are applied in later stages after the germination of the crop and during crop growth to control weeds competing with the desired crop species.

Different rates, and the form in which the herbicide is applied to the non-crop vegetation, varying from granular to liquid are used. Application modes range from mechanical (blanket treatment with boom sprayers), to manual (hand treatment in rows of the crops or spot treatment using hand held devices) depending on the target non-crop vegetation as well as the sensitivity of the crops to the chemicals (Walstad *et al.* 1987, Auld *et al.* 1987).

A lot of debate has been focused on the advantages and disadvantages of using chemicals to control weeds. Advantages include a wide range of selectivity with control success, low labour inputs, fast adoption and execution all of which can reduce the costs of treatment (Walstad *et al.* 1987, Auld *et al.* 1987). The use of chemicals, which in other literature is sometimes referred to as conservation tillage, also reduces soil erosion risk and deterioration of soil structure resulting from extensive tillage.

Disadvantages of chemicals include a higher risk of damage to crop trees than in other methods especially in post-plant situations where tree damage is a possible consequence of errors. For example, incorrect choice of chemicals, wrong formulations (concentrations) or use of wrong equipment and the unpredictable responses of some non-crop vegetation to chemicals, can all lead to serious damage to desired crops (Walstad *et al.* 1987, Auld *et al.* 1987). Continued use of some chemicals may systematically and gradually reduce some weed flora with the result that resistant species become more dominant, as in cases of repeated use of 2,4-D or Phenoxy herbicides (Walstad *et al.* 1987, Auld *et al.* 1987). This is corroborated by Nambiar and Zed (1980) who found out that low formulations of the chemical Atrazine favoured Sorrel abundance on a site and reduced that of grass. Consequently, herbicide mixtures are used to avoid selection problems. However, this may not be a "real" risk in forestry monocultures where herbicides are applied to a given unit of land usually only once or twice per rotation.

In addition, chemicals which have long residual effects may actually end up increasing the risk of soil erosion in the next season or two. This may be due to the fact that in the next season or two following the herbicide treatment, the weeds' roots which under normal circumstances hold the soil particles together rot and disintegrate. With the residual effects still strong in the soil substrate, no new weeds can re-establish. Eventually, wind and water erosion prevail. But with the availability of environmental friendly chemicals this is not a major worry any more.

Chemical drift and leaching have also caused concern, especially with respect to water systems and non-target flora and fauna. Furthermore, wrong combinations of temperatures, rainfall, light intensity, soil structure and organic matter may cause failure and make chemical use uneconomical. Thus, the timing of application and the herbicide type have to be considered, as well as the long term exposure to the chemicals and residual effects to humans, wildlife and the environment (Walstad *et al.* 1987, Auld *et al.* 1987).

(3) Biological control methods. Biological control involves the "*use by man of living organisms to control undesirable plants*" (Markin and Gardner 1993). Classical biological control methods target introduced weeds by importing their natural enemies or manipulating the unwanted species to favour multiplication of the natural enemy populations. Biocontrol methods may be potential candidates where other control methods have not been very successful or are unapplicable, for example in nature reserves. In New Zealand biocontrol started in the 1920s when insects were imported for the first time from U.K. to control blackberry (Sutherland and Hill 1990). Organised biocontrol started even earlier in the U.S.A., Australia and Hawaii.

Biocontrol methods have a lot of potential in New Zealand as most of the weed species were introduced (exotic) and also they bear little similarities to local genera. Furthermore, a lot of new planting is going on in pasture land away from natural ecosystems. Hill and Gourley (1990) name 3 main approaches as:

1) inundative - where a disease is used as a mycoherbicide to inundate the weed species;

2) augmentative - where the activity of the control agent is promoted; and

3) inoculative - where imported control agents are released into the population.

Some examples of biocontrol programmes in New Zealand include:

1) grazing by livestock to control pampas grass (Dale and Todd 1988, West and Dean 1990), gorse (Hansen 1988, West and Dean 1990) and bracken fern (Breach 1988, West and Dean 1990);

2) using insects to control blackberry (Sutherland and Hill 1990), nodding thistle (*Carduus nutans* L.), and Californian thistle (*Cirsium arvense* L.), (Jessep 1990), gorse (*Ulex europeaus* L.) (Hill and Gourlay 1990), broom (Harman and Syrett 1990), buddleia (*Buddleja davidii* Franchet), (Kay and Smale 1990), and bracken (Taylor 1990); and

3) using Fungi or mycoherbicides to control bracken (McElwee *et al.* 1990), blackberry (Johnston 1990).

Johnston (1990) reports Fungi to be suitable agents as they cause serious plant diseases, can spread efficiently over wide areas and often show high host specificity. Meanwhile, successful use of Fungi agents to control weeds has been reported in Australia (Johnston 1990, Wapshere 1990). Fungi may be especially useful in natural ecosystems and nature reserves where chemical use may be inappropriate. Failure of biocontrol agents has been cited to occur when: 1) proper "eco-climatic matching" between adopted and native countries of control agents is not done; 2) interaction with native predators, parasitoids and diseases occurs; and 3) target species evolve resistance to the agents, especially sexually reproducing weeds e.g. *Lantana camara* and *Salvinia molesta* (Lawton 1990).

However, biocontrol approaches (classical methods) have potential dangers too, for example fear of introduced organisms spreading and destroying non-target plant species (Markin and Gardner 1993). It is also hard to restrict the spread of the control organisms once they have been released into the wild. Furthermore exotic organisms can:

i) attack different plant species other than the targeted one;

ii) not discriminate against and therefore spare non-crop vegetation that may have other benefits like fodder for livestock and wildlife; and

iii) become potential pests for agricultural crops.

Moreover, where plantations are established in areas which previously supported native vegetation the native vegetation constitutes most of the non-crop vegetation species. These species may be protected by environmental laws. Thus the decision to introduce some exotic organism with potential to kill native vegetation may be irrational (Markin and Gardner 1993). However, Zabkiewicz and Richardson (1990) while discussing costs, constraints and future options of weed control in New Zealand forests, cited use of insects to be cost effective. In view of this they recommended further research. Further reading on biocontrol methods can be referenced from FRI Bulletin 155.

(4) Integrated approaches. Integrated approaches, which have been borrowed from agriculture, form the backbone of non-crop vegetation control technologies. Many control mechanisms are employed together with the aim of reducing crop damage and increasing productivity at affordable cost (Auld *et al.* 1987, Stewart 1987, Walstad and Kuch 1987). Integrated approaches take into account the pros and cons of the adopted control measures and the resultant physical and environmental consequences. Lawton (1990), McElwee *et al.* (1990), and Taylor (1990) report integrated approaches to have greater potential especially for hard-to-control weed species, for example *Lantana camara* and *Salvinia molesta*.

2.3 VEGETATION MANAGEMENT AND PLANTATION ESTABLISHMENT

Non-crop vegetation management should aim to achieve management objectives by using knowledge of the responses of individual non-crop vegetation populations to silvicultural and management practices. Successful vegetation management and plantation establishment, demands a clear understanding of tree crop - 'non-crop' vegetation dynamics. Many studies have indicated an urgent need for information on: i) ecology and biology; ii) constraints imposed by non-crop vegetation on tree crop productivity; and iii) research on factors influencing weed population trends (Fryer 1987, Mason 1992).

Stewart (1987) suggested an ecological approach to forest vegetation management. He named four important areas as; 1) population and individual plant interactions with the environment (autecology), 2) interactions among plant populations (inter- and intra-specific competition), 3) community and ecosystem dynamics (including succession), and 4) patterns of tree growth and development of forestry stands (biometrics). Knowledge in these areas should enable both forest managers and researchers not only to answer important questions in plantation establishment and management, but also to come up with better, more effective and affordable non-crop vegetation control technologies.

Walstad and Kuch (1987 p.3) give a concise summary of the questions relevant to managers as:

i) how important are competing non-crop vegetation plants in the development of commercial forests?
ii) when do they exert their maximum influence?
iii) for how long do these effects persist?
iv) what control methods do we have available? and
v) what trade-offs are involved?

Answering these questions should help both researchers and managers alike, to develop more sensitive non-crop vegetation control strategies, and therefore use resources more efficiently.

2.3.1 The need for vegetation management in plantations

In plantation forestry, silvicultural systems aim to successfully regenerate, maintain and improve the stands. Competition from weeds can lead to establishment failures and should be eliminated in good time. Tappeiner II and Wagner (1987), cite the following reasons for controlling non-crop vegetation; timber production, wildlife habitat management, forage production, watershed management, recreation and aesthetics, soil stability and roadside maintenance. Vegetation control in forests aims to inhibit or retard initial establishment of weeds by reducing size and abundance while ensuring ecological integrity over the long run.

Two types of pressures have faced vegetation management. The first type is socio-economic in nature while the second relates to success of control procedures. In the first group are; resilience of some weeds to herbicides, high costs of chemical treatments, and concern about the use of some chemicals (cost of some chemicals has actually fallen e.g. Round up and selective chemicals with low residual effects are also available (Richardson pers comm.)). In the second group, failures have been reported where: 1) the weather and/or soil conditions are unfavourable; 2) inappropriate treatments are used so as to lower costs; 3) relevant products are inaccessible because of government restriction on imports; 4) improper application equipment is used; and 5) relevant and adequate know-how on best treatment technologies is wanting (Fryer 1987).

Thus, even though numerous opportunities for vegetation management exist in plantation forestry, declining budgets, and increased public awareness and negative perception of some control procedures need to be addressed.

2.3.2 Non-crop vegetation management as part of the silvicultural system

Non-crop vegetation control is an integral part of successful silviculture and forest management and is essential for successful commercial forestry. In order to integrate vegetation management into the silvicultural system appropriately, it should be borne in mind that:

i) treatments applied during site preparation and release operations may be similar in importance to harvesting and thinning;
ii) site preparation and release operations normally occur within a very short time and hence they form a small part of the total silvicultural system; and
iii) the management goals will normally determine the severity of silvicultural treatments.

For example, heavy pre-commercial thinning can lead to increased undergrowth of non-crop vegetation; but this may be good when wildlife and aesthetics are among the management objectives. However, in a stand managed purely for timber production, such a move may lead to unnecessarily increased risk of fire and inter-specific competition (Tappeiner II and Wagner 1987). Thus by considering vegetation management in the context of a silvicultural system, one may expose alternative management approaches and thus avail opportunities for enhancing forest resource values.

Therefore, the rightful place of vegetation management in a silvicultural regime is best considered within the context of silvicultural prescriptions, with management goals in mind. This is because the choice of appropriate silvicultural operations reflects site factors and control options.

2.3.3 Evaluating non-crop vegetation management needs at different stages of stand development

Forest managers need to select stands with greatest potential gains if non-crop vegetation is controlled and direct available resources to them. Accurate prediction of stand development especially under inter-specific competition may be quite difficult, especially for young stands where inter-specific competition is not only dynamic but sometimes, the long-term effects may be difficult to predict. Due to factors associated with risk, for example wind throws, disease out breaks, or bad weather, future stand development may be altered considerably (Tappeiner II and Wagner 1987).

Four stages are generally recognised in even-aged stand development when vegetation management needs can be evaluated. These are:

1) before harvest;
2) after harvest but before site preparation;
3) after site preparation and during stand establishment; and
4) after stand establishment.

Potential vegetation management problems, control objectives, treatment choices or alternatives and their constraints can be identified for each specific stage and treated accordingly.

2.3.3.1 Before harvest. A valuable opportunity to identify and prevent future vegetation management problems presents itself before harvest. Potential competitors are often more apparent, thus a manager could estimate presence and quantities especially of woody species like *Acacia* spp, broom and gorse. Species seeding or those whose seeds' germination can be triggered off by harvesting operations or land preparation methods should be noted. Mechanical land preparation methods may distribute and favour colonization by rhizomatous species, while prescribed burning may favour that of legumes (Tappeiner II and Wagner 1987). The presence of animals, insects or other vermin with potential negative effects on young stands and whose populations can be manipulated by vegetation control should also be documented.

Early identification of potential future vegetation problems before harvest will ensure use of correct harvest methods, avoiding those which could result in massive proliferation of competing species. In cases where this is not possible appropriate mitigation measures can be taken (Tappeiner II and Wagner 1987).

2.3.3.2 After harvest. After harvesting, effects of logging and any pre-harvest non-crop vegetation management treatments become apparent. Site preparation methods should aim to prevent potential competition from flourishing. Newly harvested sites can be surveyed before site preparation to assess the composition, abundance and distribution of any unfriendly and aggressive species (especially their residual stumps and root systems). The presence of any aggressive, woody non-crop vegetation and any seed sources nearby whose germination may be favoured by the envisaged site preparation methods should be reported.

The presence of animals and insect pests with potential to damage the crops and whose populations can be reduced if correct site preparation methods are used, should also be documented. Further, the need for improving site access by removing logging debris and hence reducing fire hazard and hiding grounds for some animal pests should not be overlooked (Tappeiner II and Wagner 1987, Newton *et al.* 1987, Comeau *et al.* 1993).

2.3.3.3 After site preparation and during stand establishment. The years immediately following site preparation are critical to crop establishment and stand development. Stand structure and species composition at this early age can often determine a long-term growth trajectory which could affect any silvicultural and management objectives (Tappeiner II and Wagner 1987). Consequently, early release treatments play an important role in many silvicultural prescriptions.

Often, frequent evaluations during this period pay off as many vegetation problems in early stand establishment are usually apparent within the first few seasons following site preparation. Moreover, early losses in survival and growth cannot be recovered, as blanking may be ineffective (Chavasse *et al.* 1981). On the other hand, replanting is often expensive and may even be unsuccessful (Tappeiner II and Wagner 1987), and/or may lead to lost opportunity if the planting season is over. The importance of controlling weeds at this early age can not be over-emphasized. Nambiar and Zed (1980) reported early weed competition to override some nursery practices for example conditioning and root wrenching. Moreover, controlling established vegetation is more expensive and can be less effective than for young newly growing vegetation.

Note should be made of non-crop vegetation species' abundance, distribution and size. Resprouts (sprouts are more aggressive as they normally have a well established root base), (Gjerstad and Barber 1987) or seed germination, and the abundance of herbaceous vegetation especially in areas with limited moisture availability (Squire 1977, Sands and Nambiar 1984, Balneaves 1982, Balneaves and Clinton 1992), should be treated. Control is best done before they seed. A note should also be taken of any other species with low abundance but with potentials for rapid population explosion or seed sources nearby. Appropriate treatments should be designed to minimise their invasion and expansion. The presence of noxious animal and insect pests should be assessed as well. Damage from animals or insects to young trees can eliminate any benefits gained by vegetation control (Tappeiner II and Wagner 1987, Wagner and Radosevich 1991b). Lastly, the effects of previous treatments should also be determined so that any modifications that are necessary can be undertaken to ensure success of future control methods.

2.3.3.4 After stand establishment. Following establishment, emphasis normally shifts from inter-specific competition to intra-specific competition. This is normally ushered in by canopy closure of the trees, and it is not uncommon for managers to stop non-crop vegetation control at this stage, apart maybe from climber and liana cutting (Evans 1982, Tappeiner II and Wagner 1987). Opportunities for vegetation management after stand establishment include improved form and species composition of the stand, increased growth (Lauer *et al.* 1993), improved forage and/or preventing vegetation problems in the next rotation. Studies on the long-term effects of vegetation control have indicated that significant growth gains exist (Balneaves 1981). In some situations weed control treatments can be undertaken together with thinning or stand improvement operations (Walstad and Kuch 1987, Tappeiner II and Wagner 1987).

Relevant information to be gathered includes:

1) presence of dominant competitors affecting growth or tree form (especially shade tolerant competitors);

2) understorey abundance of non-crop vegetation which can sometimes even eliminate thinning gains, (where wildlife management or livestock production are also part of the management objectives, then management for desired forage and cover species can be undertaken together);

3) assessment of the success of previous management operations, for example thinning operations may encourage the development of undesirables; and

4) reduction of understorey vegetation and fuel loads for fire protection.

2.3.4 Effects of competing non-crop vegetation on stand development

By documenting vegetation control needs during different stages of stand development, managers can predict with certainty the growth and development patterns of forest crops. The effects of weeds on survival and tree crop growth plus their potential reinvasion from adjacent areas or residual seed banks should also be determined (Tappeiner II and Wagner 1987).

It is from such predictions that managers may assess if the desired stand will grow as envisaged under the prevailing competition levels and how serious the reduction in growth and final yields, if any, will be suffered by the crop trees. Consequently, the expected delay and reduction in harvest quantity and/or quality can be estimated (Tappeiner II and Wagner 1987). Moreover, managers can get an insight of situations where competition is so severe as to make development of a manageable stand worthless. Figure 2.1 shows five different hypothetical scenarios of stand development under different competition levels.

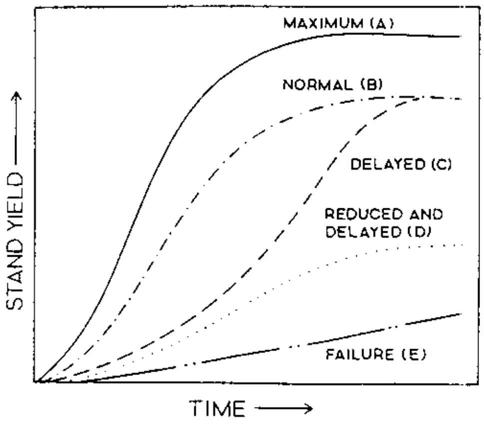


Figure 2.1: Hypothetical scenarios of possible stand development under different

competition levels from non-crop vegetation (After Tappeiner II and Wagner 1987).

Curve **B** shows the normal stand development as commonly portrayed using yield tables or growth models developed with unknown levels of non-crop vegetation competition. **C** shows a delayed but normal stand yield following a competition-induced growth reduction early during stand development. This could be as a result of early grass competition which slows growth but does not cause high mortality (Tappeiner II and Wagner 1987). Examples are true firs which can have a delay of as much as 30 years trying to overcome early evergreen shrub suppression.

An important point to note here is that even though the final yield is the same, curve **B** peaks (flattens) earlier than **C**. This has important implications for management. Curve **D** has suffered reduced and delayed growth and yield from the competition. This can occur where persistent woody competitors abound in a site causing mortality of conifers leading to a stand with few trees of merchantable size. **E** shows a near complete mortality with no merchantable stand developing, while curve **A** shows an intensively managed stand with insignificant competing vegetation levels resulting in a higher than the normal predicted (upper limit) growth and biomass accumulation. This is species-, genotype- and site-specific (Tappeiner II and Wagner 1987).

2.3.5 Vegetation surveys

Periodic vegetation surveys provide information about the need for vegetation management. Surveys can give descriptions of the non-crop vegetation species abundance and growth status. This is useful for predicting effects of competition on stand development. Surveys can be subjective (providing qualitative information) or objective (giving consistent information with less bias and accurate permanent records for use in standardizing future treatment prescriptions), (Tappeiner II and Wagner 1987).

From the survey results, treatment prescriptions can be developed. These can be based on treatment evaluation records documenting vegetation management objectives and constraints for evaluating alternatives and quantitative comparisons of potential efficacy and economic efficiency of the control methods adopted. In addition, the potential for adopted treatments to encourage reinvasion from adjacent stands or residual seeds and the possible effects of adopted treatments on other forest resources, values and off-site impacts on ecology and environment should also be documented.

Moreover, with advances in remote sensing and the Geographical Information Systems (GIS), there is potential for aerial surveys to provide information for vegetation management. Information provided by surveys should include species types, abundance, distribution, origin and growth trends. This information can be used to assess need for release operations or stand improvement treatments (Tappeiner II and Wagner 1987).

2.4 DECISION MAKING IN FOREST VEGETATION MANAGEMENT

2.4.1 Types of decisions

The drive behind the emphasis in non-crop vegetation management in plantations is the expected benefits accruing from vegetation control and the increased volume, quality and quantity plus value of the crop. Stewart (1987), classifies management decisions under the following two groups, i.e. strategic and tactical.

2.4.1.1 Strategic decisions. These are decisions involving evaluation of the effects of alternative management and silvicultural regimes or reforestation systems on the costs of control strategies. They can also be used to examine impact of non-crop vegetation populations on the entire production cycle. Managers can then choose control regimes that minimise development of non-crop vegetation on the site and which maximise net present value for the entire rotation.

2.4.1.2 Tactical decisions. Tactical decisions help the manager to select practices at various points in the management cycle within the scope of the existing strategic decisions. The focus is on treatment selection and application procedures that produce responses which are compatible with the strategic analysis and which can lead to re-evaluation of long term stand management policy.

Managers should be prepared to anticipate consequences of their management treatments and consequently modify or mitigate particular control technologies. For example, economic analyses including direct and indirect costs of treatments, given as net present value, or accrued benefits from increased value and volume. Alternatively, the ease with which future treatments can be conducted, (for example controlling thorny vegetation can lead to easy pruning and thinning in the future and therefore save funds), (Stewart 1987), can be used.

2.4.2 Computer software for vegetation management decision making

A conceptual model of plantation establishment showing the main factors influencing the state of a radiata pine stand before first thinning (usually age 5 in New Zealand) was presented by Mason (1992), figure 2.2. He discussed the importance of field management practices in modifying the site micro-environment and how seedlings' physiology and morphology as determined immediately after planting could be used as indicators of stock quality and future crop performance.

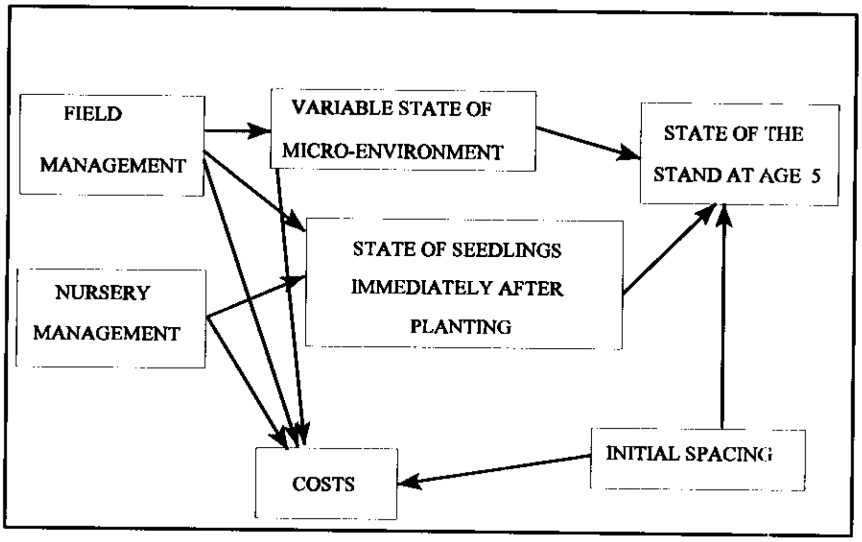


Figure 2.2: Conceptual model of plantation establishment (After Mason 1992).

The importance of non-crop vegetation management in successful crop establishment has already been mentioned and to expose the role of weeds in the establishment scenario more clearly, a modification of the establishment model by Mason (1992) integrating the likely vegetation management decisions to be made is shown in figure 2.3. Figure 2.4 details specific aspects of vegetation management which need to be considered.

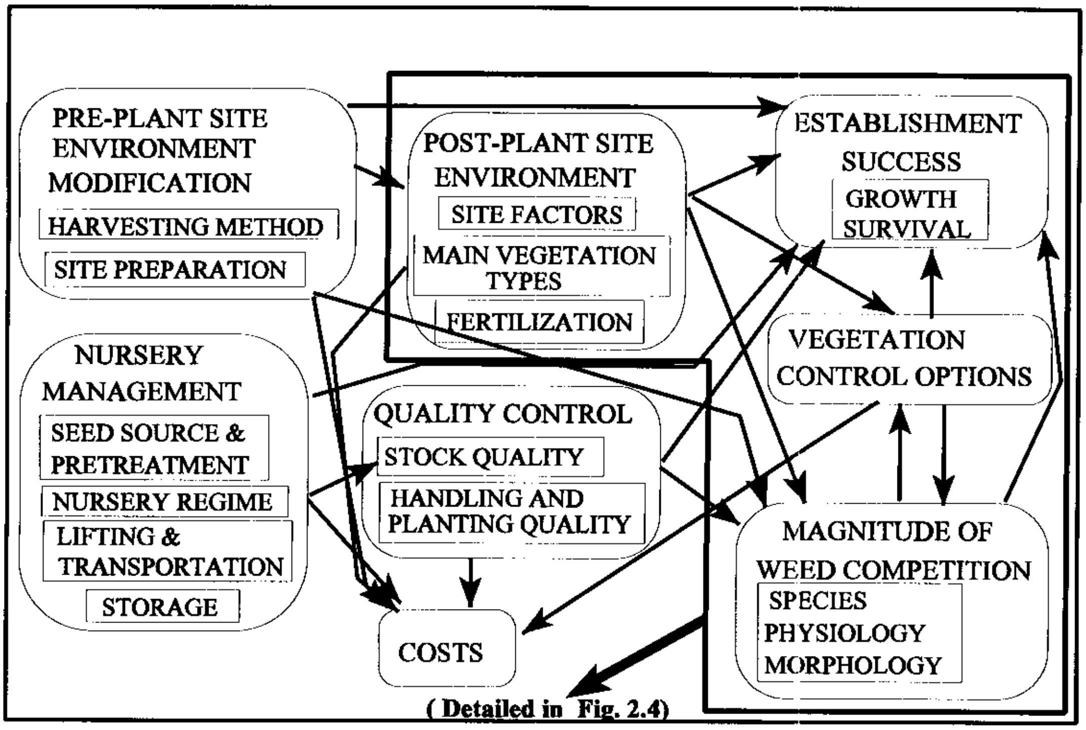


Figure 2.3: A conceptual model of plantation establishment highlighting vegetation management (arrows show influence).

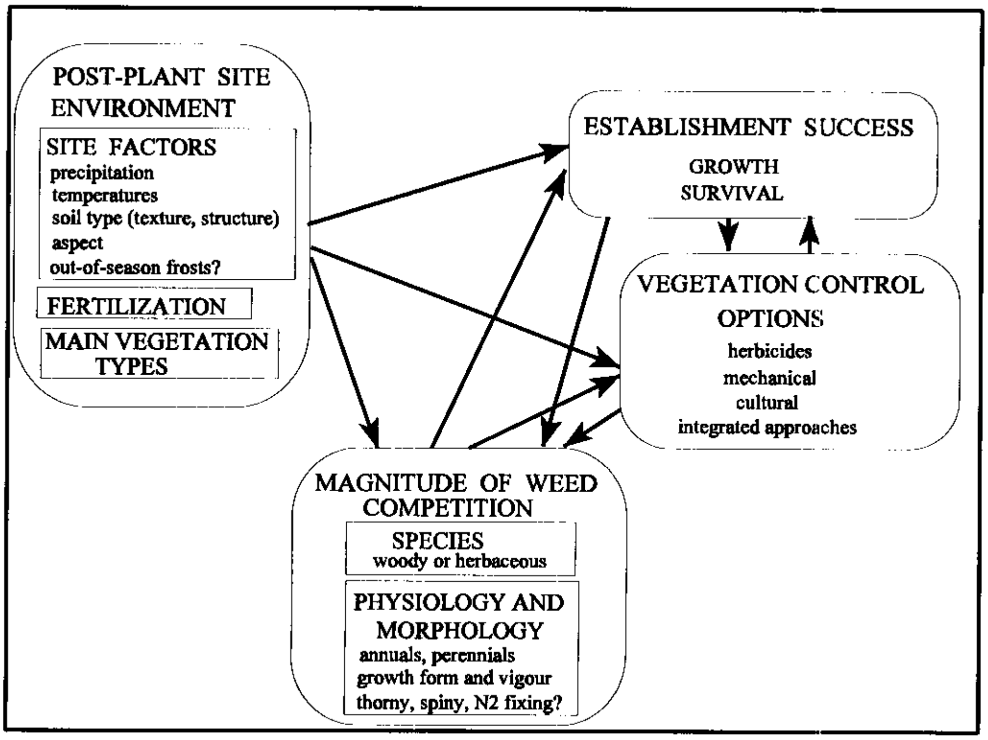


Figure 2.4: A detailed representation of vegetation management.

The decision criteria should use developed relationships between tree growth and non-crop vegetation densities. Decisions should consider the influence of the treatments on crop performance. Linkages in growth and yield simulations with young stand development in the presence of competition from non-crop vegetation at different levels (Stewart 1987) and the competitive interaction between the desired forest tree crops and the non-crop vegetation need to be evaluated, as well. Evaluating complete reforestation and management systems including the choice of silvicultural and management regimes, (pre-harvesting methods, site preparation methods, species, planting stock quality, timely release and control against damaging agents) may be a more robust approach to vegetation management.

A decision support system (DSS) to help New Zealand managers choose herbicides cost-effectively has been developed (Mason 1992). The DSS uses 2 programmes: 1) Vegetation Management Adviser for storing information; and 2) Vegetation Management Tools for retrieval and analysis. Further, a user interface is provided. Inputs include site data, weeds type(s), and growth season. The DSS then selects a treatment method and shows the expected outcomes. Mason (1992), further stressed the need to integrate numerical and non-numerical information appropriately. For example, qualitative information from managers' experiences is combined with quantitative models or other similar numerical tools. The DSS has demonstrated that proper characterisation of information in computers using knowledge-based systems can greatly aid in management decision-making.

Morris and Forslund (1991) also developed a computerised decision tool for vegetation management in jack pine plantations. The program used site factors, stock type and competitor data as inputs. From these data a competition index was calculated using predefined equations in the system. The program used this information to give a YES/NO tending decision based on thresholds and the desired growth reduction.

Figure 2.5 is a diagrammatic representation of software for vegetation management decision-making showing all the inputs and outputs. Such software if developed properly could be a vital aid to managers facing day to day decision-making on non-crop vegetation control needs. It is crucial to note that such software does not substitute for the manager but merely aids in decision-making. Therefore, managers will still be responsible for the final decisions taken.

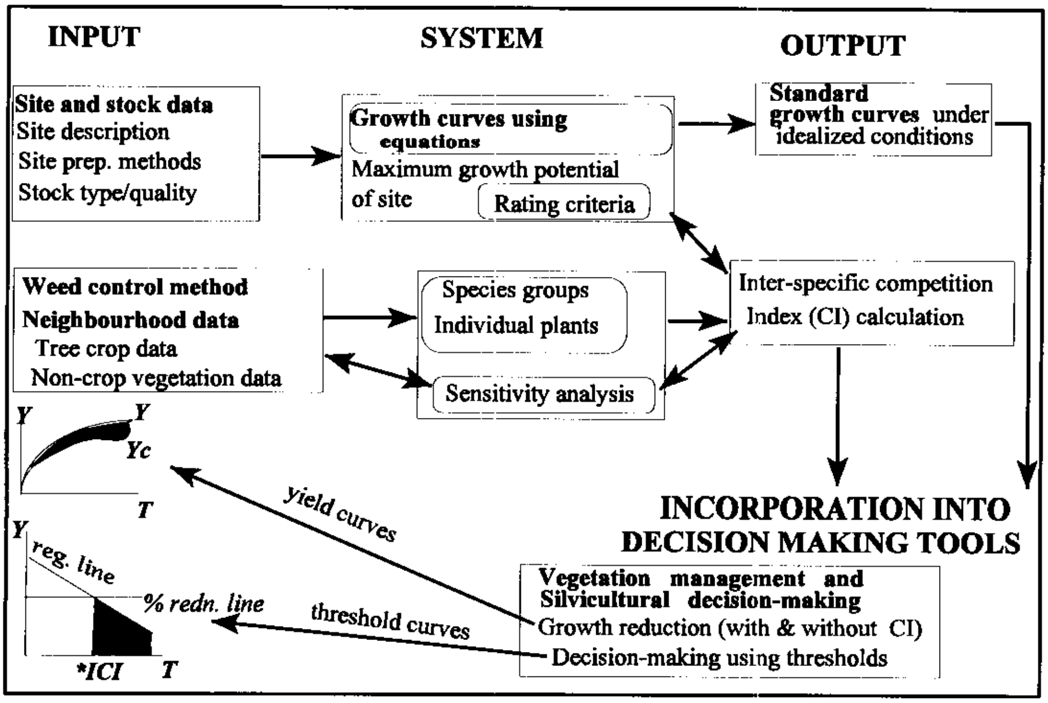


Figure 2.5: Envisaged structure of vegetation management decision-support tool showing possible linkages with stand growth models (arrows show information flow). In Figure 2.5 the following abbreviations were used; prep. = preparation, redn. = reduction, and CI = competition index.

CHAPTER 3

COMPETITION AND PLANT GROWTH

3.1 PLANT COMPETITION

Radosevich and Oysteryoung (1987) define competition as the negative interaction between two or more plants of the same species (intra-specific) or different species (inter-specific) sharing the same environment; whereby one species or individual deprives the other of a resource (water, light, nutrients or space) which is vital for growth and consequently limits its development and well being. Generally, competitors establish dominance and stature over their counter parts. However, physiological influences like photosynthetic rate, morphology and health all come into play (Radosevich and Oysteryoung 1987, Berkowitz 1988). This chapter will describe competition from the "negative interference" point of view but will not cover other aspects for example amensalism (one plant depressing another by producing allellopathic substances) or parasitism (one plant deriving its livelihood directly from another).

3.1.1 Types of competition

3.1.1.1 Symmetric or two-sided competition. Plants competing for water, nutrients and light are likely to exhibit symmetric or two-sided competition. It is then possible for shorter plants to have adverse effects on taller plants even though larger plants may acquire more of the above- and below-ground resources (Cannell and Grace 1993, Richardson 1993).

3.1.1.2 Asymmetric or one-sided competition. Competition for light is mainly asymmetrical or one-sided. Large differences in light quality and quantity occur between full daylight and infiltrated light, and taller plants may have an advantage over their shorter neighbours (Cannell and Grace 1993).

3.1.2 Mechanisms of competition

3.1.2.1 Physiological basis of competition. A given site can produce a finite amount of crop biomass in a given time (Walstad and Kuch 1987). However, the capacity of the environment to support growth decreases with time (the site becomes exhausted). Crop productivity can be lowered further by neighbour proximity or the presence of high amounts of non-crop vegetation (Balneaves 1981, 1982, Radosevich and Holt 1984, Radosevich and Oysteryoung 1987, Walstad and Kuch 1987, Snowdon and Khana 1989, Balneaves and Clinton 1992). Radosevich and Holt (1984) name two categories of environmental factors that influence growth: 1) environmental resources - these are "consumed" by the plants for example, CO_2, light, H_2O, nutrients and O_2; and 2) environmental conditions which are not directly consumed, e.g. temperatures, soil PH and compaction (bulk density).

Most studies have shown a general inverse (negative) relationship between crop growth with increased non-crop vegetation density in a site (Radosevich and Holt 1984, Radosevich and Oysteryoung 1987, Auld *et al.* 1987, Wagner *et al.* 1989, Cousens 1987). However, to understand the underlying mechanisms of inter-specific competition and to be able to elucidate crop responses to variations in limiting factors, it is important that we understand and characterise the physiological responses to resource limitation in the micro-environment (Radosevich and Oysteryoung 1987, Berkowitz 1988, Nambiar and Sands 1993).

Rigorous well controlled experiments are necessary if we desire to get accurate response effects from plants. Two groups of growth determinants have been named: 1) those that express relative rates of addition and uptake of resources (mass transport); and 2) those that influence these rates (Ingestad and Agren 1995). In the first group are factors that show flux rates of carbon and mineral nutrients in relation to plant size and its needs. These factors would therefore affect relative growth rate (RGR). But they act singly. Thus under abundant resource supply, the growth of a plant will be determined by the factor(s) in lowest supply. This is "Liebig's Law of the minimum" (*cited from*: Ingestad and Agren 1995). On the other hand, factors for example light, water, genotype and temperatures act to regulate carbon and mineral flux rates. These would interact at various levels with the first group. However, in the natural environment conditions are never static even for a few seconds. Thus such experiments where resources are well controlled are therefore only possible, in theory, in green houses or growth chambers. Further, Cannell and Grace (1993) add that the inter-relationships between crops and weeds are dynamic. Consequently, the environment is continually modified, with both biotic and abiotic, as well as above- and below-ground resources bound together.

Light availability is fundamental for photosynthesis. Unlike water or nutrients which can be linked to some reservoir, light comes as energy (photon). Thus a leaf must make use of it or lose this energy (Radosevich and Holt 1984). In forest environments light may limit growth. Successful competitors show tolerance and can grow in low light (Radosevich and Oysteryoung 1987). Shade-tolerant species normally have lower photosynthetic rates at light saturation point than their counterparts and may also retain their leaves for longer periods. Allocation patterns of plants may change under the influence of competition to ensure survival (Berkowitz 1988, Nambiar and Sands 1993). High light levels may increase root/shoot biomass ratio in conifers and their total dry weight (Radosevich and Oysteryoung 1987). Light quantity and quality influence the rate and amount of photosynthesis. With increased light more photosynthate is produced per unit of chlorophyll or leaf area per unit time. In low light there is increased apical control leading to columnar crown forms (Radosevich and Oysteryoung 1987).

Water is more crucial for many plant physiological processes than light. Consequently, it limits plant growth in more environments than light (Radosevich and Oysteryoung 1987). Generally, trees growing in environments with limited moisture grow more roots so as to explore new soil horizons. Further, Berkowitz (1988) adds that most plants show increased root-to-shoot ratios in response to decreased water or nutrient status. The converse happens if irradiance is reduced. However, many studies with conifers have shown a constant ratio of root:shoot biomass under different competition regimes. Moreover, Radosevich and Oysteryoung (1987) caution that the correlation between precipitation, root depth, root-to-shoot biomass ratio and the presence of tap root may be poor; these factors being dictated more by soil physical characteristics than genetic adaptation to drought. Moreover, water availability also affects stomatal opening and closure.

Physiological responses to nutrient stress include higher root absorption capacity, lower photosynthetic capacity, lower tissue production and lower rate of senescence and leaf cast (Radosevich and Oysteryoung 1987). However, effects of nutrient stress may be confounded with moisture availability. Increased nutrient availability leads to increased chlorophyll content of individual leaves which can result in increased leaf area of individual trees. Nutrient stresses can have varied effects on crown development but generally lead to reduced density and distribution of leaves. Increased nutrient availability may lead to increased needle retention and function, as well (Radosevich and Oysteryoung 1987).

3.1.2.2 Competition effects and responses. The interaction and interference effects between crop trees and non-crop vegetation, change over both time and space (Richardson 1993, Perry *et al.* 1993, Fredricksen *et al.* 1993, Comeau *et al.* 1993, Nambiar and Sands 1993, Burton 1993), with many factors coming into play. In a stand, both inter- and intra-specific competition affect tree growth (Radosevich and Oysteryoung 1987, Cannell and Grace 1993), and therefore, silvicultural intervention should be aimed at minimising growth constraints. The benefits of controlling non-crop vegetation have been reported to be greatest before canopy closure (Nambiar and Sands 1993).

The dynamic nature of competition calls for a greater quantitative understanding of growth dynamics and interference effects of non-crop vegetation, (Cannell and Grace 1993, McDonald and Fiddler 1993, Fredricksen *et al.* 1993, Harrington and Tappeiner 1991, Wagner and Radosevich 1991a, 1991b) and/or oversown species in order to minimise competition effects.

Snowdon and Khana (1989) discussed at length possible growth responses of radiata pine to site improvement either by controlling non-crop vegetation or fertilization or both. They named 2 possible radiata pine responses as type I and type II. Response type I influences the rate of development temporarily. For example, controlling competing non-crop vegetation results in short-lived beneficial effects on soil characteristics and consequently on crop plants. The result being parallel growth trajectories between treated and untreated stands. Mason (1992) further explained the implications of response type I. He defined parallel growth to occur when the time gained as a result of a treatment remained constant throughout the rotation. Moreover, he suggested 5 assumptions were required if growth projections were based on type I responses:

i) the growth input change due to the treatment is temporary;

ii) the treatment should not lead to deficiencies as a result of changes in growth rate;

iii) future treatment effects should not bring about a resumption of the growth input change;

iv) allometric relationships, for example shoot and root ratios or biomass, should not be affected; and

v) at time of equivalent yields, there should be insignificant physiological age differences between treated and untreated stands.

These assumptions will not be discussed further here and reference can be made to Mason (1992) for further discussion.

Response type II results in major changes in productivity comparable to an increase in site quality and/or carrying capacity and hence causes a divergence of growth curves between treated and untreated stands (Snowdon and Khana 1989). Examples of type II responses are broom competition (New Zealand) and bracken competition (Australia) (Richardson 1993). Snowdon and Khana (1989) reported a type II response on fertilized compared to unfertilized stands. Another response type, III, is envisaged where nitrogen fixing weed species rapidly occupy a poor site causing reduced resource availability to crop trees initially. However, after crown closure, the weeds perish due to shading effects. Such "weeds" have two potential advantages; that of preventing the nutrients from being leached and availing the fixed nitrogen and other nutrients to the crop trees when they (weeds) die (Richardson 1993). This latter situation may cause a divergence of the growth curve for the untreated crops, which is initially below that of the treated, to shoot up and surpass that of the treated stands.

Snowdon and Khana (1989) also highlighted the biological basis for response types I and II. They reported significant increases in foliar biomass resulting from weed control during establishment to enhance both water and nutrient availability. This could lead to extended periods of resource availability to the trees leading to the responses observed.

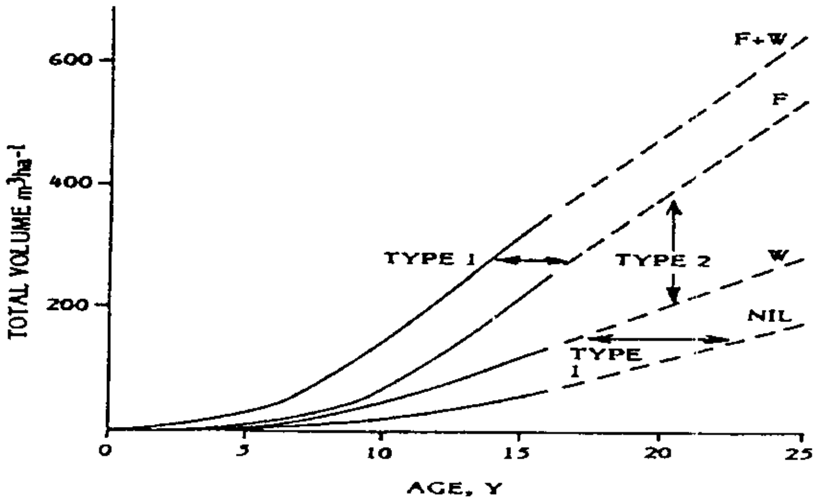


Figure 3.1 shows possible radiata pine growth responses to inter-specific competition and/or fertilization (After Snowdon and Khana 1989).

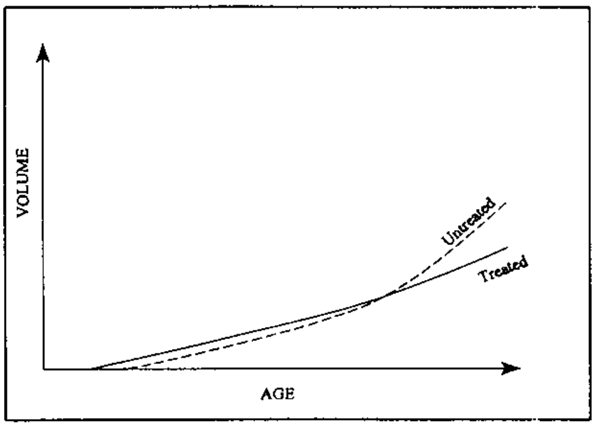


Figure 3.2 highlights possible envisaged radiata pine growth responses to oversown legumes in nutrient poor sites (After Richardson 1993).

3.1.2.3 Response identification. Many sources have reported increased growth effects of tree crops resulting from reduced woody and herbaceous vegetation, for example Squire (1977), Cellier and Stephens (1980), Nambiar and Zed (1980), Balneaves (1981, 1982), Balneaves and Clinton (1992), but the magnitude of competitive effects and the resultant responses depend largely on the species involved, their genotype, age and plasticity of growth habits leading to differences in interactions and resource use capacities (Nambiar and Sands 1993, Wagner and Radosevich 1991b, Radosevich and Oysteryoung 1987).

Trees register competition for water and nutrients as deficits. The responses to release from competition may therefore be the same as those for dealing with deficiencies (Nambiar and Sands 1993). These responses give plants a competitive edge over their neighbours and/or weeds. Plants respond to deficiencies by: 1) acquiring a greater proportion of the deficient resource; 2) using the limiting resource (water or nutrients) more efficiently to produce biomass; and 3) allocating assimilates in ways which maximise growth and survival (Nambiar and Sands 1993).

Trees react to above- and below-ground resource shortages by allocating more photosynthate to offset the limiting resource. Brand (1991) and Tesch *et al.* (1993) report trees to reduce shoot growth and increase root growth under increased water and nutrient stress. Normally, water and nutrient deficits manifest themselves when there is a low supply from the soil or competition from neighbouring plants or weeds. Leaf area index has been reported to be the most sensitive measure of stress, whether the causes are abiotic (light, water, nutrients) or biotic (defoliation or disease) or as a result of competition and deficiency. Water potential on the other hand has been the most widely used measure of moisture stress (Nambiar and Sands 1993).

3.1.2.4 Separation of effects from responses. Researchers conducting competition studies have difficulty separating effects and responses of crop trees. The dynamic nature of plant interactions and the confounding effects of some resources especially water and nutrients, for example, complicate competition studies. However, proper experimental design and interpretation of results in terms of specific processes may shed more light on interference mechanisms (Harrington and Tappeiner 1991, Tesch *et al.* 1993, Brand 1991, Burton 1993, Cousens 1995). Nambiar and Sands (1993) suggested researchers supply abundant nutrients so that they are not limiting when studying water stress.

3.2 PLANT GROWTH AND THE ENVIRONMENT

Both biotic and abiotic environmental stresses can reduce plant growth to levels below those genetically feasible (Pallardy 1986, Morgan 1984). Plant growth and productivity is a composite function of that of individual parts. Moreover, the timing of cell initiation and the number initiated play a major role, as well.

Site conditions and the micro-environment of the tree are thought to influence both the growth rate and the absolute height attainable by conifers (Radosevich and Oysteryoung 1987). The height asymptote is influenced by physiological controls of moisture transport and soil moisture availability combined with atmospheric demand of the site. Competition from non-crop vegetation limits resource availability and consequently reduces height growth.

Diameter growth results from various physiological processes which lead to cell division and thickening in the cambium. Competition affects the size and vigour of conifer crowns and may affect diameter distribution. Stress affects the pattern of bole development by interfering with the sheath volume laid around the bole (Zedaker *et al.* 1987). Generally, most trees under stress favour shoot growth over diameter growth (Harrington and Tappeiner 1991). As a result, competition may affect diameter growth more than height growth. Wagner and Radosevich (1991a) found that height was generally less sensitive to inter-specific competition than were diameter, stem volume and crown volume index.

Stressed conifers can exhibit different crown forms from unstressed ones. After crown closure an individual tree crown's development depends on tolerance of the species and competition from neighbours. Most species tend to shed lower branches as these receive less light and contribute less to photosynthesis. However, tolerant species with lower light compensation levels may keep their lower branches longer. The live crown ratio (live : total) has been used in some cases to indicate vigour. Zedaker *et al.* (1987), reported that most conifers were vigorous when the ratio was greater than 30 %. In mature trees competition causes crown differentiation. The resultant crown classes i.e. dominant, codominant, intermediate and suppressed have been used to classify mixed stands (Evans 1982, Zedaker *et al.* 1987).

3.2.1 Individual conifer tree growth patterns

3.2.1.1 Height growth. Genetics and environment are the main factors that influence height growth patterns of different plant species (Zedaker *et al.* 1987) although silvicultural manipulations have significant contributions too. Conifers generally show two basic patterns in seasonal height growth; fixed and free growth. In fixed growth (also called determinate growth), all height growth is achieved within the first few weeks of the growing season. In free growth (or indeterminate growth), height growth may continue under favourable conditions throughout the growing season.

Zedaker *et al.* (1987), named two basic processes to be important for height growth of individual trees. These are the size and number of cells produced and cell elongation. Conifers under moisture stress close stomata, leading to reduced uptake of carbon dioxide and hence fixation of carbon. This in turn reduces the amount of material available for production of new cells and thickening of existing cell walls; both of which are important for growth. Positive turgor pressure is vital for cell elongation. Stressed trees show reduced or even negative turgor pressure leading to a decline in height growth. Under extreme moisture stress crowns may become small and shrub-like with a loss of apical dominance.

Conifer height growth has been shown to be generally consistent, deviations mainly occurring as a result of outplanting shock and/or competition from non-crop vegetation. In plantations it is normal to classify trees by their developmental stage relative to height. These stages are: 1) seedling; 2) sapling; 3) pole; 4) thrifty-mature; and 5) mature stages.

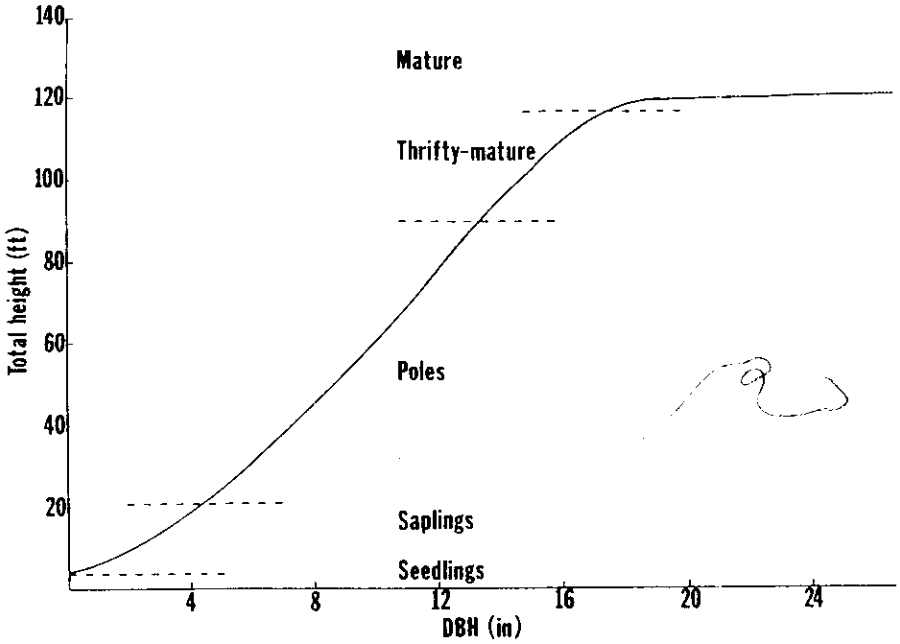


Figure 3.3: Five stages of height growth of forest trees (After Zedaker *et al.* 1987).

(1) Seedling phase. This is generally a slow growth phase. Planting shock can reduce the ability of seedlings to absorb water and nutrients. This may lead to reduced root growth which can further restrict height growth (Zedaker *et al.* 1987). Naturally growing seedlings do not suffer any planting shock and may have a high growth rate initially. However, low foliage mass may restrict growth. Also competition from non-crop vegetation can affect growth of tolerant species; intolerants tend to have very short growth periods and thus avoid excessive competition.

(2) Sapling phase. This stage is characterized by accelerated height growth. During the sapling stage competition can retard growth or even cause death of intolerants if severe. Conifers may "tolerate" intermediate competition and even increase a little in height but normally this is at the expense of both root and diameter growth (Zedaker *et al.* 1987).

(3) Pole stage. Height increment is almost linear. Zedaker *et al.* (1987) report growth rates of 0.6 to 1.6 m/year to be common. Competing vegetation may have very minimal effect on dominant and codominant height growth of conifers during this stage.

(4) Thrifty-mature phase. Height increases at a decreasing rate, with a sharp decline in relative growth rate. This stage can be short or long depending on the crop tree species and their tolerance to competition.

(5) Mature phase. Mature growth is normally signified by height tending to an asymptote indicating an upper limit for the particular site and prevailing conditions. In some cases it is possible that height growth may decline altogether, as in cases of die-back.

3.2.1.2 Diameter growth. In conifers, diameter growth generally takes a sigmoid shape decreasing rapidly with age. Temperate conifers form a distinct ring each year, the ring thickness being determined by genetics, tree age, position along the bole and the environment (Zedaker *et al.* 1987). Diameter growth results from cell division and thickening in the cambium. It begins with bud break and progresses downward from the top to the bottom of the bole. The number and diameter of individual cells produced determines diameter growth. Further, increased space resulting from thinning or lower stocking favours diameter growth. This may cause a redistribution of growth in response to mechanical stresses and also as a result of increased resource availability following reduced competition due to less numbers.

3.2.1.3 Crown development. The crown provides the photosynthate manufacturing areas (leaves or needles). The crown shape, size and rate of development will therefore determine height and diameter growth in conifers (Zedaker *et al.* 1987). Conifer crown forms have been described as excurrent if they are conical and show strong apical dominance as in young, actively growing conifers. But as they mature they become more stunted, less vigorous and more susceptible to disease and insect attacks.

Zedaker *et al.* (1987) named two main forms of conifer crown development: 1) fixed growth form where preformed primordia overwinter in the bud and elongate during the coming summer; and 2) free growth where the primordia elongate during the same season they are formed.

Most conifers show only free growth during the first or second year as seedlings. Douglas fir and true firs have been shown to exhibit fixed growth pattern. Such species can flush again under favourable conditions resulting normally in reduced shoot growth from the overwintering bud the following year (Zedaker *et al.* 1987). This is called lammas growth. Normally, conifers exhibiting fixed form will have crown growth closely relating to competition and the environmental conditions of the previous year when the number of cells and the amount of carbohydrates allocated to cell expansion are determined.

3.2.1.4 <u>Height and diameter relationships.</u> It is important to understand the relationship between height and diameter because:

1) the end product of value in forestry is volume, weight or fibre quantity (and quality) all of which can be derived from some functional forms of height and diameter; and

2) knowledge on this relationship can enable construction of taper and local volume tables which are important in forest management, yield forecasting and harvest scheduling.

Therefore stress factors which affect height or diameter growth or both can result in reduced crop value. The characterisation of stress in relation to resource availability is the subject of the next section.

3.3 COMPETITION AND RESOURCE AVAILABILITY: COMPETITION FOR LIGHT, WATER AND NUTRIENTS

Proper characterisation of competition from non-crop vegetation depends on correct identification of the limiting resources that are characteristic of the micro-environment. Resource capture is a function of availability and capture efficiency. Therefore, determining the physiological controls for growth and development of both the crop and non-crop species is an important requisite. The following brief discussion on resource availability expands on this.

3.3.1 Competition for light

Light is the driving force of photosynthesis and therefore a fundamental requirement for plant growth. Competition for light manifests itself when one species shades another because of more rapid growth, established dominance or taller stature (Radosevich and Oysteryoung 1987). Plants will rarely compete for light alone, but also for nutrients and water (Cannell and Grace 1993, Nambiar and Sands 1993). Different plant species have been shown to have different abilities to grow and survive under shade. Generally, species with high photosynthetic capacities show poor growth under shading compared to their counter parts growing in full light or species with lower photosynthetic capacities (Radosevich and Oysteryoung 1987).

Shade tolerant plants can be shocked if suddenly released to full light as after delayed thinning. Conifers may limit their own growth and productivity through self shading as a result of poor mosaic, needle density and branch orientation (Radosevich and Oysteryoung 1987). Under exposure to high light intensities though, conifers could increase their shoot and total root elongation as well as biomass.

Competition for light is normally by overtopping. Overtopping vegetation alters both the quantity and quality of light reaching the seedlings leading to a loss in production (Cannell and Grace 1993). Shading reduces the red:far red ratio. Most plants show physiological differences in response to light changes by photo adaptation to different light regimes, resulting in differences in carbon allocation due to changes in resource availability (Horsley 1993).

These changes can lead to:

1) etiolation, for most pioneer species;

2) increased leaf area in other species; and

3) change in leaf mosaic and arrangement of plastids in ways as to capture more photons of light per unit photosynthetic area (Cannell and Grace 1993).

Horsley (1993), showed that light below hay scented fern cover was poor in the 400 - 500 nm (violet - blue) and 600 - 675 nm (orange - red) parts compared with above the vegetation canopy. An increase in far red light was also detected with red:far red ratios of 0.50 under canopy shade above the vegetation compared to 0.07 in openings and 0.04 in shade areas below the vegetation; while that above was 1.10. This difference in light quality may explain, in part, the low survival and growth under shade. The magnitude of competitive effects for light from overtopping vegetation also depend on the species and the growth habits of the vegetation, whether short-lived like grasses and annuals, or long-lived, for example perennials (Nambiar and Sands 1993).

In forest environments light availability changes stochastically (unpredictable changes in full light, cloud cover, under shade or in canopy gaps). Young plants or those in the understorey experience great variability in irradiance (Berkowitz 1988). Plants cope by undergoing photomorphogenetic responses. They can allocate assimilates in ways that compensate for poor irradiance or a shift in the spectrum. Further, Cannell and Grace (1993) report that the phytochromes in young plant tissues can actually detect red:far red shift caused by shading from very low angles and a plant sensing this would react by extended growth.

Brand (1991) found that non-crop vegetation control improved light use efficiency but there was confounding as this could also arise for a variety of other reasons, for example:

1) improved light availability;

2) competition causing significant moisture and nutrient stress, hence limiting photosynthesis; and

3) low light levels before vegetation control such that seedlings spend most of their time below photosynthetic compensation point.

Light availability may also affect plant water status indirectly through its effects on transpiration, stomatal opening and closure, temperatures, humidity and internal CO_2 concentrations (Radosevich and Oysteryoung 1987, Nambiar and Sands 1993).

3.3.2 Competition for water

Water is an important resource and it can limit the growth and productivity of trees. Moisture availability may actually override light in importance (Radosevich and Oysteryoung 1987). Water stress can cause stomatal closure thus reducing gaseous diffusion, and consequently limiting carbon fixation i.e. photosynthesis (Teskey and Hinckley 1986, Radosevich and Oysteryoung 1987). Water has direct or indirect control over many other growth processes. For example, cell elongation and expansion, translocation activities, and maintaining turgor pressure which keeps the tree erect (Teskey and Hinckley 1986, Radosevich and Oysteryoung 1987). Moreover, water is also important as a solvent for gases and nutrients. Roots absorb water for the plant's physiological processes and have the ability to expose new soil horizons (rhizospheres). Radosevich and Oysteryoung (1987) explained that differences in the amount of photosynthate allocated to root growth could affect tree growth and relative competitive ability.

Direct relationships between water potential and competition do exist. Non-crop vegetation can reduce water availability to the crops and hence reduce water potential (Nambiar and Zed 1980, Sands and Nambiar 1984). For example, radiata pine showed decreased needle water potential with increased sorrel infestation from 0 % to 45 % with a closely related reduction in fascicle weight (Nambiar and Sands 1993). In another experiment in Victoria (Australia) on 2 year old radiata pine, reduced net photosynthesis, stomatal conductance and mid-day needle water potential of current year needles and volume growth from spring to summer were observed in unweeded compared to weeded plots on the same site, although confounding for nutrients was inevitable (Nambiar and Sands 1993).

Teskey and Hinckley (1986) point out that under severe competition plants may suffer moisture stress leading to various physiological and biochemical processes for example osmotic adjustment, foliage abscision, and even increased fine root turnover. Moreover, stand productivity may suffer as a result of competition effects on individual tree leaf areas, photosynthesis and carbohydrate allocation. This is supported by Berkowitz (1988) who reported that some plant varieties carry out "trade-offs" under stressful conditions. He reported that plants change allocation patterns, a strategy which made some varieties to be more productive under stress.

3.3.3 Competition for nutrients

Plant nutrients requirements fall into two groups: 1) Macro-nutrients - these are required in large amounts for example Carbon (C), Hydrogen (H), Oxygen (O), Nitrogen (N), Phosphorus (P), Potassium (K), Calcium (Ca), Sulphur (S), Iron (Fe), and Magnesium (Mg); and micro-nutrients which are required in small amounts e.g. Cobalt (Co), Boron (B), Manganese (Mn), Copper (Cu), Zinc (Zn), Molybdenum (Mo), Chlorine (Cl), Sodium (Na), Aluminium (Al), Silicon (Si), and Gallium (Ga). Rapid growth in plants could come about as a result of a variety of physiological traits that allow rapid exploitation of soil nutrients and absorption by roots (Radosevich and Oysteryoung 1987, Troth *et al.* 1987). Plants with high respiration and photosynthetic rates exhibit rapid growth especially under full light. Such plants have high levels of foliar nitrogen which influences the photosynthetic process (Radosevich and Oysteryoung 1987). Nambiar and Zed (1980) reported nitrogen depletion due to competition to lower growth rate considerably.

Photosynthesis and root absorption decline with tissue age. Different species may exhibit adaptations to retain and use nutrients efficiently (Radosevich and Oysteryoung 1987). Some of these adaptations are long lived ever-green leaves or long lived root structures, effective translocation of nutrients between tissues or morphological traits like pubescence which minimise foliar leaching of nutrients.

Nutrients absorption takes place in water solution. This makes them hard therefore, to quantify because of confounding effects with water. Will (1985) summarised some of the common observable effects of nutrient deficiencies.

1. Nitrogen -	all over yellowish green to yellow colour with narrow crowns, small branches and short needles.
2. Phosphorus -	short foliage with normal colour but turning yellow at the tips on minor branch ends in late summer. Narrow crowns with small branches and poor needle retention with some needles fused together can also occur.
3. Potassium -	bright yellow needle tips in the mid - lower crown of the tree observable especially in late winter on previous season's foliage.
4. Magnesium -	golden yellow needle tips on previous year's foliage seen in spring to early summer.
5. Boron -	death of the leader and shoots of top branches, especially in mid to late summer of dry years.
6. Copper -	severe wobble or twisting of leaders and branches. Under severe deficiency, leaders may assume "horizontal" growth habits.

3.3.4 Space capture and density

The space occupied by an individual plant has been used in some studies as an indicator of resource capture and use. The mutual effects of individuals sharing the same environment could be assessed assuming that each one acts as the biological indicator of space-use by the other and using space, therefore, as an integrative resource (Radosevich and Oysteryoung 1987). However, caution should be exercised where the identity and availability of a limiting resource can alleviate deficiencies exacerbated by neighbours. Space is better treated as a composite factor and the other resources treated independently. This is because early occupiers of a site have been shown to have a competitive edge over neighbours established later in the site (Radosevich and Oysteryoung 1987).

Density can be defined as the number per unit area or more precisely, as the amount of biomass per unit area (Davis and Johnson 1987, Radosevich and Oysteryoung 1987). As plants grow a density is reached when they start to interfere with each other. Generally, plants at high initial stocking have been shown to experience competition from neighbours faster than those established at lower initial stocking levels (Radosevich 1988). Radosevich (1988) explains further that in fully occupied stands the yield per unit area is claimed to be independent of density; this is known as the "law of constant final yield". At higher densities, the resource limiting power of the environment becomes a critical factor and the final yield may be determined by many small plants or by fewer larger ones as a result of density dependent mortality (Radosevich and Oysteryoung 1987). Rapid colonization and fast juvenile growth of plant size and ample spacing can lead to successful use of limited site resources resulting in a competitive edge over others. Most monospecific commercial forestry establishment methods mimic this situation to give desired crop trees an advantage over non-crop vegetation (Radosevich and Oysteryoung 1987).

3.3.5 Competition and root growth

Roots play an important role in a tree's life including anchoring the plant firmly in the soil substrate and acquiring water and nutrients for various important life processes. The magnitude of root competition is a function of:

1) co-existence of different plants' roots in the same soil zone;

2) partial or temporal segregation of the different plants' demands; and

3) differences in morphology and anatomical features of the root systems.

Generally, competition would occur where depletion zones overlap, even though nutrient uptake depends on a particular plant's demands and the ability of the soil to meet the demand. Also the demand can be nutrient specific especially for immobile nutrients like phosphorus (Nambiar and Sands 1993). Thus, plants with the same rooting habits, like those of the same species, will compete regardless of the nutrient mobility status. This may explain why woody non-crop vegetation, with similar rooting habits like crop plants can compete aggressively and for very long periods of time, sometimes even after canopy closure (Balneaves 1981). Balneaves (1981) reported that woody weeds, for example broom and gorse in particular, growing with radiata pine showed preferential uptake for nutrients, especially boron and phosphorous in some New Zealand sites.

Roots have also been shown to exhibit growth plasticity and morphology in different environments, a strategy to cope with resource depletion. Berkowitz (1988 p.99) listed some studies which demonstrated total root length, root volume, density (numbers or root surface area), root placement and geometry to be important factors influencing competitive ability. Trees tend to cope with competition or deficiencies by: 1) spatial segregation of roots to avoid competition; and 2) increasingly taking resources from soil depths out of reach of competitors. This may be the reason why competition for moisture from shallow rooted weeds would normally decrease after one or two seasons' growth. However, nutrients abound in the top soil layers mostly (unless leached), where high numbers of roots especially from herbaceous vegetation and grasses are found, and competition may be very aggressive (Balneaves 1982, Richardson 1993, Lauer *et al.* 1993, Nambiar and Sands 1993). Moreover, Balneaves and Clinton (1992) add that grass competition for nutrients and water may continue to be aggressive even after the first 2 years following establishment, especially on dry sites.

3.3.6 Competition and allocation

Trees carry out compensatory growth to offset the effects of limiting resources. In most trees, cambial growth has a lower allocation of photosynthate than shoot growth (Harrington and Tappeiner 1991). Therefore, under moisture stress, shoot growth tends to be favoured over diameter growth when both are actively growing (Harrington and Tappeiner 1991, Wagner and Radosevich 1991a). Plants grown in low light show fewer root tips. They allocate less carbon to their roots and end up with lower root:shoot weight ratios than their counterparts in full light (Berkowitz 1988, Horsley 1993).

Moreover, trees on poor sites tend to have more fine root turnover than those on fertile sites, because more assimilate is used on fine root production (Nambiar and Sands 1993). Seedlings however, may favour root development to shoot growth during their first growing season. Morphological changes may also occur as a result of competition rather than shifts in allocation between roots and shoot (Tesch *et al.* 1993).

3.3.7 Other factors affecting plant growth

Other factors, for example nursery and handling practices (Brunsden 1981, Cullen and Mason 1981, Menzies *et al.* 1981, van Dorsser 1981), site preparation, topography and aspect, initial seedling size (Mason 1992, South *et al.* 1993a) and animal damage (Wagner and Radosevich 1991b) can have significant effects on young conifer growth and survival. Thus the development of appropriate silvicultural interventions to improve plant growth should consider the effect of these factors as well.

The gene pool of a species may make it a better competitor, or more resilient to deficiencies brought about by competition (Nambiar and Sands 1993). The genetic quality of the stock can help it outcompete weeds. These gains normally occur in the nursery and in the first two growing seasons after out planting (McDonald and Fiddler 1993). Tree age can also affect inter-specific competition significantly. In one study it accounted for 34-42 % of tree size variation, 42 % for height, 38.1 % for diameter, 40.1 % and 34.4 % for stem volume index and crown volume index respectively (Wagner and Radosevich 1991b).

CHAPTER 4

QUANTIFYING COMPETITION EFFECTS IN PLANTATIONS

4.1 ESTIMATING THE COMPETITIVE EFFECTS OF NON-CROP VEGETATION ON CROP PRODUCTIVITY

4.1.1 Overview: measuring competition

Competition studies can be very useful especially when yields of all species in the experiment are measured. Yield loss of the desired tree species can be expressed in terms of the yield (volume or biomass) of the other species (Radosevich and Holt 1984). In forestry, destructive methods are not very popular and when used, the data are very important. Regression models relating tree growth to competitor density or biomass are commonly employed. In some cases it may be possible to have several measurements. For example, when the competitors are woody, it is then possible for changes in dominance or abundance of both competitor and desired crop species to be evaluated.

A more useful technique of measuring competition is to use growth rate instead of the final yields. This method lends itself useful to growth analysis. Growth analysis is a dynamic procedure which uses periodic harvests, dry weights, biomass or proportions of the various components (Radosevich and Oysteryoung 1987). However, absolute growth rate depends, in part, on the amount of material already present. Therefore, individuals of different sizes cannot be adequately compared. Expressing growth rate relative to the amount of growing material already present (relative growth rate, RGR) is more meaningful especially when growth rate comparisons are made at different times, for mixed species growing together (competition) or under different environments (treatments). However, RGR comparisons must be made **only for plants with similar initial size**, otherwise there is potential confounding with size (Britt *et al.* 1991). This will be explained in detail later in this chapter. Further, regression models which use functions of the form $dY/dt = Y(\text{relative growth modifier})$ are even more powerful.

This chapter discusses how competitive effects from weeds on crop productivity are estimated, and the common methods i.e. experimental designs and analyses used. The chapter ends with a brief review of some competition models which were developed from previous studies.

4.1.2 Growth; productivity; and relative growth rate

Growth is defined as the increase in size or weight with time. **Yield**, on the other hand is the accumulated growth expressed over a time period or the total amount of product harvestable at any given time (Davis and Johnson 1987). **Productivity** refers to the total amount of above- and below-ground biomass or dry weight. However, total biomass and dry weight may involve destructive methods and are not appropriate where repeated measures are required. Therefore, many competition studies have used basal area and height growth (and sometimes above ground biomass) to express plant productivity.

Individual conifer tree growth results from the summation of all cell processes including division, elongation and cell thickening. Rates vary slightly between species. Expressed as a cumulative function it takes the form of a sigmoid curve (Evans 1982, Clutter *et al.* 1983). In fact all tree dimensions or variables i.e. height, diameter, basal area, volume and weight exhibit this general form when plotted against age. Expressed as an equation, it takes the form of the logistic growth curve. Thus, young trees would grow relatively slow at first, then increase their rate to the point of inflection. Thereafter the rate declines with age, slowing down in mature trees and finally approaching zero towards senescence.

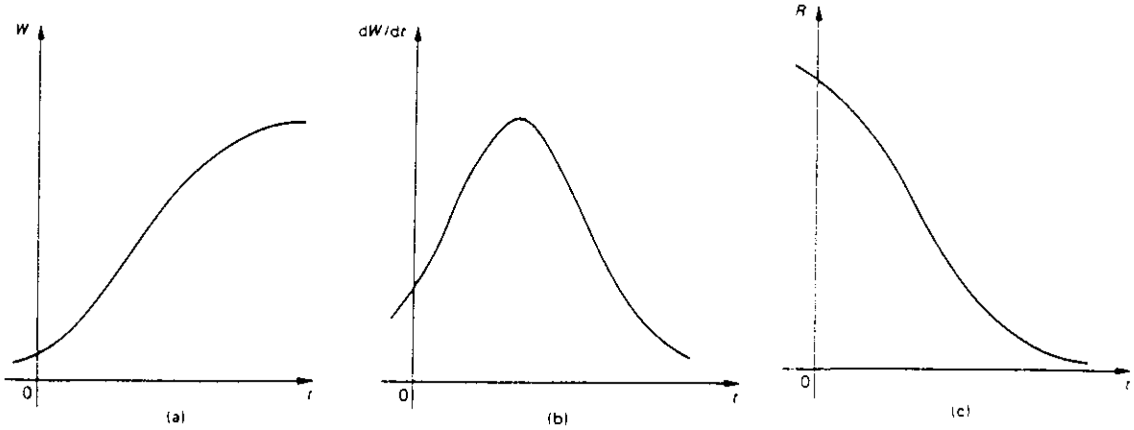


Figure 4.1 shows curves for conifer growth (a) increase in size or weight (W), (b) absolute growth rate (dW/dt) and (c) relative growth rate (R = dW/dt*1/W) as functions of time (After Causton 1983).

Competition in plantations has been assessed using subjective measures employing some estimates of absolute tree growth characteristics (Wagner *et al.* 1989, Zedaker *et al.* 1987, Wagner and Radosevich 1991a). In some cases some quantification of growth or yield has been attempted using single crop tree measurements taken once either at harvest or within the rotation by destructive sampling procedures. However, growth analysis is a dynamic technique calling for the use of periodic estimates of yield of both the tree crop and the competing non-crop vegetation (Zedaker *et al.* 1987). This is important especially in some forestry situations involving woody non-crop vegetation. Observations taken periodically can then be used to express changes in species growth and dominance patterns which occur over time. This has necessitated objective study approaches which manipulate both the crop and non-crop vegetation densities (Brand 1986, Radosevich and Oysteryoung 1987, Zedaker *et al.* 1987, Radosevich 1988, Wagner *et al.* 1989, Wagner and Radosevich 1991a).

(1) Estimating growth loss. Production analysis methods using regression procedures relating a non-crop vegetation variable (volume, density or weight) to probable crop tree biomass or volume have been very useful. These relationships have used crop yield and non-crop vegetation density to derive crop tree growth loss functions. Crop tree yield increase or resultant productivity is then estimated after non-crop vegetation release treatments (Zedaker *et al.* 1987).

(2) Yield loss forms. Radosevich and Oysteryoung (1987) have described the relationship between crop yield and non-crop vegetation density to be sigmoid. However, Auld *et al.* (1987) and Cousens (1987) describe the most common generalized form to be a hyperbolic curve with negative concavity. In both cases there is little loss in growth at very low non-crop vegetation densities. But as weed density increases to higher levels crop yield decreases sharply to a point below which further increases in weed density are not followed by proportional yield reduction (Auld *et al.* 1987, Wagner *et al.* 1989, Cousens 1987).

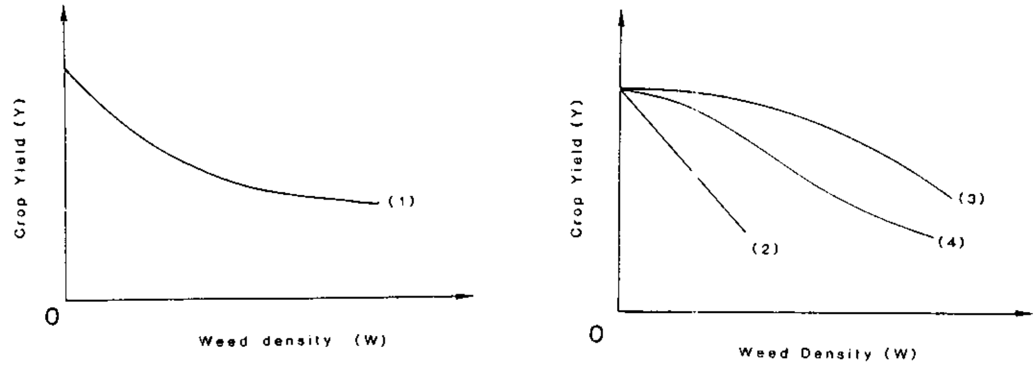


Figure 4.2: The relationship between desired cop yield (Y) and non-crop vegetation density (W); (a) common type, (b) other forms (After Auld *et al.* 1987).

Other forms of crop yield/non-crop vegetation density curves have been suggested. These are highlighted in figure 4.3 with their corresponding yield loss curves. However, a detailed discussion on these curves is not included and interested readers can refer to Auld *et al.* (1987).

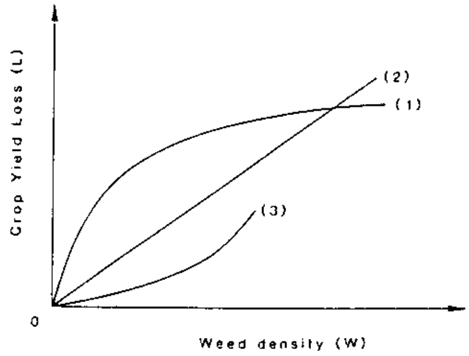


Figure 4.3. Three forms of yield loss (L) by non-crop vegetation density (W) derived from the relationships in figure 4.2 (After Auld *et al.* 1987).

4.1.2.1 Relative growth rate. Growth rate has normally been expressed as the arithmetic mean of the desired crop measures over time. However, absolute measures of growth tend to over estimate the effects of competition (Brand 1986). The use of relative growth rate (RGR) which is a whole plant measure of vigour accounting for size-related variation in plant productivity can overcome this problem. RGR is expressed as $(\ln w_2 - \ln w_1)/(t_2-t_1)$; w_1 and w_2 are growth estimates at time/age t_1 and t_2 respectively (Causton 1983, Zedaker *et al.* 1987, Brand 1991).

Relative growth rate (RGR) is therefore defined as the change in dry weight per unit time per unit growing material. It is an efficiency measure of production of a given unit of plant size (Causton 1983, Radosevich and Holt 1984), and can be expressed mathematically as:

$$RGR = (dW/dt)(1/W);$$

where:

dW = change in dry weight;
dt = change in time (unit time); and
W = growing material.

Relative growth rate (RGR) has been used successfully as an index of productivity. It is an index that compares the rate of growth at different times and expresses it relative to the amount of growing material already present. This is more meaningful compared to absolute growth rate which depends on the absolute amount of growing material and is therefore influenced by initial plant size, environmental changes and competing vegetation which affect all tree dimensions (Causton 1983, Radosevich and Oysteryoung 1987, Stewart 1987, Zedaker *et al.* 1987). However, Britt *et al.* (1991) report that RGR does not separate effects of treatments and tree size at the beginning of each period. This can be accounted for by comparing RGR using trees of equal size from each treatment.

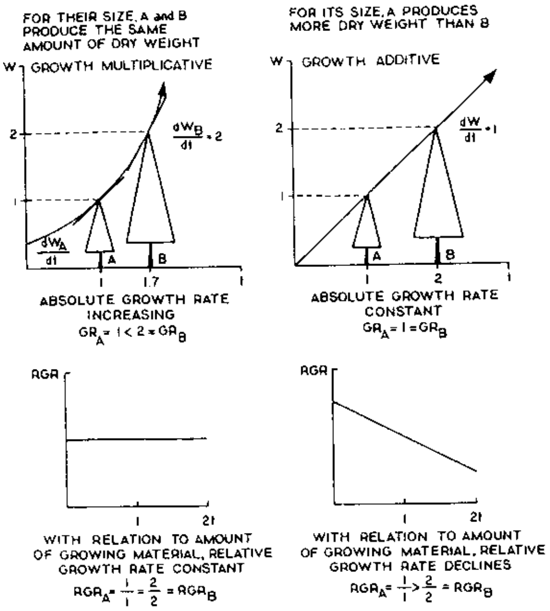


Figure 4.4 shows the relationship between growth rate and relative growth rate under multiplicative and additive dry weight (W) growth in time (t), (After Radosevich and Oysteryoung 1987).

However, Radosevich and Oysteryoung (1987), and Zedaker *et al.* (1987), cited difficulties in measuring dW/dt as this is not directly observable and recommended use of average growth rate over time. They expressed average growth rate mathematically as;

$$dW/dt = \overline{G} = (\log W_{t_2} - \log W_{t_1})/(t_2 - t_1)$$

where;

$\overline{G}$ = average growth rate,

W_t = size or weight at time t, and

log = logarithm to base 10.

RGR can further be partitioned into net assimilation rate (NAR) and leaf area ratio (LAR). Net Assimilation Rate (NAR), is the rate of increase in total dry weight (dW/dt) per unit leaf area (LA). NAR can thus be expressed as (dW/dt)(1/LA). Leaf area ratio (LAR), on the other hand, relates the degree of assimilatory surface to biomass and is expressed as LA/W; where LA is the total leaf area or assimilatory surface and W is the total weight (Radosevich and Oysteryoung 1987, Causton 1983).

The partitioning of growth components enables certain features of the tree crop and shrub physiology and morphology which are influenced by competition, to be investigated more closely (Causton 1983). This may allow the development of alternative management strategies to increase crop growth. It also allows an inner view of the allowable level of co-existence between tree crops growing with non-crop vegetation.

4.1.2.2 Improvement of relative growth rate (RGR) measures. Growth analysis equations are superior to models that use process-oriented equations in estimating development and physical performance or growth of trees (Brand 1991). They use environmental factors as the determinants of growth. Generally, soils (Davis and Johnson 1987) and rainfall are the major limiting factors, but so are local environmental resources in a site for example, light, moisture and nutrients (Berkowitz 1988). Brand (1986) states that RGR has not been used extensively in forestry studies because of the tendency for perennial trees to accumulate non-productive material with time leading to an artificial decline in RGR. Moreover, if we assume $dY/dt = kY$, we find that $k \neq$ constant and that it changes with size (Mason 1992) and/or silvicultural treatments e.g. fertilization. Sigmoid functions can represent the change in k.

Several modifications of RGR have been used. Brand (1986) used relative productive rate, x_i/x_{i-1} where x_i is current season growth of height or basal area, and x_{i-1} is the previous season's increment of the same variable. Further, Brand (1991) partitioned RGR into physiological yield components using net assimilation ratio (NAR) - a measure of foliar efficiency, and leaf area ratio (LAR) - a measure of allocation between photosynthetic and non-photosynthetic tissue. Moreover, LAR was divided into leaf weight ratio (LWR) - an index of biological allocation and specific leaf area (SLA) -

an index of foliage morphology all in a bid to highlight effectively the causal mechanisms of growth responses. Britt *et al.* (1991) estimated the direct response to silviculture and management interventions by removing the confounding effect of initial size. They used an integrated approach where direct and indirect effects were partitioned using regression models. The models related direct growth responses to continued treatment effects and indirect effects to size differences induced by the treatments. By using this approach (integrated approach) Britt *et al.* (1991) observed similar patterns for both RGR and biomass, but RGR was a better indicator of treatment induced effects on conifer seedling responses to light than biomass. They also used classical growth analysis to try to remove confounding due to size differences. However, RGR did not remove this confounding. As a result they proposed another approach i.e. comparing RGR at times when tree size at the beginning of each period was identical. This approach "appeared" to have removed confounding effects of size.

4.2 COMMON DESIGNS USED IN COMPETITION STUDIES AND THEIR PROBLEMS

Studies on the effects of non-crop vegetation abundance on crop yield have identified the following three factors as being very important. These are: 1) total density of undesirable plants; 2) proportion of each species involved; and 3) spatial arrangement of the species relative to each other (Radosevich and Oysteryoung 1987, Radosevich 1988). Most studies have used relationships based on density and final crop yield or biomass. Dry weight, which is a better indicator of competitive ability is impractical as it may involve destruction of crops and the harvesting of large volumes of non-crop vegetation.

Density (numbers of plants per unit area or % cover), used as a variable, is advantageous because it can be determined early enough during crop tree life when decisions on non-crop vegetation control are really important (Auld *et al.* 1987, Radosevich and Oysteryoung 1987). The relationship between density and crop yield loss is species specific. Moreover, externalities like environmental conditions, time of sowing and additional non-crop vegetation which may establish later in the life of the crops can also influence this relationship.

4.2.1 Designs used

Various experimental designs have been used in studying inter-specific competition effects. Radosevich and Holt (1984), Radosevich and Oysteryoung (1987), Radosevich (1988) and Cousens (1995) discussed additive, substitutive and systematic designs extensively. Further, Radosevich (1988) names another design, "the neighbourhood design" useful in investigating neighbour-related stress factors. This approach will be discussed fully in section 4.3 under "Approaches to evaluating competition in young conifer stands".

4.2.1.1 Additive designs. Additive design experiments use an artificial weed population sown at different densities but keep the crop density constant. The crop acts as the indicator of aggressiveness of the non-crop vegetation species (Auld *et al.* 1987, Radosevich and Holt 1984, Radosevich and Oysteryoung 1987, Radosevich 1988, Cousens 1995). The method is accurate and relevant to many field situations as normally the crop is established at constant stocking. The approach uses yield loss to express the degree of competition and provides insight into weed control economics with the cost of competition expressed as yield loss. Cousens (1995) narrates further, that prediction of the long term dynamics of a single non-crop vegetation species is possible using this design under a fixed cropping system. However, difficulty in determining the degree of interaction between the species or individuals arising from failure to control proximity based influences (density, proportion) is still a drawback in yield loss assessments.

4.2.1.2 Substitutive designs. These designs are also called replacement series (Radosevich and Holt 1984). Total biomass or density of the weed and crop species are both assessed but the two are established in varying proportions. The crop species is also established alone to estimate intra-specific competition (Radosevich and Oysteryoung 1987, Cousens 1995). Radosevich and Oysteryoung (1987) further argue that weed thinning experiments, as they are also known, are quite practical and have several predictive advantages. Cousens (1995), singles out this design as being useful in determining which of two non-crop vegetation species is more aggressive.

Radosevich and Holt (1984) suggested four general models based on substitutive designs (Figure 4.4). Model I shows both the weeds and crop species to exhibit identical resource demands on the environment and can therefore, substitute each other. Model II shows that there is competition, the result is that one species provides more to the final yield. This is the more usual case under normal circumstances. Species A is more aggressive than species B and may eventually replace B in model IIa. However, this is reversed in model IIb where species B is more aggressive than A (see also page 72). Model III shows that neither species contributes its expected output to the final yield. This is a case of mutual antagonism. Model IV shows that both species yield more together than either on its own. This could be as a result of each species "shying off" and not competing with the other. It is a case of mutual gain or symbiosm.

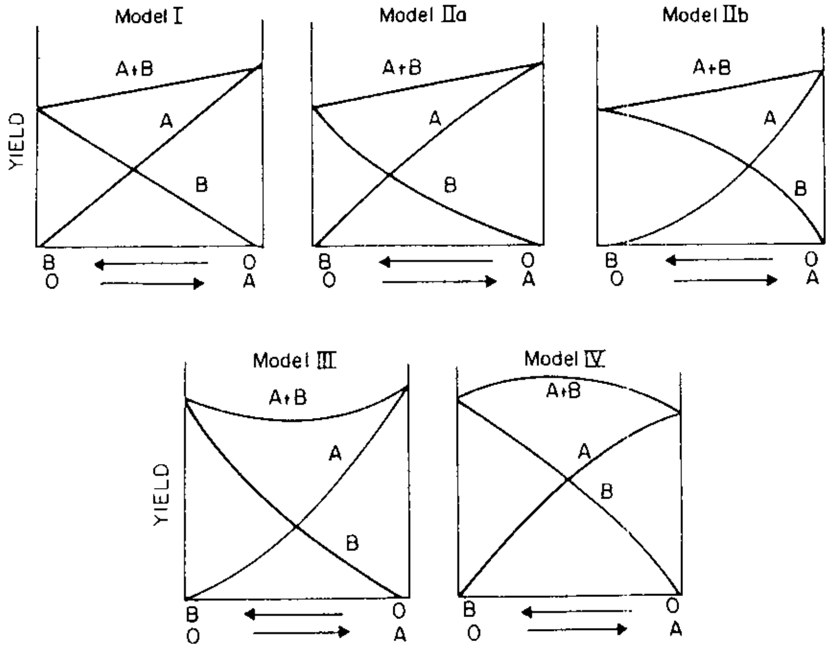


Figure 4.5 depicts models from replacement series experiments showing yield (Y) vs. proportion of each component in the mixture (After Radosevich and Holt 1984).

4.2.1.3 Systematic designs. These designs have been referenced as Nelder designs in other literature (Radosevich and Holt 1984, Radosevich and Oysteryoung 1987, Radosevich 1988). The crop species' density and arrangement are both taken into account. These designs have not been used a lot in forestry but are more useful in accounting for spatial arrangement of the competitors.

4.2.2 Problems of competition studies

Advances in studies quantifying the competition effects of non-crop vegetation have been slow because of problems in proper design and interpretation of results and confounding effects of treatments for water, nutrients and site preparation techniques. Other problems are the influence of weed management on other resources (Mason 1992, Richardson 1993, Nambiar and Sands 1993, Fredricksen *et al.* 1993, Shainsky *et al.* 1992, Burton 1993), and restrictive environmental conditions for water and nutrients i.e. temperatures, soil PH and compaction may influence water and nutrients availability significantly. Finally, seasonality of growth of different plant parts and genetic predisposition and plasticity of responses which influence allocation (Burton 1993, Tesch *et al.* 1993, Harrington and Tappeiner 1991, Brand 1986,1991) have also made studies difficult.

4.2.2.1 Problems of Design. Earlier models concentrated on comparing various control methods. These led to advances in new technologies and demonstrations of weed control methods (Radosevich 1988, Wagner *et al.* 1989). The methods were mostly based on subjective measures of non-crop vegetation and could not be used to evaluate objectively the need for vegetation management.

Mechanistic models were used to describe below and above ground competition using root length, diameter and density in soil and hydraulic conductivity as variables. Methods using extractable nutrients from the soil were also employed. However, Wagner *et al.* (1989) mention that these are poor indicators of the dynamic nature of competition. Moreover, changes in nutrient uptake relations, growth patterns, translocation and tissue senescence can lead to nutrient fluxes due to the non-crop vegetation making such methods unreliable.

4.2.2.2 Interpretation problems. Problems of interpretation of competition effects in terms of specific processes may be due to the influence weed control can have on soil water relations and soil temperatures which can in turn influence nutrient availability. Site preparation methods can also influence the composition and abundance of non-crop vegetation. This can confound certain treatment effects. For example, herbicide effectiveness depends on the rate and time of application, and the weather and may result in some non-crop vegetation being more suppressed than others depending on their physiological state at the time (Mason 1992, Nambiar and Sands 1993). Moreover, the nature of competition and soil resources may change with time as trees grow. Thus in early years there is intense competition for water while in later years competition may shift to nutrients and/or light (Nambiar and Sands 1993, Wagner *et al.* 1989). Competitive effects have also been reported to accumulate with time and thereby to limit future potential growth due to restricted size and morphological development. The magnitude of growth in a current season is therefore closely related to the previous season's growth (Harrington and Tappeiner 1991, Brand 1986,1991).

Despite these problems, studies on competition from non-crop vegetation in plantations have made significant advances. Inter-specific competition has been evaluated using growth performance relative to treatment by measuring quantified indices of competing vegetation. The cost and biological performance plus the time taken to do the task have all to be considered for cost effectiveness and feasibility of the control regimes (McDonald and Fiddler 1993, Shainsky *et al.* 1992, Nambiar and Sands 1993).

4.2.3 Summary: which Experimental design is best?

Cousens (1995) discussed incisively the "dogma" behind justifying certain designs but labelling others as "non-starters". He cautioned that logic should prevail, for a good design was one that answered a researcher's questions best, a view shared also by Radosevich (1988). Moreover, no one single design could adequately answer all the researcher's and/or manager's questions (Radosevich 1988). Therefore, the choice of design, analysis procedures and interpretation should conform to the objectives. Consequently, useful experiments are those that bear resemblance to actual field situations.

4.3 APPROACHES TO EVALUATING COMPETITION IN YOUNG CONIFER STANDS

4.3.1 Overview: what and how to assess

Two approaches (quantitative and qualitative) have been used with varying degree of success. Many studies have emphasised the important contribution of quantitative approaches in examining inter-specific competition. Indices using quantified measures of competing vegetation for example, density, foliar cover, height and proximity, have been developed to describe the interference effects of non-crop vegetation on crop height and stem diameter growth. Many researchers have reported such indices to have great potential in forecasting need for silvicultural release treatments (Brand 1986,1991, Comeau *et al.* 1993, McDonald and Fiddler 1993, DeLong 1991, Burton 1993, Cannell and Grace 1993, Wagner and Radosevich 1991a, 1991b).

Subjective measures used previously have not been useful in explaining the highly dynamic nature of competition effectively. Quantitative measures of competition, on the other hand, are important for management and silvicultural manipulation to succeed in preventing crop suppression and in identifying sound and effective non-crop vegetation management regimes (Brand 1986, Fredricksen *et al.* 1993, Shainsky *et al.* 1992). Thus, experiments which manipulate the crop as well as the non-crop vegetation densities have been useful in quantifying the discrete effects of competition, notwithstanding the problems of confounding of resources (especially water and nutrients, Nambiar and Sands (1993)) or interpretation of specific effects (Shainsky *et al.* 1992).

The following variables have been used in many competition studies.

4.3.1.1 Crop tree measures. Water potential and stem diameter and leaf area have been used widely. Water potential measures are useful in expressing stress. However, they are static measures and even continued measures would not explain changes separately from environmental and climatic influences on competition. Stem diameter is a good measure of competition severity in seedlings of conifers but plant density, foliar cover and height of non-crop vegetation affect crops differently.

4.3.1.2 Non-crop vegetation measures. Reliable measures of non-crop vegetation may need to incorporate abundance or cover, density, and height. Foliar cover is often inadequate, especially for species like grass and forbes due to their low above-ground biomass. But it can give adequate horizontal estimates for species with multiple stems and well developed crowns. Foliar cover is also easy to estimate and interpret. Plant density (abundance) is an important measure for species exhibiting strong competition but with low above-ground biomass, for example grasses. Height of competing vegetation can easily be seen, indicating when control treatments can be best applied, usually before overtopping (McDonald and Fiddler 1993; Shainsky *et al.* 1992).

4.3.2 Qualitative or subjective methods

It has already been stated that previous methods of expressing competition effects used subjective measures of absolute height or diameter (basal area) growth, and control measures were applied whenever weeds overtopped crop trees (Brand 1986). Absolute height and basal area measures are, however, influenced by past performance more than by current crop vigour (Causton 1983, Radosevich and Oysteryoung 1987, Brand 1991). Absolute growth measures also diminish as trees increase in size and are very sensitive to variation in environmental changes (Brand 1986, Zedaker *et al.* 1987). This coupled with the fact that interference effects are highly phenological in nature and that competition itself is highly dynamic, make subjective methods less reliable.

4.3.3 Quantitative or objective methods

Quantitative approaches make use of well designed and controlled experiments to manipulate tree crop and non-crop vegetation densities. They try to identify and separate competition processes into discrete mechanisms of effects and responses (Brand 1986,1991). They are also based on sound biological relationships between competition effects and tree growth responses (Morris and Forslund 1991). These attributes make them to be superior to qualitative approaches.

Generally, two approaches have been used to evaluate inter-specific competition in young conifer plantations. They are the **whole stand** approach and the **neighbourhood** approach. Both methods have shown decreased growth in tree crops with increased vegetation abundance. However, the neighbourhood approach allows more detailed examination of interference processes among plants than the whole stand approach (Wagner and Radosevich 1991a).

4.3.3.1 Whole stand approach. With the whole stand approach, the yield of the average tree or whole stand is estimated from average measures of non-crop vegetation attributes (abundance, height, leaf area, percent cover) throughout the stand (Wagner and Radosevich 1991a). The method is useful to assess impacts of competition on growth and yield of the whole stand. However, unevenness of competition within the stand is not properly addressed in many cases.

4.3.3.2 Neighbourhood approach. The neighbourhood method estimates the growth and yield of individual trees from the degree of local crowding by neighbouring non-crop vegetation (Radosevich 1988). The approach allows more detailed examination of competition processes among plants than the former (Radosevich 1988, Wagner and Radosevich 1991a). It also allows competition impacts from various conditions within the site to be investigated. Thus variation in micro-environmental factors and their effect on growth can be investigated more closely. An implicit model describing the performance of an individual tree P(T) can be written as:

P(T) = f(numbers, biomass, cover, aggregation, proximity), of neighbours.

Improvements on the design include variation in aggregation, distance, and density of the neighbours (Radosevich 1988). This is important as micro-site variation, which may come about as a result of site preparation methods (Newton *et al.* 1987, Mason 1992), or weed control treatments (Balneaves 1981, 1982), may greatly influence the growth and productivity of individual trees. Ultimately, managers may improve the productivity of the whole stand by concentrating their efforts and resources on individual tree growth.

Five relationships between weed density and tree growth have been reported. Figure 4.6 shows these relationships.

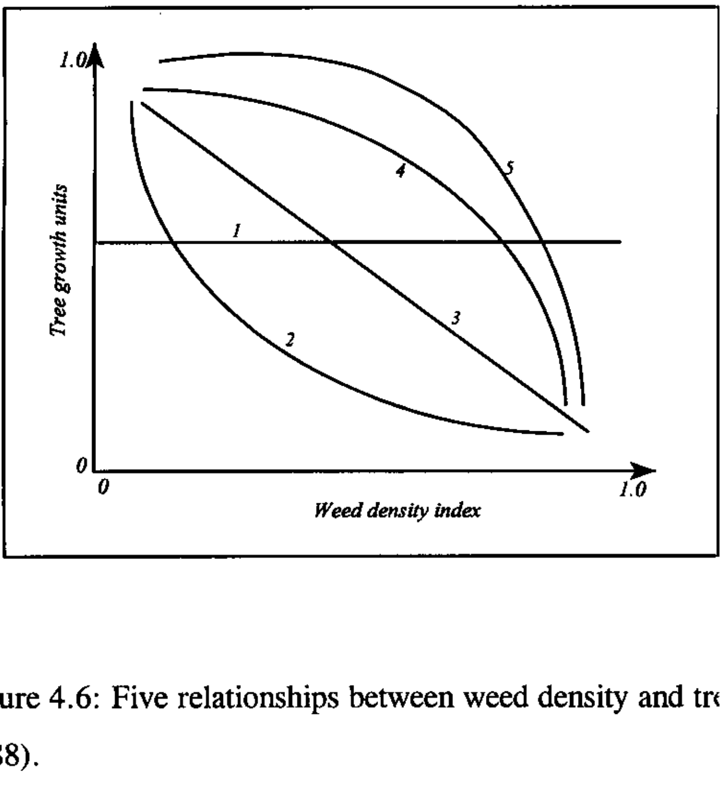


Figure 4.6: Five relationships between weed density and tree growth (After Radosevich 1988).

1 = no interaction; slope not significantly different from zero.

2 = negative exponential function showing decrease in competitiveness with increase in neighbour abundance (cover, biomass, leaf area).

3 = linear relationship.

4 = curvilinear with positive slope; minimal competitive effects at low densities but increasing in severity at higher weed densities.

5 = curvilinear with positive slope; characteristic quadratic function with peak at some intermediate neighbour density. In this case neighbours have beneficial effects at low densities, for example reducing temperature variations at the soil surface as a result of shading effects. However, they become competitive at higher densities.

4.4 MODELLING COMPETITION EFFECTS

4.4.1 Overview: Growth Modelling

A model is a simplified representation of reality. It is an abstraction of real world processes and actions (Conway and Murdie 1971, Christiansen 1975). Because real world processes are complex, models tend to use only important variables and established relationships all the while aspiring to give adequate precision. Consequently, they aid in understanding complex systems. For example, forest managers need sound predictions of the future growth trends and expected yields of forest stands. Stand models are used to describe changes in growth and yield and/or mortality (Davis and Johnson 1987, Clutter *et al.* 1983). Therefore, growth models give insight into future effects of present silvicultural and management actions. Vanclay (1994) summarised growth models to be "*syntheses of dynamic inventory data indicating growth change in forests*".

4.4.1.1 Why model growth? Growth models are important for sustainable forest management. Optimal management decisions regarding intensities and duration of various management inputs and their timing require accurate objective predictions. They are vital for yield forecasting and harvest scheduling, and economic analysis of forestry ventures (Clutter *et al.* 1983). Moreover, models can also be used to explore silvicultural alternatives. Also, when used in combination with other information, for example environmental data, growth models form a formidable tool for making sound policy prescriptions (Vanclay 1994).

4.4.1.2 Types of growth models. There are many categories of models depending on the emphasis, sensitivity and detail of the results required (Clutter *et al.* 1983, Davis and Johnson 1987). Some models are useful for predictive purposes and are therefore, extremely important in forest management, for example whole stand, size class or single tree models (Vanclay 1994). Other models can help link isolated bits of knowledge and identify knowledge gaps. Such models are called models of understanding e.g. process models. Further, models can be either deterministic or stochastic. Deterministic models give estimates of the expected growth under certain initial conditions. These models do not incorporate the possibility of future changes and will always give the same results. In contrast, stochastic models try to include probability of occurrence of catastrophes or variation in climate for example, wind throws or cyclones. Thus depending on the circumstances the estimated growth and/or yield may vary.

Clutter *et al.* (1983) and Davis and Johnson (1987) named three main types of predictive models. These are whole stand, size class and individual tree models.

(1) Whole stand models. This category of growth models uses population estimates at the stand level (Sph, BA/ha, Vol./ha etc.) to predict growth and yield of the forest. No individual tree details are given.

(2) Size class models. These are considered by some people to be in between whole stand and individual tree models. They provide information on stand structure. A commonly adopted technique is the stand table projection which provides a histogram of stem diameters.

(3) Single tree models. Individual trees are the basic units of modelling in single tree models. Data from every tree is required and this makes these models complex. Single tree models link easily with harvesting and conversion simulators (Vanclay 1994).

Process models, also known as physiological models, attempt to model growth processes using light, photosynthesis, respiration rate or allocation as the input variables.

Succession models on the other hand try to explain changes in vegetation i.e. succession trends.

4.4.2 Modelling competition effects

The approaches used for modelling competition effects from non-crop vegetation in young plantations are quite similar, in many respects, to those used for mature even-aged monocultures. However, important differences do exist. Models of inter-specific competition involve many non-crop vegetation species with different and diverse growth habits, physiological demands and morphological characteristics. Consequently, their effects on the micro-environment will differ and so will their interaction with desired crop trees. Moreover, as Mason (1992) states, early growth modelling has certain peculiar and characteristic aspects which make it quite different to late growth modelling of mature trees. For example: 1) seedlings are yet to close canopy thus there is little or no intra-specific competition; 2) growth processes are before the current annual increment (CAI) peak; and 3) initial tree size is independent of site quality. Also, the micro-site environment may have a significant influence on growth and so may the site preparation methods and the treatments used before planting.

Various quantitative ways of assessing competition effects have led to development of static or one-time models of tree growth reductions under various competition levels. But these models are not very useful for projecting long-term competition effects on stand development. Most of the models describe past events (Cannell and Grace 1993) and may therefore give poor predictions of the future of a stand. A notable exception may be the model used by Burkhart and Sprinz (1984), to predict loblolly pine yield based on the hardwood basal area at crown closure (age 11 years). Tappeiner II and Wagner (1987), discussed effective competition models as those that identified probable short- and long-term growth reduction under continued competition from non-crop vegetation. The models should also be useful in ranking and prioritising stand treatment and consequently, facilitating wise use of resources by determining the efficacy and economy of applied weed control treatments.

4.4.2.1 Neighbourhood models. The dynamic nature of competition means that effects on individual trees can differ significantly depending on the vegetation types surrounding target crop trees, their growth form, age, density and spatial distribution. Neighbourhood models allow competition impacts from various conditions within the site to be investigated. However, Wagner and Radosevich (1991a) caution that proximity based models can be insensitive to tree size, and may give variable indices of competition from one tree to another.

Several neighbourhood models have been proposed in quantifying inter-specific interference. Examples include models that:

1) quantify competition around individual trees as determined by the degree of crown overlap with neighbouring non-crop vegetation;
2) use the number of neighbours surrounding the desired crop plants;
3) incorporate the area available to the crop plant; and
4) include a composite statistic for size, distance and spatial arrangement of the neighbours.

The last 3 types reflect the degree of local crowding (Wagner and Radosevich 1991a).

4.4.2.2 Competition indices. Burton (1993) defines a competition index as a measure showing the extent to which growing space and/or resources of a plant are shared by others. It is an important measure to predict growth of individuals in mono-specific stands. Competition indices are useful in predicting the need for non-crop vegetation control and silvicultural or management interventions during the establishment phase to ensure good growth and survival (Burton 1993, Cannell and Grace 1993).

Competition indices may also indicate measures of critical levels of non-crop vegetation cover above which detrimental effects to crops occur (competition threshold levels) irrespective of the species or local abundance (Radosevich and Holt 1984, Wagner *et al.* 1989, Brand 1986). Competition Indices (CI) have thus a great potential as decision support tools in plantation establishment especially as they assume asymmetrical partitioning of interference effects and target plant responses to altered resource pool. This differentiation of effects and responses strengthens the neighbourhood relations to be evaluated (Burton 1993).

Comeau *et al.* (1993) defined an ideal competition index (CI) as one that was easy to assess, applicable under a range of conditions, and described competition levels which the desired crops effectively faced.

4.4.2.3 Influence zone overlap indices. These indices assign resources in areas overlapping to both plants for two-sided competition while for one-sided competition, resources are assigned to larger plants only (Cannell and Grace 1993). Early competition for light between seedlings is generally two-sided but later it changes to one-sided with increased density in monocultures. This may be due to an increased coefficient of variation in plant sizes (Cannell and Grace 1993). One-sided competition models generally follow a bimodal distribution while two-sided competition models do not.

4.4.3 Examples of competition indices developed in other studies

1. Cannell and Grace (1993) developed a quantitative approach to evaluate light interception based on empirical evidence that for a well established plant community (LAI > 2) growth rate is linearly related to the amount of intercepted radiation. Dry matter production of a stand was expressed as:

$$\Delta W/\Delta t = I_o[1-\exp(-kL)]\varepsilon \qquad (1)$$

where;

$\Delta w/\Delta t$ = daily dry matter production.

I_o = light flux density at the top of the canopy,

L = leaf area index in m^2 leaf per m^2 ground,

ε = average efficiency with which light is used to produce dry matter less the net respiration and other losses, and

k = canopy light extinction coefficient.

2. Comeau *et al.* (1993), while studying the effects of overtopping vegetation on light availability and growth of Engelmann spruce developed a simple competition index based on visual estimate of percent cover and height of each vegetation species within a 1.26 m radius around the crop tree. They used it to estimate full sunlight reaching the seedlings. The competition index was given by;

$$\sum_{i=1}^{N} (\%cover*Ht)/Hs \qquad (2)$$

where;

Ht = non-crop vegetation height and *Hs* = crop tree seedling height.

3. Brand (1986) used percentage cover, non-crop vegetation height, crop tree height and proximity to crop tree to estimate light interception around crop trees;

$$CI=\sum_{i=1}^{N} (Hb/Ht)[((Rb/Rt)+1)^{-1}](C) \qquad (3)$$

where;

Rb = average distance to non-crop vegetation,
H*t* = total height of crop tree,
Rt = tree crop crown width,
H*b* = height of competing species,
C = percent cover of competing species,
N = number of individual woody weed plants in a plot.

4. DeLong (1991) developed a competition index using non-crop vegetation cover, height and proximity to tree crop to describe light penetration through vegetation canopies. The equation used was:

$$LII=\sum_{i=1}^{N} C_i*Ht/P_i \qquad (4)$$

where;

LII = light interception index,

C_i = percent cover,

Ht_i = height of non-crop vegetation,

P_i = proximity of non-crop vegetation to tree crop

N = number of species in a plot.

5. Wagner and Radosevich (1991a) found percentage cover of woody non-crop vegetation more effective in describing D. fir seedling growth variation in the Oregon Coast Range - USA. The following equation was used for the competition index (CI):

$$CI=\sum_{i=1}^{N} a_i(1-d/r)^w \qquad (5)$$

where;

a_i = abundance of species i or size of individual plant i in the neighbourhood,

d_i = distance from crop plant,

r = neighbourhood radius, and

w = weighting parameter

Further, Wagner and Radosevich (1991a) did some sensitivity analysis on their model to investigate the effect of neighbour spatial arrangement. They showed that evenly distributed neighbours had more effect than when aggregated on one side. Angular dispersion (z) was calculated using the equation;

$$z=1-\sqrt{((\sum_{i=1}^{N} \sin a_i)^2+(\sum_{i=1}^{N} \cos a_i)^2)}/N \qquad (6)$$

where;

N = number of species or individual plants in the neighbourhood, and

a = azimuth of individual plants.

The competition index (CI) was given by:

$$CI=Az^{w} \qquad (7)$$

where;

A = abundance,

z = angular dispersion, and

w = weighting parameter.

When $w = 0$, the index (CI) measures abundance. As w increases, widely dispersed neighbours are weighted more than closely aggregated neighbours.

4.4.4 Limitations of competition indices

Competition indices have limitations. These limitations stem mainly from the fact that they are static measures, being representations of one time assessments. However, system dynamics cannot be represented by such one time measures, nor do they (CI) prove causation (Wagner and Radosevich 1991a). Therefore, they (CI) should preferably be based on data taken over a period of time during several growing seasons. Moreover, the indices should undergo screening and calibration (Burton 1993, Cannell and Grace 1993, Comeau *et al.* 1993). And even then, Cannell and Grace (1993) caution that the indices effectively describe past events. Ultimately, one should also ascertain the role of competition in constraining crop establishment at the site before using any measures of competitive stress to identify silvicultural and management interventions. The indices should also be used only for the species and for the site developed or else calibrated on. Finally, subjectivity in assessing percentage cover, which has been difficult to avoid in many cases (Cousens 1987), could lead to errors in CI estimations especially if the assessments are done by different people or people unfamiliar to the site and/or species.

4.4.5 Summary: "of qualitative and quantitative approaches in evaluating competition"

This short review on quantifying competition in young conifer plantations has discussed the need for quantitative understanding of growth and competition dynamics to elucidate interference effects from non-crop vegetation or oversown species correctly and promptly if improved growth and productivity (quality and quantity) and low weeding costs are the management goals. A brief, concise discourse on the various methods and experimental designs used to study competition effects from non-crop vegetation has also been presented. A good design is one that meets the objectives of the research effectively and also mimics real field conditions (Cousens 1995). Also, it should be noted that subjectivity in the assessment of some variables for example, percent ground cover may be unavoidable.

Quantitative methods for evaluating competition have been argued to be superior to qualitative or subjective approaches (Wagner and Radosevich 1991a, Brand 1991, Wagner *et al.* 1989). Qualitative methods use absolute growth measures while quantitative approaches endeavour to identify and separate competition processes into discrete mechanisms of effects and responses. Consequently quantitative approaches have greater potential as decision support tools in vegetation management in young conifer plantations.

Moreover, the neighbourhood approach (Wagner and Radosevich 1991a), which uses the degree of local crowding by neighbouring non-crop vegetation to estimate the yield loss of individual crop plants allows competition impacts from various conditions within the micro-site to be investigated. This method involves a more detailed examination of competition processes than the whole stand approach (Wagner and Radosevich 1991a). Competition indices developed from this approach can also show measures of the extent to which growing space and resources of a plant are shared by other individuals (Burton 1993) and may therefore be extremely useful in predicting critical vegetation levels when control measures are necessary to avert excessive damage to crops (Wagner *et al.* 1989) or economic loss (Cousens 1987).

It is this approach that the study adopted to quantify the effects of non-crop vegetation in a young plantation of radiata pine (*Pinus radiata* D. Don) at Rolleston Forest, in Selwyn District of the South Island of New Zealand.

CHAPTER 5

MATERIALS AND METHODS

5.1 SITE DESCRIPTION, EXPERIMENTAL DESIGN AND ASSESSMENT

The method used in this study was the neighbourhood approach (Wagner and Radosevich 1991a). This approach allowed competition effects from various conditions within the site, for example micro-site modification (due to weeds proximity or site preparation methods), to be investigated more closely. Moreover, with the development of intensive silvicultural interventions, managers have realized that they can improve the productivity of the whole stand better by concentrating on individual trees. The experiments used in this study were set up by Dr. Brian Richardson of the New Zealand Forest Research Institute (NZ FRI - Rotorua) in September of 1993.

5.1.1 Study site, site preparation, experimental design and layout

5.1.1.1 Study site. The trial site was located at Rolleston Forest (Selwyn Plantation Board Ltd.) in Selwyn District of the South Island of New Zealand. It was at an altitude of 55 m above mean sea level and 28 km from the sea. Mean annual rainfall at the site is 700 mm with mean temperatures of 11.5 degrees centigrade, (rainfall figures and mean temperatures are of Christchurch city). The soils have been described as Templeton stony loam.

5.1.1.2 Site preparation and planting. The site was windrowed, with rows spaced 50 m apart. All the cutover was cleared including stumps, leaving the area clean. 1/0 radiata pine stock was machine-planted in September 1993 along rip lines which were 60 cm deep. A post-plant spray with Velpar (2 kg/ha) was applied along the strips.

5.1.1.3 Treatments. Eight treatments were chosen to cover an appropriate range of weed densities and to account for delayed time of emergence as in some operational situations, for example in pre-plant spray. All treatments were randomly allocated to each of four blocks. The treatments were as follows:

1. Completely weed free from year 1;
2. Conventional standard weed control regime i.e. 1 m band spraying along planting lines;
3. 15 percent weed ground cover from year 1;
4. 40 percent weed ground cover from year 1;
5. 75 percent weed ground cover from year 1;
6. Completely weed free in year 1 and then 15 percent weed ground cover from year 2 onwards;
7. Completely weed free in year 1 and then 40 percent weed ground cover from year 2 onwards; and
8. Completely weed free in year 1 and then 75 percent weed ground cover from year 2 onwards.

These treatments generally fall under 2 groups; in group I (Treatment 3, 4 and 5) some weeds were left to grow with the trees right from planting; and in group II (Treatment 6, 7 and 8) trees were kept weed-free in year 1, and thereafter from year 2 onwards some weeds were left to grow with the tree crops. Treatment 1 served as the control.

5.1.1.4 Design and Layout. Randomised block design with four blocks was used. Trees were planted at 2.5 X 4 m spacing, with each plot containing 36 trees i.e. (6 X 6). Assessment was in the inner 4 X 4 (16) trees in a plot. Treatments ran across the entire plot with weed cover manipulated accordingly by maintaining weed free areas.

5.1.2 Treatment allocation and neighbourhood maintenance

Treatments were defined quantitatively by maintaining predefined weed ground cover percent in a plot. Weed percent cover in a treatment was achieved using the following procedure:

1) plots were sub-divided into horizontal and vertical strips of known dimensions;

2) some strips were then randomly chosen, all the while ensuring a fair representation over the whole plot. The number chosen depended on the percent weed ground cover to be maintained in a plot; and

3) spraying was done (once only) where the strips intercepted.

Planting lines were marked normally (as if no weed-free strips were present). Thus, a given plot had normal predefined weed percent cover but individual trees had large variations in weed cover around them as depicted in figure 5.1. Weed-free strips were maintained using knapsack sprayers and selective herbicide (Velpar 2 kg/ha).

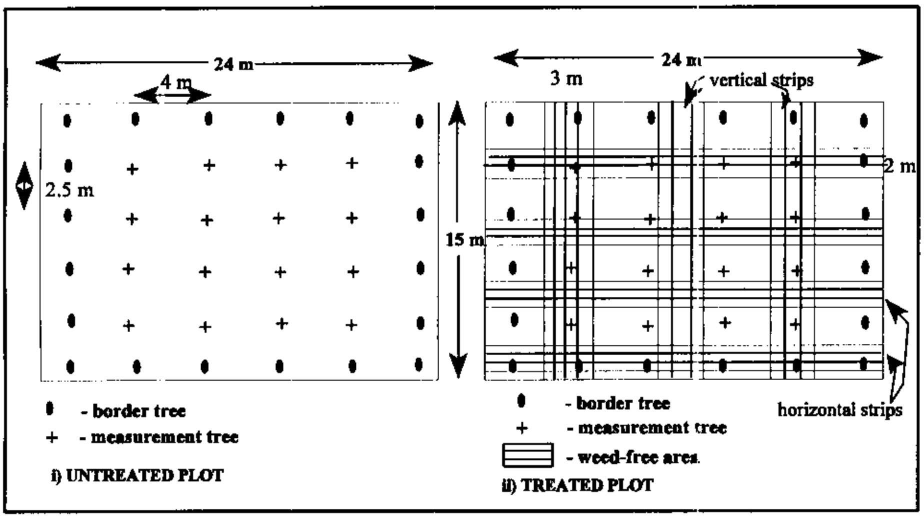


Figure 5.1: Treatment layout showing how weed free strips were used to manipulate the levels of competition and create a gradient of competition levels around individual radiata pine crop trees (where strips intersect the area was sprayed only once), (After Richardson 1993. Unpublished report).

Worked example: determining percent weed ground cover.

In figure 5.1, the horizontal strips 4(24*2) = 192 m^2, vertical strips occupy 3(15*3) = 135 m ^{2}. Total weed free area = 192+135 - (72 i.e. where strips intersect) = 255 m^2. But the total plot area = 15 m by 24 m = 360 m^2, so the weeded area = 255/360 = 0.7083. Therefore, the percent weed ground cover in the plot is 30 %.

5.1.3 Assessments

Measurements were taken twice, in summer (February) and winter (July) of every year. All measurements were done at the same time for both crop trees and non-crop vegetation. Neighbourhoods of 1 m and 2 m radius from crop trees were used during assessments.

5.1.3.1 Tree crop data. Total stem height (H cm) and root collar diameter (rcd mm i.e. diameter at ground level) were recorded at time of planting and during every assessment. Any growth deformities and damage (animal or herbicide) were also recorded.

5.1.3.2 Non-crop vegetation data. Within each neighbourhood, assessment was carried out during the first winter after planting and thereafter annually during summer and winter for the following:

1) visual estimate of percent ground cover of herbaceous vegetation and/or any other low stature weeds (employing some form of scoring to the nearest 5 percent). To ensure consistency of estimates, the same people did the assessments every time. Also, before any assessments were taken the team normally did some form of self-calibration exercise. Below is a description of how this was done.

i) Some few plots would be randomly chosen in each block (a fair sample of all the treatments in the experiment).

ii) Each member in the team would go round and estimate the percent cover independently.

iii) Values from each member would then be compared and if some values differed by more than 5 % then the exercise was repeated.

Once satisfied, the team started visual estimate of percent weed ground cover of each neighbourhood size, but this time working together. Each member would shout their estimates for the neighbourhood size. It should be mentioned that percent cover estimates were quite consistent after the calibration exercise. Only in a few cases did some individual estimates differ by more than 10 %, and these were reassessed.

2) For woody non-crop vegetation, the following were measured and recorded:

i) stem height to highest growing point (wht cm);

ii) distance of weed crown from crop tree, nearest and furthest distance (dist1, dist2 cm). In cases where the weed crown overlapped with the crop tree crown, a negative value equal to the amount by which they overlapped was recorded for dist1. If they just touched then zero was recorded for the nearest distance;

iii) crown diameter in two directions at right angles (diam1, diam2 cm);

iv) visual estimate of crown density (cd i.e. percent crown foliage cover); and

v) angle measure clockwise, (azimuth, in degrees) of woody stem from sample crop tree.

5.2 DATA ANALYSIS TOOLS

5.2.1 Data used

The data used in the analyses were from the initial crop tree size measurements and 3 remeasurements i.e. July 1994 age 10 months, February 1995 age 1.33 years and September 1995 age 1.92 years. Relative growth rate was calculated as $((size_{t2} - size_{t1})/(T_2-T_1))*(1/size_{t1})$, while the non-crop vegetation data used were assessed during the middle of summer (February) 1995. The July 1994 non-crop vegetation data were not used in the analyses because weed growth was poor, especially woody weeds.

Data from measurements of weeds taken in February 1995 were assumed to have a direct influence on radiata pine growth. February is in the middle of summer and therefore, it was assumed to be the point of highest competition especially for moisture. Moreover, the amount of weeds present at this time were also assumed to reflect the volumes and/or intensities that prevailed throughout the growth season, especially of annual weeds like grasses.

5.2.2 Analysis tools

Data from the field were keyed into a personal computer. The Quattro Pro spread sheet package, version 5.0 (Borland International Inc. 1993) was used to arrange the raw data into appropriate forms which could be submitted to the Statistical Analysis Software package (SAS), (SAS Institute Inc. 1987, 1990) for analyses. Once the analyses were completed, Quattro pro was used to draw residual plots and plots of mean tree growth by competition intensity.

5.3 DATA ANALYSIS PROCEDURES: OVERVIEW

5.3.1 Methods for analysing trial data: Block and treatment design

The method of least squares was used to analyse data from the experiment. This method minimises the sum of squares of the residuals (Cochran and Cox 1957). A general mathematical model was built on the following components: 1) a mean growth value (μ) about which observations were assumed to vary; 2) treatment and block effects; and 3) an error (residual) component. A fourth term representing environmental effects was excluded as the design was supposed to have eliminated it. The general model was represented thus:

$$Y_{ij} = \mu + T_i + B_j + E;$$

where, μ = general mean, T_i = treatment effect, B_j = block effect and E = experimental error. Subscripts i = treatment number and j = block number.

Experimental effects were estimated by $\sum(x_i - \bar{x})^2$. In this experiment the object of analysis was to: 1) see how treatment effects related to actual competition; and 2) find out if there were any significant growth differences between treatments. GLM procedure in SAS was used to do these analyses.

5.3.2 Analysis of Variance: tests for treatment differences

Analysis of variance and Tukey's multiple range test were conducted to investigate if:

1) treatment and blocking had significant effects in the experiment;

2) there were significant treatment differences in mean tree growth; and

3) there were significant seasonal differences in competition intensities.

To compare treatment effects adequately, initial tree size at the beginning of the growth period was used as a covariate. It was also intended to investigate if seasonal variation in competition intensity was significantly different among treatments as expressed using RGR. General linear models (GLM) procedure in SAS (SAS Inst. Inc. 1990) was used for the analyses.

5.3.3 Analysing competition effects

Data analysis procedures for measures of competition were aimed to:

1) develop mathematical expressions of competition indices from the non-crop vegetation variables assessed; and

2) fit regression models to express the effects of non-crop vegetation competition on crop tree height and root collar diameter growth (and their derived variables).

To achieve these objectives plots of tree crop variables and non-crop vegetation variables were plotted. Regression models were later fitted to the data.

5.3.3.1 Formulation of competition indices. Competition indices were constructed using the following steps:

1) plots of non-crop variables versus tree growth variables were constructed, and their trends duly noted;

2) simple linear correlations between crop tree variables and non-crop variables which had linear trends in their plots were carried out;

3) single term competition indices were constructed from all the significant factors, on their own and in combination.

The competition equations used were of the general form as those used by Wagner and Radosevich (1991a), Comeau *et al.* (1993), Brand (1986) and DeLong (1991). The formulation of the competition indices was based on the following theoretical assumptions.

1) Competition from herbaceous or low stature weeds was proportional to their percent ground cover (**hpc**)......**I.** Competition was assumed to be symmetrical or two-sided.

2) Competition from shrub and woody non-crop vegetation was a factor of:

i) crown area (**ca**) i.e. (pi*{mean crown diameter/2}^{2}) - massive crown size indicates dominant stature and establishment, hence more competition effects;

ii) height (**wht**) - taller weeds overtop young plants and exacerbate competition especially for light (asymmetrical competition). Also, taller weeds were expected to have extensively developed underground structures based on allometric relationships.

This however, may not always be the case and was not used as an important criterion because competition for other resources, especially nutrients may be symmetrical or two-sided;

iii) crown density (**cd**) i.e. percent foliage cover of the crown - denser crowns cast more shade and alter the quality and quantity of light reaching the young trees.

Moreover, denser crowns may also indicate vigorous root activity or established stature; and

iv) proximity (**dist**) i.e. distance from woody competitor crown to the crop tree stem - weeds closest to the crop plants were expected to have more deleterious effects than those farther away.

From these main assumptions, a theoretical implicit model for woody competition effects was constructed. This general model was:

weeds' stature and hence competitiveness= f(ca, wht, cd, dist).

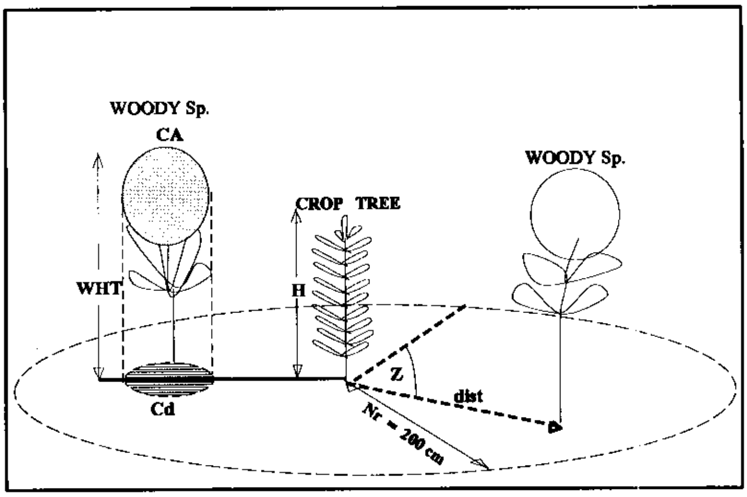


Figure 5.2 illustrates the variables used to formulate competition indices. CA = crown area, WHT = woody height, Cd = crown foliage density, H = crop tree height, Z = azimuth, dist = distance from weed to crop tree main stem, and Nr = neighbourhood size.

From the theoretical competition model, competition indices were formulated. The general form of an index was;

competition index (CI) = f(abundance, k, 1/crop tree height),

where k = distance weighting factor for a given neighbourhood size. The following abundance measures were used.

1) crown area (**ca**) = {pi*(mean crown diameter/2)^2}.................**II**

2) crown volume index (**cvi**) = (ca*wht)...............................**III**

3) crown shade index (**cvip**) = (cvi*cd).................................**IV**

The abundance measures were weighted by K to give two other indices i.e.

4) distance weighted crown volume index (**dcvi**) = (cvi*k)..........**V**

5) distance weighted shade index (**dcvip**) = (dcvip*k)...............**VI**

Further, equations II to VI were multiplied by the reciprocal of crop tree height (1/H). This put more emphasis on weeds that were taller than the crop trees. It also ensured that the indices were sensitive to crop tree size, therefore minimising CI variation from one tree to another. All weeds that were shorter than the target crop trees were subsequently multiplied by a factor of less than 1, while taller weeds were multiplied by a factor greater than 1. The result was functions VII to X below.

6) **cvi/H**..**VII**

7) **cvip/H**..**VIII**

8) **dcvi/H**..**IX**

9) **dcvip/H**..**X**

Also, the following competition indices from previous studies were used.

10) A modified DeLong (1991) shade index; LI = cd*wht/k......**(XI)** by; where cd = crown foliage density, wht = weed height, and k = (1-dist/Nr). The Light interception index was given by;

$$LII = \sum_{(i=1)}^{N} LI_i$$

where;

LII = light interception index and N = number of individual woody non-crop vegetation plants.

11) A modified Brand (1986) function; CI = $\sum(\text{wht}/H)*[((\text{dist}/Nr)+1)^{-1}]*(\text{cd})$...... **(XII)**, where wht = weed height, H = crop tree height, dist = distance, Nr = neighbourhood size and cd = crown foliage density. 12) CI = $\sum(\text{cd}*\text{wht})/H$....**(XIII)** by Comeau *et al.* (1993); where cd = crown foliage density, wht = weed height and H = crop tree height.

The competition index formulations, **II** - **XIII**, were calculated for all woody non-crop vegetation in each neighbourhood. Two main approaches were used to analyse woody effects. These are species and individual tree approaches.

1) species approach - all woody non-crop vegetation in a neighbourhood were

grouped by species. Mean measures for each species were then used.

$$CI=\sum_{i=1}^{N}(a_{ij}*k_{ij})/n_{i}$$

where;

a_{ij} = abundance or size of individual *i* of species *j*,

k_{ij} = distance weighting of individual *i* of species *j*,

n_j = number of individuals of species *i*,

N = number of species groupings.

2) individual tree approach - each woody non-crop plant was considered separately, and for each neighbourhood summation of all the individual attributes were used.

$$CI=\sum_{i=1}^{N}(a_{i}*k_{i})$$

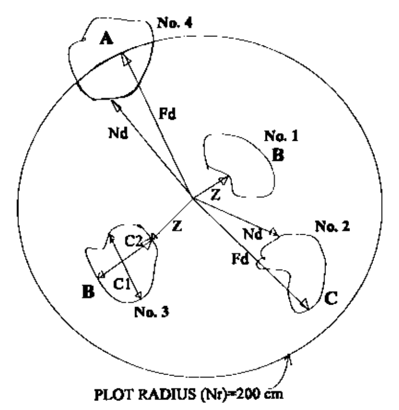
where;

a_i = abundance or size of individual *i*,

k_i = distance weighting of individual *i*,

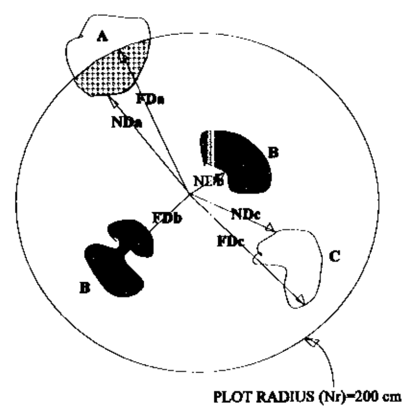
N = number of individuals in the neighbourhood.

Fig. 5.3a INDIVIDUAL-PLANT APPROACH



A, B, C =species; 1, 2, 3,4 = INDIVIDUAL TREES
modified from Wagner and Radosevich (1991a)

Fig. 5.3b SPECIES APPROACH



A, B, C =species groups
modified from Wagner and Radosevich (1991a)

Schematic diagrams detailing how woody non-crop vegetation around individual crop trees was assessed and analysed. Figure 5.3a shows the individual-tree approach where each woody non-crop plant was considered separately. Figure 5.3b shows the species approach where all woody non-crop vegetation within a neighbourhood were aggregated by species.

5.3.2.2 Plot procedures: Methodology and analytical approaches. The plotting procedure, PROC PLOT, in SAS (SAS Institute Inc. 1990) was used to display scatter diagrams of tree crop growth by competition index formulations. The trends indicated the kind of relationships that existed between the assessed tree variables and the competition indices, and therefore, the type of models which could be fitted to best describe the observed relationships.

(a) Variables used. The following dependent and independent variables were used.

1. Dependent variables - tree crop height (H cm) and root collar diameter (rcd mm) and their derived variables were plotted on the Y-axis. Absolute growth of individual trees (i.e. all data), and mean tree size and growth (by treatment) for height (H), root collar diameter (rcd) and basal area at ground level (Ba) were used. Tree crop

growth was calculated as the change in tree size with time. Three growth periods were used namely July 1994 to September 1995, July 1994 to February 1995 and February 1995 to September 1995.

2. Independent variables - competition index formulations **I** to **XIII** were used on the X-axis.

5.4 REGRESSION ANALYSIS PROCEDURES

5.4.1 Modelling approach

The main analytical approach used in the study involved: 1) fitting appropriate functions (regression equations) to the data to describe the relationship between weed competition and tree growth using SAS (SAS Institute Inc. 1987, 1990); 2) analysis of residuals using the univariate procedure (PROC UNIVARIATE), in SAS; and 3) the Chart procedure (PROC CHART; VBAR NORMAL PLOT), to show normal plots of residuals and their departure from normality. Mean square residuals (MSQR) and the distribution of residuals were the main test criteria. The Statistical Analysis System, SAS (SAS Institute Inc. 1987, 1990) was used to do the analyses.

Emphasis was placed on eliminating any possible bias in fitting the models and ensuring a normal distribution of residuals, or as close to normal as possible. The normality of the residual plots was checked using measures of skewness and kurtosis. Also, normal plots of residuals by predicted values were used to check for bias because sometimes a mean of 0 may be achieved even when the model is biased. Below is a more detailed discourse on some specific aspects of modelling.

5.4.1.1 Proc univariate. Measures of variability and shape output from Proc Univariate in SAS were used to assess model fitness.

(1) Skewness. Skewness shows the tendency of deviations to be larger in one direction than the other. The population skewness is unbound. It can be positive or

negative and it is given by $E(x_i-\mu)^3/\sigma^3$. As the deviations are raised to the third power they therefore keep their signs. The sample skewness is given by,

$$(n/(n-1)(n-2))\sum_{(i-1)}^{n}(x_i-\bar{x})^3/s^3$$

(SAS Inst. Inc. 1990).

(2) Kurtosis. Kurtosis is the heaviness of the tails. The population kurtosis is given by $E(x_i-\mu)^4/\sigma^4-3$ and it must lie between -2 and positive infinity. The deviations are raised to the fourth power, so both positive and negative deviations make same contributions with large deviations being more strongly emphasised. The sample kurtosis is given by,

$$(n(n-1)/(n-1)(n-2)(n-3))\sum_{(i-1)}^{n}(x_i-\bar{x})^4/s^3-3(n-1)(n-2)(n-3)$$

(SAS Inst. Inc. 1990).

(3) Probability values. The p-values give an indication of the strength of evidence for rejecting the null hypothesis ($\propto$ = likelihood of being wrong if one assumes there is a difference). The null hypothesis states that the mean or variance of an unbiased random sample should be exactly ideal to that of the population from which it was drawn i.e. Ho: $\mu = 0$ or $\sigma^2 = 0$ (SAS Inst. Inc. 1990). If the p-value is less than the significance level used in the test then the alternative hypothesis Ha: $\mu \neq 0$ or $\sigma^2 \neq 0$ is taken in favour of the null hypothesis.

5.4.1.2 Proc chart (PROC CHART VBAR NORMAL PLOT). Proc chart produces a histogram, the shape of which looks like a bell for normally distributed data (SAS Inst. Inc. 1990). The histogram also shows the skewness and depending on how bad it is, and/or the uses of the model further investigations of the data set may be needed.

5.4.2 Choice of models

5.2.4.1 Models fitted. The following models were used to depict the relationship between tree growth and competition indices.

1. $Y=\alpha+\beta*(X)$
2. $Y=\alpha+\exp(X)$
3. $Y=\beta*\exp(-\gamma*X)$ i.e. $\ln Y=(-\gamma*X)^b$
4. $Y=\alpha+\beta*\exp(X)$
5. $Y=\alpha+\exp(-\gamma*X)$ i.e. $\ln Y=\alpha+\beta*X$ (Wagner *et al.* 1989)
6. $Y=\alpha+\beta*\exp(-\gamma*X)$
7. $Y=\alpha+(\beta-\alpha)*\exp(-\gamma*X)-X*(\beta-\alpha)*\exp(\gamma)$ (Mason pers comm.)

In these equations, Y is tree growth while X is either herbaceous cover index or woody competition index and α, β and γ are regression coefficients to be estimated.

5.2.4.2 Selecting appropriate models. (1) Coefficient of determination (R^2). The coefficient of determination, R^2, has been used (and sometimes misused) in many studies as a test criterion for model fitness. R^2 is calculated as 1-(model residual sum of squares/residual sum of squares about the mean). It shows the proportion of variance of the response variable that is explained by the independent variable (Clutter *et al.* 1983, SAS Inst. Inc. 1990). It is therefore a ratio independent of units that compares the fitted model with a simple leverage ($R^2 = 0$) and with a perfect fit ($R^2 = 1$). However, undue emphasis on the use of R^2 as the only test criterion for model fitness or predictive capability could be dangerous. This is because R^2 tends to confound natural variation (pure error) and lack of fit by the model (Vanclay 1994). Thus, an R^2 close to 1 is no cause for excitement as it does not necessarily imply that the model is the "best" or "perfect" model which will provide good predictions. Other arguments against using R^2 as the sole test criterion are that it does not take into account the number of terms in the model. Thus, including more terms in the model will result in a higher R^2 even when these terms are insignificant. Also, Yield equations which include initial size in the response variable or transformations may influence the R^2 value.

Vanclay (1994 p.125) describes an example where a model ($\hat{Y} = a+b*X$) fitted to 4 data sets gave the same R^2 value. However, further investigation of the residuals revealed cases of pure error, wrong model selection, an outlier and a point with high leverage. In this example only the first model showing pure error may need no further investigation.

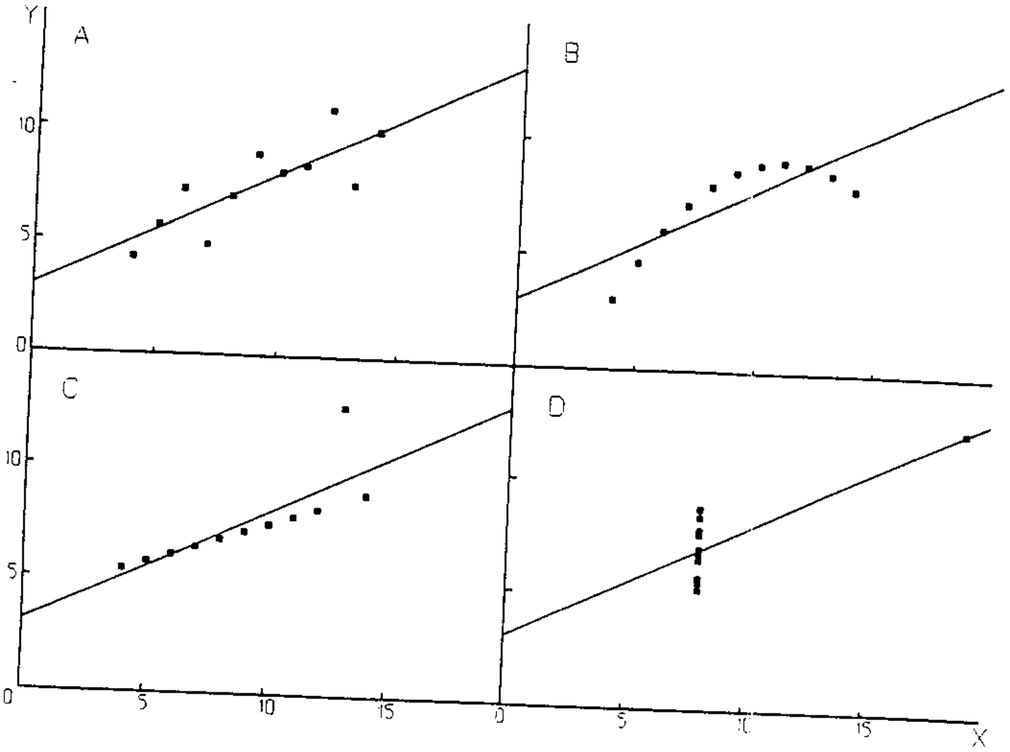


Figure 5.4 highlights the danger of using R^2 as the only test criterion for model fitness and/or predictive capability. Plot **A** shows a case of pure error, **B** is a case of wrong model selection, **C** highlights an outlier and **D** displays a point with high leverage. All cases had reportedly the same R^2 value (After Vanclay 1994).

(2) Residual plots. Residual is the difference between the observed and the predicted value (SAS Inst. Inc. 1990). Residual plots are useful indicators of outliers, and places where anomalies in variances occur. They can also show when transformations are necessary or when a variable should be included in the model (Clutter *et al.* 1983).

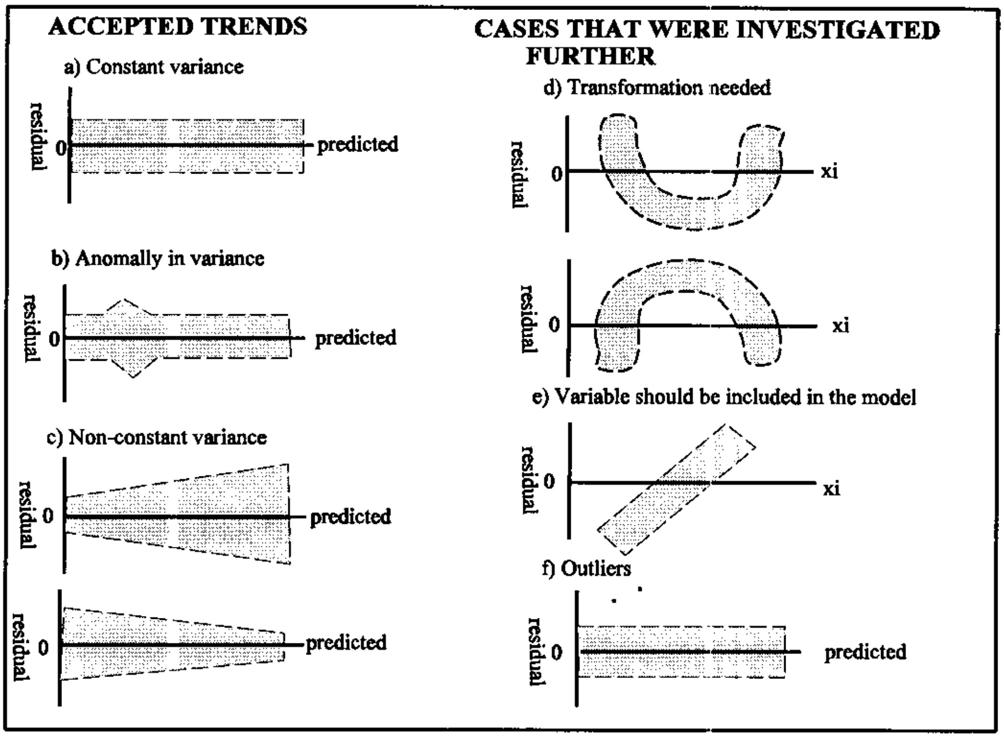


Figure 5.5 illustrates some common residual plot trends. Acceptable residual trends are on the left and cases that need further investigations are shown on the right (After Vanclay 1994).

5.4.3 Summary

On the strength of the foregoing discussion this study opted to use the following as the main criteria for model selection:

1. all models with least mean square residual values were initially selected; and
2. the chosen models (in 1 above) were further scrutinized for bias and normality by studying their residual plots and the output from the Univariate and Normal chart procedures in SAS.

CHAPTER 6

RESULTS

6.1 RESULTS OF PLOT PROCEDURES

6.1.1 Plots of crop tree growth versus competition indices

6.1.1.1 Effect of increasing non-crop vegetation density on individual tree growth. Plots of individual radiata pine growth by weed density (herbaceous or woody) showed the same general trend for all competition indices. They followed a hyperbolic curve function. The curve described an "upper limit" of growth. Generally, low non-crop vegetation densities were associated with high tree growth. However, as weed densities increased, tree growth decreased sharply at first and then slowly. Many points in the scatter were in the low competition index zone but showed low growth (Fig. 6.1). This observation has been made by others, for example Wagner *et al.* (1989) (Robert Wagner called it the "Rich-Kid Effect" (Richardson pers comm.)).

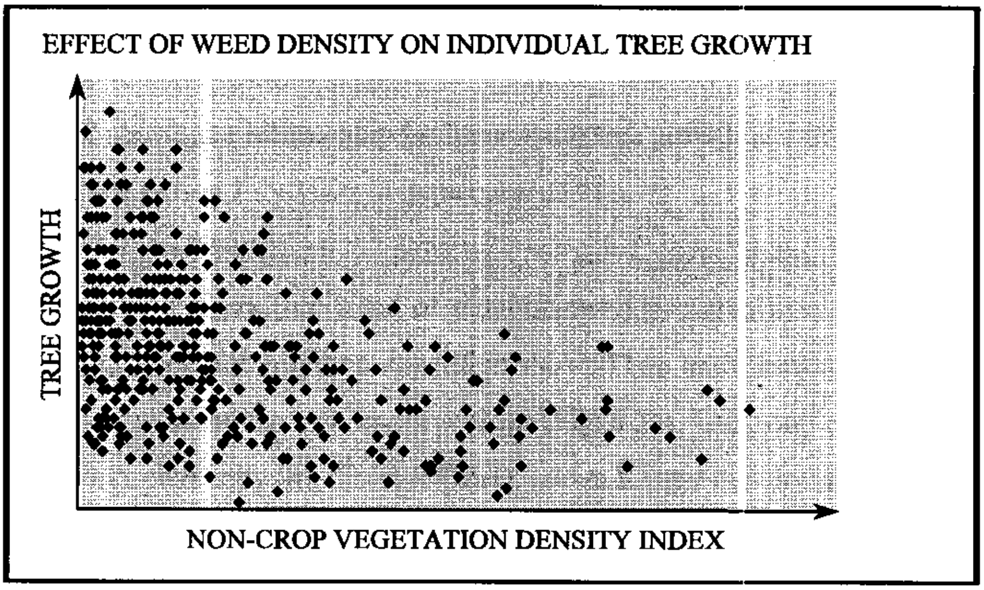


Figure 6.1 shows the generalized relationship between individual radiata pine tree growth and increasing weed density.

6.1.1.2 Effects of increasing herbaceous cover index on mean tree growth.

Plots of mean tree growth under herbaceous weed competition followed a hyperbolic curve function with negative concavity (Fig. 6.2). It should also be noted that most points of treatments 2 (conventional control = 90 % weed cover) and 5 (75 % cover from planting) were at the bottom. This may be due to the fact that these treatments experienced most inter-specific competition effects right from the start of the experiment.

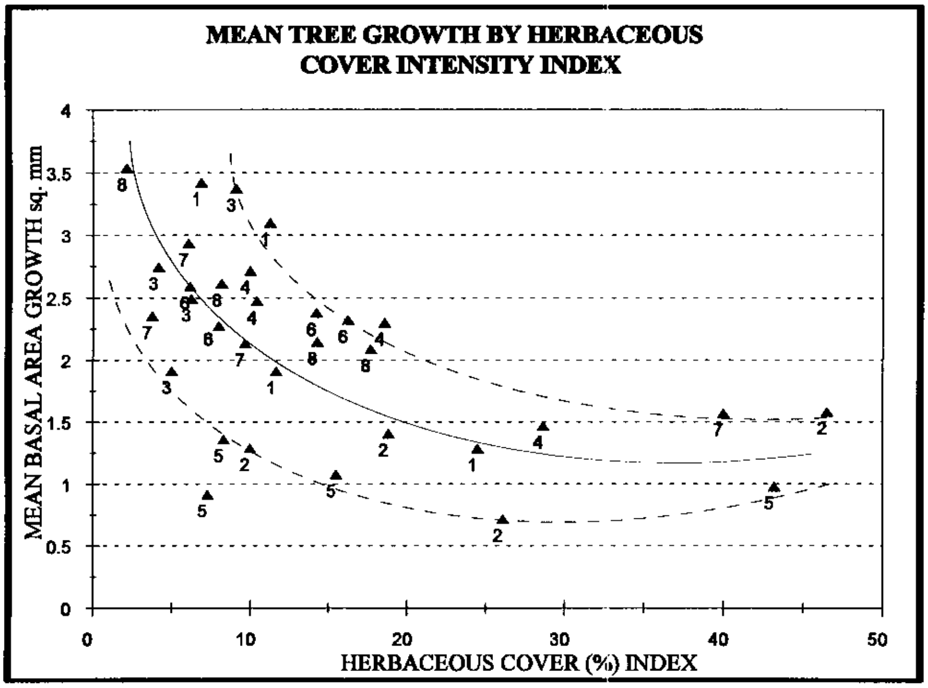


Figure 6.2 shows the relationship between mean tree growth and herbaceous weed cover index for the period July 1994 to September 1995.

6.1.1.3 Generalized trend of plots of mean tree growth under woody non-crop vegetation. Plots for woody competition showed two main trends: 1) Type I displayed strong linear relationship with negative slope (Fig. 6.3a). This was characteristic of woody height (**wht**), proximity (**k**), distance (**dist**), crown foliage density (**cd**), cd*wht/k = (**XI**), (wht*H)*[((dist/nr)+1)$^{-1}$] = (**XII**) and cd*wht/H = (**XIII**); and 2) Type II showed a weak curvilinear relationship (Fig. 6.3b), i.e. hyperbolic curve function with positive concavity. Competition index formulations II to X displayed this trend.

Fig. 6.3a MEAN TREE GROWTH BY WOODY WEEDS' INTENSITY INDEX

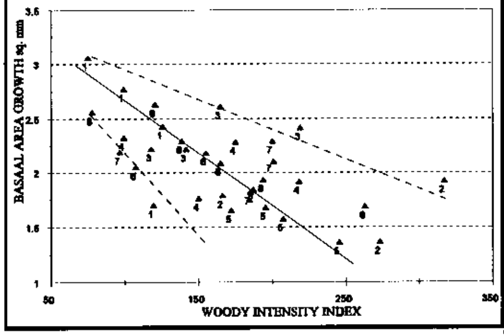
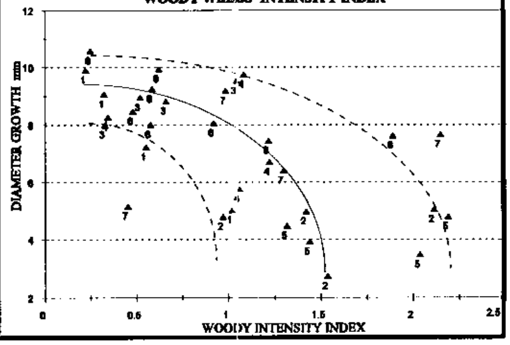


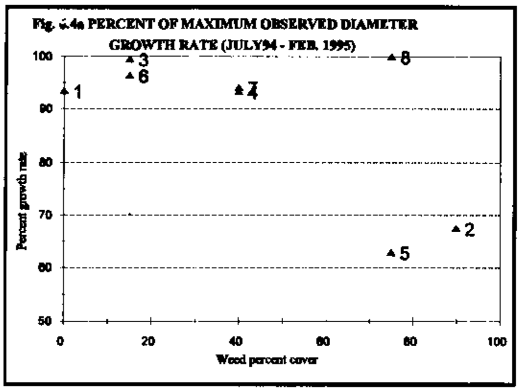
Fig. 6.3b MEAN TREE GROWTH BY WOODY WEEDS' INTENSITY INDEX



Figures 6.3a and 6.3b show two types of relationships of mean tree growth under increasing woody weeds' density. Figure 6.3a shows a linear relationship with negative slope. Figure 6.3b shows a curvilinear trend.

6.1.2 Growth Analysis: absolute growth and relative growth rate

6.1.2.1 Effect of increasing weed intensity on mean tree growth. Figure 6.4a shows the effect of increasing weed density (percent cover) on absolute mean tree growth. The relationship between weed density and absolute growth is poor. It shows little change in tree growth with increasing weed intensity up to 70 % cover. Figure 6.4b is more informative. It shows that by considering the initial tree size, plants growing in plots with lower weed density were more efficient in accumulating biomass (diameter, height and basal area at ground level) than their counter parts growing in plots with higher weed densities.



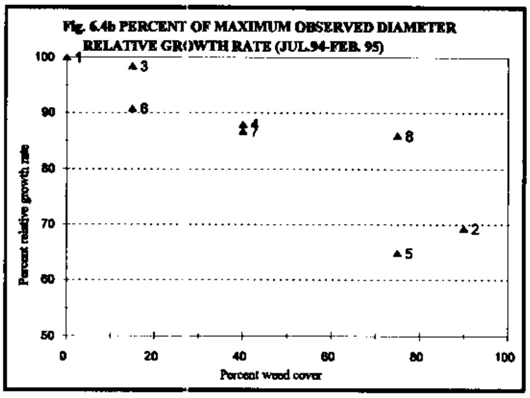


Figure 6.4a and 6.4b show effect of weed density on mean tree growth and relative growth rate respectively (percent of maximum observed values are used).

Further, because of the potential confounding of size and treatment effects RGR measures were plotted against size at the start of the growth period. The trends showed that nominal treatments with low weed density (1 = control, 3 and 6 = 15 %) had higher RGR than their counterparts with higher weed cover percentages (4 and 7 = 40 %, 5 & 8 = 75% and 2 = 90 %).

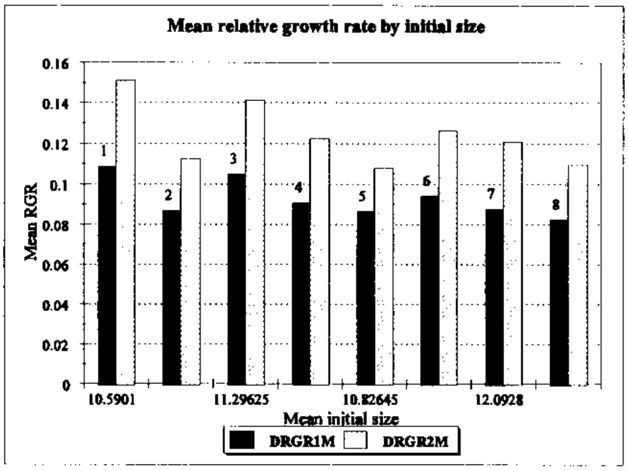


Figure 6.5: Treatment mean diameter relative growth rates for period 1 (July 1994 - Sept. 1995 =DRGR1M) and period 2 (July 1994 - Feb. 1995 = DRGR2M) as functions of mean size at the beginning of the growth period. RGR was calculated as: $((D_{t2}-D_{t1})/(T2-T1))*(1/D_{t1})$, (labels show treatment numbers).

6.1.2.2 Effect of growth season on competition intensity. Figures 6.6a and 6.6b (below) show the general trend of mean absolute growth rates of root collar diameter and height. The trend was generally similar, both starting low in July, rising to a high in February and falling down to a low in September. It should be noted that by September, mean diameter growth rate was still higher than it was in July 1994. The same was however, not true for mean height growth.

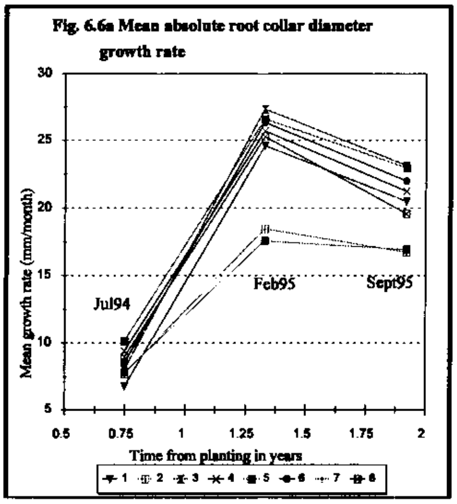


Fig. 6.6a Mean absolute root collar diameter growth rate

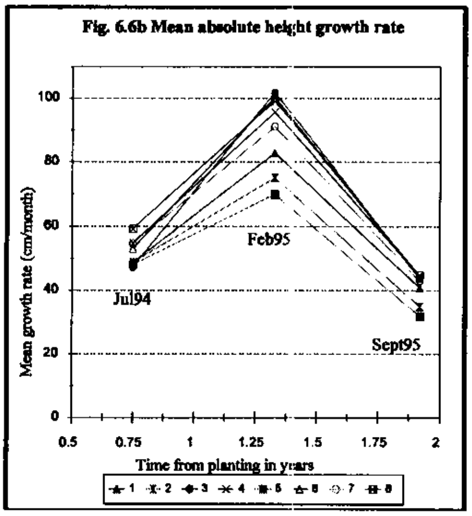


Fig. 6.6b Mean absolute height growth rate

Figures 6.6a and 6.6b show seasonal absolute mean growth rates of diameter and height.

Relative growth rate (RGR) trends of root collar diameter and height are shown in figures 6.7a and 6.7b. It is evident that the relative growth rate trend of root collar diameter was different from that of height. Root collar diameter relative growth rate started low at the beginning of the season (July 1994) and peaked in mid-summer (February 1995), before slumping down to a low in winter (September 1995). Height relative growth rate, on the other hand, started the season quite high (July 1994) and decreased sharply from spring to mid-summer (February 1995) and then gently thereafter from mid-summer to end of winter (February - September 1995).

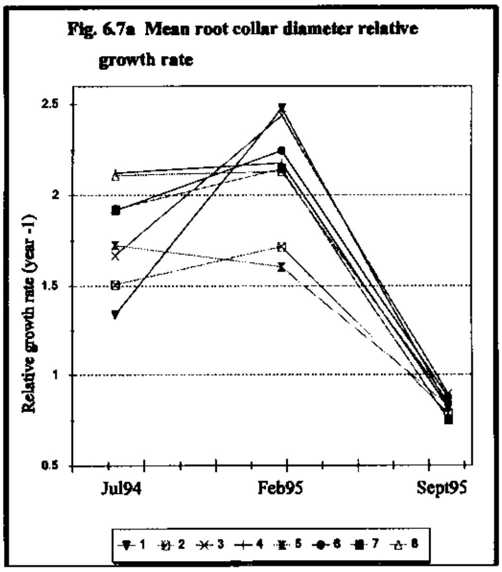


Fig. 6.7a Mean root collar diameter relative growth rate

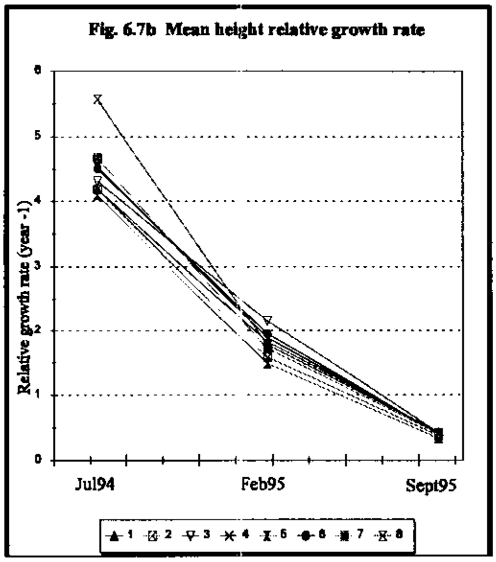


Fig. 6.7b Mean height relative growth rate

Figures 6.7a and 6.7b show mean relative growth rates RGR of root collar diameter and height for the period July 1994 (mid-winter) - February 1995 (mid-summer) - September 1995 (end of winter).

6.1.3 Relationship between woody weed density and herbaceous weed ground cover %

Herbaceous weed abundance was negatively related to woody weed density, as expressed by crown shade index, equation **IV** i.e. $\sum$(**wht*ca*cd**). Plots of the two showed that herbaceous weeds were most abundant in areas where woody densities were low. As woody weed density increased to medium levels, herbaceous abundance decreased significantly. At higher woody densities very few herbaceous weeds were present.

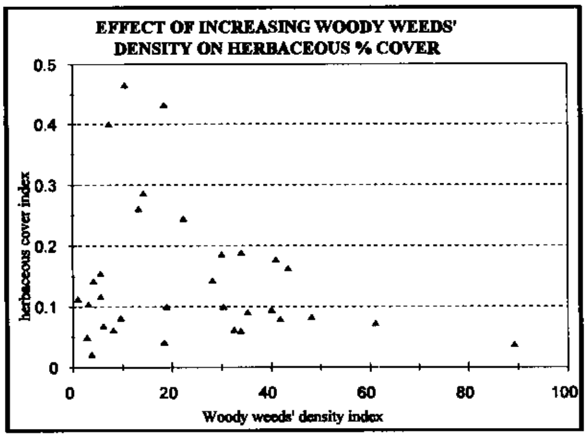


Figure 6.8: Effect of increasing woody weeds density on herbaceous percent ground cover.

6.2 ANALYSIS OF VARIANCE: TESTS FOR TREATMENT DIFFERENCES

6.2.1 Analysis of variance (Anova)

Analysis of variance showed treatment effects were highly significant for both root collar diameter and height mean growth ($R^2 = 0.7847$ for diameter and 0.8492 for height) for the period July 1994 to September 1995 ($Pr > F = 0.0001$ and 0.003) at the 0.05 level. Blocking (0.063) was not significant. However, by accounting for initial size (using relative growth rate), both treatment effects ($R^2 = 0.828$ for diameter and 0.787 for height) and blocking were highly significant. Further, division of the growth period into 2 i.e. July 1994 to February 1995 (period 1) and February 1995 to September 1995 (period 2) did not have any significant changes in the results.

6.2.2 Tests for significant differences between treatment means

6.2.2.1 Absolute mean growth. Tukey's test showed that treatments 2 and 5 had significantly lower growth than all the others (1, 3, 4, 5, 6, 7, and 8) for both height and root collar diameter growth. Dividing the growth period into 2 i.e. period 1 and 2, did not give different results.

6.2.2.2 Covariance analysis. To account for the effects of initial size, covariance analysis were performed. Initial tree size at the beginning of the growth period was used as the covariate. The results of the adjusted means showed that initial size, blocking and treatments were all significant at the 0.05 level. Dividing the growth period into 2 (July to February and February to September) showed that blocks and treatment effects were not significant during the period February - September. Moreover, in spring-summer, treatments with higher weed ground cover (7, 8, 2, and 5) were less efficient in dry matter production (height or basal area). However, only treatments 2 and 5 had significantly lower rates compared to the others. Table 6.1 shows the results of Tukey's multiple range test for RGR for the period spring to mid- summer (July - February 1995).

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ADJUSTED MEANS		Treatment
Period 1(Jul.94 - Sept. 95)	Period 2 (Feb. 95 - Sept. 95)	
30.104	16.180	3
28.795	15.996	1
28.601	15.084	6
27.557	14.371	8
26.906	14.438	4
25.788	14.430	7
21.658	11.392	2
21.317	10.864	5

Table 6.1: Mean adjusted values for diameter growth for the whole growth period (July 94 - Sept. 95) and for spring-early summer growth period 2.

6.2.3 <u>Summary of growth analysis results</u>

Growth analyses using both relative growth rate (RGR) and absolute growth rate showed that competition from weeds was limiting growth of trees at the site. Competition was shown to be critical during summer season when large variations in relative growth rates of the different treatments were exhibited. Thus competition intensity varied depending on the growth season. Moreover, plots of RGR by weed ground cover (%) showed that treatments with low weed densities (i.e. 1, 3 & 6) had higher RGR values than those with high weed intensities (i.e. 2, 4, 5, 7 & 8). Using initial size at the beginning of the growth period as a covariate gave similar results to RGR.

Plots of herbaceous by woody weeds showed that the weeds also competed with each other for site dominance.

6.3 COMPETITION MODELS: RESULTS OF REGRESSION ANALYSES

Non-linear equations $\alpha+\beta*\exp(-\gamma*X)$, $Y = \alpha+\beta*\exp(X)$ described herbaceous weed competition adequately. On the other hand, equations $Y = \alpha+\beta*X$ and $Y = \beta*\exp(-\gamma*X)$ adequately represented the competition effects of woody weeds for both diameter and height growth and their derivatives. In the equations, Y = tree growth, X = herbaceous cover index or woody index. These models had the least residual sum of squares. Further, their residual plots were also better than those of other models fitted. An overall model for competition was built: Y= **Y_i(Hpc, wci + Error)**; where Y_i = initial mean tree size, Hpc = herbaceous cover index and wci = woody index (i.e. **cd*wht/H** or **cd*wht*k/H**). The results showed that initial tree size had an insignificant improvement on the model R^2 (0.62 for diameter and 0.52 for height). The intercept and Hpc were highly significant (0.0002) for both mean height and diameter growth. Woody weeds were shown to have had a significant effect on mean diameter growth (0.02) but not on mean height growth (0.39) during the period July 1994 to September 1995. Thus diameter was more sensitive to competition than height.

6.3.1 Effect of herbaceous cover intensity on tree growth

The effects of increasing herbaceous ground cover on tree growth were modelled using hyperbolic curve function; $Y = \alpha+\beta*\exp(-\gamma*hpc)$. However, for height growth the "γ" coefficient was not significant. The following plots highlight the residual trends of the selected models.

6.3.1.1 Residual plots of models of mean root collar diameter growth.

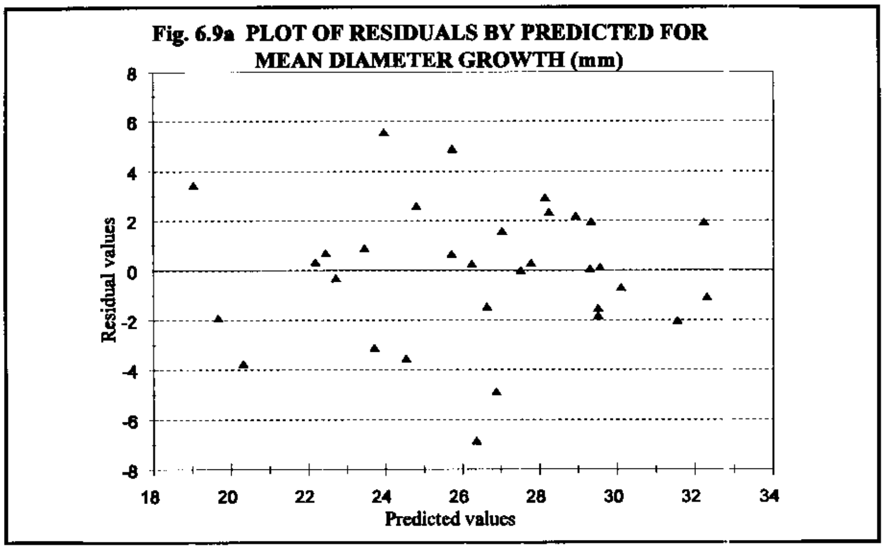

Fig. 6.9a PLOT OF RESIDUALS BY PREDICTED FOR MEAN DIAMETER GROWTH (mm)

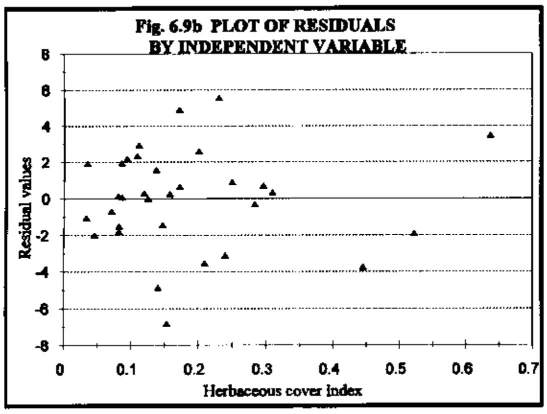

Fig. 6.9b PLOT OF RESIDUALS BY INDEPENDENT VARIABLE

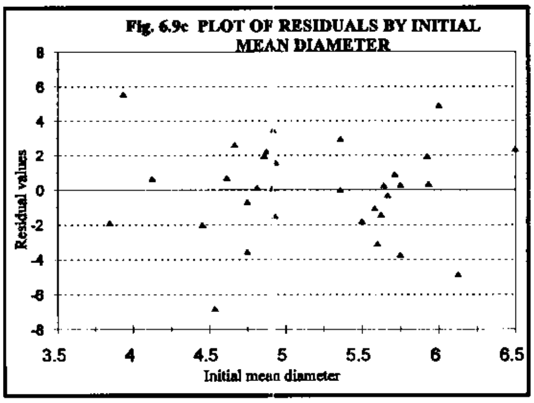

Fig. 6.9c PLOT OF RESIDUALS BY INITIAL MEAN DIAMETER

Figures 6.9a, 6.9b and 6.9c show plots of residuals by predicted, independent and initial tree size for mean root collar diameter growth.

6.3.1.2 Models of mean height growth under herbaceous weed competition. The following plots show residual patterns for mean height growth.

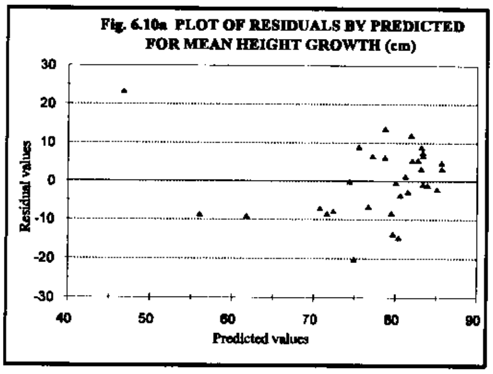
Fig. 6.10a PLOT OF RESIDUALS BY PREDICTED FOR MEAN HEIGHT GROWTH (cm)

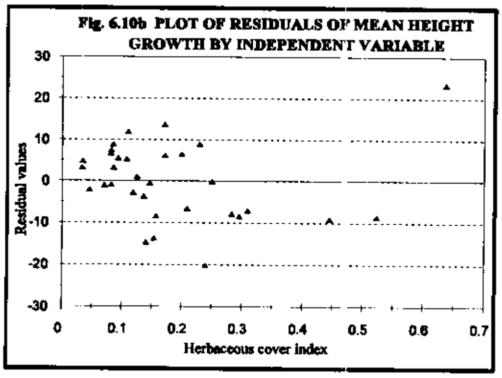
Fig. 6.10b PLOT OF RESIDUALS OF MEAN HEIGHT GROWTH BY INDEPENDENT VARIABLE

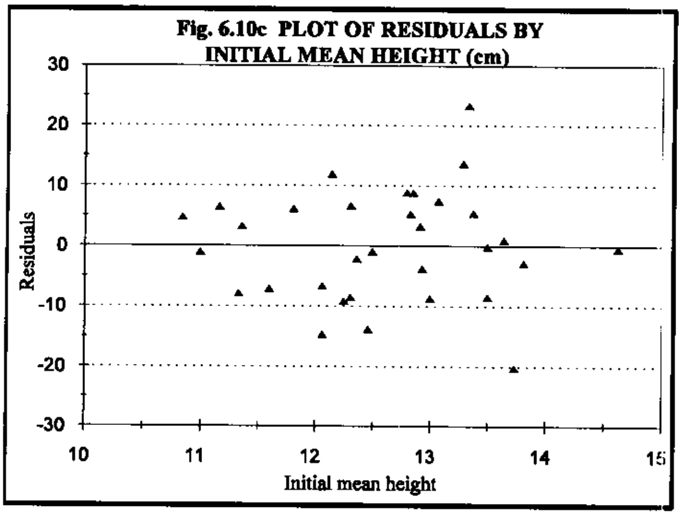
Fig. 6.10c PLOT OF RESIDUALS BY INITIAL MEAN HEIGHT (cm)

Figures 6.10a, 6.10b and 6.10c show plots of residuals by predicted, independent and initial size for mean height growth.

6.3.2 Effect of woody weeds' density on tree growth

Competition effects of woody non-crop vegetation were best described by functions $Y=\alpha+\beta*X$ and $Y=\beta*\exp(-\gamma*X)$ where; Y = tree growth and X = **(cd*wht/H)** or **(cd*wht/H)*(1-dist/Nr)**. Both functions gave similar fit. Function $Y=\alpha+\beta*X$ had a residual mean sum of squares of 12.34 and function Y=β*exp(-γ*X) a residual sum of squares of 12.14. However, the linear function was preferred to the non-linear because its residual plots were better.

Figures 6.11a and 6.11b: Plots of residuals by predicted and independent variables for mean diameter growth under woody competition.

6.3.3 Investigating the nature and form of competition effects on tree growth

Regression coefficients out put from SAS were used to plot growth trends under competition from herbaceous and woody non-crop vegetation. The curves were constructed from estimated coefficient values for **α**, β and/or γ output from the regression procedures. Figure 6.12 shows the effect of increasing herbaceous competition on mean tree growth (mean root collar diameter growth is used in the graph). Figure 6.13 depicts mean height growth under competition from herbaceous weeds. Figure 6.14 shows the fitted regression line describing the effects of woody competition on mean diameter growth.

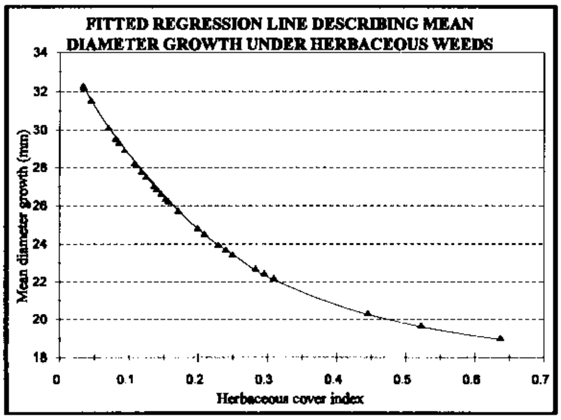

Figure 6.12 shows the fitted regression line describing mean diameter growth under increasing herbaceous percent cover index.

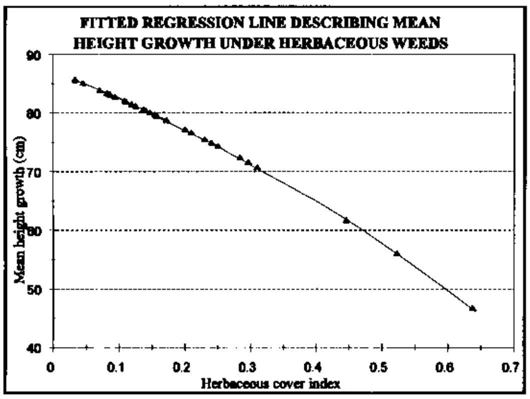

Figure 6.13 shows mean height growth under herbaceous weed competition index.

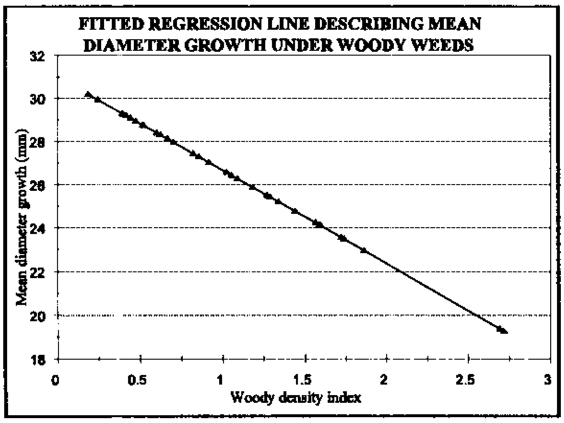

Figure 6.14 shows mean diameter growth under woody weeds' competition.

6.3.4 Summary

Regression analysis procedures showed that:

1) herbaceous weeds reduced tree growth significantly at the site;

2) woody weeds had no significant effect on height growth but had a significant effect on diameter growth;

3) initial tree size at planting time had an insignificant effect on tree growth; and

4) root collar diameter growth was more sensitive to competition from non-crop vegetation than height.

CHAPTER 7

GENERAL DISCUSSION

This chapter discusses the implications of the observations made in the results section. A concise summary of the answers to the objectives of the study is included. Implications and possible dangers of relying too much on some competition index formulations are pointed out. A brief discourse on the implications of the results on present and future vegetation management regimes in young plantations is also presented. Finally, the chapter closes with brief discussions of possible improvements of the present methods of vegetation control.

7.1 MEETING THE STUDY OBJECTIVES

The study had three objectives:

1) to identify practical and easily measurable indices of competition;

2) to provide a method of quantifying competition from non-crop vegetation in young radiata pine plantations; and

3) to derive an index of competition from neighbourhood predictors to estimate inter-specific competition.

These objectives have been fully achieved. Neighbourhood predictors of inter-specific competition were demonstrated to be quite useful and superior to methods which estimated competition effects at the stand level (whole stand approach). Non-crop vegetation density and species abundance were found to be ample indicators of competition severity. Percent ground cover gave reliable estimates of competition severity of herbaceous vegetation (grasses). Crown foliage density*weed height/tree height i.e. **(cd*wht/H)** and/or weighted by the distance i.e. **(cd*wht/H)*(1-dist/Nr)** were demonstrated to be adequate indices of inter-specific competition from woody weeds. This was supported by previous studies which also found percent cover (Wagner and Radosevich 1991a) and specific composition of weeds (Nambiar and Zed 1980), to be ample indicators of competition severity in young conifer stands. The woody index was in effect a shade index weighted by neighbour proximity factor (k). DeLong (1991) and Comeau *et al.* (1993) found similar indices useful in explaining inter-specific competition from overtopping vegetation. Moreover, the woody index demonstrates that foliar cover (leaf area) and vegetation height are good indicators of competition from overtopping vegetation. Further, competition from herbaceous weeds was shown to more aggressive on root collar diameter growth than on height growth.

7.2 RELATIONSHIP BETWEEN TREE GROWTH AND WEED DENSITY

7.2.1 The "rich-kid" effect

The "rich-kid-effect" observed in plots of individual tree growth, where most points in the plots were in low competition zones but displayed low growth contrary to expectations is not a new phenomenon. Studies by Wagner *et al.* (1989), Brand (1986) and Burkhart and Sprinz (1984) reported similar (negative hyperbolic curve) relationships between tree growth and weed density on a site. In explaining this phenomenon, the following factors were thought to be important.

(1) Poor measures of competition. Some of the significant terms for example, herbaceous percent cover were subjectively assessed. This is often a limitation of competition studies. Wagner and Radosevich (1991a) and Britt *et al.* (1991) assessed percent cover subjectively. Meanwhile, Nambiar and Zed (1980) and Sands and Nambiar (1984) employed the services of "experienced estimators" to quantify percentage cover. Cousens (1987) says that subjectivity in non-crop vegetation assessments and control may be a necessity for some time to come. Pitt and Glover (1993, 1995) reported successful use of large-scale 35-mm aerial photographs in assessing woody vegetation crown areas. They reported the method to be feasible with up to 40% savings on costs. Therefore there are possibilities of using video pictures and image analysis techniques in the near future to assess vegetation cover.

(2) Uneven vegetation cover from one tree to another. Enough evidence was presented to the effect that there was a poor relationship between treatments and actual competition. This can be attributed in part to the highly sensitive nature of neighbourhood measures of competition compared to whole stand measures which were used to define the treatments. Moreover, re-establishment of weeds after planting or treatment may vary greatly and thus influence resource availability (see also photographs 7.1, pp. 115 and 7.2, pp. 116). Many sources in the literature have reported significant effects of site preparation and weed control methods on future weed population dynamics. Nambiar and Zed (1980) reported that weed control regimes influenced not only total densities but also species composition of future weed populations. They also reported that use of some chemical formulations favoured the dominance of some weed species but reduced that of others.

(3) Confounding between competition intensity and genotype. Different genotypes may respond differently to competition leading to the "rich-kid-effect".

(4) Other factors (other than weed competition) at the site may have affected tree growth significantly e.g. nutrient variation. Site preparation methods used may have affected tree growth. The site was windrowed, thus all the slash was piled up in windrows. Common methods used nowadays aim to distribute slash evenly on a site (slash retention) to avoid scraping the site bare of nutrients and/or organic matter. The Edaphic factors have been reported to affect the tree-weed state and functional abilities (Cellier and Stephens 1980, Carter *et al.* 1984). Wagner and Radosevich (1991b) and Newton *et al.* (1987) reported insect and animal damage to affect tree growth. Nursery practices for example; nursery spacing (Bowles 1981), seedling conditioning (van Dorsser 1981), stock size (South *et al.* 1993a), and quality and handling and planting practices (Trewin 1981, Brunsden 1981, South *et al.* 1993b) can also affect establishment vigour and future tree growth. Proper cultivation of the site, especially in poor sites or those in harsh environments is necessary to ensure good growth and survival (Cullen and Mason 1981, Balneaves 1982).

7.2.2 Competition effects on mean tree growth

Competition effects from grass were more important at the site than those of woody weeds. Competition for resources was therefore, assumed to be symmetrical (two-sided) with shorter neighbours having more adverse effects on taller neighbours. Most grass species have roots close to the soil surface. They can therefore, compete aggressively for nutrients which abound in the top soil horizons unless leached. Moreover, grasses also intercept any moisture falling to the ground and can thereby prevent soils from rewetting (Balneaves and Clinton 1992). Positive effects on tree growth and survival resulting from grass control have also been reported by Squire (1977), West (1981), Balneaves (1982), Gjerstad and Barber (1987), Newton *et al.* (1987), Tappeiner II and Wagner (1987) and Balneaves and Clinton (1992). Moreover, Balneaves and Clinton (1992) add that grass competition is particularly serious in low rainfall areas for example the Canterbury plains.

Models of herbaceous intensity showed better distributions of residuals than those of woody and most models were significant at the 95% level. However, most models for woody non-crop vegetation were not significant. This had already been evidenced by their weak trends in the scatter plots. This may be due to the fact woody weeds (*Acacia* species) were not numerous and had very low leaf areas at the time of assessment. As a result minimal shading was experienced by the radiata crop trees. Competition effects from woody species have been reported to be largely through reduced light quantity and or quality (DeLong 1991, Cannell and Grace 1993). Moreover, *Acacia* species have massive root systems (Hugh Stevenson pers comm.) and they may persist and compete even when the crop has closed canopy as was reported for other woody weeds (gorse and broom) by Balneaves (1981).

The results also served to demonstrate the superiority of the neighbourhood approach. Treatment definition was based on average measures of percent weed ground cover of non-crop vegetation in a plot (whole stand approach). But these related poorly to actual competition. Therefore, managers stand to benefit if they adopt the neighbourhood approach when evaluating and controlling non-crop vegetation in young conifer plantations.

Moreover, treatment 1 which was considered weed free had some herbaceous vegetation. This should not be very surprising because as photographs 7.1 to 7.6 (pp. 115-117) indicate, site preparation and/or planting practices normally aim to modify the micro-environment and therefore, favour the growth of the desired crop trees. But there are cases when the effects of micro-site modification are not long-lived. Moreover, even where weed control was recently undertaken the result may be that individual trees either end up completely weed free as desired or may actually have some low stature weeds close by which could interfere significantly with resource availability.

By using neighbourhood predictors of inter-specific competition and the resultant competition indices, which indicate how resources of individual trees are shared by their neighbours, managers can get feed back on the effectiveness of control measures after they have been executed. The competition indices developed have therefore, great potential as useful tools to aid in silvicultural and management decision-making regarding weed control needs as well as for assessing the effectiveness of control procedures used to treat non-crop vegetation in young plantations of radiata pine.

7.2.3 Neighbourhood sensitivity analysis

Because woody weeds were not numerous only very basic sensitivity analyses could be performed. Furthermore, lack of adequate consistent assessments meant that the time dimension, which could have shown changes in weeds dynamics could not be included in the analyses.

7.2.3.1 Neighbourhood abundance. The effect of grouping woody weeds by species was not investigated fully because most of the woody weeds were of only one species i.e. *Acacia* species. The results reported in this study used 2 major groups (herbaceous and woody). Herbaceous effects were intense compared to those of woody, particularly on diameter growth as shown by the curvature (or gradient) of fitted regression lines (Berkowitz 1988). This could also be attributed to the scarcity of woody weeds at the site or their low leaf areas.

7.2.3.2 Neighbour height. The effect of stratifying neighbours on the basis of their height relative to subject crop tree was investigated. Multiplying the competition indices by the reciprocal of crop tree height (1/H) resulted in significant models for woody weeds at the 0.05 % level. Thus, as would be expected, neighbours that were taller than target crop trees had more interference effects than those that were shorter.

7.2.3.3 Neighbourhood radius and neighbour distance. Effect of varying neighbourhood size i.e. 1 m and 2 m was studied. The distance weighting factor k, (k = 1-dist/Nr) was meant to achieve this sensitivity. Using a neighbourhood radius of 200 cm, all neighbours that were 50 cm from the target crop tree were multiplied by 0.75, while those that were 100 cm away by 0.5 and those that were 150 cm away by 0.25. Thus, nearer neighbours in the neighbourhood were given more emphasis than those that were farther. The results showed that closer neighbours had more adverse effects on tree growth than far away neighbours. This kind of analysis should normally give insight into effective neighbourhood size in relation to competition i.e. determine an efficient zone of influence. However, woody weeds were not numerous and no further firm deductions could be made from these analyses. Furthermore, using neighbourhood size 1 (100 cm radius) did not result in any significant improvement in the models fitted.

7.2.4 Comparison of treatment groups I (3, 4 & 5) and II (6, 7 & 8)

Relative growth rate (RGR) was used to compare dry matter production efficiency of different treatments. Absolute growth rate was not very useful in displaying differences in above ground biomass (height, root collar diameter and basal area at ground level) accumulation with time because absolute growth rate did not account for size differences resulting from treatment differences. By comparing RGR as a function of initial size therefore, the different treatments could be compared adequately. This is corroborated by Causton (1983), Radosevich and Holt (1984), Stewart (1987), Radosevich and Oysteryoung (1987), Zedaker *et al.* (1987), and Brand (1991). Moreover, Brand (1986) reported that absolute growth rate tended to over estimate competition effects.

At the end of the first growing season in July 1994 treatments in group II (i.e. 6, 7 and 8) generally recorded superior relative growth rates than those in group I (i.e. treatments 3, 4 and 5) and even the control (treatment 1). These treatments (6, 7 and 8) had been growing in weed-free conditions. During the second growing season (July 1994 to September 1995) only treatment 1 remained weed-free. Treatments 6, 7 and 8 had 15 %, 40 % and 75 % weed cover respectively. In mid-summer (February 1995), it was observed that root collar diameter relative growth rate of treatment 1 increased drastically from being the lowest to be the highest. It was followed closely by treatment 3 (15 % weed cover) and then treatment 6 (15 % weed cover). This indicated that competition from weeds was a major debilitating factor to tree growth at the site. Trees in treatments 6, 7 and 8 which had been weed-free (in the first year) had started to feel the effects of weed competition, hence their lower relative growth rates compared to the previous season. On the other hand, treatments 5 (75 % weed cover from planting) and 2 (conventional weed control regime) were at the bottom. In fact the conventional control (treatment 2) was only slightly better than treatment 5 (75 % weed cover from planting) at the hight of summer (February 1995).

By the end of the first growing season (July 1994) mean volume growth for group II was 37 % higher than that of group I. This advantage was carried on to the second year although individual treatment trends had started to change in favour of treatments with low weed densities. By September 1995, total mean volume of group II was 29 % higher than that of group I.

7.2.5 Possible cases of micro-site variability in this study

The following photographs are included so as to share some of the experiences gained in this study.

Photo No.7.1. Most managers would like to see very clean sites. But completely weed-free sites may not actually mean maximum growth will be achieved. In fact, there is danger of erosion which could end up reducing the nutrient status of the site. This could also expose the young tree roots which are still close to the surface to desiccation agents (wind or sun).

Photo No.7.2. An obvious case for control, because the weeds overtop the desired crop tree(s).

Photo No.7.3. It is a historical fact, that most foresters and managers alike, do not normally consider grass and other low-stature weeds to be a major deterrent to tree growth. Thus in the photograph (above), managers may opt not to control the weeds. This misconception that overtopped weeds have insignificant effects on conifer growth and productivity is quite unfortunate. Grasses can compete aggressively for site resources (Squire 1977, Balneaves 1982, Balneaves and Clinton 1992). Furthermore, in areas with severe pest problems, tall grasses can provide hiding and breeding grounds (Newton *et al.* 1987). Such pests may later devastate crops. On the other hand overtopped weeds (woody) can also affect conifer growth significantly and can lead to mortality in severe cases (Balneaves 1981, Balneaves and Zabkiewicz 1981, West 1981, Burkhart and Sprinz 1984, Gjerstad and Barber 1987, Wagner *et al.* 1989, Wagner and Radosevich 1991a, Comeau *et al.* 1993, Horsley 1993). (Note: causes of branch damage were unclear).

Photo No.7.4. Site preparation and planting methods may modify micro-sites in various different ways, and thereby modify competition effects as well. In most cases weed-free micro-sites are created around the desired crop trees. On average, trees in such micro-sites tend to perform very well.

Photo No.7.5. It is not uncommon for weeds to re-establish very fast following control.

Also, woody weeds with massive vegetative parts may recover very fast and use the comparatively "competition-free" conditions created to proliferate.

Photo No.7.6. Micro-site variation can make neighbouring trees grow differently (Note: causes of damage to shorter tree were unclear).

The decision "to control or not to control" is never simple or clear-cut especially if subjective methods are the basis for making decisions. Competition indices developed from quantitative methods can be effectively used as tools to aid in decision-making regarding need to control. For example, even in cases where weeds abound it is possible to have a few individual trees which may be in weed-free micro-sites. Under these circumstances, assessment and prompt control of the weeds if the competition index is very high will avoid the development of uneven and irregular crop.

7.3 SEASONALITY OF GROWTH AND COMPETITION DYNAMICS

7.3.1 Seasonality of competition

The relative growth rate analyses served to show that competition intensity varied depending on the season. Also it was shown that treatments with weed ground cover of 15% or less (1, 3 and 6) had higher RGR than the rest during summer-autumn. Nambiar and Zed (1980) reported low RGR values for treatments with high weed cover densities during summer. They associated this with low needle water potentials and water stress. These results were further supported by Sands and Nambiar (1984) and Carter *et al.* (1984)

who observed water competition intensity to be related to above ground weed cover.

Weeds restrict the growth of young trees more than older ones. Older trees tend to have well developed root systems and can cope with seasonal changes in competition intensities better. Moreover, water related stresses resulting from the presence of weeds on a site were reported to continue into autumn depending on the site and the weed species (Nambiar and Zed 1980).

7.3.2 Woody-herbaceous interaction

The plot of woody by herbaceous weeds showed an inverse relationship. It can be hypothesized that the weeds also competed with each other for site resources and consequently for dominance. Further, it can be argued that the net interference effects on the desired crop trees were a composite of intra- and inter-specific effects between the different weed species' groups. This relationship was not modelled because of paucity of woody data. But more importantly, because with only one-time measurements no meaningful deductions could have been made.

The woody-herbaceous interaction plot was therefore, intended to point out that weed species did not discriminate against or favour each other. Seasonal changes in state and function of weeds need to be captured for competition models to be robust. Seasonal adjustments influence resource use (Nambiar and Zed 1980, Carter *et al.* 1984, Sands and Nambiar 1984). This ability to readjust to sudden changes in the resource pool could be the secret of successful competitors. Therefore, incorporating seasonal changes in weed morphology and physiology should give more reliable measures of competition effects and show the changes in function and state of the weeds. Rigorous periodic measurements are therefore necessary if competition models are to be used through out the year.

In formulating competition indices it was found that the seasonality of growth was closely followed by competition intensity, be this a change on the desired crop tree size or weeds or both. Thus, it is not uncommon for some indices to be more useful than others depending on the season of the year. The following short discussion is intended to caution against treating some indices as "standard" and expecting them to show significant relationships all the time.

7.3.3 Caution: good indices should represent practical reality

The adoption of any competition measures just because the formulations have shown trends with crop tree variables in the scatter plots could be dangerous. Investigations of the indices' biological implications may be an important requisite. Good indices should, above all else, be **practical to assess** and they should also describe **biological reality**. The example given below explains this further.

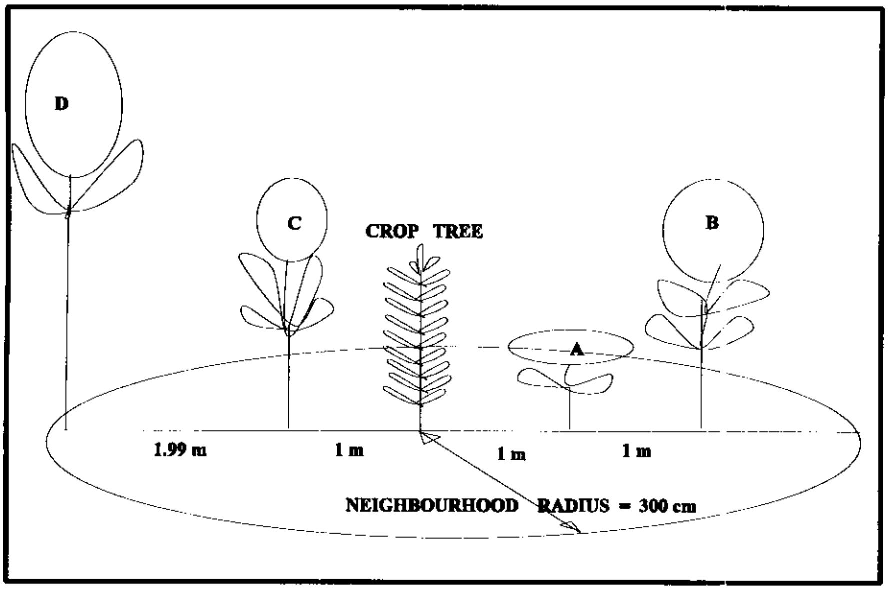

Figure 7.1 shows a schematic diagram of weeds A, B, C and D growing in the same neighbourhood with a young seedling (crop tree).

We wish to see how sensitive and sensible our competition indices can be. For simplicity's sake, the following variables are considered for each non-crop individual in a neighbourhood (Nr) of 300 cm i.e. 3 m radius;

ca = crown area = Pi*(mean crown diameter/2)^2,

cd = crown foliage cover density,

wht = weed height,

dist = distance of weed from crop tree,

cvi = crown volume index = ca*wht,

cvip = crown shade index = cvi*cd,

k = distance weighting factor = (1-dist/Nr; where Nr = neighbourhood size),

dcvip = distance weighted shade index = cvip*k.

WEED	ca	cd	wht	dist	cvi	cvip	k	dcvip
A	50	30	20	100	1000	300	0.67	201
B	50	35	30	200	1500	525	0.33	173
C	50	25	30	100	1500	375	0.67	251
D	100	35	50	299	5000	1750	0.0033	5.8

Table 7.1: Hypothetical data for calculating CI (an example).

7.3.3.1 Crown area (**ca**). Crown area is a fairly good measure because large crowns cast more shade, and hence result in more competitive effects i.e. interference. The lack of vegetation height and distance in the expression however, is a big disadvantage and can easily lead to misrepresentation of effective competition. In the example above the rating in severity is D > A, B ,C and A = B = C which is probably a misrepresentation of real differences. Furthermore, any two woody non-crop trees with same crown areas but of different heights and/or at different distances from the crop tree are expected to have unequal magnitudes of interference effects.

7.3.3.2 Crown volume index (**cvi**) and shade index (**cvip**). Indices developed using crown volume or crown shade are perhaps more meaningful measures of possible interference effects than crown area on its own as they incorporate height of the vegetation. **Cvip** goes further to incorporate the percent foliage cover. It therefore, estimates the actual shade cast on a crop tree. The weakness of these two measures is their failure to incorporate distance from the crop tree and tree height which are important neighbourhood factors. These measures can give misleading competition effects as they tend to overemphasize non-crop vegetation effects of **any massive neighbours**, irrespective of their distance from the crop tree.

In the example above, **cvi** rates the competition intensity as D > (C = B) > A. But logic and common sense tells us that C and B can not have the same effects on the crop tree because B is farther than C. **Cvip** rates the competition as D > B > C > A. But again for the same reason as in **cvi** there is overemphasis on the effects of B as compared to C, logic suggests the converse based on the given information.

7.3.3.3 Incorporating distance from crop and neighbourhood size. The column labelled K in the table shows that each woody non-crop plant in the neighbourhood is given a weight proportional to its distance from the crop tree. The weight is calculated as "**{1-(distance/neighbourhood size)}**". Incorporating **k** into **cvi** or **cvip** improves the indices and makes them satisfactory measures of competition. In the example above, the rating has now changed to C > A > B > D. Thus, D, being at the edge of the plot has been given least emphasis.

Armed with all this information, we still can not quantify competition exactly because competition is dynamic and in reality we don't know what is happening below ground. Interpretations are therefore, based on intuition and knowledge about allometric relationships between above- and below-ground tree parts. Moreover, as the crop tree grows, so does its area of influence (zone of "perception"). Thus, new neighbours or competitors are continually being recruited into the crop tree's zone of influence or perception. Also, the acquisition of below ground resources is influenced by the rooting habits of both the crop trees and the non-crop vegetation. If, for instance, the crop tree and the non-crop vegetation happen to have the same rooting habits and their roots occupy the same soil zone, then irrespective of the non-crop vegetation height and/or size, we can generally expect serious competition to be more likely, than if these neighbours had different rooting habits and their roots did not occupy the same soil zone. Sands and Nambiar (1984) reported changes in relative distribution of roots with time to be among the causes of competition change with season.

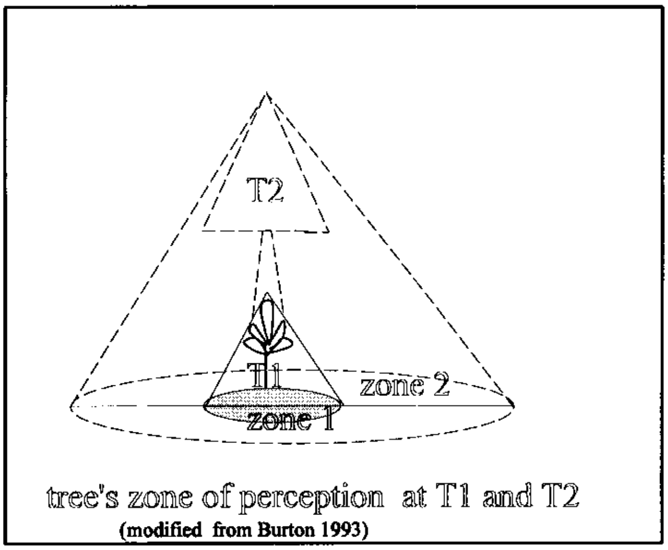

Figure 7.2: Schematic diagram showing influence zones of a tree at times T1 and T2.

Incorporating the tree crop height can improve the measures further, because non-crop vegetation which is taller than the target tree, is expected to have more deleterious effects on crop trees than shorter weeds. This also makes the CI sensitive to target tree crop height (Brand 1986). Some studies like that by Wagner and Radosevich (1991a) went further and incorporated non-crop vegetation azimuth in the competition index expressions with the result that sparsely aggregated neighbours were found to have more negative effects on desired crop tree growth than neighbours which occurred in clusters.

7.3.4 When could inter-specific competition be a critical factor?: Interpreting scatter plots

High growth can occur in highly weed infested micro-sites indicating that the micro-site is highly favourable for growth or that the resource needs of the species growing together are different. It could also indicate cases of mutual benefit with both parties "shying-off" from each other (Radosevich and Oysteryoung 1987). Here, in interpreting inter-specific competition effects the shape of the scatter and where each point or treatment appears in the plot should be taken into account.

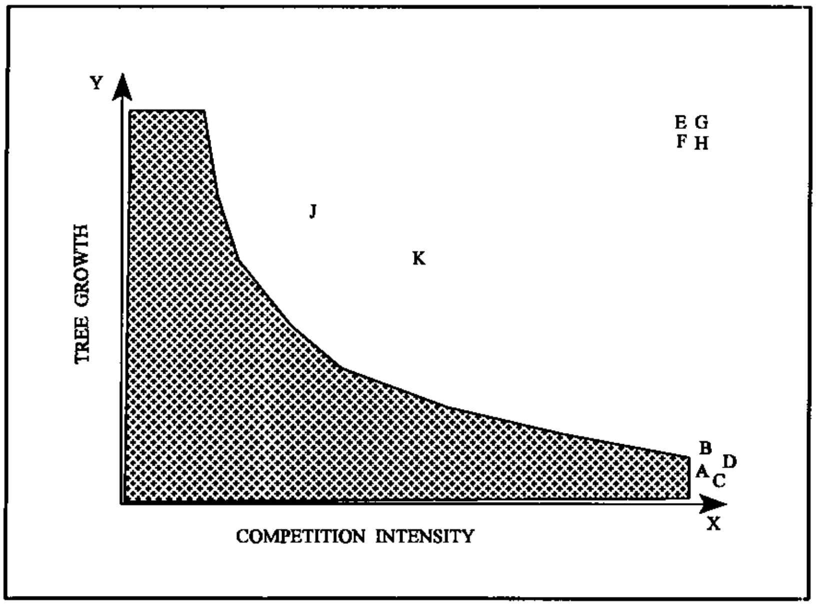

Figure 7.3: Various categories of "outliers" and their possible interpretation.

Therefore, in figure 7.3, the points A, B, C and D can justifiably be interpreted as showing poor growth due to competition intensity. But E, F, G and H even though in a high competition zone show very high growth. This can be attributed to better micro-site factors which favour growth or complementarity; assuming no errors in assessment or data recording were committed. Similarly, points J and K can be treated as outliers perhaps as a result of ineffective measures of competition being observed.

7.3.5 How effective was the first weed-free year

The gains in crop tree growth resulting from intensive weed control in the first year following planting and then controlling weeds from year two onwards (treatment 6, 7 and 8), were seen to be real and worth the effort and funds. Mean volume for this group was 30% higher at the end of the first year. Further, by the end of the second year (September 1995), these benefits were still maintained, although the gap was closing.

7.4 IMPLICATIONS OF THE RESULTS ON PRESENT AND FUTURE VEGETATION MANAGEMENT REGIMES

7.4.1 Developing weed species'-specific control regimes: the idea of competition thresholds

Figure 7.4 (below) shows the relationship between tree growth versus competition from herbaceous and woody weeds on a site.

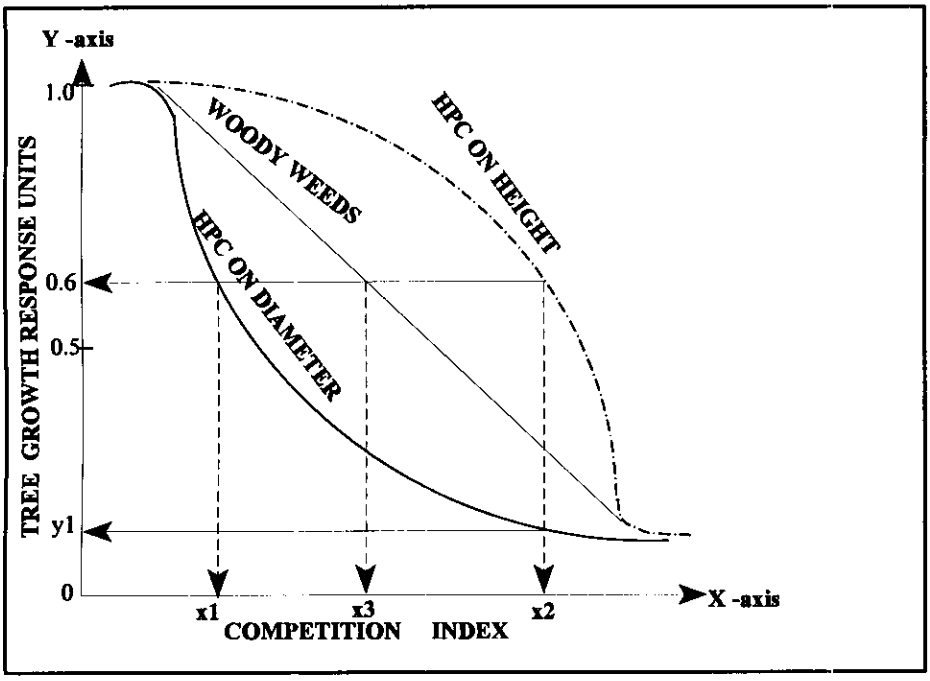

Figure 7.4: Competition threshold levels for tree growth under herbaceous and woody competition. N.B. only **x1** and **x2** are comparable on the same scale as they represent the same weed-crop mixture.

This scenario was reconstructed from the observations made in the previous chapter (6) using the competition models fitted. A point of interest to note is the fact that had more deleterious effect on diameter growth than on height growth. Using these thresholds it can be seen in figure 7.4 that under competition from herbaceous weeds, the critical region for diameter growth was **x1**. However, at this threshold value (x1) height shows only minimal effects. The management implications are that managers who use height growth as the only indicator of crop tree vigour and/or competition severity may be misled. For example if a manager desires 0.6 growth units, then using height growth as the indicator of crop vigour the index is x2. But at this index value diameter growth is already suppressed to levels below 0.3 units (y1).

However, this depends on the threshold criteria used. Cousens (1987) compares and contrasts between economic, statistical and competition thresholds. Ultimately, economic decisions may influence the type of vegetation management decisions which managers make. However, for the purposes of this study it was intended to show that with similar tools available, forest managers would be able to make decisions regarding weed control better. Managers would also be able to assess the effectiveness of control treatments applied to growing stands. These results follow closely those from similar studies by Morris and Forslund (1991) and Wagner *et al.* (1989).

In figure 7.4 no comparisons were made between woody and herbaceous threshold lines. This is because the methods used to calculate the two were different. Moreover, as woody weeds were not numerous and had low leaf areas, the threshold at this stage could actually represent very low values of normal situations (for herbaceous weeds the values were between 0 and 100 % cover). Also threshold comparisons should be made for same crop-weeds species mixture. The values can also change with time, place and environmental conditions (rainfall, temperatures, fertility).

7.4.2 Future control strategies

Radosevich *et al.* (1990) discussed the need for judicious utilization of weed control technologies. Moreover, with increasing population pressure in some areas, the same land is competed for by a myriad of possible uses. Consequently, multiple land use technologies have become the order of the day, pitching foresters against other land-users. At the same time, increasing concern for the environment has also put foresters (and other land users) under surveillance calling for wise use of chemicals (Radosevich *et al.* 1990, Zabkiewicz and Richardson 1990). The efficiency of future control methods, as indicated by tree crop performance (Wagner *et al.* 1989), may need to incorporate not only economic considerations, but also ecological and environmental factors (Zabkiewicz and Richardson 1990). The move to reduce herbicide use through selectivity, better formulation and improved potency (Zabkiewicz and Richardson 1990), is a positive one. Reducing the areas treated while maintaining efficacy is one way to achieve this goal.

Future control strategies therefore, need to achieve more success and save resources. The neighbourhood approach to assessment and weed treatment is seen by the author as a good starting point. The use of different weed-free spot sizes around crop plants is seen as one such approach. This may need to integrate other cultural practices for example, slashing tall weeds adjacent to young trees. Such an integrated approach will make future silvicultural treatments relatively easy to undertake in the long term, while at the same time reduce hiding grounds for insects and animal pests with potential to devastate crops in the short term.

7.4.2.1 Economics of spot-size treatment (individual tree approach) versus plot-area (whole stand approach). The results from this study indicated that treatments with high weed densities faced serious competition in spring-summer compared to those with weed covers of 15 % or less (treatments 1, 3 and 6). Further investigation showed that if managers used weed free area (spots) around individual radiata pine plants, then the maximum spot size at the present spacing in the trial would be 1.25 m. This implies that the optimal weed free area (assuming circular plots) would be:

$$(\text{spot area}*\text{no. of trees})/\text{plot area} = (\pi*(1.25)^2*36)/360 = 0.49.$$

The implications are that by using spot size treatments, total weed free area (in a plot) of more than 50 % would result in overlapping treatment areas and hence resource use inefficiency.

This study was not designed to investigate the economics of weed control. But the inferences made here were obvious from the results. It was therefore intended to highlight them under this section.

CHAPTER 8

SUMMARY AND CONCLUSIONS

This study showed that non-crop vegetation control regimes which were based on whole stand quantitative measures of weed abundance gave unreliable estimates of the actual competition experienced by individual crop trees. Thus:

a) weed abundance in the neighbourhoods of trees was poorly correlated to nominal treatments; and

b) tree growth was better related to actual measurements of weeds in the neighbourhoods of trees than to the nominal treatments.

This indicated that quantitative approaches to evaluating inter-specific competition at the individual tree level using neighbourhood predictors, were more reliable than whole stand approaches.

Further, using individual woody competitor effects (individual plant approach) was more useful in expressing competition effects from woody non-crop vegetation. Grouping woody competitors by species did not improve the fit of the models (species approach).

Results from the analyses of competition data showed that crop tree height growth, root collar diameter growth and basal area at ground level (and their sizes) were sensitive to competition from herbaceous weeds as expressed using percent ground cover. For woody non-crop vegetation, however, the relationships were still weak. Consequently, most models for woody non-crop vegetation were not significant at the 0.05 percent level. On the other hand, models of herbaceous weed intensity showed better distributions of residuals and all the models fitted were significant at the 0.05 % level. Moreover, herbaceous weeds had more deleterious effects on diameter growth than on height growth, as indicated by the shape of the fitted regression equations.

Competition effects of herbaceous weeds were different from those of woody weeds. Mean diameter growth was related to a decay function of the form $Y = \alpha + \beta*\exp(-\gamma*hpc)$; where Y = mean growth, hpc = herbaceous percent cover index and α, β and/or

γ were regression coefficients. Woody competition effects were described best by the function $Y = \alpha + \beta*\exp(wci)$, where wci = woody competition index expressed by **∑(cd*wht/H)** or **∑(cd*wht/H)*(1-dist/Nr)**.

Crown area {pi*(crown diameter/2)^2} and/or a crown volume index {weed height*pi*(crown diameter/2)^2}, on their own, were found to be unreliable measures of actual competition. Incorporating the estimated crown density (percent crown foliage cover) and proximity to target crop tree into these measures gave theoretically sound and more useful measures of inter-specific competition. Moreover, multiplying these indices by the reciprocal of crop tree height put more emphasis on taller weeds that cast shade on crop trees and the resultant indices were also significant.

Sensitivity analyses of the relative effects of woody weeds showed that most competitive effects came from weeds that were taller than the crop trees and especially from those in the first neighbourhood (100 cm radius from crop trees).

Finally, the study found the following to be effective indices of inter-specific competition:

(i) herbaceous vegetation and any low-stature weeds - percent ground cover (**hpc**); and

(ii) woody weeds - **∑(cd*wht/H)*(1-dist/Nr)**.

CHAPTER 9

RECOMMENDATIONS AND FUTURE RESEARCH DIRECTION

9.1 VEGETATION MANAGEMENT RESEARCH NEEDS

Appropriate research should involve treatment development and evaluation, treatment decision criteria and appropriate control methods. Emphasis should be placed on reducing treatment needs, with treatments being targeted only to areas where they are needed and at reduced intensities (Zabkiewicz and Richardson 1990), with an overall aim of providing alternatives to achieve management objectives (Stewart 1987, Radosevich *et al.* 1990). Alternative direct control methods for competing non-crop vegetation during site preparation and release operations plus treatment costs and their effectiveness, as well as their biological and physical attributes are important considerations which need to be incorporated into the decision process.

Lack of adequate knowledge and/or poor organisation of information on weed ecology and physiology (Stewart 1987, Fryer 1987, Mason 1992) and the long-term interactive effects of weeds and crops (Radosevich *et al.* 1990) need to be addressed. Computer models and expert systems could be useful to integrate competition information with stand growth models incorporating socio-economic and environmental factors.

Future control technologies may need to be based on assessments of the areas around individual trees. The use of different spot sizes as the trees increase in size may be one possible solution.

It is recommended that further research be taken to: 1) examine in details the possible effects of genotype and weed competition (a pilot study was set up at Delthorpe, Canterbury in November 1995 by Balozi Kirongo; School of Forestry, FRI-Kenya, and Dr. Euan Mason, School of Forestry, University of Canterbury); 2) ensure consistent measures of abundance for example by using image analysis techniques; 3) investigate effect of other factors particularly nutrients, and possible animal damage, nursery, handling and planting practices.

Finally, complementary studies like those by Peter Clinton in Eyrewell forest, Canterbury, (New Zealand) investigating the impacts of understorey vegetation on radiata pine growth and nutrition (Clinton pers comm.) should be encouraged. Future successful non-crop vegetation control procedures may rely on quantitative studies of the interactions between weeds and radiata pine. Knowledge on specific processes of weed control levels, fertilizer application, moisture availability and nutrient use employing physiological and morphological measures of both the crop trees and the weeds (for example, biomass, needle water potential, stomatal conductance, vapour pressure deficits) would help researchers and managers understand better the effects of common weed species on radiata pine. This may call for rigorous periodic data collection to capture interference dynamics. Important questions for example, the price for using nitrogen fixers in terms of moisture and nutrient use before nitrogen fixation levels are significant in the site, or the loss in growth incurred by crop trees if control treatments are deferred so as to maximise net dollar returns, need to be answered incisively and objectively. Such information would mean that in future researchers may be able to estimate the seasonal changes in competition severity. As Cannell and Grace (1993) put it, "our present information implies that the competition analyses we normally do are an a posteriori activity reporting past events". There is a need, therefore, to develop objective and practical approaches which are active rather than reactive, so as to predict what may happen under changing micro-environmental conditions and or tree and weed physiology and morphological changes.

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APPENDICES

Appendices are provided in the form of a single diskette. The use of the diskette is however, restricted to FRI, Selwyn plantation board Ltd. and the School of Forestry, University of Canterbury.

The programs used in calculating the competition indices are given. Also some of the models fitted are given in their final forms and can be run directly from SAS without any modifications. Below is a description of the terms in the models and their meanings. However, the data are not included because they are the property of NZ FRI.

The following files are contained in the diskette.

1) GARAMA.LST, contains SAS programs for calculating competition indices from the neighbourhood data.

2) NB2PLOTS.LST, contains SAS programs for running herbaceous percent cover index models. Multiple range tests for treatment differences and analysis of covariance are also included.

3) TREMODEL.LST, contains SAS statements for running woody models.

Further, abbreviations are used in the INPUT statements of the SAS programs. These and their meanings are as follows.
Bl = block, Trt = treatment, Trn = tree number, D93 = initial diameter, H93 = initial height, D94 = July 1994 diameter, H94 = July 1994 height, D95f = February 1995 diameter, H95f = February 1995 height, D95s = September 1995 diameter, H95s = September 1995 height. D1, D2, D3, H1, H2 and H3 relate to diameter and height growth for periods 1, 2 and 3 as described in the materials and methods chapter. D1sq, D2sq and D3sq relate to basal area growth at ground level.

The following abbreviations are used for non-crop vegetation. Hbpc95 = herbaceous cover, Wht95 = weed height, Ca95 = crown areas, Dist95 = mean distance to crop tree, Cd95 = crown foliage density, K95 = distance weighting factor, cvi95 = crown volume index, cvip95 = crown shade index, q95 = distance weighted crown volume index, ici95 = distance weighted shade volume index, Cap95 = ca*cd, Cak95 = ca*k, whtk = wht*k. The calculation of these indices has already been described in the relevant sections of this thesis and will not be repeated here. Further, where the above indices were divided by tree crop height, the name(s) appear with an "H". For example Cah = crown area/tree height.