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SEED PRODUCTION IN GARDEN NASTURTIUM

(*Tropaeolum majus* Linn.)

A thesis presented in partial fulfilment
of the requirements for the
Degree of Master of Agriculture Science
in Seed Technology
at Massey University
Palmerston North
New Zealand

VILIAMI TISILELI FAKAVA

1992

ABSTRACT

This thesis reports the results of research on seed production of garden nasturtium (*Tropaeolum majus*). The research programme was begun in late 1991 with an investigation on the effects of plant density on *Tropaeolum majus* cv. Choice Mixed grown under field conditions. The plant responses to changing plant density in terms of the vegetative growth and morphology, flowering pattern, seed yield and yield component were investigated using four different densities ranging from 3 to 45 plants per m^2. The results of this research showed that increasing plant density decreased branch number, dry weight, leaf number and area, and flower number per plant. It was also shown that seed yield is primarily determined by the number of flowers produced per m^2 and this character was identified as an important aspect to be manipulated for improving seed yield. Although increasing plant density resulted in decreased seed yield per plant, seed yield per unit area was similar at all densities.

Nasturtium flower and seed development studies showed that irrespective of density it takes about 12 days for the green floral bud stage to complete flowering and each flower needed 40-50 days from pollination to reach physiological seed maturity. Seed started shedding at 40 DAP at a moisture content of 78-80% and a maximum seed weight of 0.18 grams. Seed ripening occurs after 50 days from pollination after seed shedding on the ground surface. Maximum seed yield was achieved at 40 days after peak flowering at all densities.

The second stage of the study involved an assessment of the tolerance of nasturtium to various selective herbicides. This experiment was conducted in January-June 1992 in the glasshouse and was designed to provide information on the phytotoxicity of herbicides to nasturtium seedlings and plants. A wide range of soil and foliar applied herbicides were evaluated for their phytotoxicity to nasturtium. Four pre-emergence chemicals, chlorpropham (3.2 kg ai/ha), alachlor (2 kg ai/ha), oryzalin (3 kg ai/ha) and trifluralin (0.8 kg ai/ha) were considered to be the most selective and are recommended for direct sown nasturtium crops. Post-emergence applications of asulam (1.6 kg ai/ha), haloxyfop (0.3 kg ai/ha), methabenzthiazuron (1.4 kg ai/ha) were also well tolerated by nasturtium seedlings.

Seed production possibilities for the production of garden nasturtium seed under New Zealand conditions are also discussed.

ACKNOWLEDGEMENTS

There are many people I wish to thank for their support and contribution to the completion of this thesis. Even though I can only mention a few I do appreciate and thank them all.

Firstly, I would like to thank God for his love, blessings and his guidance enabling me to complete my study.

I wish to express my most sincere thanks and gratitude to Prof. Murray J. Hill, my chief supervisor and Director of the Seed Technology Centre, for his wise supervision, understanding, encouragement and support throughout my study. His constructive criticism and patience in reading and correcting this manuscript is widely acknowledged.

I am also greatly indebted to my co-supervisors, Mr. K.C. Harrington for his wise advice, constructive criticism and patience in supervising my herbicide trial. Dr. P. Coolbear for his extremely valuable suggestions and guidance with my study.

I would also like to thank Mr. M. Laurenson of the Horticultural Research Department, for his expert guidance and support especially in assisting with computer and data analyses.

My sincere thanks are also extended to:

The New Zealand Government, through the Ministry of External Relations and Trade

Overseas Development Assistance Programme for financing my study at Massey University. The Ministry of Agriculture in Tonga for awarding the scholarship for the completion of this study.

All the staff and students at Seed Technology Centre for their help, understanding and their hospitality, especially Mr. C.R. McGill and Mr. R.C. Southward for helping in my field work. All my friends for their friendship and assistance especially those who helped out in my field work, special thanks to Pifeleti, Vini, Melo, Ui and Taivei.

Finally, I wish to express my deepest gratitude to those people who are so close and very dear to me. To my parents, families, relatives and all those one way or another, who have provided the much needed help, prayers and inspiration towards my study. Special thanks to Gavyn and Salote, Loutoa and Tony and their families for their utmost support. And my wife Tufitaufa'ao, for her love, devoted support and for being by my side throughout this course of study has been invaluable to me. To her, I am so grateful, this thesis is being dedicated.

TABLE OF CONTENTS

CHAPTER 4 HERBICIDE TRIAL

LIST OF TABLES

LIST OF FIGURES

Page

LIST OF PLATES

LIST OF APPENDICES

Page

CHAPTER 1

INTRODUCTION

Tropaeolum majus L. is commonly known as a Garden Nasturtium, but also as Great Indian Cress or Creeping Canary. The plant is native to Peru and was introduced to New Zealand in the mid eighteenth century. *Tropaeolum majus* belongs to the family Tropaeolaceae, a small family comprising only 3 genera; *Tropaeolum* which consists of 86 species distributed from Mexico to central Chile, and Argentina, *Magallana* which contains only two species from Patagonia and *Tropheastrum* which consists of only 1 species (Sparre and Andersson, 1991). In *Tropaeolum*, 9 species are important to horticulture. This small family of climbing succulent herbs includes the cultivated *Tropaeolum majus* (garden Nasturtium - not to be confused with the genus 'Nasturtium', family Cruciferae). It is a relatively diverse genus of soft-wooded annuals and herbaceous perennials from South and Central America valued for their showy foliage and flowers, and their ease of culture (Rowell, 1986).

Most important of this genus is *Tropaeolum majus* which is effective as an ornamental flower crop or vegetable plant. The colourful nasturtium flowers make splendid cut flowers or with bouquets and can be combined with young leaves to make an attractive garnish in salads (Macoboy, 1986). Pickled seeds are used as a substitute for capers (Heywood, 1978). It also has potential as a bedding plant or for trailing walls, edging, screens, hanging baskets or a floor covering in orchards. It can also be used effectively as a soil stabilising plant on steep slopes (Rowell, 1986). The fruit when green contains oil which can be used for cooking. As a herbal plant, nasturtium leaves are found to contain a natural antibiotic which is an useful remedy for brochitis, catarrah and emphysema (Culpeper, 1983) and has been used in the past in folk medicine especially for treatment of scabies. Such potential uses have been more widely recognised recently and considered to be of commercial importance. According to a 1975 National Garden Bureau survey in the USA, *Tropaeolum majus* was fourth behind zinnia, marigold and petunia in top seed packet sales and popularity (Whiting, 1983). The value of commercial seed is surprisingly high with an average price of 10 cents per seed, about 7 seeds per gram, and with an average yield of 470 kilograms per hectare (Boulton, 1986).

In the literature there are many publications on the production of agricultural and horticultural seeds. However there is comparatively little published information on flower seed production (Vis, 1980). In the case of *Tropaeolum majus*, virtually no research has been carried out on the crop but some general cultural information is available. Garden nasturtium blooms best in sunny situations and is well suited to porous or well drained soils and to rather poor or low fertility soils. Rich soils result in much more attractive foliage or vegetative growth even though fewer flowers are produced (Hartmann *et al.*, 1981 ; Rowell, 1981). It performs excellently on sandy soils since it sheds its seeds early and these can be readily recovered at harvest by allowing this shedding to occur and by separating the seed and sand subsequently (Vis, 1980). It is suggested that Tonga, because of its generally favourable warm climate, and suitable soil conditions, coupled with an ability to grow the crop on a small land area and produce seed based on cheap hand labour might well be a suitable situation for *Tropaeolum majus* seed production and that this crop could be grown for seed for export. The present study, however, was carried out to provide information on the potential of this crop in New Zealand as a summer crop.

A major obstacle which severely limits seed production in *Tropaeolum majus* is its indeterminate growth habit and flowering behaviour which results in plants flowering over an extended period of time (Boulton, 1986). This is an advantage for a garden blooming plant but creates problems in seed production. During flowering, young flower buds, blooming flowers, wilted flowers, young seeds and mature and shedding seeds may all be found on an individual plant at any one time. This makes it extremely difficult to determine the correct time to harvest the crop for the recovery of maximum seed yield. Nasturtium seeds shed at a high moisture content of about 78% and, as a result, commercial seed yield in *Tropaeolum majus* is often low and unreliable. Boulton (1986) has stated that actual yield of the plant in some cases proved to be 40%-70% of the plant's potential yield and this yield gap is highly contributed from shed seeds. She stated a peak viable seed yield of 471 kg/ha as an average yield.

The current research programme began as a result of the need for a better understanding of plant development and the need for information on appropriate management strategies for better seed production. The emphasis was also on identifying factors affecting garden nasturtium seed yield and quality. This work was carried out to identify those aspects of vegetative and reproductive growth which contribute most significantly to seed yield and quality in plants grown at different plant densities and also to provide information on the tolerance of nasturtium to various herbicides appropriate for weed control.

The present study comprises three main experiments which are presented separately in the three following chapters. The first experiment (Chapter 2) reports on a plant density trial designed to provide basic field information on the effects of plant competition as determined by variation in plant population density, on vegetative and reproductive development and on seed yield and quality in *Tropaeolum majus*.

Particular attention has been directed to the effects of plant competition on vegetative and reproductive development which contribute most significantly to seed production.

The second experiment considers the sequence of seed development in *Tropaeolum majus* (Chapter 3) with particular reference to seed yield. An important factor in this study was an attempt to determine the optimum or 'most appropriate' time to harvest seeds. The final experiment (Chapter 4) examines the tolerance of nasturtium seeds or seedlings to various herbicides used for weed control, and explores their effects on vegetative growth and reproductive capacity of nasturtium.

The overall research aim of this study was to determine the potential of nasturtium seed production in New Zealand and to examine ways of improving or maximising seed yield and quality by proper management, including optimum planting density and the most appropriate herbicides for weed control.

Plate 1.1 A view of the *Tropaeolum majus* crop at peak flowering (5^{th} February 1992).

CHAPTER 2

PLANT DENSITY TRIALS

The first part of this review will concentrate on literature pertaining to the general description including the origin, nomenclature and history, botanical and agronomic characteristics of *Tropaeolum majus* to provide a general agronomic understanding of the crop. The second part of the review considers aspects of plant competition on vegetative and reproductive development. Most of the information in this review is necessarily of a more general nature and in many cases reviews information on other species. This simply reflects the paucity of previously published work on garden nasturtium generally, and on nasturtium seed production in particular.

2.1 REVIEW OF PLANT DESCRIPTION

2.1.1 Origin and history

Tropaeolum (nasturtium) is a group of rapid growing annuals and perennial climbers native to South America from Mexico to Peru. They are alternate-leaved vines or low annuals, noted for their brilliant, yellow to orange to red funnel shaped, and spurred flowers which are produced in the summer (Wyman, 1971 ; Whitehead, 1971). This major genus of creeping and climbing plants can successfully and easily be propagated from seed (Taylor, 1961 ; Browse, 1981). Only nine species of Tropaeolum, *T. azurenum, T. polyphyllum, T. speciosum, T. peregrinum, T. tuberosum, T. pentaphyll,* *T. minus, T. tricolor* and *T. majus* are considered to be of agricultural and horticultural importance. The most important and commonly grown nasturtium is *Tropaeolum majus* which consists of many cultivars but is broadly classified into three main types:

a. Tall Hybrids which extends to a distance of up to 3 metres long with single flowers. Cultivars are available in crimson, scarlet, orange, or yellow, and many intermediate shades.

b. Nanum Hybrids which are commonly known as 'Tom Thumb', compact or dwarfing varieties. All are 20-25 cm high with mostly single flowers often scented and bloom in a wide range of colours for different cultivars.

c. Gleam Hybrids which form robust, vigorous, bushy plants up to 30 cm high, with semi-double fragrant blooms in shades of salmon, golden yellow, orange-scarlet, cherry-red, primrose orange (Rowell, 1986).

The most commonly grown nasturtium, one of the most easily grown of annual flowers, is derived mainly from *Tropaeolum majus*. Its many cultivars reflect hybridity between this and other species. They range from low-growing dwarf cultivars, such as the crimson-flowered 'Empress of India' and 'Tom Thumb', with a wide colour range, for edging and for flower borders, through to semitrailing types, such as the double-flowered 'Glorious Gleam' developed especially for hanging baskets. Taller climbing plants are suited to trellis, fences and other supports (Halliwell, 1987).

Tropaeolum majus (common nasturtium) has a long history in English gardens and has been known under a number of names (Halliwell, 1987). Before Linnaeus based his binomial system of classification on floral characteristics, earlier botanists had used other criteria. One was based on practical use because the taste of the leaves of these species of *Tropaeolum* resembled the watercress so it became 'Indian cress'. Indian here is indicative of the West Indies, which in the sixteenth and seventeenth centuries were less precise geographically than it is today, including besides the Carribean Islands, parts of Central America and Peru, the country from which the plants originated. Linnaeus in 'Species Plantarum of 1753', called the genus *Tropaeolum* which had been derived from a Greek word for a trophy. Perhaps this was intended to refer to a post set up on a battlefield after combat on which shields and helmets of the defeated were hung. The round leaves were compared to the shields and the flowers to a spear-pierced blood stained gold helmet ornamenting such a memorial or statue of victory (Halliwell, 1987 ; Huxley and Griffiths, 1992 ; Beckett, 1987). Tropaeolum majus is derived from the Greek for trophy in allusion to the shield shaped of leaves and flowers with *majus* derived from Latin meaning 'large' (Taylor, 1961). The Latin meaning of nasturtium is 'distortion of the nose' referring to the offensive smell the early types of plants emitted.

2.1.2 **Botany**

Tropaeolum majus (garden nasturtium) is a glabrous aromatic annual or shortlived perennial with long trailing or scrambling succulent smooth stems sometimes climbing or trailing on the ground up to 2 metres long. The plants are usually succulent herbs with an acid mustard oil present in the sap, as in the family Cruciferae. Sometimes root tubers are produced. The stems are prostrate, though frequently climbing by means of sensitive petioles, which twine around any support in a similar manner to those of 'Clematis'. Even though the stems trail on the soil surface they do not form adventitious roots as in stoloniferous plants, and the roots are fusiform and sometimes tuberous (Bailey, 1943). The leaves are simple, shield-shaped, rounded or somewhat kidney-shaped, and orbicular up to 12 cm across. The leaf margins are wavy, lobed or angular with about 9 nerves radiating from the petiole. The colour of the blade is bright green above and pale green below. Petioles are up to 25 cm long, but are usually not coiling (Rowell, 1986).

The showy bisexual flowers are irregular and grow singly on succulent stalks. They are large with vivid colours in the familiar yellow-orange-red-mahogany range. The flower is 6-8 cm across on a 20-25 cm pedicel arising from the leaf axil. The calyx is of 5 distinct sepals, produced in a somewhat irregular pale orange, 1.5-2.2 cm long, narrow-ovate to narrow ovate-oblong. The dorsal and 2 lateral sepals are larger, with a spur 2.5-3.3 cm long usually curved, tapering and pale orange in colour. The five petals of the corolla are usually yellow or orange to scarlet, sometimes semi-double with 7-8 petals, the lower petals having a very slender claw and a broad-ovate to almost reinform limb. The limb is fimbriate at its base and either sinuate or undulate. The upper two petals bear a claw often with crimson markings. The flowers contain eight stamens, distinct and unequal and yellow to reddish in colour similar to the corolla. Anthers are two-celled which are and boned on a solitary pistil. The ovary is superior, formed in three fused carpels, with three locules each containing one axile; pendulous ovule. The single apical style has three stigmas. The fruit is a three-seeded schizocarp, each mericarp separating to become an indehiscent seed lacking endosperm. The embryo is straight and has thick fleshy cotyledons (Heywood, 1978). Such features are shown in Figure 2.1.

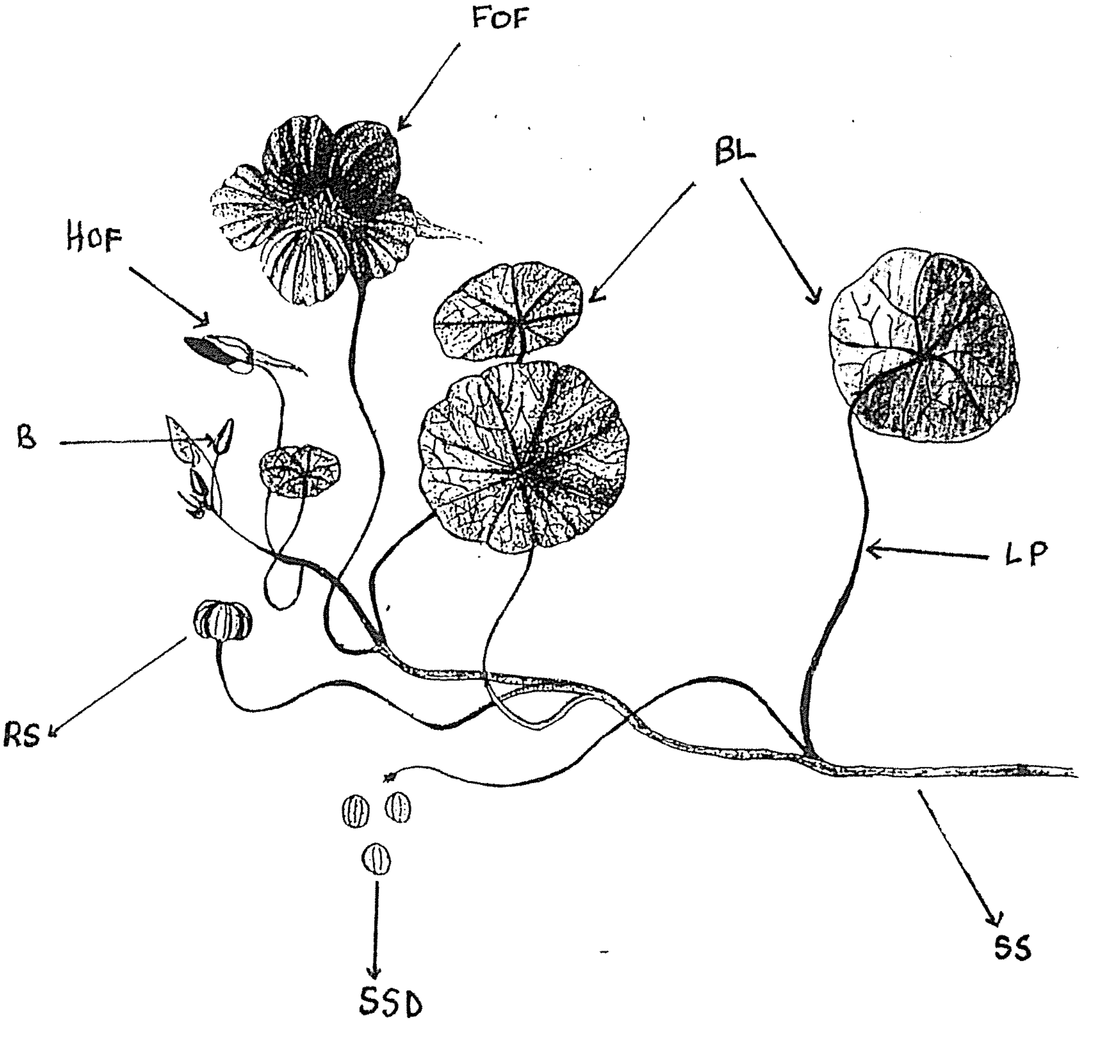


Figure 2.1 General features of *Tropaeolum majus*.

BL - beltate shield shape leaves, SS - smooth stem, LP - long petioles

FOF - fully open flower, HOF - half open flower, B - buds

RS - 3 seeded flower head, SSD - mericarp separating to produce 3 shed seeds.

Pollination is the transfer of pollen from the anther to the stigma and plants where this is performed by insects are called entomophilous (Sebanek, 1992). As such *T. majus* is primarily cross pollinated. Insects of the hymenoptera, mainly bumble bees and honey bees are considered to be the most effective and chief transporters of pollen. Bumble bees, insects and humming birds are attracted by the vivid colours and the petals have guide marks which are like runway markings to a pilot, leading the bee to the nectar chamber (Heriteau, 1990). To reach this nectar guide a pollinating insect must clamber over the anthers which dust it with pollen. After a few days, the anthers wither and the three stigmas are ready to receive pollen from other plants. Insects in search of nectar now dust the stigmas with pollen. Each nasturtium flower blooms for a number of days and may receive dozens of insect visitors in search of nectar. After the flower been pollinated the petals wither. The flowering period is from October to May in New Zealand, but nasturtium may be found in flower all the year in favourable habitats (Boulton, 1986).

Plate 2.1 *Tropaeolum majus* cv. Choice Mixed flower being pollinated by a bumble bee.

Nasturtium has an indeterminate growth habit which results in a long flowering period. The meristems continually replenish themselves remaining youthful. The growth of the floral axis is also indeterminate, the lower or outer flowers opening first and the axis continuing growth (Halliwell, 1987 ; Wyman, 1971). In an indeterminate plant, a long flowering period may be caused by any one of a number of factors, including the sequential development of different shoot orders (main shoots vs. lateral branches); the delayed development of flowers along stems in which there are several vegetative nodes between successive flowers such as in white clover (Thomas, 1987); or the sequential development of shoots against at different times. In this age hierarchy, early shoots are often the first to flower because of their earliness of formation whilst flowering in late formed shoots tends to be delayed resulting in a long total flower production duration (Li, 1989). Apart from the effects of any one of these causes, it is also possible that the extended flowering period may be caused by a combination of some or all of these factors.

This trend and sequence is followed during seed ripening. This means that as a single destruction harvest is often made in commerce, its timing will necessarily influence the physiological composition of seeds in each seed lot. These differences in physiological composition may arise simply because of variation in the maturity of seeds from different flowers. Therefore, in the case of Nasturtium, differences may also arise because some of the shed seeds may remain on the ground for a prolonged period before they are harvested with a consequent loss of viability as a result of being exposed to changing moisture and temperature (Matthews, 1980).

2.1.3 Agronomy

2.1.3.1 Commercial flower seed production

The history of commercial flower seed production goes back only to the latter half of the 18^{th} century. At that time established seed companies in Germany, France, Holland and the United Kingdom began growing and marketing some flower seeds in conjunction with their extensive vegetable seed production trading (Mullet, 1981). Until after World War 11 production was confined to a few specialist areas in Europe, but after the war, expansion took place with production commencing in many countries with suitable climates in many different locations. There are ample literature references available on seed production of grasses, cereals and vegetables, but until recently, information on the production of flower seed crops was almost non-existent. Vis (1980), in a paper on annual flowers seed production in Europe, however, maintains the principles of vegetable and herbage seed production are equally applicable to flower seed production, with one important exception, that hand harvesting is an essential practical measure obtaining acceptable recovery of highly expensive hybrid flower seeds produced in small quantities.

2.1.3.2 Production areas

Flower and vegetable seed production tends to be concentrated in rather limited geographical areas compared with field crops (McCorkle and Reed, 1961). The production of high quality seed is possible only in a favourable environmental growing conditions, with a climate which will ensure optimum maturity of the crop can be achieved before harvesting (Delouche, 1980 ; Mullet, 1981). These conditions include good soils, available moisture supply through irrigation, and bright sunny weather which all contribute to stability of production. Delouche (1980) and George (1985) recommend sufficient rainfall to ensure complete development and seed maturation, and a rainfree period with relative little wind during flowering for successful pollination, seed ripening and to allow harvesting operations to be completed with minimal seed deterioration and crop loss. These are all very important factors in successful flower seed production (Vis, 1980 ; Mullet, 1981 ; Salunkhe *et al.*, 1987).

The conditions during flowering and seed set are of utmost important, as extremes of either wet and cold or dry and hot during these processes can result in low yield and poor germination because they interfere with the fertilization process and encourage death of developing embryos (Scott and Longden, 1978). A lack of inclement weather during the final stages of development is quite important from a disease control point of view as a low relative humidity with minimal rainfall and moderate temperatures minimises the spread of seed borne diseases in some vegetable seeds (Delouche, 1980; Gaunt and Liew, 1981). Although low humidities generally favours seed production, there are exceptions. For examples, the high relative humidity in coastal areas in California prevents over-drying of unthreshed material in the field and can assist in reducing loss from shattering during harvesting (Hawthorn and Pollard, 1954 ; George, 1985). Excessive wind not only increases water loss from the crop and soil but carries wind-borne pollen over long distances and increases loss of seed by enhancing shattering during ripening but may affect pollination efficiency in insect pollinated crops.

2.1.3.3 Horticultural importance of *Tropaeolum majus*

Nasturtium was introduced into New Zealand in the 18th century but with little knowledge of its importance other than as a garden plant. For such a purpose, an indeterminate vegetative growth habit and a long flowering period proved to be desirable. However, in the last few years nasturtium has been recognized as having other importance and uses which have seen it develop a place commercially. Today *T. majus* is much used in flower gardens amongst collection annuals, as a bedding plant, as a temporary filler, and in window boxes or for hanging baskets. Besides having flowers in a range of bright colours it also gives of its best in poor soils. Today it is grown for ornamentation and yet all parts of the plants can be used as food. The leaves are used in salads; the fresh flowers can be put into salads during summer or pickled or crystallised for winter use while chopped stems or roots may be added to soups and stews. It is also an attractive cut flower when used with its own foliage in bouquets. In order to keep plants flowering strongly, flowers should be picked frequently (Rowell, 1986).

Nasturtium is also effective as a vegetable plant. Flowers can be combined with leaves in salads (Heywood, 1978). The leaves have a tangy, watercress-like flavour and are used in salads, sandwich spreads, vegetable dishes, or are stuffed like grape leaves (Facciola, 1990 ; Marshall, 1979). Flowers have a similar flavour and use and also make an attractive garnish, or can be added to vinegar (Heriteau, 1990 ; Garland, 1979). Both the flowers buds and young fruits (Facciola, 1990) and pickled seeds (Heywood, 1978) may be used as substitute for capers (Lys de Bray, 1976). Mature seeds are eaten roasted or make a good pepper substitute (Heriteau, 1990). The seed and fruit, like all parts of the nasturtium plant, are rich in bitter tasting acid mustard oil. Sometimes the fruit with its mericarp rich in oil is picked when green and used for cooking. As a herbal plant nasturtium has been found to contain a natural antibiotic which is a useful remedy for bronchitis, catarrh, and emphysema. The recipe is 14 g of nasturtium leaves added to 568 ml of boiling water, and the dose is 56 ml, two or three times a day (Culpeper, 1983).

The trailing feature of *Tropaeolum majus* makes it a good floor cover plant, for example, in orchards, where the spreading and trailing has the advantage of suppressing weeds and an ability to establish well even in poor soil fertility areas (Hartmann *et al.*, 1981). Mantinger and Gasser (1989) showed nasturtium has been used as a practical alternative to herbicide strips in apple orchards in Italy. It also has potential as a bedding plant (Davies, 1977), trailing on walls as screens (Mathias, 1976), as pot plants in hanging baskets (Marshall, 1979), and on steep slopes for soil stabilisation purposes. Macoboy (1986) recommended the more compact varieties where the foliage almost hides the flowers. These varieties are bushy, and make excellent subjects for basket, window box or container (McKee, 1990). Lys de Bray (1976) suggested that both woolly aphids and white fly are repelled by the presence of nasturtiums and experiments are continuing with the symbiotic association of this plant grown at the same time as potatoes, radishes and tomatoes. Nasturtium plants also contain a high proportion of sulphur, and an excellent hair lotion may be made from it (Lys de Bray, 1976). He suggested a recipe, involving 85g each of fresh nasturtiums (leaves, seeds and flowers), stinging nettle leaves and box leaves, and 0.6 litre (90% alcohol). Mince the leaves in an ordinary mincer, retaining all juices. Allow to marinate in the alcohol for a fortnight. Strain and add a few drops of oil of Rosemary (or lemon verbena). Use often for brisk scalp massage, and sprinkle on the hairbrush before brushing the hair. Garland (1979) also described various uses of nasturtium as herbs such as pepper substitute, in herb vinegars (buds, flowers and unripe seeds), herbs for hair growth (leaves), crushed nasturtium seed blend use as an eye compress, and in wound herbs.

2.1.4 Seed production practices

2.1.4.1 Climate

Tropaeolum majus or garden nasturtium is good easy cover and displays flowers well if feeding is kept to a small amounts of complete plant food at sowing time (Seales, 1979). McKee (1990) showed that it takes about 10-12 weeks from sowing to flowering, while nasturtium loves the sunniest place available it produces a greater abundance of flowers in poor soil (Verey, 1981 ; Rowell, 1986 ; Heriteau, 1990). Seeds should be sown where the plants are to flower, in clumps of 3 to 5, at 25-60 cm intervals depending upon vigour of growth (Rowell, 1986). Nasturtiums are not hardy in cool climates and should not be sown outside until the damage of frost is past (Verey, 1981). Where frosts are only light, nasturtiums will grow almost all year, but are principally a 'summer flowering plant'. In warm zones such as coastal areas of New South Wales best results come from August to September sowing with subsequent flowers from October to November onwards until the first frosts check plant growth (Rowell, 1986). In New Zealand sowing time is October or November, with flowering starting in January or February and expected seed harvest before winter frosts intervene (Boulton, 1986). Seeds develop quickly on the plants and germinate freely beneath old plants resulting in a succession of new plantings which prolong the flowering season. In cool climates sowings are made after the frosts, usually November or December for the production of summer and autumn flowers.

2.1.4.2 Soil and fertilizer

Tropaeolum majus L. (nasturtium) performs excellently on pure sand or sandy soil. Since it sheds its seeds easily it can be readily harvested by allowing this shedding to occur and then separating the seed and sand subsequently (Vis, 1980). Plants bloom best in porous and rather poor soil. Rich soil results in much attractive foliage (Rowell, 1981 ; Ferguson, 1984) which is produced at the expense of flowers (Pavel, 1977 ; Matthews, 1979 ; Seales, 1979 ; Verey, 1981), and results in flowers being hidden under the foliage canopy (Hay and Synge, 1988).

The overall important requirement is a reasonable soil nutrient status particularly with respect to nitrogen, potassium and phosphorus. Soils deficient in any of these elements are not suitable for flower seed production unless amended with suitable fertilizer (Vis, 1980). In the case of nasturtiums, high nitrogen fertilizer should be avoided as it tends to encourage an excess of foliage. To obtain a real abundance of bloom, it is advisable to use fertilizers with a high percentage of phosphorous (Pizzeti and Cocker, 1975). Work by Esponda and Sivori (1961) showed that P-deficiency in nasturtium caused stunted growth, with particularly small leaf blades; dark and opaque green leaves with reddish margins; and retardation or complete inhibition of flowering. Work on nasturtium by Schutte (1959) showed that plants grown in water culture deficient in micro nutrients (B, Cu, Mn or Zn) had lower transpiration rates than controls grown in full nutrient solutions, the disparity being greater with more acute deficiency. The control plants were smaller, with fewer and smaller leaves than the deficient plants and their foliage was greener and healthier in appearance. *Tropaeolum majus* are sensitive to excessive moisture, requiring good soil drainage, but also need an even supply of moisture during the growing season, so soil should contain a good proportion of sand to ensure adequate aeration and loose texture. All *Tropaeolum* species grow best in acidic or low pH soil with a good humus content (Jelitto and Schacht, 1984), and respond well to phosphate rich fertiliser and the avoidance of over watering (Macoboy, 1986). They also tolerate dry soil conditions and are hardy in coastal area (Edwards, 1986).

2.1.4.3 Sowing and planting

It is important to sow and plant at the optimum time. In the case of late sowing, time lost cannot be made up by forcing the crop and plants become weak with a consequential influence on seed setting. In addition, many crops need to have undergone a minimum vegetative growing period before they will bear flowers and set seed (Vis, 1980). Correct time of sowing and transplanting also avoids delays in harvesting which may carry with it the risk of less favourable late season weather conditions including frost damage. In nasturtium, the recommended sowing time is October. This is preferred to avoid later frost effects to which the plants are highly susceptible and allows an opportunity to harvest seed during dry periods before rain and winter conditions increase the weathering of seeds on the wet ground surface. Sowing can be done by hand or by a conventional sowing machine since the large round seeds are easy to handle. Heriteau (1990) and Wyman (1971) suggested that nasturtiums do not transplant easily with bare roots so direct sowing in the field or indoors in plantable peat pots are the best sowing methods. It is a good practice to soak the seeds for 24 hours in warm water before planting them in the soil (Wyman, 1971). Nasturtium seed should be covered with a layer of soil to a depth of 3 cm for better establishment (Beckett, 1987). Germination in 8 to 10 days after sowing at 19-20°C (Edwards, 1986). Once the plants develop in the spring they will grow rapidly and vigorously provided they are kept frost free and receive sufficient water. Feeding should be limited in order to encourage flowers, high feeding levels merely encouraging vegetative growth (Browse, 1981).

2.1.4.4 Plant density

It is advantageous to observe the correct sowing and planting distances. Too dense a plant stand increases the risk of disease as the plants can remain wet over a long time providing ideal conditions for the development of fungal pathogen. Too high a population produces thinner, weaker plants which may have less tolerance to unfavourable climatic conditions. Conversely at very low plant populations, weeds have the opportunity to enter the crop and indeed overgrow it (Vis, 1980). Well developed plants with sufficient space at the fully grown stage, which also allows plants to dry quickly after rain or dew, can produce seed of high germination. In garden nasturtium a plant spacing of 45-60 cm is considered to be optimum but variation does occur with different cultivars. Strong growing climbing cultivars should be planted at a 60 cm spacing and dwarf cultivars at 25 cm (Rowell, 1986).

2.1.4.5 Weed control

One means of ensuring successful seed production is by protecting crops against disease, insect pests and weeds which reduce yield and quality. Weeds can have a direct effect on crops by smothering and thus reducing yields and continue to be a problem when the weed seeds are harvested along with the crop increasing good seed losses during cleaning (Vis, 1980). Weed control in the field is therefore of utmost importance for two reasons, removal of soil nutrients by weeds causes a considerable reduction in seed yield due to competition for nutrients, light, water and growing space and poorer quality seed due to the reduced nutrient status of the parent plant. Traditionally this has been a highly work intensive operation in crop production because much of the cultivation and mechanical methods are done to control weeds. The use of weed control chemicals in flower crops is limited by lack of knowledge and understanding of the tolerance of crop species to different herbicides, despite the fact that herbicides eliminate the weed flora with great ease. Herbicide application also facilitates the use of modern harvesting machines because the problems of weed seed contamination on the harvested seed crop and as a component of the seed lot after threshing is reduced. The process of cleaning seed lots involves time and expense, therefore controlling weeds in the field is very important.

For many years the Centre for Agrobiological Research, in the Netherlands has carried out successful experiments on chemical weed control in flower crops including nasturtium and Vis (1980) has produced the following recommendations:

a. Pre-emergence or pretransplanting applications of herbicide, paraquat 20% ai, 30 ml/100m^2 of weeds including grasses. Diquat 20% ai, 20-30 ml/100m^2 for control of weeds excluding grasses.
b. Cultivation of the land sometime before sowing to allow weed seeds to germinate. Flower seeds should be sown at the time when weeds are germinating or in the seedling stage. Herbicide is then applied as soon as the weeds emerge without risk of damaging the crop seedlings that have not yet emerged.

In *T. majus* there is no published information on selective chemical weed control following crop emergence. In Tanzania, where nasturtiums are commercially grown for seed, the main method of weed control is by hand weeding.

2.1.4.6 Pest and disease control

T. majus is most susceptible to attack by aphids, Heterosporium leaf spot, and by spotted wilt and mosaic virus. Wyman (1971) reported that black aphids thickly clustered on the stem and under side of leaves are a common pest. Careful spraying with insecticides Malathion or Thiodan (endosulfan) is recommended. Serpentine leaf miner and other leaf miners disfigure the leaves but seldom require control. If necessary, they can be controlled by an application of insecticides such as Malathion or Lindane (Gamma BHC). Dusting or spraying with a contact insecticide is also effective (Hawthorn and Pollard, 1954). A wilt disease which also attacks tomato, potato, eggplant and pepper also attacks nasturtium causing wilted, yellow leaves. Control is by planting into new or sterilized soil or by avoiding rotation with other host plants. Nasturtiums are also excellent subjects for gardens in districts that are plagued by rabbits, ground-hogs and such: their spicy flavour obviously has little gastronomic attraction for these pests.

2.1.4.7 Harvesting

The last stage of seed production is one where mistakes can be made leading to poor seed quality and reduction or complete loss of yield. All seeds have an optimum maturity level for harvest at which the chances of producing high quality and seeds with good storability are greatest (Wyman, 1971). The timing of harvest is a crucial decision as harvesting too early will lead to a high percentage of immature seeds which will be removed later by cleaning otherwise they will have a very short storage life. On other hand, if crops are harvested too late, yield may be lost through shedding and reduced quality of seeds can occur through weathering (Delouche, 1980; Vis, 1980). A major problem in nasturtium is that seeds are shed at a very high moisture content. This, along with the long flowering period make the decision on the optimum harvest timing and method critical. Work by Boulton (1986) showed that in the cultivar 'Dwarf Double', *T. majus* reached peak flowering 76 days after sowing and seed took a further 22 days to mature. Shedding began 31 days after pollination at a high moisture content of 78%. With these factors taken into consideration, several methods of harvesting are recommended.

a. Seeds may be removed as they ripen by hand every seven days.

b. Plants may be cut and lifted and dried on racks erected over a canvas tray.

c. Plants may be cut and removed from the field and the shed seeds picked up from the ground by hand, or if soil is sandy and free from gravel, any shed seed can be scooped up or sucked up by a vacuum machine and later separated by screening.

d. Harvesting by machine, can be used. Plants can be cut with a blade below the ground surface and rolled up to prevent seed shedding. As soon as plants dry, seed can be removed using a small thresher (Hawthorn and Pollard, 1954 ; Boulton, 1986).

2.2 REVIEW OF PLANT COMPETITION EFFECTS

2.2.1 Plant density

One of the most important factors influencing yield in any crop is plant population density ie. the number of plants per unit area. Each crop and each cultivar has an optimum plant density for maximum yield. Yield can be expressed vegetatively as in some vegetables such as lettuce and cabbage or in terms of modified leaf, stem or root structures or in the reproductive mode by flowers and seeds as in cut flowers and seed crops. Plant density effects on seed yield is very complex because of the plasticity of yield components and the interaction between the environment and genotype. This relationship is extensively reviewed by Willey and Heath (1969). This relationship can be summarised by two types of curve: parabolic relationship where yield of a crop reaches a maximum at a given production density and then declines; an asymptotic relationship where yield approaches a maximum and is relatively constant at high density. The selection of the optimum plant density to obtain maximum yield in a given environment involves consideration of planting pattern, planting date, environmental factors, varietal maturity and plant type. These have been considered in previous work by Weber (1966), Dougherty (1969), Lueschen and Hicks (1977), Dominguez and Hume (1978), McGormick and Poll (1979), Alessi and Power (1982), Reicosky *et al.* (1985) and Duncan (1986). The relationship between yield per unit area and plant population is now well understood, if we are thinking in terms of the total plant biomass. There is an asymptotic yield density relationship which shows that density has an effect on yield above and below a critical population. Decreases in population below this critical level results in a linear decrease in yield. Decreases in population above this level results from the onset of competition. Depending on the species, continued increase in population may result in either little change in plant morphology or in a reduction in yield. Studies have been conducted to investigate the relationship between plant density and morphology or crop physiology and seed yield in soybeans and other legumes. However, there is no published information on the effects of plant density on nasturtium. However, other work on legumes such as soybean has shown that different cultivars have a different optimum plant density for maximum seed yield (Wilcox, 1974). Also, plants exhibiting different types of growth habit (determinate or indeterminate) respond differently to density stress (Villalobos-Rodriquez and Shibles, 1985). As one example, Nienhuis and Singh (1985) found significant interactions among location, growth habit and plant density in *Phaselous vulgaris* and these factors affected yield.

2.2.2 Plant competition

Variations in plant population density arise, generally, from variation in seeding rates and can lead to very different and severe levels of plant competition in the field or glasshouse. These competitive effects have been well documented over the years by many scientists including Donald (1963), Kirby (1977) and others and commences when the supply of a necessary resource falls below the combined demands of the population. This definition was accepted by Hill and Shimamoto (1973). Competition results from the fact that plants need space to grow. The specific factors for which they compete are mainly light, carbon dioxide, nutrients, and water. In special circumstances competition may approach the level of physical strife (for example, the strangling effects of certain vines), but normally competition is essentially a passive process (Bidwell, 1979). Competition for resources not only occurs 'between plants' but can be 'within plants' and this is refer to as intra-plant competition or internal competition (Chanprasert, 1988). Interplant competition also most commonly occurs as a result of limited supplies of radiant energy (light), nutrients, water and carbon dioxide (Etherington, 1983). Plants and cultivars differ in their competitive ability ie. their ability to emerge quickly, form a canopy rapidly, to exploit the environment efficiently for growth factors and to slow growth of other competing plants. Interplant competition for all environmental resources is influenced by the spatial arrangement of these plants. In an agricultural context, this may be affected by plant density (ie. the number of plants per unit area), by distance between adjacent rows of plants or by a combination of the two. Interplant competition will intensify if the plant density increases but inter-row spacing remains constant, or if the distance between the rows increases while plant density remains unchanged. Different plant parts compete with each other for growth factors. For example, vegetative growth competes with reproductive growth as in leaf and seeds. In other cases, leaves compete with each other at different canopy levels for light. As suggested by Donald (1963), the most intense kind of internal competition exists between leaves for light because light cannot be redistributed. If a leaf is heavily shaded, it will be unable to maintain itself above compensation point. Addicott (1982) suggested that flowers and fruits are also to some degree in competition with other flowers and fruits on the plant. Competition between vegetative and reproductive organs is also recognised as an important phenomenon and in many instances can affect agricultural crop yield (Williams and Joseph, 1976). Chanprasert *et al.* (1989) showed that a high degree of intraplant competition exists in indeterminate soybean cultivars during the early stages of reproductive development and a partial reduction of competitive sinks by leaf removal causes a re-direction of photoassimilate in favour of reproduction and seed development.

2.2.2.1 Competition for light

Competition for light occurs as soon as one leaf shades another, whether it belongs to the same plant, or a neighbouring plant. Donald (1963) suggested that of all the factors influencing competition in crops, light becomes the major limiting factor to production. Similarly, competition for light is implicated as the major factor inducing morphological changes in plants when plant density is increased (Herbert and Litchfield, 1984). One indication of the prime influence of competition for light is the stimulation of internodal elongation and promotion of plant height under mutual shading conditions (etiolation effects). Also, the interception of light is important in that most other limiting factors ultimately operate through competition for light (Etherington, 1983). Light distribution within a soybean canopy may also be important in affecting pod set including spectral distribution changes as light penetrates the soybean canopy (Singh *et al.*, 1968). As a consequence, photosynthetic rate is reduced for leaves lower down the plant. If assimilate supply regulates pod set, then pods per node, seeds per node and seed weight per node are all expected to decrease at progressively lower levels in the canopy (Heindl and Brun, 1984). Egli (1976) suggested the objective of any crop management system was to intercept as much solar radiation for as long as possible to maximize production. To accomplish this objective, he proposed that an adjustment of planting date and plant population density may be required.

2.2.2.2 Competition for water

Competition for water can have a major effect on growth and yield. The effect of water stress depends on the degree and duration of stress and on the stage of plant growth at which stress occurs. In soybean, the pre-flowering stage of growth is the most tolerant, whereas the periods of anthesis and pod filling are most sensitive to water deficits (Doss and Thurlow, 1974 ; Wien *et al.*, 1979). In plant communities, competition for water usually occurs together with other forms of competition, for example, lack of nitrogen or light. In cases where competition for water and nitrogen is intensified, and growth is restricted, competition for light may be less important. Results of a study with cauliflower clearly demonstrated the increasing yield/ha with increasing plant density, with irrigation greatly superior to no irrigation (Fisher, 1988).

2.2.2.3 Competition for nutrients

Donald (1963) derived a relationship between plant population density and competition for nutrients in pasture. As fertility status is improved, so the density required to give maximum yield by annual crops will increase. For example, the effects of phosphate on the yield (total plant biomass) of onion bulbs, at 40 plants/m^2 (low density) produced a yield increase of 6.5 t/ha while a high density of 160 plants/m^2 resulted in a yield increase of 22.8 t/ha (Fisher, 1988). This effect applies to crops exhibiting an asymptotic yield density relationship. The effect is even more outstanding for a crop such as maize which displays a parabolic yield density relationship. With such crops the application of N fertilizer which is limiting yield increased the yield at optimum density. But maximum yield increase was obtained by further increasing the plant density at a medium nitrogen level, or at higher densities at a high nitrogen application rate.

2.2.2.4 Competition for carbon dioxide

In much crop physiology work, a direct relationship is believed to exist between leaf photosynthetic rate and economic yield. Both light intensity and atmospheric CO_2 concentration are known to limit photosynthesis and dry matter production (Hardman and Brun, 1971). CO_2 enrichment has been found to be highly and positively correlated with crop yields of many species (Krenzer and Moss, 1975 ; Sionit *et al.*, 1987). Yield or dry weight increase by CO_2 enrichment is obviously due to increased photosynthetic activity. However, high CO_2 concentration tends to affect leaf senescence. Hardy and Havelka (1975) reported that high concentration of CO_2 delayed senescence in soybeans. A delay in leaf senescence will increase yield in those cases where the length of the fruit and seed growth period would otherwise be limited (Baker and Enoch, 1983).

2.2.3 Effects of plant density on vegetative morphology

Plant population density effects on vegetative growth and morphology are significant in many crops and this mainly concerns the total dry weight, and leaf, branch, stem and root morphology and their respective dry weights. A number of workers have reported increases in dry matter production with increasing plant densities; eg. in lucerne (Kowithayakorn, 1978), in Wimmera rye grass and subterranean clover (Donald, 1951) and in rape (Holliday, 1960). All of this work has highlighted the fact that total crop dry matter shows an asymptotic response with increasing plant density. Juntakool's (1983) work with siratro showed that dry weight per plant and plant size were consistently reduced as density increased. Also, plants at wide spacing had a larger leaf area than plants at narrow spacing. Phetpradap (1992) showed that aster plants grown at low densities showed greatest branch development and subsequent leaf and flower production, which thus increased potential seed production sites. Also, increasing plant density decreases dry weight of plant, branch and leaf numbers but increases plant height (Phetpradap, 1992). A study on bud yield of blackcurrants as influenced by plant density and light interception by Kerslake and Menary (1986) also showed that increased competition for available light resulted in smaller plants at high as compared to low plant densities.

Some morphological characteristics such as plant height, node number, internode length and branch number are affected by interplant competition. A number of morphological characteristics have been reported to be affected by plant density. Among these characteristics, plant height is the first characteristic affected by increasing plant population density (Wilcox, 1974 ; Wallace, 1986). Plants at high densities increased their height faster than that of low density plants, for example in maize (Balico, 1984 ; Tolentino, 1985) and in soybean (Wilcox, 1974 ; Chanprasert, 1988) due to elongation of internodes (Basnet *al.*, 1974). Along with increase in plant height, the stems at high densities became thinner making them more susceptible to lodging (Wilcox, 1974 ; Lueschen and Hicks, 1977). In soybean, the number of nodes per plant, the number of nodes with pods (Enyi, 1973) and the number of branches per plant (Costa *et al.*, 1980) normally decrease with increasing plant population densities. This is confirmed in Chanprasert's (1988) work on two cultivars of soybean. Increasing plant density led to a 10-fold (5 node) reduction in node numbers at final harvest. High densities also slow down node production rate and result in high density plants producing both fewer nodes and increased stem height through internodal elongation. Paris *et al.* (1986) studied the effect of plant density on courgette or zucchini and showed that widely spaced plants were more advanced developmentally and producing more nodes and leaves per plant than plants grown at higher densities.

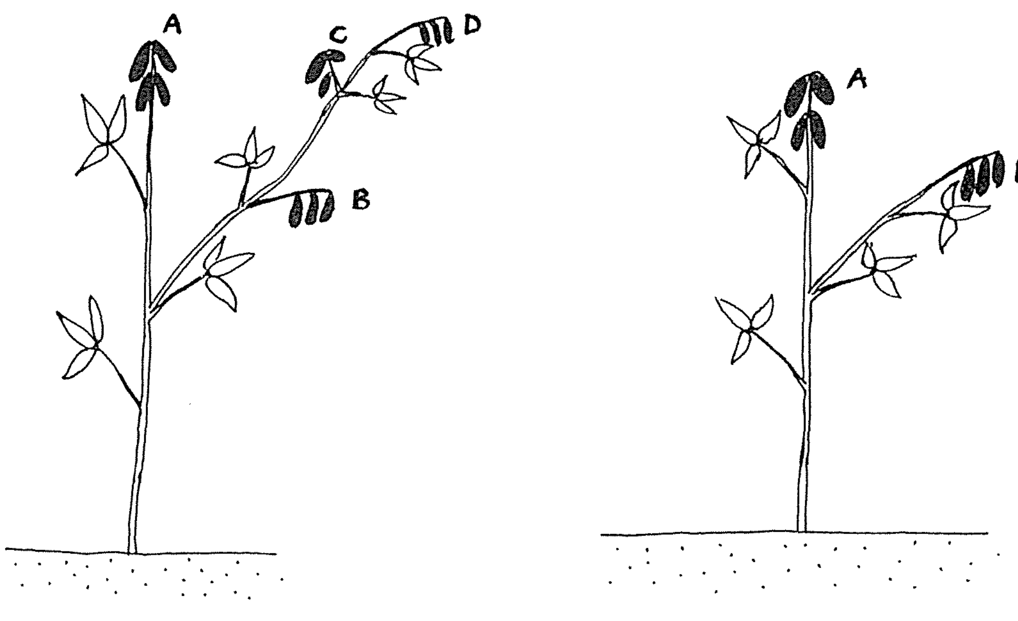
Leaf Area Index (LAI) is widely used to indicate the ratio of leaf area of a crop to the ground area which that crop covers, and consequently varies with both species and planting density. LAI is regarded as an indicator of the intensity of competition for light experienced by individual plants within a stand. Plants grown at high densities reach maximum light interception earlier than plants at low densities. LAI increases rapidly during the early reproductive stage and reaches max LAI at about the end of flowering. LAI then declines progressively as a result of the increasing abscission of lower leaves. Herbert and Litchfield (1984) showed in soybean that increased plant density leads to a greater LAI and greater Net Assimilation Rate (NAR) and correspondingly a higher Crop Growth Rate (CGR) than in lower density plantings. Studies on the effects of plant density on leaf area in siratro have shown that at wide spacings plants had a larger leaf area than plants at narrow spacing but that maximum LAI was recorded at the closest spacing (Juntakool, 1983).

Salter *et al.* (1984) showed in broccoli that head shape and head colour both varied with plant density, ie. heads were flattest at densities below 20 plants m^{-2}. Head colour was purple but with increasing density it tended progressively towards green. Work by Thompson and Taylor (1976) with calabrese showed that high population densities resulted in subsequent competition which was sufficiently intense to induce failure of some plant to produce marketable spears. Increased population also produced a reduction in bractiness and auxiliary bud development and reduced hollow-stem incidence. Stofella and Fleming (1990) reported that low plant density has increased cabbage head size but reduce marketable yield per hectare. Macchia *et al.* (1988) showed in *Salvia officinalis* L. that increased plant density from 1.6 to 2.5/m^2 showed reduced numbers of primary and secondary branches and also a markedly reduced dry matter production per plant from 236 to 97 g/plant.

The density of plants affects not only plant height, branch number, node number and length but also the root system and plant mortality. For example, Rickert and Humphrey's (1970) work on Townsville stylo found poorer root growth with rising plant density. Tamaki *et al.* (1973) also showed that root dry weight per plant decreased as plant density increased due to poorer secondary and tertiary root formation. Haynes and Sayre (1956) stated that root patterns in individual corn plants at close-spacings changed from circular to oblong while in pigeon pea (*Cajanum cajan* L.). Ahlawat and Saraf (1981) reported that root length was not increased at higher densities due to limited supplies of inputs available per plant. Zaleski (1964) also noted that in dense crops, the majority of white clover plants had a tap root present, but in open swards, the tap root was dead in most plants. In the latter situation, the plant stolons developed adventitious roots, which were absent in plants grown in dense swards. Despite the great plasticity of plants, competition at high densities may be so severe that considerable numbers will die as reported by Wynn-Williams and Palmer (1974) in studies on lucerne. Similar results were found by Meadley and Milbourn (1970) in vining peas where they reported increasing plant mortality with increasing stand density. Work carried out on sunflower crops by Sadras *et al.* (1989) has also shown that root length and leaf area per plant decreased markedly with plant population increase.

2.2.4 Effects on plant maturity

Plant density can also affect the maturity characteristics of vegetative yield components and flowers, fruits and seed yield components at harvest. For example lettuces mature later at high density, while onions mature earlier at high density. Perhaps more important than time of maturity is the effect that plant density can have on the spread of maturity. This is a particularly important characteristic with crops which are mechanically harvested as a once over operation such as peas, beans, sweet corn, and tomatoes which are grown for processing. Much can be done by plant breeders to obtain compactly maturing crops but plant density also has a part to play. Within determinate plants like dwarf beans and tomatoes the effect of increasing the plant density is to restrict the number of laterals and sub-laterals which develop, with a consequent advantage in narrowing the spread of crop maturity (Fisher, 1988).



Low density (5 pl/m²) High density (15 pl/m²)

Figure 2.2 Plant density effects on dwarf bean development (Fisher, 1988).

Figure 2.2 shows that, at low plant density there is a time difference between pods maturing at A-B, B-C, C-D so that pods at A may be mature when pods at D is just flowering. At high density only A, and occasionally a B lateral will develop, due to competition, so that not only is yield increased at the higher plant density, but the spread of maturity is reduced (Fisher, 1988). With peas, which develop on an indeterminate plant the effect of high plant density is to reduce the number of flowering nodes, as the plants run out of assimilate (light, moisture, nutrients). This produces more compact maturity. With sweet corn the spread of maturity is reduced at high density since the plants do not produce cob bearing tillers, which develop slightly later than the cob or cobs on the main stem.

With brussel sprouts, at low density the sprouts (swollen buds in the axils of the leaves) develop sequentially, and require hand harvesting 4-6 times through the winter. Increasing the plant density delays the maturity of the lower sprouts, and allows the whole stem to be harvested at one time, allowing sprouts to be stripped off by machine. Strawberries can also be mechanically harvested by ensuring that only a single fruiting truss develops per plant. This is obtained by growing the strawberries at a very high plant density. Work by Salter and James (1975) has shown that certain varieties of cauliflower (*Brassica oleracea var bortrytis*) mature very uniformly at high densities. In a less-competitive situation created by low plant densities, curds do not reach a uniform size at maturity.

2.2.5 Effects on reproductive capacity

Holliday (1960) suggested that those forms of yield which constitute the vegetative parts of the crop conform to an asymptotic relationship while crops which produce reproductive forms of yield such as flowers, fruits, buds and seeds conform to a parabolic relationship. There are many different type of models that have been used to describe the effects of spacing on plant growth. Each model differs in its underlying assumptions and there is no general agreement as to which model is the most accurate. However, Holliday's (1960) proposed model has been the most commonly used to determine and relate individual plant yield to population density. His model, is a reciprocal equation: ($Y^{-1} = a + bd$) where Y is individual plant weight or yield, d is plant density, and a and b are parameters of the model. This linear form of the equation describes an asymptotic response of area yield to plant density, whereas expanding to a quadratic equation describes a parabolic response. This yield-density model is commonly used over other models because the estimates of the parameters have been shown to be less biased (Gillis and Ratkoursky, 1978). For the asymptotic relationship the parameters a and b can be given simple biological interpretations (Willey and Heath, 1969 ; Frappell, 1979). Here, when density approached zero, the value of yield, (for example dry weight per plant) tends to a^{-1}, and this value is considered to be a measure of the genetic potential of a crop in a particular environment, ie. a measure of plant size when competition free. As density tends to approach infinity the yield per unit area approach the asymptotic value of b^{-1}, and this value is considered to be a measure of the potential of the environment.

Research has been conducted to investigate the effect of plant population density on reproductive capacity in terms of flower and seed production. Competition for nutrients during seed development is critical in affecting seed yield and quality in legumes (Pasumarty, 1991). Brevedan *et al.* (1978) illustrated the importance of the nitrogen nutrition of the soybean plant during flowering increased the seed yield in the greenhouse by 40% and field studies by 22% to 32%. Cooper *et al.* (1976) found that maximum demand for nitrogen in *Vicia faba* bean is associated with pod and seed development, while McEwen (1970) found greatest yield increase in response to a heavy dressing of nitrogen applied during or after anthesis. Brevedan *et al.* (1978) showed that applying nitrogen at the beginning of anthesis decreased soybean flower abscission from 55% to 45% but N applied at the end of anthesis had no effect. This evidence clearly suggests that competition effects for nutrients is most critical before anthesis in soybeans. Carlos and Hume (1978) reported that the percentage of reproductive structures aborting in soybeans increased at high density. Work on *Vicia faba* by Hodgson and Blackman (1956) also showed that the number of podless stems increased with increasing plant density and that the number of productive stems per plant diminished more rapidly in high density stands. Meadley and Milbourn (1970) compared vining peas at three plant densities, 43, 97, and 172 plants/m^2. They found no difference in the yield of green peas over these densities. Although peak numbers of flowers and pods were found in the highest density, there was a greater loss (34%) from abscission than in the lower plant density which resulted in a similar number of pods per unit areas for all densities. In lupin, Herbert and Hill (1978) reported that in dense populations, plants produce fewer inflorescence orders, thus resulting in a shorter flowering period. Also, work by Juntakool (1983) on siratro, showed that in terms of plant spacing the beneficial effects of wide spacing on inflorescence numbers per plant was very evident but decreased to a minimum at the narrowest spacing. Pod number per plant also increased as plant spacing increased while seed numbers per pod was unaffected.

It has been long known that competition for light by mutual shading of leaves is especially evident in soybeans (Chanprasert, 1988). Johnston *et al.* (1969) revealed the apparent photosynthetic rate of leaves under the canopy increased 73% and leaves from middle canopy increased 41% when plants were illuminated by fluorescent lamps at different canopy levels. The treated (light enriched) plants had more seeds, nodes, pods, pods per node and seeds per pod than untreated plants. Similarly, Schou *et al.* (1978) showed that seed yield from shaded soybean plants was lower than from unshaded plants especially when shading occurred during early seed filling (Baharsjah *et al.*, 1980). In other words, yield increase in soybean is limited by the availability of photoassimilates during seed development. Gray *et al.* (1983) showed in carrots that increasing plant density reduced the number of umbels per plant, the reduction being greater in those lateral branches furthest from the apex of the plant, particularly at highest plant density. Also a reduction in the number of seeds per plant and mean weight of seeds occurred from the higher order secondary umbels. Patil *et al.* (1987) in work with (*Callistephus chinesis* L.), showed that transplanting at the highest plant density gave the highest number of flowers for cutting per plant and also highest seed yield, although Phetpradap (1992) showed that increasing plant density decreased flower number in the same species. Macchia (1988) showed that increased plant density from 1.6 to 2.5/m^2 increased overall seed yield by about 50% in *Salvia officinalis* L.

The effects of plant population density have been found to be significant in a wide range of crops and even in different cultivars of the same crop. The interplant competition for resources and growth factors created at high densities induces changes morphologically (vegetative structure of leaf, branch, stem and root) which can be expressed in terms of changes in structure, respective dry weight and time of maturity. Similarly, levels of flower and seed production can be altered in terms of both quantity and quality. Such factors are of importance in that they give growers the ability to partially manipulate yield more towards full crop potential and meet market time related requirements through proper crop management by adjusting plant population density.

2.3 OBJECTIVES

The present experiment was carried out to investigate the plant growth response to competitive stress at the four different densities in *Tropaeolum majus*. Nasturtium with its indeterminate growth habit and prolonged flowering period is subject to plant competition. To observe differences in both vegetative and reproductive capacity and the effects of plant density on seed yield and quality, a study was initiated at the Seed Technology Centre, Massey University, New Zealand, the principle objectives which were:

a. to study the effects of plant spacing induced by varying plant density on vegetative morphology of nasturtium.

b. to determine the effect of nasturtium plant density on reproductive development in nasturtium.

and c. to study the effects of plant density on nasturtium seed production, seed yield and quality.

2.4 MATERIALS AND METHODS

2.4.1 Experimental site and land preparation

The plant density field experiment was conducted from October 1991 to early May 1992. It was sited at Massey University, Palmerston North (40°S 21°E), New Zealand. The experimental site covered approximately 0.3 hectares of Tokomaru silt loam (Cowie *et al.*, 1972) classified as an aeric fragiaqualf (gleyed yellow-grey earth) (Cowie, 1978), Scotter *et al.* (1979) which is part of the rolling hill country at the foot of the Western Tararua ranges (Barker, 1983). Details of soil analysis are given in Appendix 2.1 and climatic data for the period November 1991-May 1992 in Appendix 2.4 -2.8. The land used was cultivated on early October, ploughed and harrowed. No fertilizer or irrigation was applied prior to sowing, or during the growing season.

The experiment utilised a split block design with 5 replications and 4 different plant spacings. The arrangement of each replicate was according to the field layout design below (Figure 2.3) and was arranged to allow the most efficient use of land by using different sized blocks. Individual plot size was adjusted to provide approximately the same number of plants on each density for experimental use.

Density	Plant spacing	Plot area (m^2)	Plants/m^2	Plants/ha
1	15cm x 15cm	5.06	45	450000
11	30cm x 30cm	20.26	11	110000
111	45cm x 45cm	45.56	5	50000
1V	60cm x 60cm	81.0	3	30000

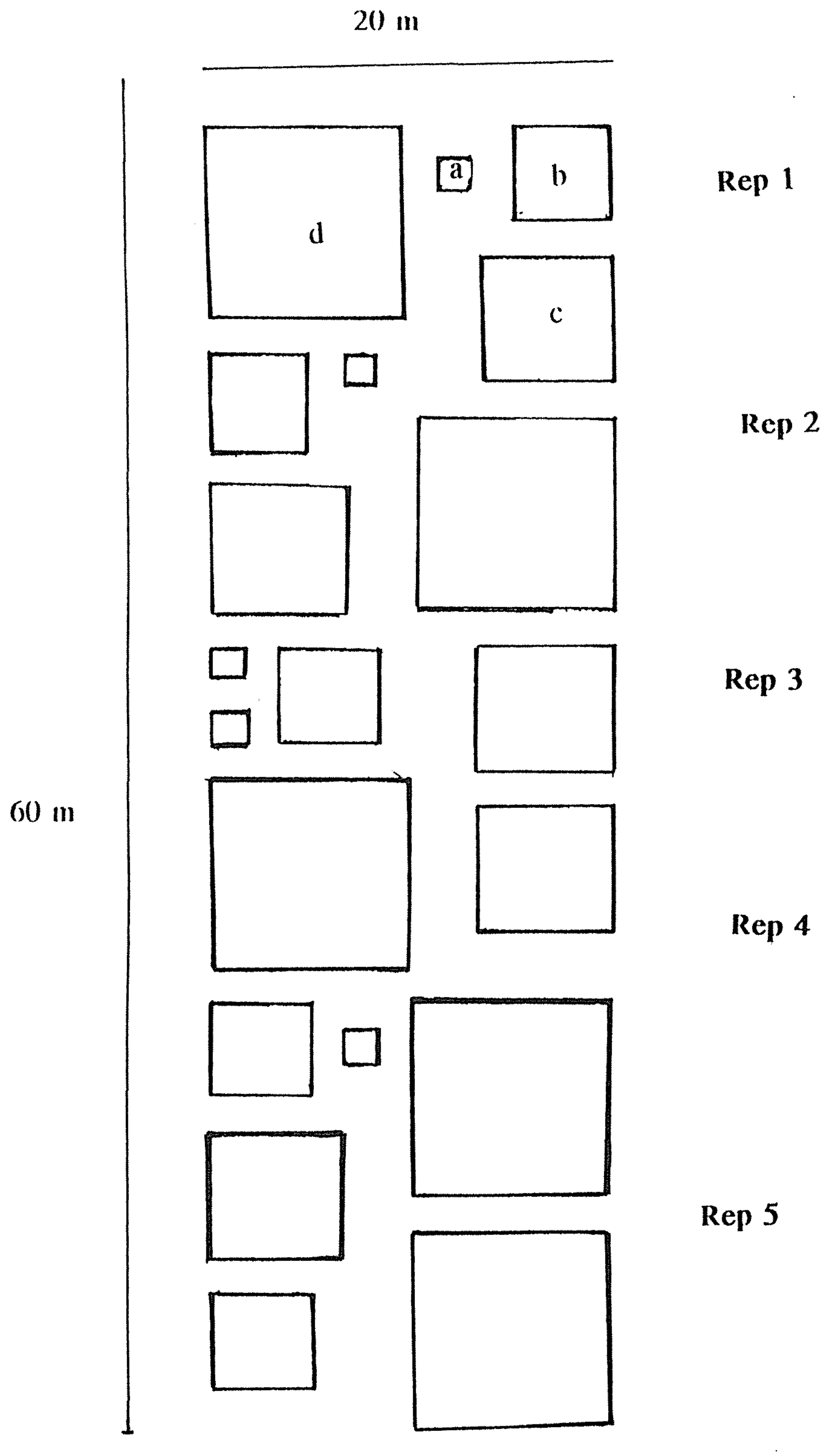


Figure 2.3 The Field Layout design.

a = 45 pl/m^2 b = 11 pl/m^2 c = 5 pl/m^2 d = 3 pl/m^2

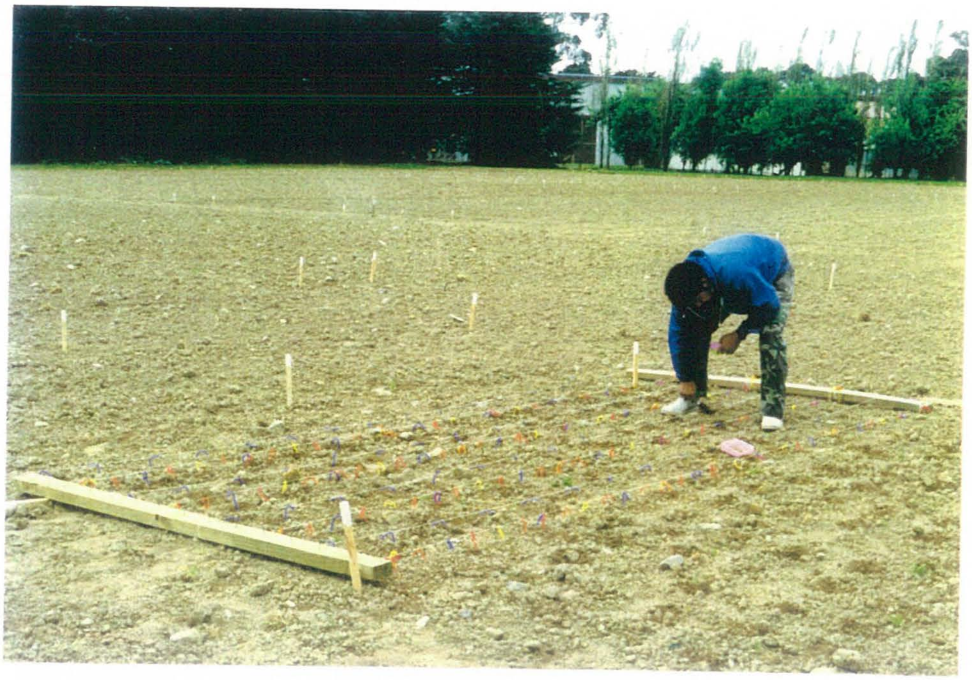


Plate 2.2 Hand sowing nasturtium seeds at required spacing.

Each plot comprised 225 plants. Strings marked at the required spacing were used to obtain the square planting used in this experiment. Seeds were direct sown by hand at the required distance on November 1, 1991 with approximately 2-3 seeds per hole being sown at a depth of about 2-3 cm. Sowing was completed within two days. Seedling emergence occurred 10-14 days after sowing, seedlings then being thinned to one plant per position at two weeks after seedlings had emerged. In the case of missing plants, these were replaced by transplanting seedlings of similar age raised in a nearby glasshouse. Transplants were tagged and identified to avoid their use during sampling and data collection.

The trial area was maintained by herbicide spraying initially and subsequently by hand weeding. Buster, an ammonium phosphate containing 200 g/l of glufosinate ammonium in the form of a soluble concentrate is a non selective contact herbicide and was used to effectively control a wide range of grass and broadleaf weeds and clover. This herbicide was used as a blanket spray after covering the plants with plastic cups until the plants reached the 4-5 leaf stage. Unsprayed weeds closest to the plant were removed by hand. Nasturtium plants established rapidly and tended to grow and trail very fast. This limited the use of buster to only 2 application dates, ie. 26/11/91 about 4 weeks after sowing and 10/12/91 about 6 weeks after sowing. An application rate of 13-15 ml/l was used. Subsequently, the plants grew too wide and the only means of controlling late weeds within plots was by hand weeding. The weeds growing in area between plots were controlled by rotary hoeing.

2.4.2 Initial seed quality

The seed lot of *Tropaeolum majus* used in this study was provided by the Royal Sluis Company of the Netherlands through Lefroy Valley Seed Company (NZ) Ltd. The seed lot was of a Tall hybrid and cultivar 'Choice Mixed', a climbing type nasturtium with stems trailing up to 2-3 metres. This hybrid is normally used for ground cover and trailing embankments. The 'Mixed' nomenclature refers to the different flower colours of the single flowers produced. A preliminary quality assessment on the initial seed lot in the laboratory showed a purity of 99.5%, germination 96.0%, moisture content 7.75% and TSW of 109.5g. Emergence in the field trial was 92.0%.

2.4.3 Harvesting

The sampling procedure involved randomly selecting and hand harvesting 3 plants from each plot at each of 13 harvest times commencing 12[th] December 1991 (Table 2.1).

Table 2.1 Sampling date.

Harvest	Date	Stage of Growth	Days After Sowing
1	12/12/91	5 weeks after sowing	40
2	27/12/91	first visible floral bud	55
3	06/01/92	first open flower	65
4	16/01/92	10 days after first open flower	75
5	26/01/92	20 days "	85
6	05/02/92	30 days "	95
7	15/02/92	40 days "	105
8	25/02/92	50 days "	115
9	04/03/92	60 days "	125
10	14/03/92	70 days "	135
11	24/03/92	80 days "	145
12	04/04/92	90 days "	155
13*	20/04/92	108 days "	170

* - Final Harvest

2.4.4 Data collection and analysis

2.4.4.1 Vegetative study

Three plants were chosen at random from each plot at each of the first 12 harvests. Each plant was cut at ground level and separated into leaf, stem and branch components to determine the following characteristics:

a. Number of green photosynthetic leaves (true leaves)

b. Total area of green leaves determined on an automatic leaf area meter (Li-cor model 3100)

c. Leaf fresh and dry weight

d. Stem or shoot fresh and dry weight

e. Total plant fresh and dry weight

Both leaf and non leaf component dry weight determinations were by oven drying constant dry weight after 3 days at 80°C.

2.4.4.2 Reproductive study

Flowering pattern was determined at each plant density from harvest 4. Three plants were randomly harvested from each density and each replicate as for vegetative study. From each plant the following reproductive features were determined:

a. Number of reproductive buds (BN)

b. Number of half open flowers (HOF)

c. Number of fully open flowers (FOF)

d. Number of wilted flowers (WF)

e. Number of seeds (SN - retained seeds)

f. Seed fresh and dry weight (SFW, SDW)

g. Reproductive fresh and dry weight (RFW, RDW - buds and flowers)

Seed germination at each density was determined by selecting 4 x 50 seeds randomly for germination using the BP method and temperature of 20-30°C in dark conditions. The first count was carried out at seven days and the final count at 21 days. At the final count categories of normal, abnormal seedlings, fresh ungerminated seeds and dead seeds were made. Total viability was calculated from the sum of the normal, abnormal seedlings and fresh ungerminated seeds.

Seed moisture content determination involved 2 replicates of 30 whole seeds which were weighed and then dried in an oven at 103°C for 17 hours. After cooling they reweighed and the %SMC calculated.

$$\frac{M_1 \times M_2}{M_1} \times 100 \qquad \begin{array}{l} M_1 \text{ - weight before drying} \\ M_2 \text{ - weight after drying} \end{array}$$

The weight before and after drying was used to determine fresh and dry weights per 100 seeds.

2.4.4.3 Vegetative morphology

At harvests 10, 11 and 12, in addition to vegetative growth determination, the following morphological characteristics were determined for different plant densities:

a. Average length of the main stem from cut end (ground level) to tip and secondary branches from primary stem to tip

b. Average number of secondary branches

c. Number of tertiary branches on primary and secondary shoots

d. Number of nodes on primary and secondary shoots

e. Number of old non photosynthetic leaves and green leaves per branch

f. A schematic diagram was also drawn of the structure of each plant

g. Component dry weights were also determined at peak flowering and 40 DAP allowing vegetative dry weight to be compared with reproductive dry weight.

2.4.4.4 Final harvest

The final harvest (harvest 13) sampling method involved using quadrats of different sizes for different block sizes. A 25cm x 25cm quadrat was used for the highest density plot (45 pl/m^2), 50cm x 50cm was used for 11 plants/m^2 and 75cm x 75cm for the two low density plots (5 and 3 plants/m^2 respectively). The quadrat was randomly placed in each block, and all the plant material harvested within the square. Seeds were separated from the rest of the plant material. These seeds were divided into 4 categories according to age, colour and maturity. ie. young developed seeds, green mature seeds, brown shed seeds including seeds with mericarps that were partially to fully decayed, and germinated or sprouted seeds. For each of the four densities (5 replicates 3 plants) each of the above categories were separated and the number of seeds counted. Seed fresh and dry weight were determined as a percentage of the total seed number and weights respectively. Seed quality tests such as germination and 1000 seed weight were determined for each category.

2.4.5 Preliminary planting

A preliminary planting had been conducted in the glasshouse prior to the field trial by sowing 2-3 seeds per pot containing sand/peat mixture. The purpose of this was to provide an estimation of time taken for flower development in garden nasturtium. The different stages of development from a floral bud to a mature seed head is shown in Plate 2.3.

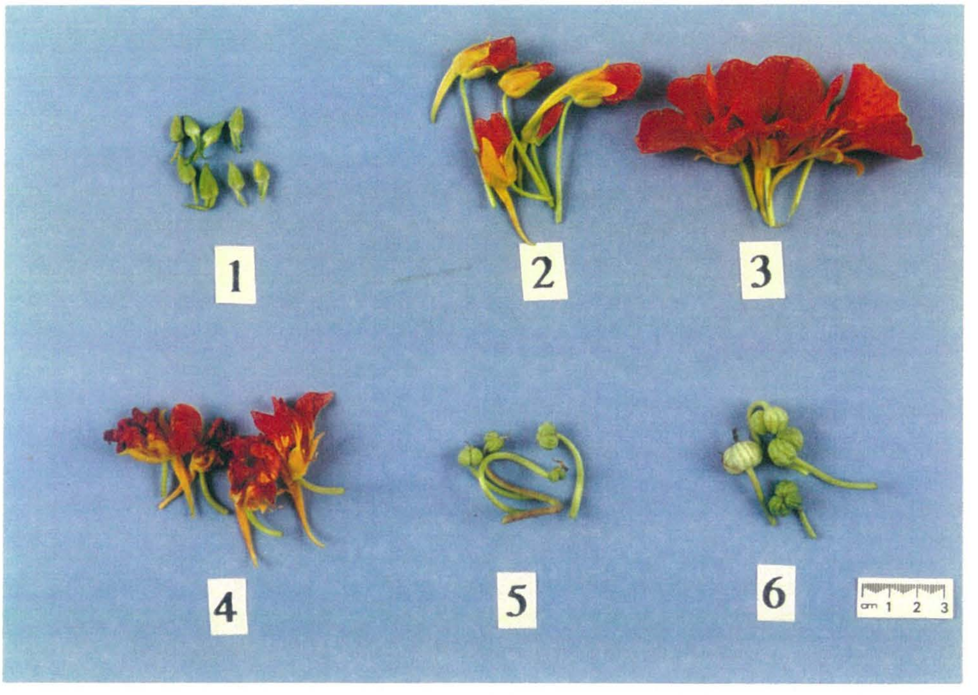


Plate 2.3 Flower development sequence in *Tropaeolum majus* cv. Choice Mixed.

The following definitions have been adopted in this study to provide a general understanding of variables used in the measurements and assessments.

Stage 1 - young green and reproductive buds, well protected by the sepal.

Stage 2 - the flower bud has started to burst, with the sepal open to reveal five bright orange petals. Petals have started to unfold outwards and flowers are half open.

Stage 3 - flowers in full bloom were petals are folded back and flower is fully open exposing the reproductive structures to ensure readiness for pollination.

Stage 4 - flowers where the petals have started to wither and shrivel and the early stages of seed development are visible.

Stage 5 - immature seed head.

Stage 6 - seed head at maturity.

Other definitions include:

Primary Stem - the main stem where both secondary and tertiary branches originate.

Secondary Branch - the stem where only lateral branches are found.

Tertiary Branch - small lateral branches that are found on primary stem and secondary branches (Plate 2.4).

Floral initiation - when flower buds are first observed.

Peak flowering period - the date/time that the plant has produced maximum flower numbers.

Plate 2.4 Typical tertiary branch originate from a secondary branch.

2.4.6 Statistical analysis

Plot means of all variables were used for statistical analysis and expressed both as mean per plant, and mean per unit area (m^2). The data collected were analyzed according to the procedure of a split-plot design experiment (Steele and Torrie, 1982).

2.5 RESULTS

2.5.1 Vegetative growth and morphology

2.5.1.1 Leaf number per plant

Figure 2.4 shows the relationship, between photosynthetic leaf number per plant and time in *Tropaeolum majus*, cv. Choice Mixed grown at different densities. The differences were significant ($P<0.05$) for the different plant densities with the exception of the two lower densities (3 and 5 plant m^{-2}), which were similar. Density effects start to occur early, even before the first sampling date. Leaf number increases rapidly at lower densities after 65 DAS to reach a maximum leaf number at 105 DAS for the 5 pl/m^2 and at 115 DAS for the 3 pl/m^2 which was around time lateral branch growth commenced. Increasing plant densities decreased leaf number per plant but increased leaf numbers per unit area.

2.5.1.2 Leaf area per plant

Total green leaf area showed similar a relationship to plant density as leaf number (Figure 2.5). At all densities, leaf area increased with time but at different rates. The higher density planting of 45 and 11 pl/m^2 reached a maximum leaf area of 1369 and 3066 cm^2 respectively at 95 days after sowing. Low density plantings showed a more rapid increase in leaf area reaching a maximum of about 10000 cm^2 and about 13000 cm^2 for density 5 and 3 pl/m^2 respectively at 105 DAS. Again leaf area dropped quickly to 3000 cm^2 at final harvest at lower densities. The effect of plant spacing on leaf area was first evident at 55 days after sowing and continued to increase through to final harvest ie. plants at wider spacing had a larger leaf area than plants at narrow spacing.

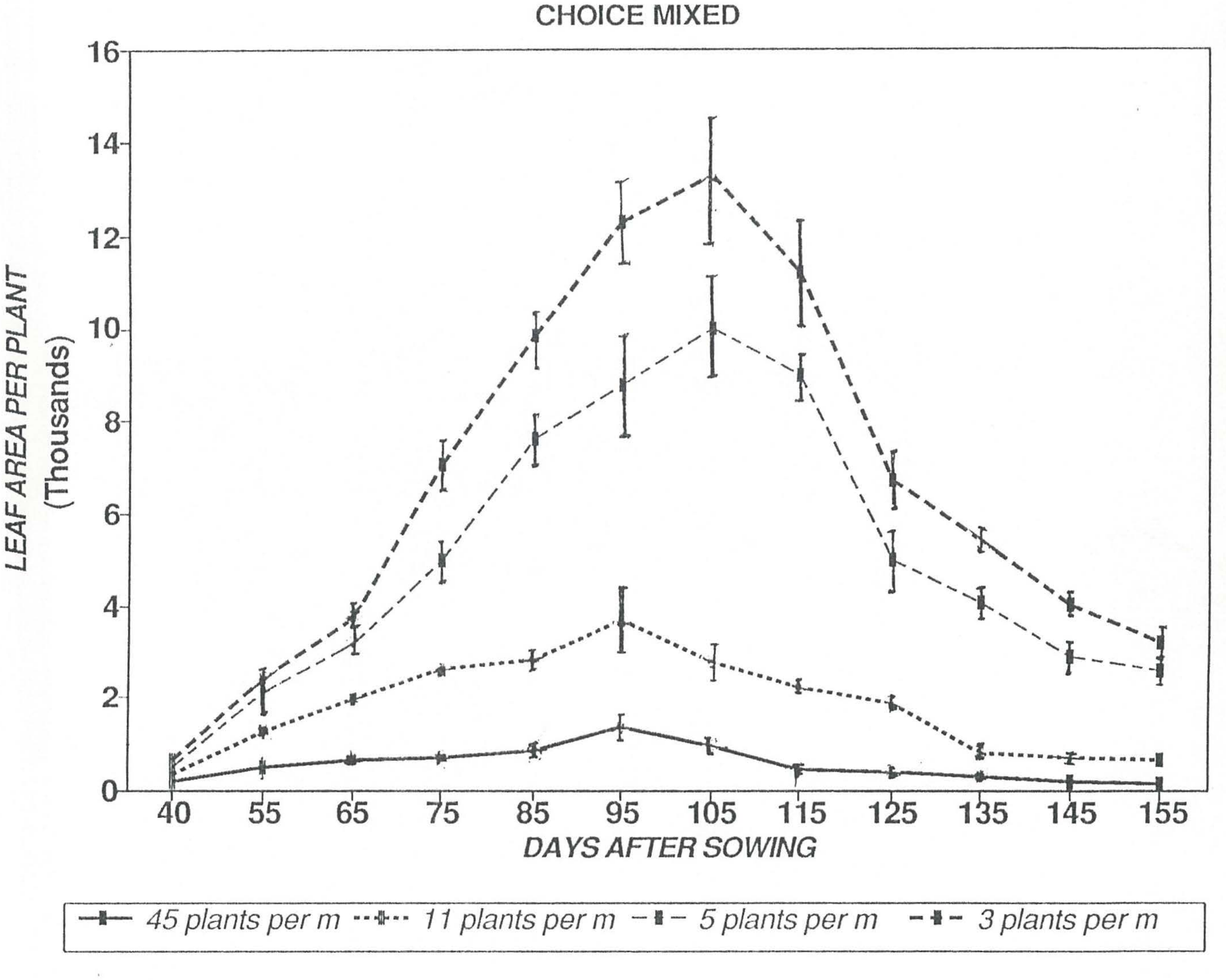


Figure 2.5 Effect of plant density on leaf area (cm^2) per plant of *Tropaeolum majus* (cv. Choice Mixed) at each harvest time. Vertical bars represent SE of the mean.

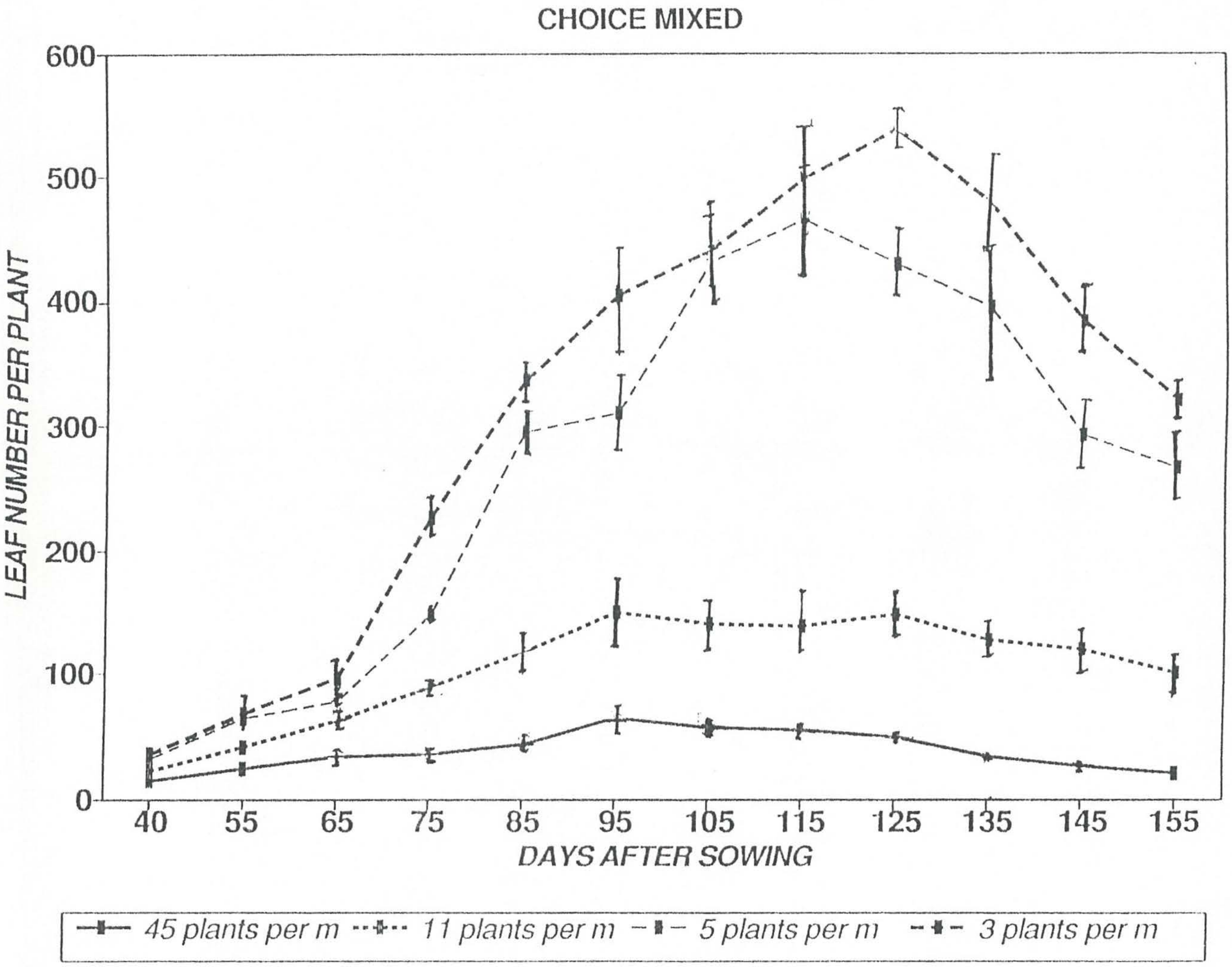


Figure 2.4 Effect of plant density on green leaf numbers per plant of *Tropaeolum majus* (cv. Choice Mixed) at different harvest times. Vertical bars represent SE of the mean.

2.5.1.3. Leaf dry weight per plant

Figure 2.6 shows the effects of plant density over time on leaf dry matter, and follows a similar trend to leaf area (Figure 2.5). Significant differences occurred in each density with lower densities exhibiting rapid increases in leaf dry weight to reach maximum dry weight at 105 days after sowing ie. 30 and 35 grams for the 5 and 3 pl/m^2 respectively. At the higher density of 11 pl/m^2, maximum leaf dry weight was twice as much as in the 45 pl/m^2 at 95 DAS. Reduction in LDW at later harvests is associated with a reduction in both LN and LA due to senescence and competition. LDW increases with decreasing density as more branches develop allowing more leaf sites.

2.5.1.4 Stem dry weight

The effects of plant density on above ground total shoot dry weight is depicted in Figure 2.7. No competition effect was found at 40 DAS, although competition due to plant density effects become apparent from 55 days onwards. Increasing plant density reduces shoot dry weight per plant. Again as in the leaf components result, the two lower densities show a rapid increase in shoot dry weight after 65 DAS and peak above 200 g/plant compare to below 50 g/plant in the two higher density plots indicating the extensive development of secondary and lateral branches. A slight reduction in shoot dry weight at later stages occurs in the two lower densities. Maximum shoot dry weight was found at 95 DAS in high densities (11 and 45 pl/m^{-2}) but was not reached until 105-115 DAS in the lower densities (3 and 5 pl/m^2).

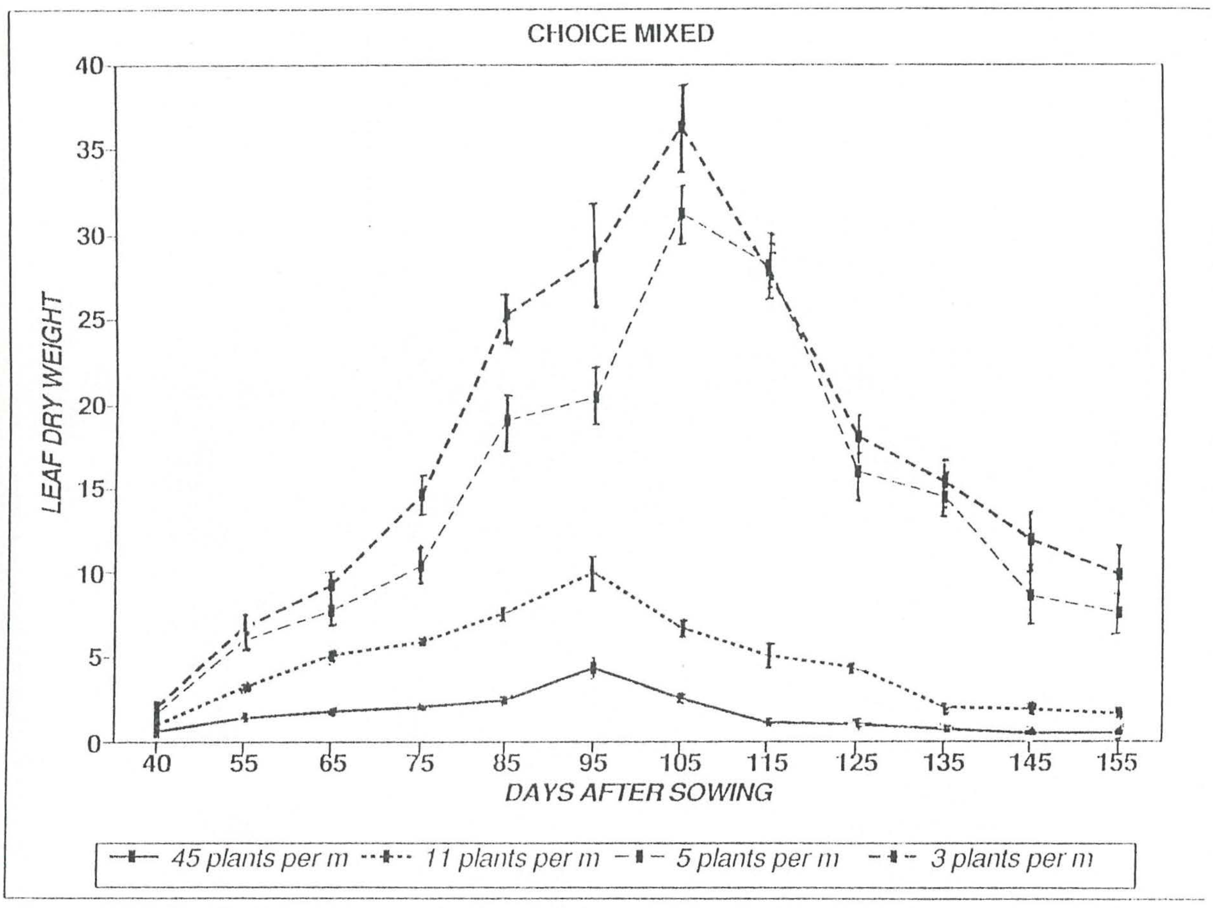


Figure 2.6 Effect of plant density on leaf dry weight (g) of *Tropaeolum majus* (cv. Choice Mixed) at different harvest times. Vertical bars represent SE of the mean.

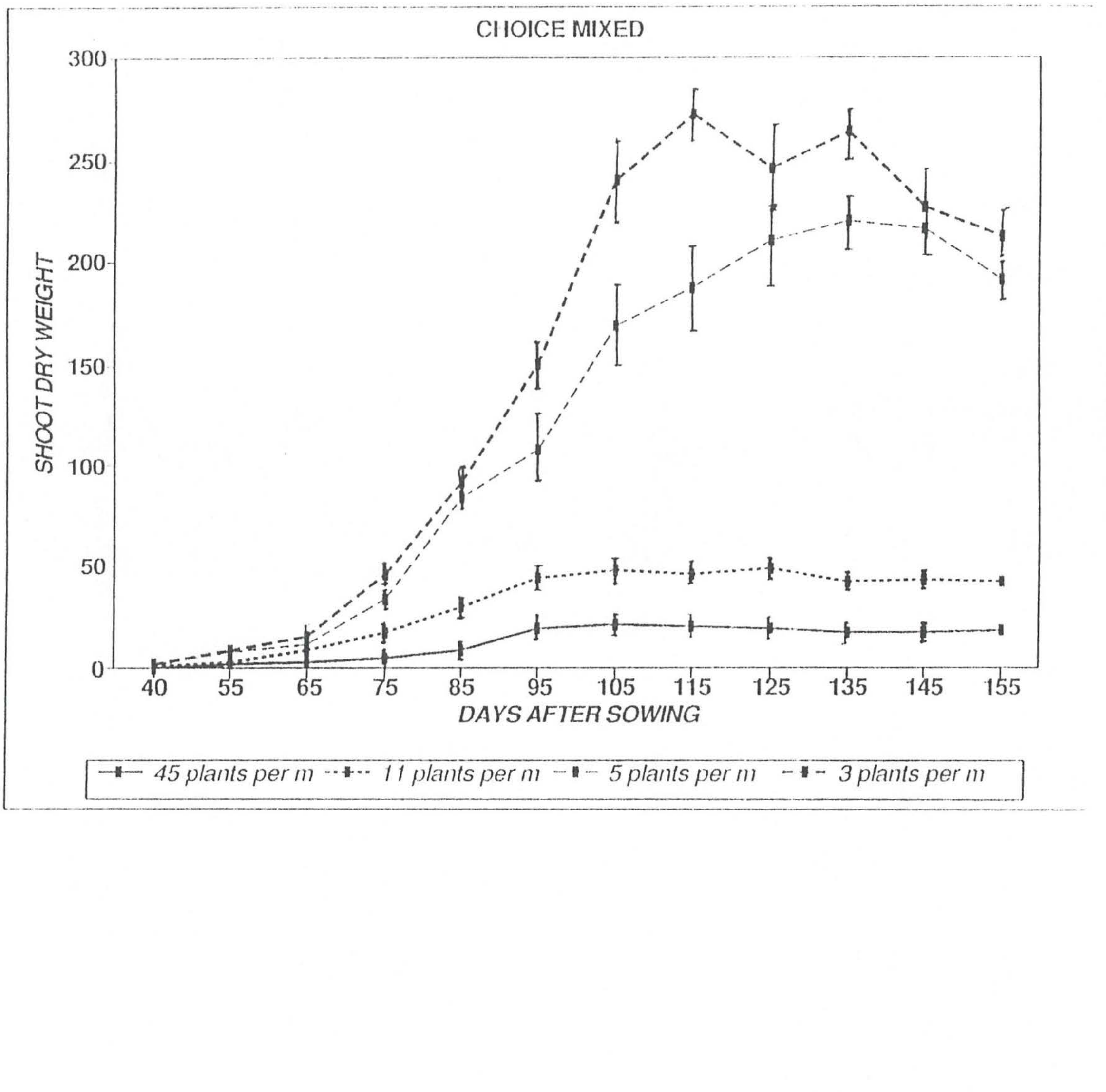


Figure 2.7 Effect of plant density on shoot dry weight (g) of *Tropaeolum majus* (cv. Choice Mixed) at different harvest times. Vertical bars represent the SE of the mean.

2.5.1.5 Partitioning of plant dry weights

The effects of plant density (3, 5, 11 and 45 pl/m^2) on the partitioning of dry weight components amongs the major plant aerial parts (ie. stems (SDW) and leaf components (vegetative), buds and flowers (RDW) and seeds (SDDW)) parts were assessed at peak flowering and 40 days later are presented in Table 2.2 - 2.5, expressed as yield/plant and per unit area and expressed as percentage in Figure 2.8.

At 40 DAP increases in SDW and SDDW occurred, compared with a significant reduction in LDW and RDW at all densities. High significant difference between the four densities, with maximum total dry weight/pl at 3 pl/m^2 and a minimum at 45 pl/m^2. Changes in total dry weight showed a small (15%) increase in high density plantings of 45 and 11 pl/m^2, compared to a significant 40-45% increase at lower densities (3 and 5 pl/m^2). Their ratio of vegetative (SDW+LDW) to reproductive growth (RDW+SDDW) at the two periods compared showed that at peak flowering, dry weight ratio VG:RP was 13-15:1 while at 40 DAP where majority of seed produced resulted in this ratio decreasing to 4 or 5:1.

2.5.1.6 Stem length

Table 2.6 shows the effect of plant density on the length of main stems (MSL) measured at 40 days after peak flowering, close to maximum seed maturity. There was no significant difference in stem length between the lower densities (3 and 5 pl/m^2) but density effects occurred compared at higher densities. Plants at 45 pl/m^2 and 11 both showed a significant reduction in main stem length. Maximum stem length in the 3 and 5 pl/m^2 was about twice that in the highest density. The length of secondary branches is shown in Table 2.7. Again, plants grown at the high density of 11 pl/m^2 showed a significant ($P<0.05$) reduction in branch length to 1/3 of that in lower densities plants. There was no significant difference in stem branch length at 3 and 5 pl/m^2. Increasing plant density cause shortening and reduction in stem length both in the main stem and secondary branches.

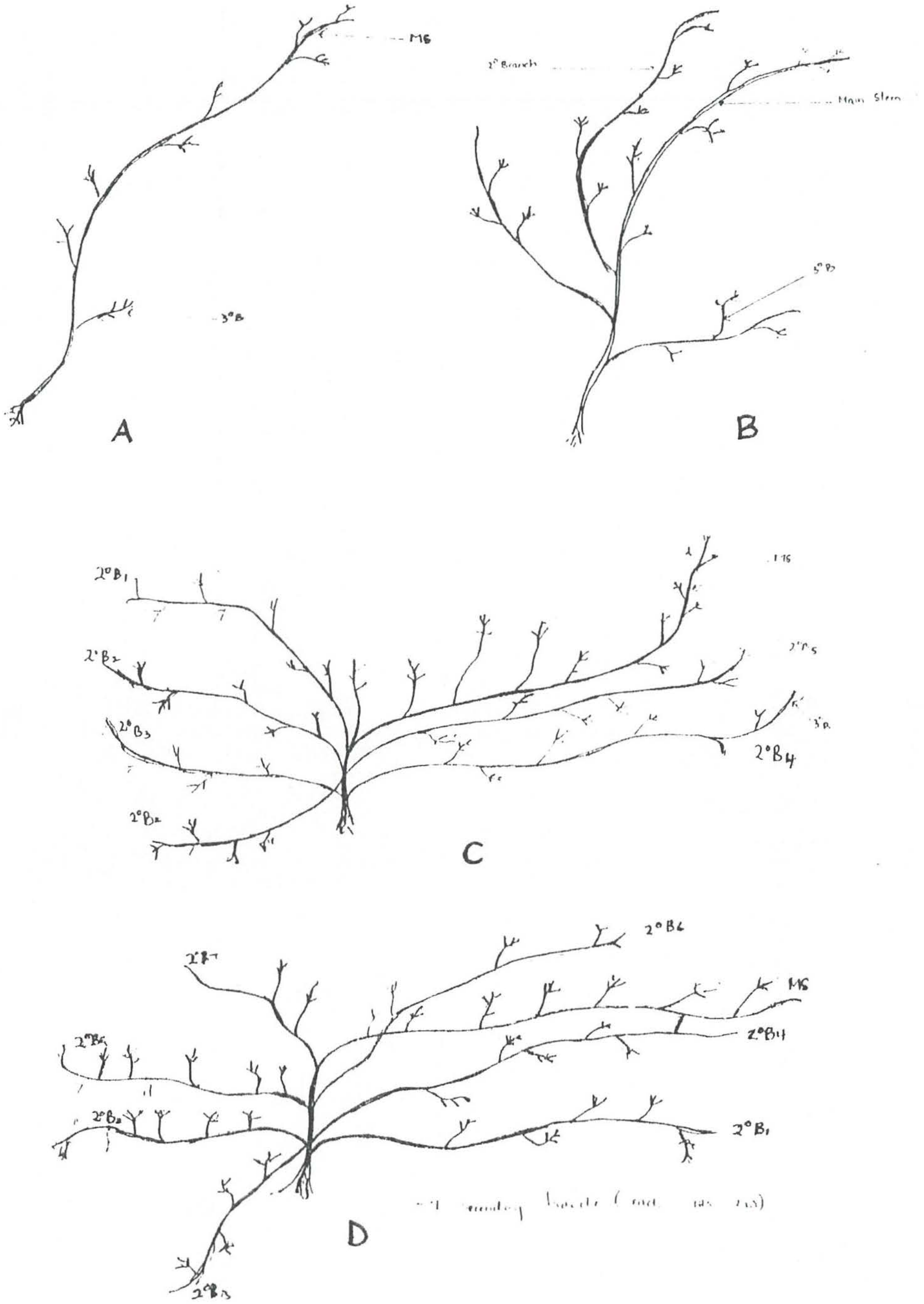


Figure 2.8 Effect of plant density on plant morphology of *Tropaeolum majus* cv. Choice Mixed.

A = 45plant/m^2 B = 11plants/m^2 C = 5plants/m^2 D = 3plants/m^2

Table 2.2 Distribution of plant dry weight at peak flowering. SDW - shoot dry weight, LDW - leaf dry weight, RDW - flowers and buds, and SDDW - seed dry weight.

Plant Density pl/m^2	Dry Weight (g/plant) SDW	LDW	RDW	SDDW
3	150.1 (14.70)	28.7 (4.36)	7.6 (0.93)	4.4 (0.65)
5	107.1 (11.46)	20.5 (16.57)	5.9 (0.93)	4.4 (0.25)
11	37.3 (5.17)	6.7 (0.78)	3.5 (0.90)	2.4 (0.69)
45	18.9 (5.62)	4.3 (1.04)	1.0 (0.13)	1.3 (0.91)

( ) = Standard error of the mean

Table 2.3 Distribution of plant dry weight at 40 days after peak flowering.

Plant Density pl/m^2	Dry Weight (g/plant) SDW	LDW	RDW	SDDW
3	263.8 (12.14)	15.34 (1.11)	2.96 (0.516)	61.9 (1.78)
5	220.3 (10.69)	14.5 (1.73)	3.02 (0.745)	40.6 (5.94)
11	32.2 (1.74)	2.7 (0.39)	0.77 (0.157)	17.9 (2.04)
45	25 (1.26)	0.70 (0.26)	0.36 (0.21)	4.0 (1.01)

( ) = Standard error of the mean

Table 2.4 Distribution of plant dry weight per unit area (g/m^2) for different densities at peak flowering.

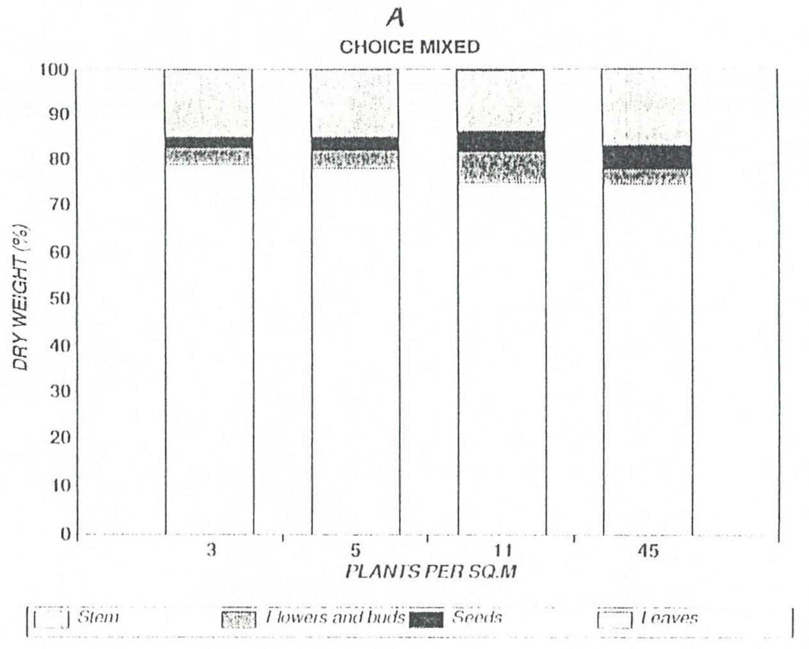
Plant Density pl/m^2	Dry Weight (g/m^2) SDW	LDW	RDW	SDDW
3	450.2 (44.09)	86.2 (13.08)	29.71 (0.47)	21.86 (0.25)
5	535.5 (57.32)	102.5 (11.46)	21.9 (0.25)	29.7 (0.47)
11	483.7 (97.2)	110.5 (18.4)	67.2 (7.57)	39.0 (9.88)
45	845.5 (252.99)	194.9 (47.00)	58.5 (13.16)	44.9 (22.66)

( ) = Standard error of the mean

Table 2.5 Distribution of plant dry weight per unit area (g/m^2) for different densities at 40 days after peak flowering.

Plant Density pl/m^2	Dry Weight (g/m^2) SDW	LDW	RDW	SDDW
3	791.5 (36.43)	46.0 (3.32)	8.9 (1.55)	186.0 (5.35)
5	1101.5 (53.46)	72.3 (8.63)	15.01 (3.73)	203.1 (29.71)
11	354.5 (19.14)	22.6 (4.28)	8.5 (1.73)	197.1 (22.47)
45	336.8 (56.39)	31.6 (11.71)	16.2 (9.47)	178.9 (45.41)

( ) = Standard error of the mean



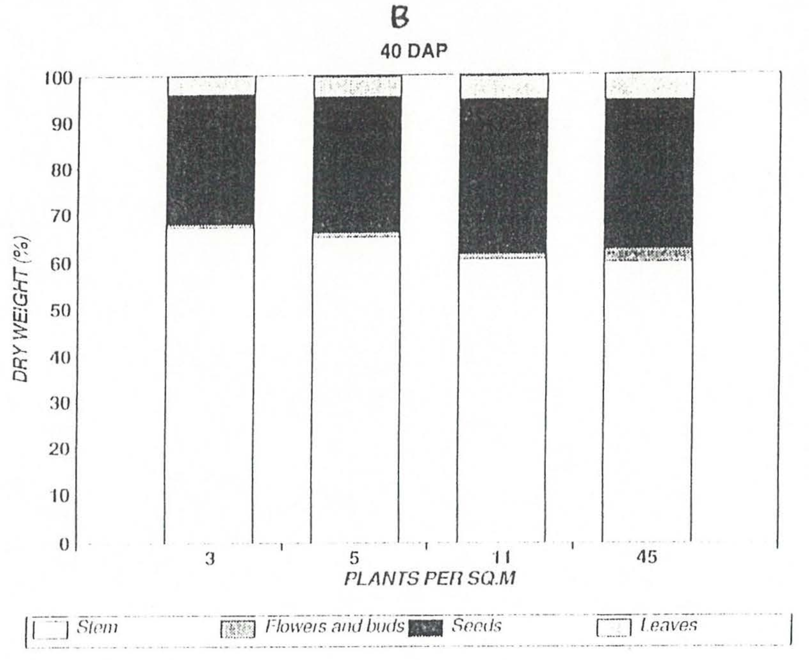


Figure 2.9 Distribution of shoot, leaf, flowers and buds, and seed weight (as a percentage of total plant weight) at peak flowering (A) and 40 DAP (B) of *Tropaeolum majus* cv. Choice Mixed.

Table 2.6 Effect of plant density on main stem length (MSL), main stem node number (MSN) and length of internodes on main stem (MSIL) of *Tropaeolum majus* (cv. Choice Mixed) measured at 40 days after peak flowering.

Plant Density	Spacing	MSL(cm)	MSN	MSIL(cm)
3 pl/m²	60x60cm	177.0a	40.8a	4.48a
5 pl/m²	45x45cm	157.0a	40.2a	4.23a
11 pl/m²	30x30cm	109.2b	39.8a	2.88b
45 pl/m²	15x15cm	78.2c	31.4b	2.54b
	LSD	26.75	5.13	0.43

Table 2.7 Effect of plant density on the number of secondary branches (SB), tertiary branches (TB), length of secondary branches (SBL), number of nodes and length of internode of secondary branches of *Tropaeolum majus* (cv. Choice Mixed) 40 days after peak flowering.

Plant Density	SB	SBL(cm)	SBN	SBIL(cm)	TB	TB/M²
3 pl/m²	6.6a	185.2a	39.2a	5.12a	65.2a	195.6c
5 pl/m²	5.4b	195.4a	38.6a	5.30a	49.8b	249b
11 pl/m²	2.8c	67.4b	26.8b	2.82b	31.4c	345a
45 pl/m²	0.0d	-	-	-	7.2d	324a
	LSD	1.19	22.81	3.73	10.18	36.8

Values within columns with the same letter are not significantly different (P=0.05).

2.5.1.7 Branch number

Table 2.7 and Figure 2.8 shows plant density effects on branch numbers. The number of secondary branches which developed increased with decreasing plant density. At the highest density (45 pl/m^2) no secondary branches developed due to strong competition effects, which effectively restricted branching to only small lateral branches on main stems. Secondary branches were only significant at the other three densities. Plants at the lowest plant density (3 plants/m^2) had the greatest number of secondary branches.

The effects of plant density on the number of tertiary lateral branches (TB) in Table 2.6 shows that the number of side branches per plant from primary and secondary stems increased with deceasing plant density due to an increase in secondary branch numbers and length. However, the number of side branches per unit area was much higher at higher densities of 11 and 45 pl/m^2 than at lower densities. Tertiary branch numbers per unit area also increased with increasing plant density.

2.5.1.8 Nodes number

The effect of plant density on node production in *T. majus* is shown in Tables 2.6 and 2.7 for main stem and secondary branches respectively. Main stems nodes at a planting density of 45 pl/m^2 were significantly different to higher densities and were affected by reductions in main stem length and also in the number of nodes produced. The other 3 densities showed no significant difference ($P=0.05$) between the number of nodes on the main stem. In terms of secondary branches, the effect of plant density Table 2.2) on branch length (SBL), showed not only a reduction in branch length at higher densities but also similar effects on the number of nodes produced and shorter internode length.

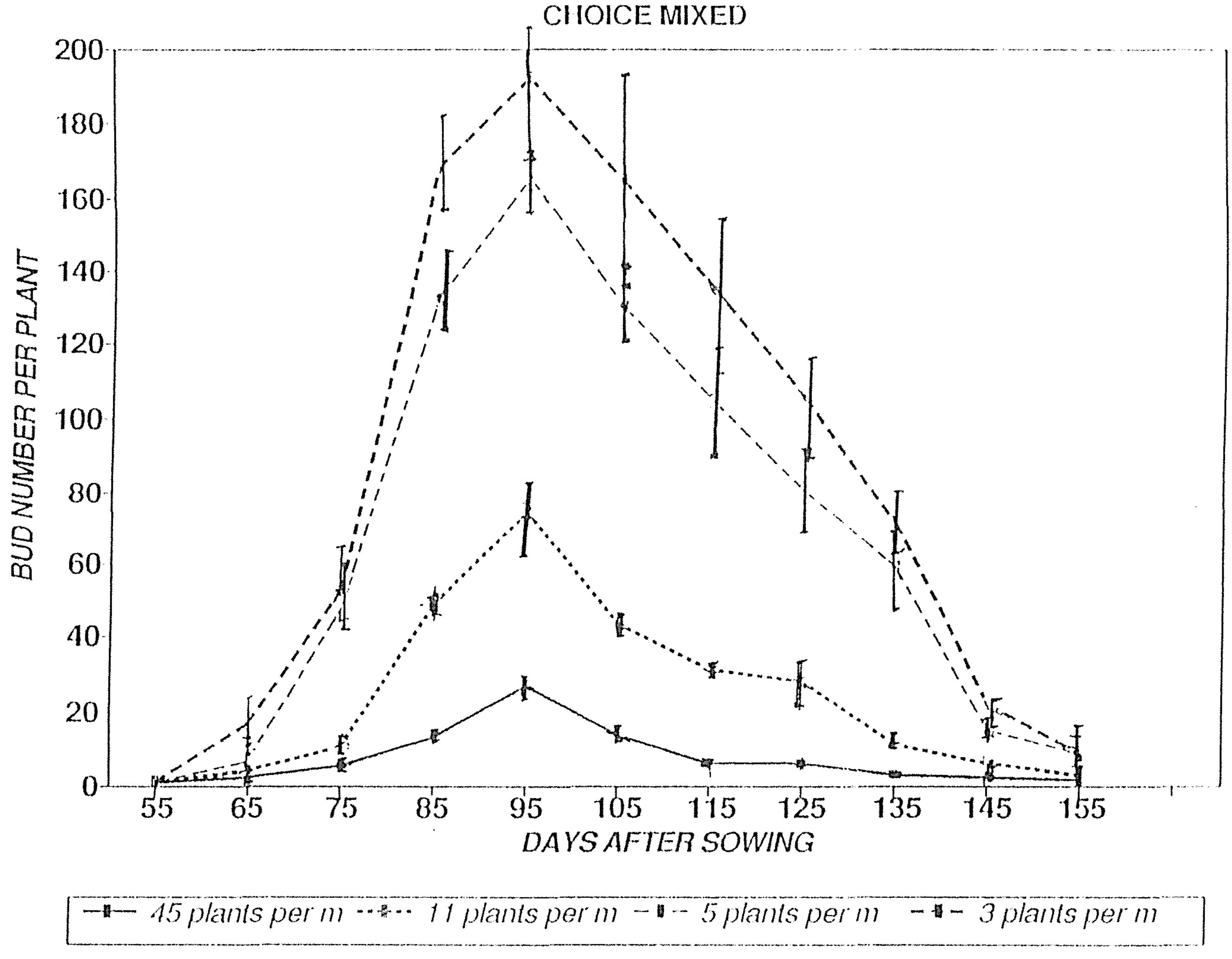


Figure 2.10 Effect of plant density on the number of buds per plant of *Tropaeolum majus* (cv. Choice Mixed) at different harvest times. Vertical bars represent SE of the mean.

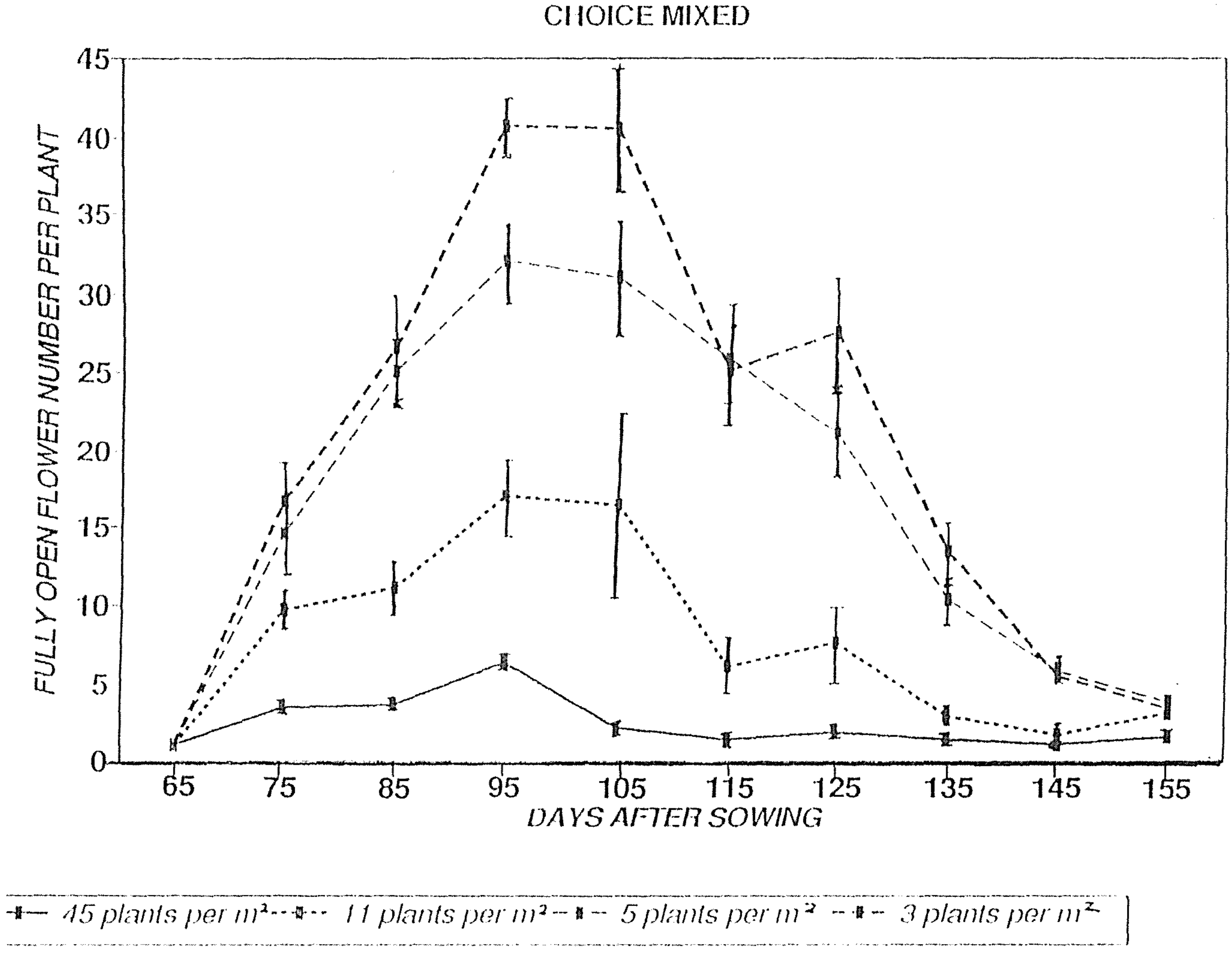


Figure 2.11 Effect of plant density on the number of fully open flowers per plant at different harvest times of *Tropaeolum majus* (cv. Choice Mixed). Vertical bars represent SE of the mean.

2.5.1.9 Internodal elongation

The effects of plant density on internodal elongation recorded 40 days after peak flowering are presented in Tables 2.6 and 2.7. In the four densities used ie. 45, 11, 5 and 3 pl/m^2). The two highest density plantings were not significantly different ($P=0.05$) but both had significantly shorter internodes ($P<0.05$) than plants at 3 and 5 pl/m^2. Similarly in the secondary branches, internodes length at 11 pl/m^2 was significantly shorter than the other two lower densities. Lower density plant had longer internodes than high density plants. The results also show that only at low density plants (3 and 5 pl/m^2) showed that main stem internode was significantly shorter than secondary branch internode.

2.5.2 Reproductive development

2.5.2.1 Bud production

Figure 2.10 shows the effect of plant density on the number of buds per plant in *Tropaeolum majus* (cv. Choice Mixed). Most floral bud production occurred prior to 85 days after sowing. The first floral bud was observed at about 55 DAS and quickly reached a peak at 95 DAP before slowly decreasing with time at all densities. New bud production occurred continuously throughout the study although there is a significant reduction in quantity. There were no significant differences ($P=0.05$) in the number of buds per plant in the lower densities (3 and 5 pl/m^2) except at 85 DAS ($P<0.05$). At these densities plants reached a maximum of about 70 and 20 in 11 and 45 pl/m^2 treatments respectively. High density plants showed reduced floral bud production.

2.5.2.2 Flowering pattern

First open flowering in *T. majus* cv. Choice Mixed occurred 65 days after sowing and peak flowering was reached approximately 30 days later (95 DAS) in all densities. All plant densities showed a similar flowering pattern but there was a significant effect on flower numbers at different densities. Highest density plantings (45 pl/m^2) showed peak flowering at 95 days after sowing and then dropped gradually at 105 DAS while the other density planting reached peak flowering 95-105 days. Flower numbers per plant at peak flowering were affected by density with the highest density producing fewest flowers (7) compared to plants grown at the lowest density of 3 pl/m^2 which produced about 40 open flowers at peak flowering which represented about 87.5% reduction. Flowering duration, however, was similar at all densities, occuping a period of approximately 90 days after sowing. Flower number per m^2 increased with increasing density.

2.5.2.3 Seed yield and yield components

Increasing plant density decreased seed yield per plant (Table 2.8a) as a direct result of fewer flowers. However, there was no significant effect of plant density on seed numbers per flower or seed weight. Since plant density had a large effect on total flower numbers per plant, it is not surprising there were significant differences in seed yield per plant at all harvests (Table 2.8a), from a maximum at the widest spacing (61.9g) to a minimum at the closest spacing of about 4 grams. This represents a 93% yield reduction. All densities reached maximum yield per plant at 40 DAP before decreasing due to seed shed. In terms of seed yield per unit area (Table 2.8b), all densities reached maximum seed yield (kg/ha) at 40 DAP but there was no significant difference (P=0.05) between densities. So plant density had no significant effect on seed yield per hectare.

Table 2.8 Effect of plant density on seed yield at different harvest times.

a. Seed yield per plant (g/pl). ( ) = Standard error of the mean.

Plant Density pl/m²	Days After Peak Flowering 10	20	30	40	50	60
3	22.2 (2.24)	41.9 (5.71)	57.8 (7.18)	61.9 (1.78)	53.2 (5.37)	24.3 (1.12)
5	19.3 (1.23)	25.7 (3.99)	33.5 (2.14)	40.63 (2.94)	33.97 (3.53)	15.4 (0.85)
11	6.1 (0.69)	7.7 (1.57)	10.9 (1.71)	17.92 (2.04)	7.8 (0.47)	0.9 (0.09)
45	2.4 (0.42)	3.0 (0.16)	3.5 (0.09)	3.98 (1.01)	2.4 (0.68)	0.2 (0.10)

b. Seed yield per unit area (kg/ha). ( ) = Standard error of the mean.

3	665 (67.2)	1258.1 (215.5)	1735.1 (171.3)	1859.7 (53.5)	1595 (161.2)	729 (33.7)
5	963.7 (61.7)	1383 (199.7)	1674.0 (107.2)	2031.5 (297.1)	1698.5 (176.6)	772 (42.7)
11	672 (75.8)	847 (172.8)	1202 (188.0)	1971 (224.7)	860 (52.0)	95 (10.2)
45	1062 (190.9)	1367 (71.8)	1561 (40.6)	1789 (454.1)	1089 (307.8)	77 (44.8)

2.5.3 Seed quality

The quality of seeds in terms of moisture content, germination percentage and viability was also examined. Results are presented in Tables 2.9-2.11.

2.5.3.1 Moisture content

There was no significant effect of plant density on the moisture content of seed. However, there was a gradual and slight decline in mean moisture content with progressively later harvests as seeds matured (Table 2.9). Minimum seed moisture occurred about 40 days after pollination. A slight increase in SMC occurred at later harvests (50-60 DAP) due to an increase in the proportion of shed seeds after 40 days resulting in a higher number of immature seeds being sampled. The rate of dehydration was surprisingly low considering seed lost less than 7% over a period of 40 days. Seed shed at maturity at very high seed moisture content and with a slow rate of moisture change presumably reflects the need for post harvest seed drying.

2.5.3.2 Percentage normal germination

Table 2.10 shows the seed germination percentage obtained on samples of seed air dried at room temperature to below 20% SMC. Plant spacing had no effect on the germination ability of seed which appeared to be more dependent on the stage of seed maturity. Over all spacings seed germination percentage increased from 30% to 57%, reaching a maximum germination 30 days after peak flowering and then gradually declining. High levels of seedling abnormality were detected prior to 30 days with a high percentage of dead seed. The decrease at 40-50 days was due to a high percentage of fresh ungerminated seeds (60-70%).

2.5.3.3 Viability

Seed viability from the laboratory germination tests (Table 2.11) again showed a similar trend to germination, no significant difference occurring between the four densities at each harvest. Maximum viability of 73% was achieved 40-50 days after peak flowering. Low viability occurred in the first 20-30 days after peak flowering but this rose to a peak after 30 days.

Table 2.9 Effect of plant density on %SMC at different harvest times.

Plant Density	Days After Peak Flowering					
pl/m^2	10	20	30	40	50	60
3	88.4	86.3	86.6	79.5	84	86
5	87.6	86.6	85.9	80.2	81.7	85.6
11	87.3	85.9	84	81.5	83.2	84.4
45	86.9	86.1	85.2	79.5	83.6	84.7
Significant	NS	NS	NS	NS	NS	NS

NS = Values in each column are not significantly different (P=0.05)

Table 2.10 Effect of plant spacing on the germination of seed (normal seedlings) at each harvest.

Plant Density pl/m^2	Days After Peak Flowering 10	20	30	40	50
3	31.5	35.7	57.4	19.2	29.3
5	29.7	32.4	49.8	20.3	28.7
11	25.7	31.5	63.4	11.4	31.2
45	33.4	34.7	58.5	20.2	27.4
Significant	NS	NS	NS	NS	NS

Table 2.11 Effect of plant density on seed viability at different harvest times.

Plant Density pl/m^2	Days After Peak Flowering 10	20	30	40	50
3	34.6	41.2	73.5	75	63.1
5	35.9	38.7	71.2	79.3	60
11	32.4	36.2	70.6	69.7	63.4
45	38.5	36.7	69.4	70.6	65.4
Significant	NS	NS	NS	NS	NS

NS = No significant different between value in each column (P=0.05)

2.5.4 Final harvest (harvest 13)

Table 2.11 shows the effect of plant density on the total seed recovered per m^2 at the final harvest (170 days after sowing). Highly significant differences ($P<0.05$) occurred between seed yield per plant in the four different densities. Seed yield per plant decreased with increasing plant density. However yield per unit area (kg/ha) and seed number/ha showed no significant differences ($P=0.05$) between all densities.

Table 2.12 Effect of plant density on the actual seed yield recovered at final harvest (170 days after sowing). Values within columns with the same letter are not significantly different ($P=0.05$).

Plant Density	Yield g/plant	Yield kg/ha	Yield seed/ha
3	65.35a	1960.4a	15555.2a
5	39.74b	1986.8a	18064.0a
11	7.85c	1963.3a	15984.0a
45	3.91d	1757.6a	16316.0a
Mean	29.21	1917.1	16479
LSD	4.63	617.1	4565.0

Seeds collected at the final harvest from quadrats showed differences in terms of size, age and colour. Table 2.12 shows these seed categorisations at each density, and expressed as percentage seed number (%SN) and seed dry weight (%SDW). The percentage of developing and immature seeds (A) are significantly different at different densities. Decreasing plant density increased the number of late seeds which developed. High density resulted in very low seed numbers. Mature green seeds (B) were significantly higher at the lowest density with 11%, but at other densities were not significantly different. At the final harvest shed seeds comprised about 90% of harvested seeds (category C). Only the lowest density showed to be significantly lower percentage of brown dry shed seeds than other treatments. In terms of % dry weight, (A) no significant difference occurred ($P=0.05$) between the 3, 5 and 11 pl/m^2 densities and 45 pl/m^2 was only significant different to 5 pl/m^2. Percentage green mature seeds was similar to SN with the lower density being significantly higher than the rest. Sprouted seed (D) showed no significant difference between treatments.

The percentage of seed yield (g/m^2) collected was categorised into total retained seed yield and shed seed yield at the final harvest. At the lowest density there was a significantly higher percentage of retained seeds compared to other treatments. Plant densities of 5, 11 and 45 plants/m^2 showed no significant difference in the weight of seeds remaining on the plant at the final harvest.

Table 2.13 Seeds covered at final harvest categorisation, A = immature seeds, B = matured green retained seeds, C = brown shed seeds, and D = sprouted shed seeds. Values within columns with the same letter are not significantly different (P=0.05).

Plant Density	%SN				%SDW			
Plants/m^2	A	B	C	D	A	B	C	D
3	2.0a	11.1a	84.5b	2.2a	0.4ab	8.6a	88.7a	2.3a
5	1.2b	5.3b	91.9a	1.6b	0.5a	5.3b	92.7a	1.5c
11	0.3c	5.7b	92.8a	1.7b	0.2ab	3.6b	94.4a	1.8bc
45	0.0c	3.5b	94.3a	2.2a	0.0b	2.5b	95.5a	2.0ab

2.6 DISCUSSION

2.6.1 Vegetative

The effects of plant density on plant vegetative morphological characteristics were similar to those reported previously in soybean (Chanprasert, 1988), maize (Balico, 1984 ; Tolentino, 1985), lupin (Herbert and Hill, 1978), siratro (Juntakool, 1983) and China Aster (Phetpradap, 1992). The present study showed that plant density had a distinctive effect on morphology of *Tropaeolum majus*. The effect was quite apparent prior to first sampling and as growth proceeded, the effects intensified. The change in plant morphology at different population densities were due to the variable development of secondary branches by plants grown at different densities (Table 2.6) therefore the plant's potential to rapidly increase sites for more lateral branches and rapidly increase leaf production (leaf number, area and dry weight) and plant dry weight accumulation (Table 2.3). In this experiment, plants grown at low densities showed the greatest branch development, and subsequently leaf and flower production, with an increase in potential seed production sites. A major aspect of plant density is its significant effect on light distribution in plant canopies (Kasperbauer and Karlen, 1986). Kerslake and Menary (1986) also showed that bud yield of blackcurrants was influenced by plant density and light interception. Increasing competition for available light occurs in a smaller plants grown at high densities as compared to low density plants.

Although individual plant dry weight was markedly depressed by increasing plant density, this effect was more than compensated for by increasing plant population particularly at the closer spacings, resulting in a similar total yield per unit area at higher population densities.

At high density (45 pl/m^2) plants showed a significant reduction in plant dry weight cause by shortening of main stems, fewer nodes and shorter internodes due to competition for light and nutrients. The effects on node production was similar to that described in soybean (Chanprasert, 1988) but differed in terms of internodal elongation where increased plant density in nasturtium resulted in significant shortening internodal length. This may be due to the trailing growth habit of the plant creating early competition for nutrients and light. Such effects restrict branches at high density (45 pl/m^2) to the point where no secondary branches are formed on the main stem. Decreasing plant density not only increased main stem length but also encouraged secondary branch elongation and both node numbers and internode length.

2.6.2 Reproductive development

The reproductive development of *Tropaeolum majus* resembles that found in other indeterminate species eg. *Vicia faba* L. (Attiya *et al.*, 1983), *Daucus carota* (Hiller and Kelly, 1985), *Lotus corniculatus* (Li, 1989 ; Supanjani, 1991), Hybrid dahlia (Phetpradap, 1992) with a varying proportion of flower buds, open flowers, and immature, mature, ripening and shed seeds being present on the one plant at the same time. This lack of uniformity in growth habit and protracted flowering increases the problem for seed production (Still, 1988). Varying plant density was tested for effects on these characteristics. This study indicates that assimilate competition is likely to occur between vegetative and reproductive plant parts as secondary lateral branches and leaves grew rapidly at the same time as buds, flowers and seeds develop due to the indeterminate growth habit and indeterminate flowering habit of nasturtiums. This type of competition has been demonstrated in other species by branch and young leaf removal which appeared to increase seed yield. For example, Miura *et al.* (1988)

showed that branch removal on the main stem of soybean cv. Toyosuzu by 53, 91 and 84%, grown at 330, 648 and 1798 plant/ha respectively, resulted in an increase in pod numbers per plant, seeds per pod and seed weight. Similar effects have been reported by Chanprasert (1988) with soybean cv. Amsoy where increased flower and pod numbers occurred without, however, significantly increasing seed yield. Assimilate competition is likely to occur between reproductive plant parts. The overlaps in flowering between the primary flower head on the main stem and the terminal flower heads of lateral branches and a time span of flowering between lateral branches may also have caused competition for assimilates required for seed setting (Farrington, 1976 ; Herbert and Hill, 1978). Under stress conditions such as light, temperature or water stress young flower buds constitute a weak sink in comparison with other developing organs, leaves, stems, fruits and storage organs and tend to be poorly placed in the competitive 'hierachy' for available assimilate (Subhadrabardhu *et al.*, 1978 ; Monselise and Goldschmidt, 1982).

From the experimental results, plant density had no significant effect on flowering pattern and duration but had a great of influence on the number of flowers produced. Flower production per plant of *Tropaeolum majus* (cv. Choice Mixed) was greater under low density conditions possibly due to less competition for light and nutrients with larger plants and more extensive branch development resulting in flowering sites. Work has also shown that competition for light not only affects vegetative plant growth but also flowering. The number of flowers changes with time and a main features of this crop is the prolonged flowering period of more than 4 months. Plant density has no effect on flowering period with peak flowering being achieved at the same time ie. 95 days after sowing in all densities.

The results from this experiment show that plant density affects seed yield per plant but has no significant effect on total seed yield per hectare which shows that low seed yield per plant was compensated for by increasing numbers of plants per unit area. Widest plant spacing produced the highest seed yield per plant as found in other crops by Chanprasert, 1988 ; Herbert and Hill, 1978 ; Juntakool, 1983 and Phetpradap, 1992. This was due largely to higher flower numbers per plant. This advantage was, however, not significant to achieve higher seed yields/ha as yield per unit area was not significantly different ($P<0.05$) to that from other higher densities.

It appears that a harvest about 30-40 after peak flowering is the most appropriate time to achieve maximum seed yield irrespective of plant population. Beyond this stage seed shattering losses are likely to be substantial. This is supported by the production of seeds of maximum seed quality in terms of high percentages of germination, viability and lower moisture content. Seed is shed at very high moisture content of about 78-79%. It is also important to know that number of seeds per pod (about 3) and seed dry weights were both relatively unaffected by plant competition in this study which confirms the fact that flower number is the most important single seed yield component for determining final seed yield in nasturtium cv. Choice Mixed and thus is an important characteristic to be manipulated to increase seed yield. Branching may be also manipulated to increase seed yield per plant due to increased numbers of secondary and tertiary branches, leaf number, leaf area, plant dry weight and flower numbers at lower densities.

CHAPTER 3

SEED DEVELOPMENT STUDY

3.1 INTRODUCTION

The production of viable seed is essential for the continued existence of annual plant species and seed is still the only reproductive method available for many perennials used in ornamental horticulture. The production of seed occupies a considerable part of the plant's seasonal life cycle beginning with the initiation of flowering and ending with seed maturation and ripeness. Most researchers agree that seed development is concerned with those processes and stages occurring during this period, including physiological changes in seed moisture content, seed weight, germination capacity and chemical changes in biochemical substances.

The most important aspects of seed development which contribute a great deal to yield at harvested time are seed maturity and seed ripening. Ideally, seed crops ought to be harvest when seed quality is at a maximum, but it its by no means clear when this occurs (Filho and Ellis, 1991). Several studies have been undertaken to determine the stage of maturity and ripening of different crops in order to guide seed growers in deciding the optimum harvest time to achieve maximum quality and quantity in seed crops (Hyde *et al.*, 1959 ; Hill, 1971 ; Kowithayakorn, 1978 ; Win Pe, 1978 ; Mullet, 1981 ; Juntakool, 1983 ; Hare and Lucas, 1984 ; Rasyad *et al.*, 1990 ; Seed Technology Centre, 1986).

However, there is generally limited information on seed development in flower crops including *Tropaeolum majus*, the only information on the length of time required for seed development of *T. majus* species being by Boulton (1986). The main objective of this experiment was to study the changes in seed moisture content (SMC), seed fresh weight (FW) and dry weight (DW) of nasturtium during seed development. In addition the relationship between various stages of seed development and seed quality including germination capacity and seed viability was also being investigated.

3.2 REVIEW OF SEED DEVELOPMENT

The term development has been defined as the process of growth and differentiation of individual cells into recognisable tissue, organs and organism (Salisbury and Ross, 1978). Seed development commences following anthesis, fertilization and seed set; and is the process or more probably a wider range of processes which lead from a fertilized ovule to a mature seed ie. formation of a potentially independent plant (Bryant, 1985). There are various physiological changes associated with this development, both at tissue level and in the seed as a whole.

3.2.1 Embryo development

The dicotyledon seed is a fertilised ovule, and a mature or ripe dicotyledonous seed, embryo consists of an embryo axis with a shoot (plumule) and root (radicle) and two cotyledons (Coolbear, 1989). The first division of the fertilized egg results in the establishment of polarity; the top and bottom of the embryo being already distinguishable. Bryant (1985) provides details of the development of this fertilised ovule to a mature embryo within dicotyledonous seeds. Typically in dicotyledons, the two-celled stage of the basal cell differentiates to form the suspensor. The suspensor is regarded not only important as an anchoring device for the embryo, but is also regarded as having an important role in the transfer of nutrients and plant growth regulators from the tissue to the embryo (Bryant, 1985 ; Singh *et al.*, 1980). Work on the suspensor in *T. majus* has been carried out by Picciarelli and Alpi (1987) and Singh *et al.* (1980) which has shown that the suspensor has three thread-like portions; one thread suspends the embryo in the endosperm cavity (suspending thread), one runs along the ovule and penetrates the carpel wall opposite the chalaza (haustorium thread) and the third grows through the integument and placenta to the point of entry of the vascular bundle to the raphe (placental haustorium).

Ultrastructural studies on the *Tropaeolum* suspensor indicate high synthetic activity of storage materials in the suspending thread, while the basal cells develop wall ingrowths which are suggestive of transfer of material from the fruit tissue (Nagl, 1976). Picciarelli and Alpi (1987) reported significantly higher amounts of auxin (IAA) and gibberellins in the suspensor than in the embryo of *T. majus* and Przybyllok and Nagl (1977) similarly showed the suspensor to contain significantly high amounts of IAA confirming earlier suggestions that the possible function of the suspensor were the nourishment of the embryo and control of its development.

Embryo development continues after the formation of the suspensor is complete. By the time the embryo contains about 50 cells, and is globular in shape (Globe stage), particular zones are committed to develop into particular organs and shortly afterward rudimentary forms of the organ themselves. This stage is known in dicotyledons as the 'Heart stage' where the heart shape is seen to be in two distinct lobes, the rudimentary cotyledons (Bryant, 1985). The dividing cells become organised into distinct meristematic regions, the epidermal and surrounding ground tissue become more distinct, the cotyledon cells taken on distinct features, often associated with deposition of reserves and the first stages of vascularisation occur. The rest of the changes occurring during embryogenesis are simply an enlargement and maturation of the embryo (Bryant, 1985).

3.2.2 Endosperm and cotyledon development

Whilst the fertilized egg cell is developing into an embryo, the triploid nucleus arising from the fusion of the two polar nuclei with one sperm nucleus starts to divide giving rise to the endosperm (Bryant, 1985). As the endosperm enlarges, it surrounds the growing embryo and acts as a source of nutrients. As the seed develops and embryo matures, the endosperm in dicotyledons such as legumes may degenerate and is filled by the expanding cotyledons (Bewley and Black, 1978). In such seeds, the cotyledons become the major storage organs. These are known as non-endospermic seeds.

As the cotyledon starts to expand, the deposition of reserves is initiated. Although there are some exceptions, such as the tiny dust-like seeds of orchid, most accumulate carbohydrates and/or lipids as a carbon source, together with proteins and minerals. eg. pea (*Pisum sativum*) - 56% starch, 24 protein, 6% lipid (Bewley and Black, 1978) soybean - 26% starch, 37 protein, 17 lipid (TeKrony *et al.*, 1979). Work with *Tropaeolum majus*, reported in Hoth *et al.* (1986) showed that mature nasturtium seeds contain protein, lipid and amyloid which contains glucose, xylose, galactose in the ration 3:2:1 as storage substance. Starch is formed during development but is not present in the mature seed. The storage materials sustain the germinating seedling until it can function independently. The general features of deposition of reserves are similar in different types of storage tissue, although obviously there are differences with regard to the actual composition of the reserves and the details of the timing of various events in the process (Bewley and Black, 1978 ; Bryant, 1985).

3.2.3 Whole seed development

The development of the seed is much more important as details of each tissue organisation are being put together in with time. This process can be easily followed by monitoring fresh and dry weight changes in developing seed and changes in viability of seeds during development. Seed is 'mature' when it has acquired its maximum dry weight, a point referred too as 'physiological maturity' the stage when the seed has also reached its maximum vigour potential (Coolbear, 1989). Food reserve accumulation is now complete. The term 'ripening' has been defined as the point when the seed has dried to a moisture content in equilibrium with the surrounding atmosphere (Hyde, 1950) or the point when the seed has dried to a moisture content suitable for harvest (Hill, 1971).

The course of seed development in almost every dicotyledonous flower crop (STC, 1986) follows a generally similar pattern of change in seed components to those described in grasses and legumes by Hyde (1959). Even though timing of these development stages varies between species and cultivar, generally all exhibit 3 main seed development stages (Coolbear, 1988 ; Win Pe, 1978).

1. The growth stage
2. The stage of food reserve accumulation
3. The ripening stage

The first stage follows pollination and is characterised by intense cell division, resulting in a rapid increase in both fresh and dry weight. During most of this time the growth rate of the ovule is logarithmic and is presumably determined by the rate of cell division in the embryo and the seed coat. This phase ceases when the cell number is fixed in various seed components. Throughout this first period the moisture content of the seed is high and constant and no viable seed is formed. The duration for this stage varies with species for example: 20 days in Maku lotus, 10 days in white clover and 22 days in lucerne (Hare and Lucas, 1978).

The second stage involves food reserve accumulation, the rate of growth being nearly uniform and presumably determined by the rate at which food reserve material can be transferred from the plant to the seed. During this period the dry matter in the seed increases approximately three-fold and reaches its maximum at the end of the stage. The actual amount of water in the seed declines slightly and fresh weight falls. Seed becomes viable at this stage ie. the embryo is sufficiently formed to be capable of growth but its chance of producing a healthy normal seedling would be extremely limited since food reserves in the endosperm are limited at this stage. The main feature of this phase is cell expansion, particularly the enlargement of cotyledonary cells due to the accumulation of macromolecules. Again, time duration after the first phase varies from 10 days for Maku lotus to 10-14 days in white clover and 17 days in lucerne (Kowithayakorn, 1978).

The third phase is the ripening stage, during which the embryo reaches full size, the deposition of reserves is completed and ripening or dehydration commences. The transport of water out of and away from what were fully turgid cells, is an active process which is nevertheless affected by environmental conditions, particularly atmospheric moisture content (Hyde *et al.*, 1959). The dehydrated seed is physiologically inert or quiescent. Its metabolic activity is extremely low, and no further transfer of materials from maternal tissue occurs. During this period the seed dries out rapidly and shrinks in size. The dry weight remains constant but the fresh weight falls to less than half as the seed moisture content declines. The seed is ready to be shed and the embryo is fully viable, although ability to germinate may be affected by seed dormancy. The time duration for this phase varies with species, for example 10 days in Maku lotus, 3-7 days in white clover and 35 days in lucerne.

Seed development is concerned with physiological and biochemical changes in the seed. These include changes in seed moisture content, seed fresh and dry weight, biochemical substances and germination capacity and viability (Hyde, 1950 ; Hyde *et al.*, 1959 ; Chow and Crowder, 1974 ; Win Pe, 1978 ; Kowithayakorn and Hill, 1982; Juntakool, 1983 ; Chanprasert, 1988 ; Miller, 1986 ; Matamoros, 1986 ; STC, 1986 ; Phetpradap, 1992).

3.2.3.1 Seed moisture content (SMC)

Workers have consistently reported a negative correlation between seed development stages and SMC. (Hyde (1950), Griffiths *et al.* (1967), Hill (1977), Juntakool (1983), Miller (1986), STC (1986), Chanprasert (1988)) for most ornamentals. In general, young seed in the early stages of seed development contains high seed moisture which decreases as seed advances towards maturity and continues during the ripening stage of development. Since SMC assessment is quite convenient this relationship between seed moisture content and seed development has become a method used by some farmers to determine seed maturity and best time to harvest seed crops (Hill, 1989). For example, Grabe (1956) suggested that at 47% SMC bromegrass seed was matured, and ready for harvest. The corresponding figure for white clover is 63%.

3.2.3.2 Seed weight

Seed fresh weight increases as seed age increases and reaches a maximum at the end of food accumulation stage. Subsequently fresh weight decreases as the seed loses moisture until it equilibrates with the relative humidity in the atmosphere when ripe (Hyde, 1950). However, seed dry weight is more useful in indicating seed maturity. Dry weight increases progressively after seed formation and reaches its maximum weight at 'physiological maturity' (Shaw and Loomis, 1950) or 'morphological maturity' (Anderson, 1955) and then remains constant. The time period from flowering to the attainment of maximum dry weight varies according to species, varieties and environmental conditions, particular temperature and rainfall ie. *Desmodium* 28 days (Chow and Crowder, 1974). Grasslands *Maku Lotus* 27 to 35 days (Hare and Lucas, 1984). China Aster 30 to 39 days (Phetpradap, 1992), *Campula medium* 21 days (Sumartini, 1986). *Viola cornuta* 10 to 14 days (Miller, 1986). *Zinnia elegans* 40 to 45 days (Janboonme, 1986).

3.2.3.3 Seed viability and germination capacity

Normally seed is not viable in the early stages of seed development (Hyde *et al.*, 1959). The seed becomes viable and can germinate at the beginning of the food reserve accumulation stage, the maximum viability of the seed being attained before the seed reaches its maximum dry weight (Hyde *et al.*, 1959 ; Kowithayakorn and Hill, 1982 ; Chanprasert, 1988 ; Witchwoot, 1987). The germination capacity in most legume seeds does not follow the seed viability curve since it drops before maximum viability is attained due to the development of hardseededness (Hyde *et al.*, 1959 ; Win Pe, 1978) or some post harvest dormancy (Boulton, 1986).

3.2.4 Effects of environmental factors during seed production on seed quality

During the reproductive phase of plant development the plant produces inflorescences, flowers, and pollination takes place, leading to the formation of seeds and fruits. The growth phase is largely determined by environmental factors. The weather the crop receives is a primary determinant of seed yield and quality. Usually environment is broadly divided into two main components, the aerial component which is the climatic conditions and the subterranean environment which is affected mainly by soil conditions. Good soils and ideal climatic conditions contribute to stability in production and high yield and quality of seeds are produced (Delouche, 1980). The effects of parental environment during seed development on seed quality have been reported for a wide range of species. Field evidence on the effect of different environmental condition during seed development comes from experiments in which plants of the same species have been sampled from different locations in the same growing season. To eliminate genetic differences as a cause of the observed variation of germinability, transplanting of material from one location to another was carried out. For example, Lacey (1984) showed that germinability (and viability) in *Daucus carota* populations declined as latitude increased. Dorne (1981) showed in *Chenopodium bonus-henricus* that germinability was negatively related to seed coat thickening and polyphenol content, both of which increased with altitude. Reciprocal transplanting confirmed that the effect was due to environment and not a local genetic difference.

3.2.4.1 Temperature

One of the most clear-cut influences on germinability of seeds is the temperature they experience during their development. With very few exceptions germinability is positively correlated with temperature during seed maturation. *Stellaria media* seed collected from the field throughout the year germinated more readily if matured in summer than it did if matured in winter. (Van der Vegte, 1978) and experiments under controlled conditions confirm this difference in behaviour to be due to the temperature during development. Chang and Struckmeyer (1976) reported the effects of seed temperature on seed development in onion. The optimum temperature for ovule and seed growth was about 35°C. Temperature in excess of this induced abortion of young seeds. For example at 43°C there was 66% seed abortion. Sofield *et al.* (1977) suggested that high temperatures in the field after anthesis of 15°C from 15/10°C to 30/25°C (day/night) imposed a major limitation on wheat yield through reduction of the duration of grain growth and grain size.

Thomas and Raper (1975) working with tobacco plants, proved that seeds produced from mother plants given high and day night temperatures (30/26°C) were slower to germinate and gave lower germination than those from plants grown at lower temperature (22/18°C). In addition, progeny of seeds produced at high temperatures were lower than those for seeds produced at low temperatures.

In some species, temperature during ripening can affect the degree or duration of post harvest dormancy. Grant Lipp and Ballard (1963) showed in *Anagallis arvensis* which requires light for germination at 25°C that seed ripened at 20/15°C (day and night temperature respectively) was almost completely dormant for 10 weeks after harvest. Seed ripened at 25/20°C showed much less dormancy, while those ripened at 30/25°C showed none. The reduction of dormancy brought about by warmer conditions during seed maturation is a very general phenomenon seen in a wide range of often unrelated species, for example *Dactylis glomerata* (Probert *et al.*, 1985).

In peas, the most distinctive effects of night and day temperatures on the growth and composition of seeds, occurs mainly in relation to sugar content. Work by Robertson *et al.* (1961) showed that at a low temperature of 10 °C, the conversion of sugar to starch is much delayed and sugar continues to increase in concentration during growth. At a higher temperature of 23 °C, the sugar entering the seed is rapidly converted to starch: thus the carbohydrate composition of seeds grown at different temperatures is markedly different. Protein synthesis is also delayed at lower temperatures and water uptake ad rate of drying out of seeds are also affected. So at low temperatures, peas are sweeter and have a higher sugar content than those grown at higher day temperatures. Higher temperatures, however, may have deleterious effects on the development of pea seeds.

Temperature can also affect the ABA content of the seed during development. Goldbach and Michael (1976) found in barley grains, ABA reached an earlier maximum followed by a sharper decline in plants matured at 26 °C compared with those at 18 °C, but it is not known if this affected germination of matured seed.

In some cases where dormancy is imposed by a hard seed coat, the ambient temperature during maturation can determine the thickness of the coat, which in turn affects germinability. For example, in *Stylosanthes hamata* the level of hardseededness has been found to be positively related to temperature during seed formation by Argel and Humphreys (1983a). Also, germinability is reduced by higher temperature in soybean (*Glycine max*) as reported by Keigley and Mullen (1986) possibly for the same reason. Thus it is apparent that the temperature regime given to parent plants both before, during and after the reproductive phase can have considerable effects on flowering, seed set, germination and vigour.

3.2.4.2 Light

The most important aspect of the light environment of a parent plant which influences germinability during seed development is day length. Much work has been done and reported in the literature on photoperiodic effects on subsequent germination. In the majority of cases, germinability is promoted by short-day regimes, while dormancy increases with increasing day length. eg. *Amaranthus retroflexus* (Kigel *et al.*, 1979).

In some cases it is clear that coat thickening is the critical characteristic affected by day length, long days promoting thick harder coats which reduce germinability; Gutterman and Heydecker (1973) showed this for *Ononis sicula*. Previous work by Lorna (1947) found that in *Chenopodium amaranticolor* the photoperiod in which seeds mature on the parent plant influenced the subsequent germination of the seed. When matured in long days the seeds had much thicker seed coats than those ripened in short days. Although seeds with thick coats could imbibe water readily when put to germinate a proportion of the embryos were unable to rupture the abnormally thick coat.

3.2.4.3 Rainfall and moisture

The effects of moisture during seed development on subsequent germinability and quality of seeds is critical. Heavy and prolonged rain at end of the flowering period in peas is detrimental because it encourages leaves to stick to young pods and become colonized by *Botrytis* which reduces yield and quality (Gane *et al.*, 1975). Moisture has a deleterious effect on pea seeds during harvest. Seeds harvested after periods of heavy rain appear to have reduced viability and increased mortality in soil (Matthews, 1973). Moisture stress situations resulting from severe drought can have similarly disastrous effects, especially during the seed development period, because it interrupts seed development and results in light, shrivelled seed (Delouche, 1980). The pea is very sensitive to moisture stress at both flowering and pod filling but it will also not tolerate water logging. Laohasiriwong (1982) observed in soybeans that water stress from the start of anthesis through to the beginning of seed maturity severely reduced yield by decreasing the number of pods per plant and slightly decreasing seed weight. Momen *et al.* (1979) found that the greatest seed yield reduction in soybean was due to moisture stress occurred during pod filling. Yield losses of 50% have been reported in field grown soybean at 10% available soil water (Doss *et al.*, 1974). Drought usually increases seed coat thickening, reducing seed permeability and hence reducing germinability. For example, in soybeans, Hill *et al.* (1986) found that seeds from drought-stressed plants were 15-33% smaller in weight, had a higher percentage of seed weight in the seed coat and had 6-37% more impermeable seeds after 72 hours of soaking.

3.2.4.4 Nutrients

The subterranean environment mainly involves soil conditions in terms of type, fertility level, and nutrient status. Plants have evolved a remarkable capacity to adjust seed production to the resources available. The typical response of plants to low soil fertility is reduction in the quantity of seed produced rather than in quality. Although the broad brush statements above are generally valid there are exceptions. Rather few studies have been carried out on the effect of parent plant nutrition on seed germinability. High nitrogen levels are reported to promote germination in tomato. *Lycopersicum esculentum* (Varis and George, 1985), *Festuca arundinacea* and peanuts (Coffelt and Hallock, 1986). Harrington (1960) found that severe potash (K) deficiency in plants of *Capsicum frutescence* gave a high proportion of abnormal seeds and seeds tended to sprout in the fruit. K may be necessary for the formation of a germination inhibition, possibly ABA in this species.

3.2.4.5 Weathering: postmaturation - preharvest environment

Following seed maturation the seed continues to dry down until it reaches maturity ie. the moisture content at which they can be effectively threshed mechanically. Climatic conditions during this post maturation, preharvest period have a great influence on the quality of the seed harvested (Delouche, 1980). Seed deterioration during the post maturation, preharvest period is a serious seed production problem (Delouche, 1980). Frequent rainfall combined with high temperature, results in a rapid losses of viability and vigour of seed in standing crops. In cotton, a negative correlation exists between the viability of cotton seeds and the amount of rain during the exposure period. For example one week exposure caused 30% reduction in viability. Delayed harvest of soybean seed caused by inclement weather results in a reduction in viability and an increase in mechanical damage during harvest (Delouche, 1980). The incidence of severity of fungal invasion of seed is also increased by weathering resulting in reduced seed quality.

The environment has considerable influence on the development and quality of seeds. In agriculture and horticulture, a knowledge of how environmental factors affect seed quality is clearly of considerable value in producing high quality seeds with appropriate germination characteristics. However, there are again various practical limitations to the production of seeds with ideal properties. Certain factors are much more readily controlled that others in the field. While growers can easily manipulate nutrient levels and water supply they can do little about controlling temperature and day length. In the more controlled conditions under in which some high-value seeds for horticultural purposes are produced, environmental manipulation may be more feasible.

3.3 OBJECTIVES

The aim of this experiment was to study the seed development sequence of *T. majus*, to provide an understanding of the production components and to use these to monitor suitable time for harvesting to achieve maximum yield and quality seed.

3.4 MATERIALS AND METHODS

The seed development study was conducted during the summer of 1992 on an area adjacent to the Seed Technology Centre, Massey University. The trial site was originally prepared for the plant density trial, and the seed development study was carried out using one of the 4 densities used in the previous trial. ie. 45cm x 45cm spacing (5 pl/m^2). In each of five replicates, 800 individual fully open flowers were tagged using coloured wires at peak flowering. Thereafter, at 10 day intervals, 80 flower heads were randomly sampled from each replicate. The following assessments were made:

a. count of the total number of seeds to calculate the number of seeds per flower

b. random selection of 100 seeds for fresh and dry weight determination and calculation of seed moisture content

c. random selection of 100 seeds for air drying at room temperature and germination and viability tests

d. Thirty seeds for Tetrazolium test.

Seed moisture content determination using two replicates of 50 whole seeds each which were weighed and then dried in an oven at 103°C for 17 hours. After cooling seeds were reweighed and the moisture content calculated as recommended by ISTA (1985).

$$\frac{M_1 \text{ x } M_2}{M_1} \quad \text{x} \quad 100 \qquad \begin{array}{l} M_1 \text{ - weight before drying} \\ M_2 \text{ - weight after drying} \end{array}$$

The weight before and after drying was also used to determine fresh weight and dry weight per 100 seeds.

Germination was assessed on air dried seeds at room temperature using the rolled paper method and temperature of 20-30°C in dark conditions as recommended by ISTA (1985). After 75 days from anthesis, seeds being predried to a moisture content of less than 20%. Each two replicates were assessed with a first count 4-7 days and a final count at 21 days. At the final count categories of normal seedlings, abnormal seedlings, fresh ungerminated seeds and dead seeds were made. Total viability of germination was the sum of the normal, abnormal seedlings and fresh ungerminated seeds.

To assess viability of different stages of seed development using the Tetrazolium test 15 seeds in each two replicates were imbibed overnight, cut through the hilum leaving two equal halves and soaked in TZ solution (0.5%) for 4-6 hours. The red-pink staining of cut seeds resulting from the topographical Tetrazolium test was used to determine viability of seed. The intensity of the stain provided a good indication of viability. Immature and non viable tended to absorb TZ solution readily and were therefore more heavily staining.

3.5 RESULTS

3.5.1 Changes in seed components

The means value of changes in seed fresh and dry weight, moisture content, germination capacity and viability of *Tropaeolum majus* seed at various stages of development is summarised in Appendix 3.1, and the graphs in Figures 3.1 and 3.2.

3.5.1.1 Seed fresh weight

As shown in Figure 3.1 changes in seed fresh weight per 100 seeds in the first 10 days of development rose quickly to 26.8 grams (40% of maximum weight). Fresh weight increased markedly in the next 20 days reaching 49.8 grams (75% of maximum weight) at 30 days after pollination. From observation in the field seeds start to shed at this stage. Maximum fresh weight of 66.4 grams was reached 40 DAP. A slight decrease in FW occurred by 50 DAP where about 90% of seeds have been shed, until at 60 DAP only shed seeds were present, which continued to dry down on ground to 60.1%.

3.5.1.2 Seed dry weight

The dry weight changes in seed during development are shown in Figure 3.2 follow a similar trend to seed fresh weight. The dry weight of 100 seeds 10 days after pollination (3.06 grams) was only about 21% of its maximum weight. However DW increased steadily reaching a peak at 'physiological maturity' around 40-50 days after pollination of about 45 grams. During this period the dry weight of 100 seeds increased more than 4 times. There was no subsequent differences in seed DW through to 60 DAP.

3.5.1.3 Seed moisture content

The moisture content of the seed was expressed as moisture content percentage on a wet weight basis and was relatively high in the early stages of seed development at about 88.6% in the first 10 days. Slight decreases occurred as seed maturity progressed. However even at seed moisture content was still high (75.5%). This is an interesting feature of Nasturtium seed in that seeds mature and shed at a very high moisture content. At 50 days after anthesis for example, about 95% of seed had shed but the corresponding SMC was 77.8%.

3.5.1.4 Germination

Germination capacity may be expressed as the ability of seed to germinate when placed in optimum conditions of moisture, temperature and aeration producing normal seedlings. The results of germination tests of seeds collected at different stages of development after being air dried at room temperature to a SMC of 13-17% are shown in Figure 3.2 and Appendix 3.2. During the 21 day laboratory germination period, no germination was recorded in the seed samples harvested 10 days after pollination. Germination capacity was first attained 20 days after pollination but a total value of less than 5%. However by 30 DAP, germination was maximal with 64% normal seedlings. Another interesting feature (Figure 3.2) was that even before physiological maturity ie. maximum dry weight, germination was drastically reduced by 40 DAP and approached 0% at 50 and 60 DAP respectively because of dormancy resulting in a corresponding increase in fresh ungerminated seeds.

3.5.1.5 Viability

The viability results obtained from a Tetrazolium test (TZ) and also total viability calculated from the germination test are presented in Figure 3.2. The interpretation of viable seed from TZ test was carried out according to ISTA rules (1985) and the total viability figure of seed from the germination test included the sum of normal seedlings, abnormal seedlings and fresh ungerminated seeds. The TZ test showed that 15% of seeds were viable by 20 days after pollination and viability rose sharply to 82% after 30 days reaching maximum viability at 40-50 days. Viability, calculated from laboratory germination test results showed; 8% viable seeds in the first 20 days and then a gradual increase to a maximum of 90% at 40 days after pollination.

Viable seeds were first detected at 20 DAP, when seed dry weight was about 43% of its maximum value and moisture content was 84.7%. These viable seeds appeared as abnormal seedlings which could not be classed as seeds of agronomic value. However, total viability the rose rapidly to about 90% when seed reached maturity about 40 days after pollination.

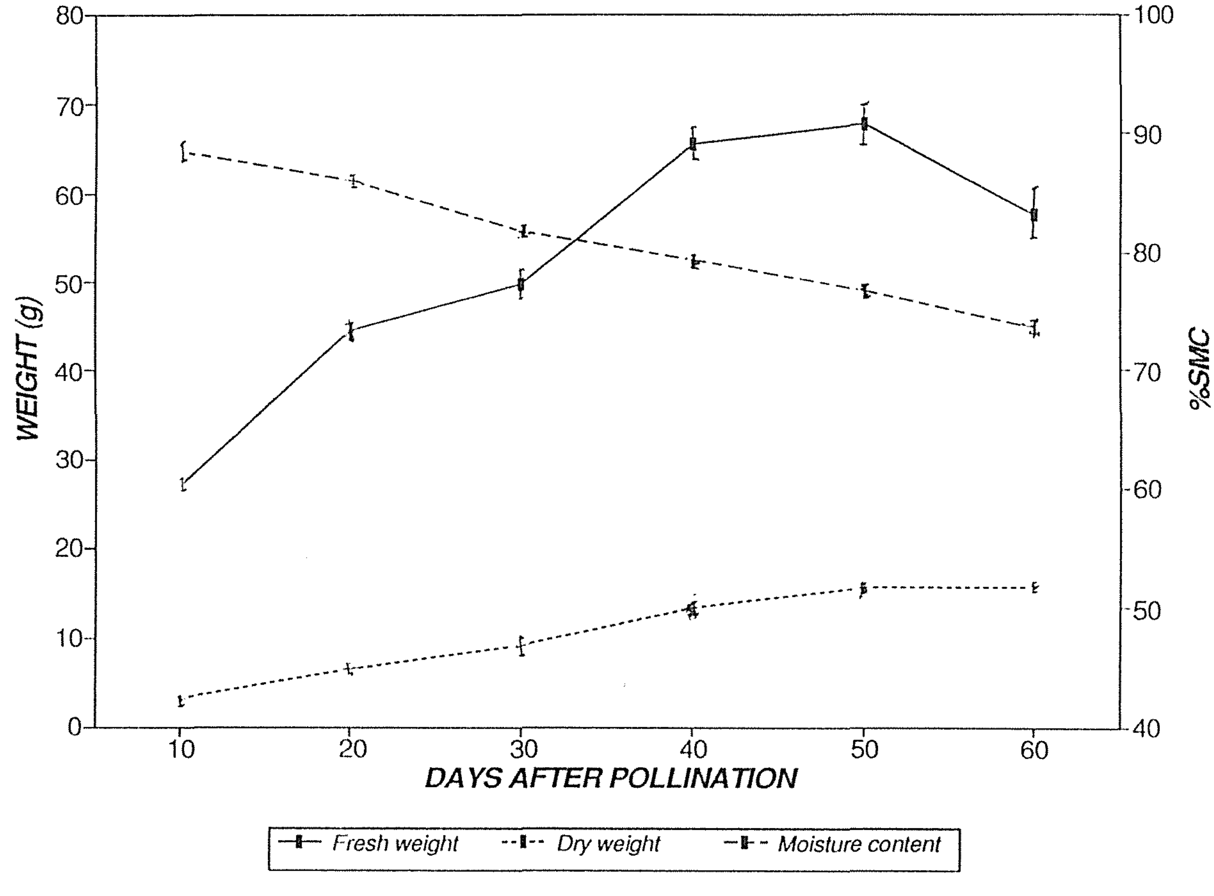


Figure 3.1 Changes in seed fresh and dry weight and seed moisture content with time in *Tropaeolum majus* cv. Choice Mixed. Vertical bars represent SE of the mean.

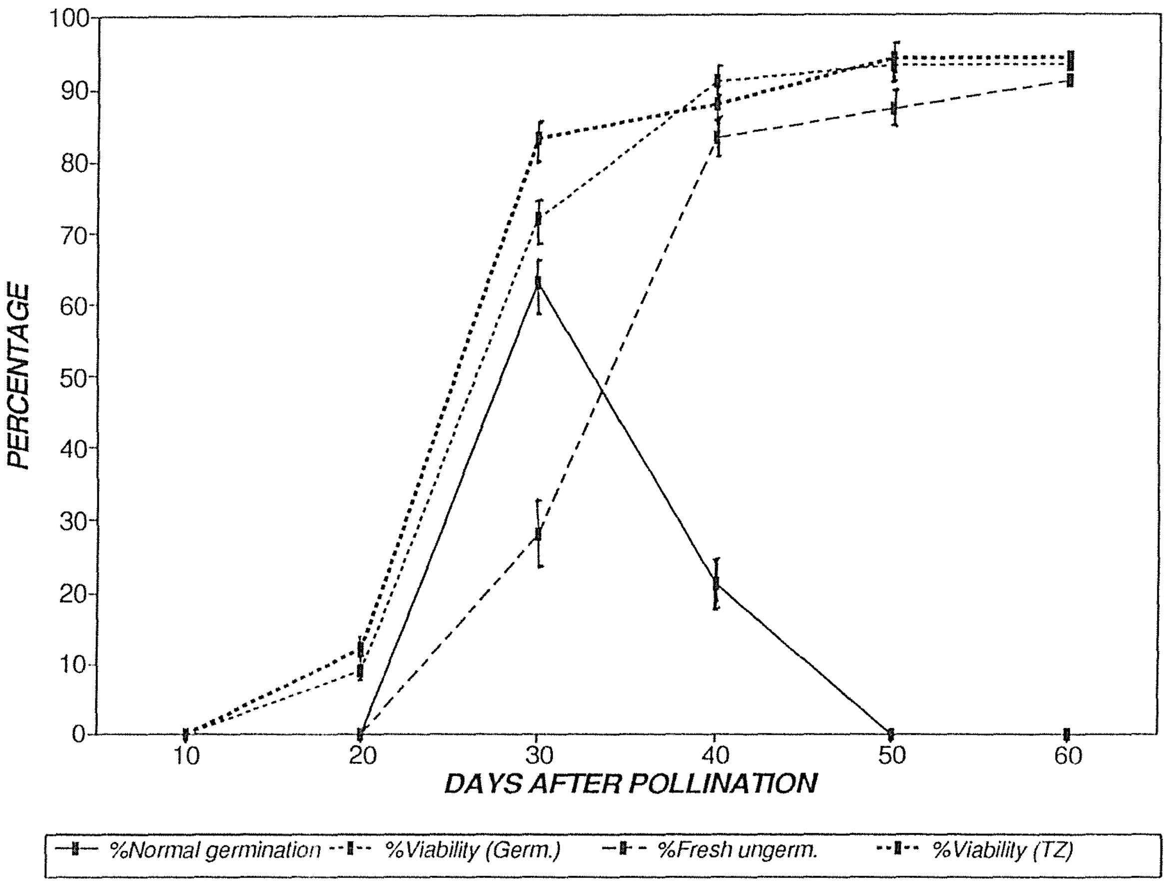


Figure 3.2 Changes in seed germination and viability with time in *Tropaeolum majus* cv. Choice Mixed. Vertical bars represent SE of the mean.

3.6 DISCUSSION

The changes in seed weight of *Tropaeolum majus* during seed development shown in Figure 3.1 follows two of the three main distinct phases typical in many legumes and grasses described in Hyde (1950) and Hyde *et al.* (1959).

In nasturtium, the growth stage refers to the period of seed development during the first 10-15 days after pollination. However at the first sampling 10 days after anthesis, a marked increase in seed size was observed and seed weight increased rapidly, seeds having achieved 40% of their total dry weight. This is presumably due to cell multiplication in both the embryo and cotyledons, confirming the statement made by Hyde (1950). Early in this stage of development the seed has a very high moisture content (88-89%) does not exhibit any viability or germination. This supports the work by Hyde (1950) and Hyde *et al.* (1959) in legumes who also showed that seeds at this stage were not viable. The growth of seed at the first 10-20 days after pollination is very rapid and seeds increase in size dramatically. However at this early stage they may not contain sufficient food reserves to assist germination. The low germination percentage of immature seeds at 20 days after pollination was due to a high proportion of abnormal seedlings.

A more gradual increase in seed weight occurred up to 40 days after pollination, where maximum dry and fresh weight occurs. This is the food reserve accumulation phase as termed by Hyde (1950). Maximum seed dry weight was first reached 40 days after pollination and at this point seed was considered to have reached physiologically maturity. This supports the work on nasturtium reported in Hoth *et al.* (1986), that accumulation of starch and amyloid begin 15 to 20 days after anthesis and continue until the 33rd and 45th day when further seed development as shown by no further weight increases. Starch is not present in mature seeds, only amyloid being the main storage material. Earlier Boulton (1986) had suggested that seed maturity was attained and seed starts shedding 31 days from pollination at a moisture content of 78%. This is earlier than in the present study, a difference which may be due to a difference in cultivar, experimental design and different environmental conditions.

Total viability of seed increased rapidly from 20-30 days and more slowly to a maximum viability at 40 days. A high level of seed viability had been attained a few days before seed maturity as in Figure 3.2. The amount of seed viability is thought to be associated with the level of food reserve material in the seed. Viable seed results obtain from TZ test are slightly higher than the values obtained from the laboratory germination test at only early stages but similar at seed maturity. Then results agree with Hill and Watkin (1975) who also found a good relationship between the Tetrazolium test and germination results.

A major feature of this development pattern is the very high moisture content of the seed when it is mature (about 78%) and seed starts to shed at 40-50 days. From observation, less than 50% of seeds were shed at 40 days after anthesis but more than 90% of seed had shed at 50 days. The strong windy climate typical of the Manawatu during the sampling period (Appendix 2.3), the position of the developing seed heads where exposed seeds would be more susceptible to earlier shedding than well sheltered seed heads under the plant canopy may be involved in determining shedding pattern. Since most seeds are shed after maturity the seed ripening process occurs on the ground depending on time of harvest. At 60 days after anthesis, seeds are still at the ripening stage, and are shed on the ground with a slight decrease in FW and slowly reduction in seed moisture depending on air temperature and soil surface moisture. Shed seeds on the ground surface are well shaded from sun, and protected from the sunlight by the plant canopy which not only increases the humidity under the canopy but moisture from the soil surface causes a very slow drying process of seeds. The germination test results during and after seed maturity showed a rapid decrease in normal germination from maximum at 30 days of 64% to less than 10% at 60 days after anthesis. In contrast, viability is at a maximum but fresh ungerminated seeds levels are also high. This agrees with work by Boulton (1986) who suggested that rather erratic germination results are due to postharvest dormancy, indicating a physiological block to germination induced in the seed from the parent plant, and which acts as a natural survival method for the seed. It is well known that seeds of many species require a short period of dry storage after ripening (Crocker and Barton, 1953 ; Cathey, 1975 ; Hess, 1975 ; Villiers, 1974). This is likely to be the situation in the present study, but need further evidence through research to confirm this.

CHAPTER 4

HERBICIDE TRIAL

4.1 INTRODUCTION

Weeds are always present and often reduce yields substantially in flower and vegetable seed crop production, so weed control must be highly efficient to maximise seed yield and quality. Unfortunately in *Tropaeolum majus*, the main weed control method is by hand weeding or cultural control because no specific herbicides are recommended. In New Zealand *Tropaeolum majus* is sometimes considered to be a weed, and Matthews (1975) recommended MCPA and 2,4-D for controlling garden nasturtium. But from a crop point of view there is a need for some selective chemicals for controlling weeds in *T. majus*.

Herbicides are particularly effective in the establishment of direct sown crops (Kinsella, 1978) and can also provide good weed control in transplanted annuals (Fretz, 1976). Since no specific herbicidal recommendations are available for *T. majus* crops, the purpose of this study was conducted to evaluate and assess the tolerance of nasturtium to a wide range of post-emergence and pre-emergence herbicides commonly used in ornamental flower, vegetable and various seed crops for selective weed control.

4.2 REVIEW OF WEED COMPETITION

4.2.1 Weeds

Weeds are familiar objects; yet they are not always easy to define. All definitions of weeds are predicated on the relationship of the plant to the activities or desires of mankind. Thus the common definition of a weed is a plant out of place (Crafts, 1975), any plant growing where it is not wanted (Anderson, 1977), a category of plants as opposed to crops (Numata, 1982) or an undesirable plant or a plant which negatively affects the growth of a crop plant (Popay, 1990). If an unsown plant is increasing the economic yield of a crop, then it can no longer be considered a weed. Weeds are thought to adversely affect crops in the following ways:

- by competing for water, light, nutrients or space during establishment, and in established crops
- by attracting insects pests which also affect crops
- by producing allelo chemicals which reduce crop growth
- by acting as alternative hosts to crop pathogens and disease
- by interfering with harvesting machinery; handling and quality
- by increasing the costs of production by, for example, delaying drying of grain (Popay, 1990) (Lawson, 1974).

Weeds have been called the most important and persistence of all crop pests (Rhoads *et al.*, 1989 ; Agamalian, 1987). Considerable reduction in crop yield can result from interference between weeds and crops for water, soil nutrients, space and light (California Weed Conference, 1989). When the supply of any or all of these essentials is not adequate for the optimum growth of the crop and weed, interference or competition occurs (Holzner and Numata, 1982). Considerable variations exists among species of crops and weeds in their competitive ability (Glauninger and Holzner, 1982). In strong plant competition either crop or weed retards the growth of other plants growing in association with it. This review will concentrate on the competitive effects of weeds of cultivated land (agrestals) which are mainly of greatest concern in agricultural and horticultural crops.

4.2.2 Competition

Competition between plants precedes recorded history and existed long before a defined term was assigned to it. Two of the earliest known references concerning effects of weed competition appear in ancient religious writings (Bible, Genesis 3 : 17-18): 'Cursed is the ground for thy sake; in sorrow shalt thou eat the herb of the field'. And in the Parable of the Sower, Matthew 13 : 7 notes that 'some fell among thorns which sprang up, and choked them' (Zimdahl, 1980 ; McGlamery, 1982). The term competition has been widely used in various horticultural situations. Donald (1963) defined competition as a phenomenon which occurs when two or more organisms seek the measure they require of any particular factor or thing, and when the immediate supply of the particular factor or thing is below the combined demand of the organisms. This definition is widely accepted among plant ecologists (Hill and Shimamoto, 1973).

Weeds as a group have much the same requirements for growth as crop plants (Crafts, 1975). Weeds compete with ornamentals for nutrients, water and light resulting in slower growth, reduced yield and poor quality plants (Spitters and Van Den Bergh, 1982). Typical experiments investigating competition are those in which the competitive power of the crop against weeds are studied by varying sowing density of the crop (Fogelfors, 1972 ; Williams *et al.*, 1973 ; Rogers *et al.*, 1976 ; Dawson, 1977). Generally crops sown at high density have an advantage compared to those with large sowing or planting distance. Glauninger and Holzner (1982) suggested that competition for space is just another expression for the combined and hidden effect of competition for light, water and nutrients.

Weeds compete with crops for light by faster and taller growth, large leaves and climbing devices (Fogelfors, 1972). So, weed species showing strong development in one of these strategies can be considered as strong competitors for that factor to the crop. A contrasting strategy is displayed by smaller or procumbent growing weed species such as *Stellaria media* which show optimal photosynthesis when not in full sunlight. Holm *et al.* (1977) showed in *Anagallis arvensis* that optimal growth occurred in 50% sunlight at early growth stages. Naturally, competition for light begins at the moment when plants begin to shade each other. Vorob'ev (1974) described comparisons between effects of shading alone and competition between weeds and crops with the result that the major losses of the inferior partner in competition could be attributed to competition for light. For crops, early vigorous growth, height and density are important for their success in competition with weeds. Wimschneider and Bachthaler (1979) investigated the effect of shading on two morphologically different varieties of spring wheat by *Avena fatua*. A weed density of 160 pl/m^2 reduced the light intensity to 16-37% and harvest yield to 15-25%. A cultivar with longer culms and more horizontal leaves was less affected than one with opposite features.

With competition for nutrients, crops may suffer severely especially for nitrogen, which cannot be supplemented as fast as it is taken up by 'greedy' fast growing weeds (Glauninger and Holzner, 1982). Many weed species show about the same rate of development as the crop and therefore about the same course of nutrient requirement. For example, perennial species such as *Agropyron repens* in maize show early and greedy uptake of nutrients due to their already well-developed subterranean stem and may thus easily develop ahead of annual crops (Hill, 1977). General remarks that certain weed species compete with ornamental crops for water and nutrients are commonly found in the literature but few quantitative studies have been conducted. Glauninger and Holzner (1982) estimated that a plant of *Avena fatua* transpires four times more water than cereals. Competition for water is very important in arid climates and during temporary drought in humid areas where water becomes a limiting factor for growth. This was illustrated by the experiments of Mohammed and Sweet (1978) showing that tomatoes are particularly affected by weed competition when they are grown under dry conditions. The prolific growth of weeds especially perennials such as *Cyperus rotundus* can severely limit the availability of water to sugarcane (Holm *et al.*, 1977).

4.2.3 Effects of weed-crop competition

The effect of competition for these growth factors are most important in vegetable and flower seed production and many reports of research have been carried out for a wide range of ornamental and agronomic crops. An important aspect for weed control is the critical period of weed interference which refers to the minimum amount of time during which a crop must be kept free of weeds in order to prevent yield loss (Nieto *et al.*, 1968). This period has been used to optimize the timing of weed control practice (Roberts, 1976 ; Dawson, 1977 ; Friesen, 1979 ; Weaver, 1984 ; Weaver and Tan, 1986). Weeds present before or after this time interval generally do not affect yields. For example, the critical period of weed interference has been studied in transplanting tomatoes (Friesen, 1979 ; Weaver and Tan, 1983). Yield losses in transplant tomatoes can be minimised by preventing weed emergence for at least 5 weeks after planting. Weaver (1984) reported longer critical periods for tomatoes grown from seeds and reductions in seed yield were correlated with weed dry weights. In reality a number of weed species occur in a crop and the time of weed removal is important. For example, *Xanthium strumarium* adversely affects cotton seed yield if allowed to compete for more than 2 to 4 weeks (Snipes *et al.*, 1987). In soybeans Harris and Ritter (1987) found that smooth witchgrass (*Panicum dichotomiflorum*) need not be removed until 8 to 12 weeks after crop emergence. In another study (Curran *et al.*, 1987) wild oats (*Avena fatua*) were shown not to affect yield of lentils if left to compete with the crop for up to 5 weeks. However, if they remained for 7 weeks, crop yield was reduced about 50%. A further complication is whether the crop is transplanted or direct seeded. For example Weaver and Tan (1986) have reported that direct seeded tomatoes are reduced in yield by 80 to 90% by nightshade (*Solanum spp.*) at a density of $8m^{-2}$ whilst if transplanted the reduction is only 20 to 30%. In ornamental crops such competition has been reported to cause between 47% to 75% loss, depending on weed species and density (Fretz, 1973). Weeds in cut flower crops are also troublesome, particularly in those crops grown under field conditions, since they tend to be more susceptible to weed infestation which is not as easily controlled as it is for cut flower crops produced in a glasshouse (Watkins, 1986). Weed competition has resulted in yield and flower panicle quality reduction in statice (Hatterman *et al.*, 1987); unattractive and displeasing bedding plant displays or landscapes (Costello and Elmore, 1987) and seed yield reduction in sunflower (Johnson, 1971).

Competition between crop plants and weeds is a critical factor in growing seed crops or ornamentals. If crop plants occupy the soil and are vigorous, weeds are excluded or retarded in their growth. On the other hand if a crop lacks vigour, weeds will flourish (Swarbick, 1976). Individual crop plants may compete with each other or they may compete with weeds. The keenest competition usually occurs when the individuals competing are most alike in their vegetative habit, method of reproduction, and demands upon the environment. For example, in small cereal crops the weeds that furnish the greatest competition are such annuals as wild oats, mustard and pennycress, the seeds of which germinate at about the same time as those of cereals; thus their top growth and root system develops simultaneously with those of the cereals, coming into immediate competition with them (Crafts, 1975). A review of weed competition literature indicates that increasing weed density decreases yield. Weed competition can thus be represented by a schematic sigmoidal relationship. A few weeds usually do not affect crop yield; also, the maximum effect, total crop loss, obviously cannot be exceeded and usually occurs at less than maximum density. The effects of weed competition varies with crop type and at different stages of growth. Such effects in field vegetables and a few ornamentals have been examined using a variety of methods (Zimdahl, 1980). Most of these experiments have been designed to measure the direct and indirect effects of weeds on vegetable and ornamental crops, or the stages of development and times of the year at which crops are particularly vulnerable.

The relationship between density of a weed and crop loss is species, so that a competition index can be applied for each species. The relationship between crop yield or weed density may be affected by environmental conditions (Chisaka, 1977), time of sowing (Reeves, 1976), crop density (Medd *et al.*, 1985), and other agronomic factors (Dew, 1972 ; Medd *et al.*, 1985). Most estimates of the effects of weeds on crop yield are based on relationships between weed density and final crop yield and density (Dew, 1972 ; Reeves, 1976 ; Chisaka, 1977 ; Scragg, 1980 ; O'Sullivan *et* *al.*, 1982 ; Snaydon, 1982 ; Svensson, 1982 ; Marra and Carlson, 1983; Medd *et al.*, 1985). These can be used to derive crop loss functions and to estimate the production or yield increase to be expected from treating weeds in a crop. The most common types of relationships between crop yield and weed density are shown in Figure 4.1.

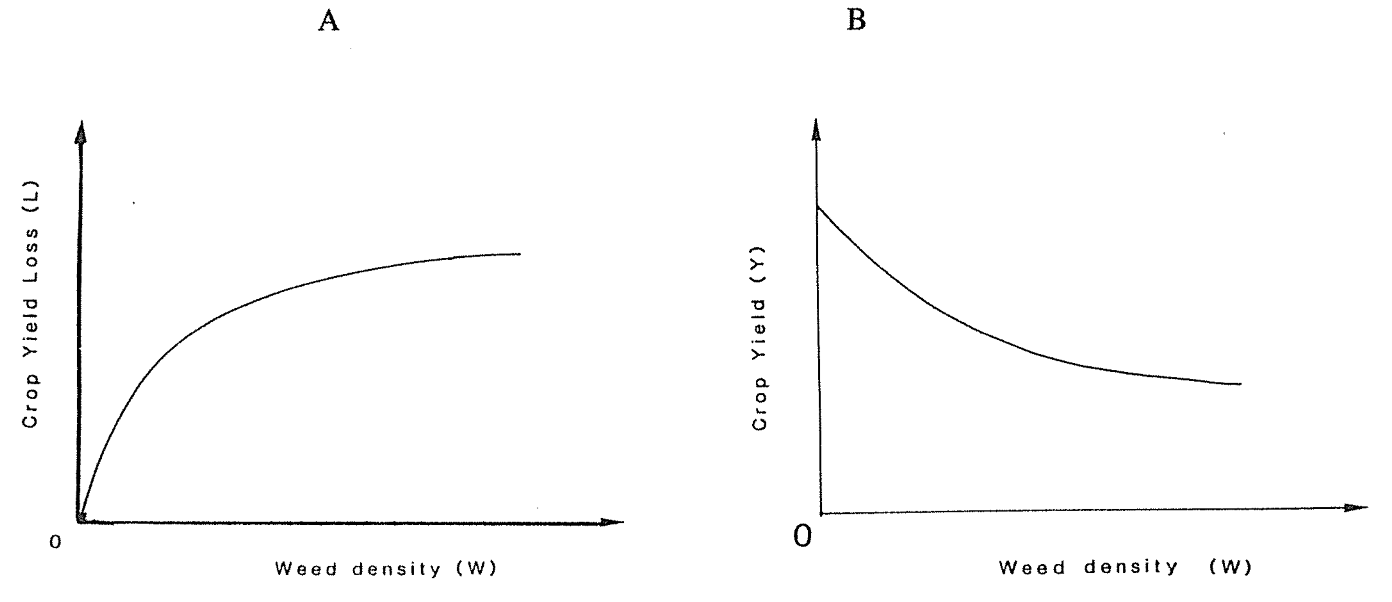


Figure 4.1 The relationship between weed density and (A) crop yield loss (after Zimdahl, 1980), and (B) crop yield (after Cousen *et al.*, 1984).

Zimdahl (1980) proposed the Graph A relationship, ie. yield falls at a decreasing rate with increased weed density. This senario was later modified by Cousen *et al.* (1984) Graph B as for the majority of weed crop interactions studied so far, the reduction in a crop yield increases at a decreasing rate as the density of weeds increases.

4.2.3.1 Effects of weed competition during crop establishment

The most critical period of weed competition in most vegetable and flower crops, is during the establishment phase (Zimdahl, 1980). Effects of different levels and durations of weediness in newly-planted raspberries are reported by Lawson and Wiseman (1976). Competition from dense infestations of annual weeds in late spring and early summer resulted in up to 70% loss of planting material and severe reduction in the number of canes produced, which resulted in 50% less fruit being picked. Published reports from Wood *et al.* (1960), Lawson (1971), Turguand (1962, 1964, 1966) and Briggs (1972) on narcissus and tulip showed that the direct effects of weeds are not only on the yield of bulbs but also on their size and distribution. The effects carry over into the successive seasons and tend to affect flower production.

Field and Sum (1985) showed that fodder beet, which is typically a slow establishing plant, is susceptible to weed invasion during early crop establishment. It was necessary for the initial 8-10 week period after crop sowing to be weed-free for high beet yield. Onions also exhibit greater susceptibility to weed competition than most other crops. Without a clean seed bed and effective weed control, onion yields shrinks nearly to zero. Because of onion's slow germination and early growth, and the absence of a dense foliage, initial competition tends to be severe (Hewson and Roberts, 1971). Early weeding always produces the highest yields. Weeds, even if present for only 2 weeks following crop emergence, can thwart crop growth (Wicks *et al.*, 1973). Other studies have shown that crops require freedom from weeds for the first third of the growing season (Palmbald, 1968). Fageiry (1991) suggested that in sunflower, early weeding 4 weeks after emergence was essential for a good oil yield; yield losses due to weed competition were large (50%-70%) for uncontrolled plots. Oil percentage was maintained at the higher yield levels obtained with weeding. Poorly weeded crops flowered later than well weeded crops. In contrast Agamalian (1981) suggested that with certain crops of non-determinate growth habit, early weed competition may not influence ultimate yield. For example, members of the cucurbit family appear to be less susceptible to early weed competition.

4.2.3.2 Effects of weed competition during vegetative growth development

Most plants are plastic in their response to competition. Thus one wheat (or wild oat, or fathen) plant grown completely on its own could be very large, with many tillers or branches and a very high seed yield. The same plant grown in a very dense crop could have one tiller and one seedhead. In general, weeds exercise their effects by reducing the vegetative growth of the crop plants. This in turn affects the yield of the crop.

Some weeds have an allelopathic effect on crop plants by synthesizing and releasing toxic or inhibitory substances that interfere with germination of crop seeds or subsequently retard growth of plants (Rhoads *et al.*, 1989). Patterson (1982) in Rhoads *et al.* (1989) stated that allelopathy is clearly related to competition because competition induced stress may increase the production of allelopathic substances, and growth inhibition caused by allelopathy may reduce the competitive ability of the affected plant. Meissner *et al.* (1980) comment on the effects of nutgrass (*Cyperus rotundus* L.), which causes severe crop losses in tropical and sub tropical countries. In vegetables and flowers they compete with crops for the available nutrients, water and light. In infestated land, the germination of seed may be affected and seedling growth is often reduced. Also, the leaves turn light green in colour in spite of adequate fertilization and the crop plants wilt easily although the soil is moist. It was also confirmed in this study that biologically active substances produced by the growing subterranean parts of nutgrass and released into the soil, have indeed a marked effect on shoots and root growth, water economy, seedling survival, radicle elongation and vegetative reproduction of other plants.

Roberts *et al.* (1977) also showed in lettuce, that natural infestation of 65 to 315 weeds/m^2 caused almost or complete loss of yield. Initially weeds reduced the number of marketable heads with firm hearts; more severe competition, depressed marketable weight and often caused total crop loss. Plants primarily competed for light as evidenced by stem elongation, chlorosis, and reduced leaf production. Lawson and Wiseman (1976) showed that dense weed growth after 3 months reduced raspberry cane growth and caused mortality. In strawberries they showed that weed competition severely limited stolon growth and later completely eliminated such growth. Stolon and runner production suffered most from weeds. Weeds primarily cause reduced bulb size in onions, though they also depress photosynthetic capacity, leaf blade production, and number of leaves (Hewson and Roberts, 1973). No new leaves develop after bulbing, and the number and size of leaves present at that time determines eventual bulb size.

4.2.3.3 Effects of Weed Competition During Flowering and Seed Development

Weed competition also affects reproductive development during flowering and seed development. It is at this stage that weed competition effects are carried over from establishment thus affecting yield in fruit, cut flower or seed crop. Much research has been done which shows that deficiencies of light, nutrients and moisture during flowering causes reduced flowering capacity by increasing flower abortion and reducing the number of flowers. Hicks *et al.* (1969) found that light penetration within soybean canopies influences yield. Severe weed growth creates a canopy over soybean plants and decreases light penetration (McWhorter and Hartwig, 1972). Zimdahl (1980) reported reductions in the yield of various seed, flower and fruit crops with increases in weed infestation. For example, Johnson (1971) showed maximum sunflower yield occurred under 4 to 6 weeks postplanting weed-free conditions.

Weeds left longer than 6 weeks decreased both head size and kernel weight. Eaton *et al.* (1973) as in Crafts (1975) found that competition from Venice mallow could reduce yields of soybean seriously. One Venice plant per 7.5 cm of soybean row reduced yield of soybean seed by 632 kg/ha after 25 days of competition.

Weeds also compete with crops for pollinating agents, especially in insect pollinated crops where some weeds may attract insects better than crops, resulting in some of the crop flowers being left unpollinated which consequently affects the final yield (Popay, 1990).

4.2.3.4 Effects of weed population on crop harvesting efficiency

Early weed competition usually reduces crop yields more than late season weed growth. Late weed growth may not seriously reduce yields but it makes harvesting difficult, reduces crop quality, reinfests the land with seeds, and harbour insects and diseases during the autumn and winter (Crafts, 1975). These late season weeds are the ones that interfere with crop harvest. Tall weeds, for example could actually slow down harvesting and damage harvesting machinery. Large dock plants in carrots disrupt harvesting by sticking to elevators and diggers jamming the harvester and slowing down harvest. Weeds with thorns can affect hand harvesting of crops, for example thistles in squash harvesting (Popay, 1990). The skin irritation of nettle (*Urtica urens*) during harvesting of lettuce and celery can cause severe reductions in worker efficiency. This affects the quantity and quality of product harvested (Agamalian, 1987).

Tall growing or scrambling weeds which are still green at harvest time can delay crop drying and can increase costs if artificial drying is needed. Also production of weed-free, high purity seed lots has become a specialized business in many countries with the introduction of seed certification schemes. For example, weed seeds are the main reason for perennial ryegrass (*Lolium perenne*) seed crops being downgraded for certification (Rowarth *et al.*, 1990). Many large corporations are engaged in the seed business and their investment in land, seed stocks and special seed-cleaning equipment are engaged. Any weed seed contaminants during harvest can be a problem in seed cleaning especially if weed seeds, colour and shape closely resemble crop seeds (Hampton, 1990).

4.3 REVIEW OF CHEMICAL WEED CONTROL

4.3.1 Significance

Weeds have co-evolved with crops, and farmers have been trying to develop satisfactory methods for their control since the start of commercial agriculture. Weeds impose a considerable financial burden in most countries economies. For example, Combellack (1987) showed that the financial losses due to weeds was about $1500 million dollars for the year 1985-1986 in Australia. Cudney (1981) estimated that weeds cost farmers in the USA $4 billion dollars per year. This loss is due to weed competition and the cost of controlling weeds to avoid competition. Cultivation and mechanical control remains one of the most widely used weed control techniques (Combellack, 1992). The type of cultivation and its frequency affect the resultant flora (Cussans, 1987), provide only temporary suppression and limited benefits to productivity (Wells, 1970) and contribute to the degradation of old fragile soils (Pratley and Rowell, 1987). Mechanical cultivation in flower crops is generally injurious to the shallow rooting system (Gilreath, 1989) and rosette growth form

(Hatterman *et al.*, 1987 ; Johnson, 1972). It may incur high costs, stimulate a further germination of weeds and lead to soil erosion and/or compaction (Pratley, 1987). Moreover, interrow cultivation or mechanical weed control is often impractical at narrow row spacing or in trailing cover plants (Gilreath, 1986) and hand weeding is laborious and in most cases expensive (Fretz, 1972 ; Davidson and Roberts, 1976 ; Gilreath, 1989), resulting in a lower profit potential for the grower (Singh *et al.*, 1984 ; Yadav and Bose, 1987). Lamont *et al.* (1985) estimated the labour costs for manual weeding in Australia can exceed $10,000 per hectare, depending on the severity of weed infestation. Lamont and O'Connell (1986) showed that soil fumigation for weed and soil borne diseases control can exceed $4,000 per hectare which is also expensive compared to herbicides.

4.3.2 Herbicides

A successful chemical weed control program depends on an appropriate interaction of the plant, the herbicide and the environment (Floyd *et al.*, 1989). When one considers the complexity of many diverse species of crops and weeds, the great array of herbicides, and the infinitely variable environment, it becomes apparent that any discussion of chemical weed control must be developed with a understanding of these three components. The discovery of selective herbicides was a major breakthrough in field crops weed management, and the use of this group of chemicals has increased consistently over the last 40 years (Poole and Gill, 1987). Herbicides are broadly categorised into two main groups, depending on the time of application and their means of entry in plant (Ashton and Crafts, 1981).

4.3.2.1 Foliar application

Herbicides applied to foliage are considered to be of two types, contact or translocated. Contact herbicides act on that part of the plant to which they are applied, usually the foliage. Since they do not move to untreated parts of the plant, they are relatively ineffective on perennial weeds with regenerative rhizomes and stolons (Floyd *et al.*, 1989). Such perennials rapidly recover from a contact-herbicide treatment. Translocated herbicides may be either selective or non selective. They are applied to the leaves and are able to move from treated leaves to other parts of the plant and may act primarily at these distant sites. They tend to accumulate in such areas of rapid growth such as growing points, root tips, and areas of rapid elongation in shoots and roots. They are effective on both annual and perennial weeds. The degree of movement of the translocatable herbicide varies considerably (Anderson, 1983).

4.3.2.2 Soil application

Most soil applied herbicides are used to control annual weeds. They interfere primarily with weed growth at the stage of germination or seedling establishment. They usually have little, if any, effect on mature weeds. Often the seedlings never emerge from the soil; and if they do emerge, they are usually stunted and misshapen (Floyd *et al.*, 1989). Therefore these herbicides must be present in the soil horizon occupied by the germination of weed seeds. This placement is accomplished by soil-incorporation or pre-emergence application followed by rainfall or overhead irrigation. Herbicides are applied to the soil as pre-emergence or preplant incorporated treatments, and they may be selective or non selective (Roberts, 1982). Pre-sowing herbicides are applied to the soil before the crop is planted, while pre-emergence herbicides are applied after sowing but before the crop or weeds emerge (Gane *et al.*, 1975). Rainfall has to occur or overhead irrigation must be applied within several days after application for many of them to be effective. Occasionally 'pre-emergence' is used to refer to a situation where the crop has not emerged but the weeds have (Floyd *et al.*, 1989). In this case, one should be more specific and indicate that the herbicide is applied pre-emergence to the crop and post-emergence to weeds.

As suggested by Roberts (1982) the activity of a herbicide following application to the soil will be controlled in part by the ability of the soil to supply the chemical to the plant and the ability of the plant to absorb it. Some herbicides may be available to the plant as a vapour in the pores of the soil but most must be present in the soil solution before they can be absorbed appreciably by plant roots or germinated weed seeds. Factors which affect the concentration of herbicides in the soil solution and the availability of this solution to plants will therefore influence the activity of the compound. Herbicide activity is often affected by soil type, usually due to adsorption of herbicides by soil. Variation in soil properties makes it unusual for a particular dose of herbicide to be equally toxic in all soil types. In practice, the recommended dose is usually varied with soil type. Result from numerous glasshouse experiments have confirmed the inverse correlation between activity and the organic matter or clay content of the soil, and have usually shown that organic matter is by far the most important. For soil applied herbicides, adsorption will interact with irrigation to control their availability. Moisture, from rainfall and irrigation, is probably the most important factor affecting the activity of soil applied herbicides, and this requirement has been recognised for many years. It is required initially to provide sufficient moisture to bring the herbicide into solution from its formulation and redistribute it from the surface. Redistribution will affect activity directly by moving herbicide away from the sun down to where weed seeds germinate and have their roots. It may also have an indirect effect by reducing possible losses from the soil surface by volatilization or photochemical decomposition. Pot experiments have shown that herbicides, including simazine, diuron and terbacil are more phytotoxic in moist compared to dry soil.

4.3.3 Mechanism of herbicide tolerance

The practical use of herbicides in agriculture is based upon the ability of chemicals to kill weeds without injury to crop plants. This phenomenon is called **selectivity** (Ashton, 1971). Ennis *et al.* (1952) defined an ideal selective herbicide as a chemical compound that could be applied at preplanting, pre-emergence or post-emergence; and which would prevent the growth of all unwanted vegetation without causing injury to the crop and would disappear from the field by the time the crop is harvested. For herbicides to be effective, weeds or target plants treated with the chemicals must react to the applied chemical. The degree to which they react is the measure of their susceptibility to herbicides. Tolerance is a lack of response to the presence of the herbicide, resulting in some growth process being unaffected, ie. the degree to which the plant fails to respond to the presence of the herbicide (Anderson, 1977). An understanding of the factors governing the susceptibility of plant weeds, and the tolerance of crop plants to herbicides is essential to understanding the effective use of herbicides in agriculture (Wain, 1955). The absorption and translocation of herbicides in plants are strongly influenced by the morphological and physiological make up of plants, as well as by inherent properties of the herbicides themselves. For a chemical to be an effective herbicide it must possess herbicidal properties, and these properties are determined by its molecular composition and configuration. A herbicide must be able to gain entry into the plants and once inside, to be transported within the plants to its site(s) of activity in concentrations great enough to induce the desired response.

The selective control of plant species with a given herbicide can be explained in many instances, by differences in plant morphology, physiology and metabolism between species which are collectively referred to as the biological factors of selectivity (Hilton *et al.*, 1963 ; Anderson, 1977).

4.3.3.1 Morphological factors

Morphological factors which allow herbicides to control one kind of plant without affecting another are those associated with the external structure of the plant and the development and location of the site or sites of herbicide entry into the plants (Aberg, 1964; Davis *et al.*, 1967). For example, leaf characteristics which influence herbicide selectivity include leaf surface, leaf angle and leaf shape (Hull, 1970). Leaves vary in the proportion of intercepted spray which they retain and many factors can affect this retention (Roberts, 1982). Leaf angle may affect retention as well as interception. The momentum of drops and the angle at which they strike a leaf will clearly affect the chances of a drop containing a herbicide adhering to a leaf rather than bouncing off (Roberts, 1982). The nature of leaf surfaces is one of the most important factors influencing the retention of spray droplets. For example, the nature and, more especially, the arrangement of the wax particles (epicuticular wax) on a normal pea leaf gives it a water-repellent character with the result that larger water droplets have very little adhesion and readily bounce or roll off. This is largely the basis for the selectivity of dinitrophenol herbicides as post-emergence sprays in peas (Gane *et al.*, 1975 ; Roberts, 1982). Waxy, smooth or densely hairy leaves are wetted less readily by aqueous sprays than are less waxy or moderately hairy surfaces (Hull, 1970). Leaf blades with an angle of 45° or more to the horizontal plane retain less spray than those which are more parallel to the horizontal plane. Narrow leaves of most monocotyledonous plants intercept less spray than do the broader leaves of most dicotyledonous plants. Leaf number and their arrangement on plants also affect the penetration of herbicide. Open foliar canopies allow for greater spray penetration than dense foliar canopies (Anderson, 1977).

Exposure or lack of exposure of the growing points (bud and stem elongation) of plants influences their susceptibility to contact type herbicides. For example, the growing points of grass plants are more protected than those in broadleaved plants therefore an advantage exists in selective control of broadleaved weeds among grass crop plants. Also the presence of coleoptile nodes in some species (that is the first node on the stem in grass seedlings), which serves as a primary site of entry for certain soil herbicides, can be important. For example, the lack of a coleoptile node in broadleaved crops makes selective control of grass weeds in broadleaved crops possible. The underground reproductive organs which are typical in perennial plants such as rhizomes and tubers make them highly tolerant to most contact herbicides (Anderson, 1977).

4.3.3.2 Physiological factors

Selectivity may be achieved by physiological differences between plant species in their response to applied herbicides. Such physiological differences can involve entry of herbicide into the plants and their subsequent effect on the plants once they have gained entry; that is, other than their effect on vital metabolic processes within the plants. Physiological factors associated with herbicide selectivity are mainly plant absorption of the herbicide, herbicide translocation within the plant and inactivation of herbicide within the plant by conjugation, accumulation and secretion (Anderson, 1983).

There are innumerable factors which influence the entry and translocation of herbicides. Herbicides are absorbed by plants via their aerial and/or underground parts (Rahman, 1982). To be effective, most herbicides must be translocated within plants from their sites of entry to their sites of activity. The translocation of a particular herbicide often determines how it is used, ie. whether it is applied to leaves or roots via soil. Herbicides translocated in the symplastic system (phloem transport) are foliage applied compounds and those translocated in the apoplastic system (xylem transport) are usually the soil applied compounds. A few herbicides such as amitrole are readily translocated in both systems (Floyd *et al.*, 1989). However, some herbicides are more readily translocated in certain plant species than in others and selectivity may be achieved by taking advantage of differential movement of herbicide in plants. For example, Colby (1966) showed that chloramben, which is root absorbed, is readily translocated to the shoots of barnyard grass, a susceptible species, but little such translocation occurs in wheat. Terbacil is not translocated from treated leaves of *Mentha piperita* (peppermint), a tolerant species, while it is readily translocated from treated leaves of *Ipomoea hederacea* (morningglory), a susceptible species (Barrentine and Warren, 1970).

Plants can inactivate herbicides by conjugation, accumulation or secretion. Once absorbed by a plant cell, a herbicide may react with chemicals present in the cell to form complexes or conjugates, which may be insoluble and/or non-translocatable. Such complexes immobilize the herbicide within the cell either in the cytoplasm or in the vacuole. Similarly, an otherwise nontranslocatable herbicide may form a complex with the cell which enhances translocation. In either case, differential transport due to conjugation occurs, and such differences contribute to a herbicides selectivity between plant species.

4.3.3.3 Metabolic factors

Herbicides in general kill plants by interfering with one or more of the metabolic processes vital to the life of plants. However, some plants possess means to detoxify certain herbicides and thus, are not killed by these chemicals. For example, a major factor in the selective control of barnyard grass (*Echinochloa crus-galli*) in rice crops is due to differences in arylacylamidase enzyme levels in the two plants. Rice plants have a high level of arylacylamidase and are tolerant to the herbicide propanil, while barnyard grass plants have a low level of this enzyme and are killed by propanil (Hoagland, 1974). Also tolerance of maize to simazine is due to a rapid conversion of a phytotoxic to a non toxic compound within the plant (Roberts, 1982). In contrast, an applied herbicide may not be phytotoxic initially but is converted to a phytotoxic derivative in susceptible species. Tolerant species lack the chemical system to effect the conversion. This type of selectivity is illustrated by the *B*-oxidation concept in which non-phytotoxic phenoxybutric acids (eg. MCPB and 2,4-DB) are converted to the corresponding toxic phenoxyacetic acids (MCPA and 2,4-D respectively) in susceptible species.

Plant species commonly differ in their tolerance to herbicides in general, as well as to a given herbicide. The tolerance of plants to herbicide is influenced by many factors. An example is the stage of plant growth when treated. In general, seedlings and young plants are less tolerant than older plants to applied herbicides, especially to contact type herbicides (Matsunaka, 1969). However, some older, established plants may be less tolerant to certain herbicides as demonstrated in the control of perennial plants. The stages of growth in which plants are less tolerant to applied herbicides are when rapid growth is taking place and when a period of rapid growth has ended and food reserves are temporarily depleted or exhausted. Some plants are susceptible to certain herbicides only at a specific stage of growth. For example, wild oats are killed by the foliar-applied herbicide barban only at the 1 to 2 leaf stage of growth. Application of Barban before or after this growth stage results in reduced growth of the plants but they will not be killed (Kobayashi and Ishizuka, 1974).

4.3.3.4 Environmental factors

Environmental factors such as light, moisture, temperature and soil conditions affect the tolerance of plants to herbicides (Lynch and Sweet, 1971 ; Caseley, 1987). Plants grown under high light intensity are more tolerant to foliage applied herbicides than plants grown in subdued light conditions. This is due to the formation of a thicker and less permeable cuticle under high light intensity. Increased light intensity has been found to enhance the uptake and translocation of many herbicides and to accelerate the development of herbicide damage (Caseley, 1987). For example, Coupland (1983) found that translocation of glyphosate from the leaf sheath to the rhizomes of couch was twice as fast at a light intensity of 117 Wm^{-2} compared to 26 Wm^{-2} over a 24 hour period but by 40 hours the rhizome had accumulated similar amounts of herbicides. Water-stressed plants are highly tolerant of foliar-applied herbicide compared with plants that are not under water stress, and this is apparently due to a less expanded, and therefore less permeable cuticle (Hammerton, 1967).

In general plants are more tolerant to herbicides applied when temperatures are above or below those favouring growth. The specific temperatures influencing tolerance vary with plant species. For example, winter annuals may respond to herbicides applied while the temperature is below 10°C while summer annuals may not respond until temperatures are above 15°C (Floyd *et al.*, 1989). Annual plants are generally less tolerant in their seedling stage to applied herbicides; but are more tolerant after seed set. Herbicides applied to annuals in their bud to early bloom stage may prevent seed formation. Perennials, on the other hand, are in general less tolerant to herbicides during their seedling stage prior to establishment. However, older established perennial plants are more susceptible to foliar-applied herbicides when vigorous growth is taking place.

4.3.4 Herbicides information

The herbicides used for this study were selected from those used in some vegetable and ornamental crops, as reported by Brosh *et al.*, 1973 ; Brosh *et al.*, 1976 ; Koster *et al.*, 1979 ; Mestre, 1981 ; Reavis and Whitcomb, 1981 ; Talbert *et al.*, 1981 ; Amos, 1980 ; Bing, 1981 ; Bowman, 1983 ; Haramaki and Kuhns, 1984 ; Wilson and Hughes, 1985 ; Lamont *et al.*, 1985 ; Lamont and O'Connell, 1986 ; Agamalian, 1987 ; Durigan and Motta, 1989 ; Cox *et al.*, 1990 ; Harrington, 1992 pers. comm.; and manuals for bedding plant culture (Kuhns and Haramaki, 1985) and plant protection (O'Connor, 1990).

4.3.4.1 Soil-applied herbicides

These herbicides are usually of two types: pre-plant herbicides and pre-emergence herbicides. The pre-plant materials are applied before sowing and are incorporated into the seedbed by cultivation. They are volatile materials which would be less effective as surface treatments. Their effectiveness is very dependent upon the efficiency of incorporation, particularly in situations where the soil is in a workable condition. Herbicides which do not need incorporation because of low volatility are usually applied at pre-emergence, ie. after the crop has been planted but before weeds or crop plants have emerged. Soil-applied herbicides include:

Trifluralin (Treflan) - a pre-plant herbicide for selective weed control in many crops, including some ornamental flowers and many other bedding plants (Kuhns and Haramaki, 1985). It controls a range of annual grass and broadleaved weeds included amaranth species, wire weed, nettle, spurrey and wild portulaca. It is volatile and must be soil incorporated to a depth of 5-7 cm, or application must be followed by irrigation immediately after application (O'Connor, 1990). The residual effectiveness is about six weeks (Kuhns and Haramaki, 1985).

Alachlor (Shell Alachlor) - an acetanilide for selective pre-emergence weed control in a wide range of crops, including soybeans, kumara, squash, pumpkins and in a wide range of annual flowering plants (Bing, 1981). It controls mainly annual grass and some broadleaf species (eg. redroot, black nightshade). It is taken up by shoots of emerging seedlings. Rain or irrigation is required within 10 days of application to activate the herbicide (O'Connor, 1990).

Chlorpropham (Chloro-IPC) - This pre-emergence herbicide belongs to the carbamate group and is registered for many crops and a variety of bedding plants (Kuhns and Haramaki, 1985). It controls many grasses and broadleaved weeds (eg. dock seedlings, willow weed, paspalum, wire weed, speedwell, spurrey and black nightshade). It is taken up by the emerging shoots of seedlings and through the roots of older plants. Adequate soil moisture (rainfall or irrigation) is necessary for effective weed control (O'Connor, 1990).

Oxadiazon (Foresite) - an oxadiazole and mainly used for control of grass and broadleaf weeds in nurseries and orchards. It is primarily a pre-emergence herbicide and should be applied to bare, moist, clod free soil. It forms a film on the soil surface which should not be disturbed by cultivation. Dry and very open soils reduce the activity of the herbicide. Oxadiazon is very crop safe once it has been applied as it fixes to the soil surface and is almost resistant to leaching. It is a surface acting residual herbicide which is absorbed by the emerging shoot of weeds preventing further development above the soil surface. Oxadiazon acts best on very young plants up to 2 to 3 leaf stage, older plants tend to be more resistant (O'Connor, 1990 ; Harrington, 1992).

Oxyfluorfen (Goal) - chemically oxyfluorfen is a diphenyl-ether herbicide and an effective herbicide for pre-emergence and/or post-emergence broadleaf weed control in many perennial crops. This herbicide is absorbed by emerging seedlings through the shoot as this passes through the layer of herbicide at the soil surface. As a result, the ground must be covered by an unbroken layer of the herbicide because if the seedling does not contact the herbicide as it emerges, it will not be affected. Oxyfluorfen is generally more active against broadleaf weeds than grasses (O'Connor, 1990).

Oryzalin (Surflan) - a selective pre-emergence dinitroaniline herbicide for the control of most annual grass and some broadleaved weeds. Susceptible weeds include red root, field speedwell, nettle, shepherds purse, willow weed and wire weed. The control of black nightshade and groundsel is variable. It does not controls established plants but affects germination after being taken up by the roots of germinating seedlings. It is relatively non-volatile so that it can be applied during any season but rainfall or overhead irrigation is required within 7-10 days of application to activate oryzalin (Kuhns and Haramaki, 1985 ; O'Connor, 1990).

Metribuzin (Sencor) - belongs to the triazinone family for selective pre-emergence or post-emergence weed control in potatoes, tomatoes, peas, lucerne, asparagus and lentils. Controls many annual grass and broadleaf weeds. Has contact action on emerged weeds and soil residual life to control subsequent weed germination (O'Connor, 1990).

Diuron (Karmex) - one of the substituted ureas, a residual herbicide for selective weed control in various ornamentals such as narcissus, gladioli and iris. It is quite effective on a wide range of germinating weeds. Karmex contains 800 g/kg diuron in the form of water dispersible granule. In ornamentals rates of 2 kg/ha are applied before emergence with a water rate of 250-500 l/ha (O'Connor, 1990).

Simazine (Gesatop) - belongs to the triazine family and is commonly used as a selective pre-emergence herbicide to control weeds in certain horticultural crops. Simazine has been used extensively for depth protection work in orchards and a wide range of crops. It is very effective in preventing the germination of a wide range of annual and perennial grasses and broadleaf weeds. Gesatop contains 900 g/kg of simazine in the form of water dispersible granules (O'Connor, 1990).

Terbacil - a substituted uracil and broad spectrum herbicide for controlling grass and broadleaf weeds in orchards. Terbacil works best if applied in spring before or shortly after weed emergence. Moisture is needed to activate the chemical and best results will be obtained when rainfall or irrigation occurs within 2 weeks of application. It is not recommended on light soils or soils low in organic matter. Sinbar contains 800 mg/kg terbacil in the form of a wettable powder (O'Connor, 1990).

Chlormethazole (Probe) - an oxadiazon and a selective herbicide for pre-emergence weed control in squash, pumpkins, marrows and courgettes. Probe contains 750 g/kg of chormethazole in the form of a water dispersible granule. It works best in mineral soils, having reduced activity on organic soils. It has contact activity on emerged foliage and residual activity as a soil applied herbicides. It controls a wide range of weeds, and rainfall will improve results when used at pre-emergence (O'Connor, 1990).

4.3.4.2 Foliage-applied herbicides

In the case of materials applied post-emergence, treatment is carried out when both weeds and crop plants have emerged. These materials must be selective, in that they must destroy weeds without unduly damaging the crops. Such herbicides include:

Asulam (Asulox) - a carbamate herbicide with specific activity on docks and bracken. It is selective to ryegrass, clovers, lucerne, radiata pine and several orchard crops. For the control of docks it should be applied during active growth; spring in pasture and orchard crops and autumn in lucerne provide best control. It is readily absorbed by foliage and translocates in the plant. The site of action is at the growing point where it interferes with cell division and expansion. Signs of action are severe yellowing of new leaves, stunting and finally death (O'Connor, 1990).

Bentazone (Basagran) - a benzothiadiazole for post-emergence control of many annual broadleaved weeds in field beans, French lima and soybeans, peas and cereals. It is a selective contact herbicide which acts by killing the foliage of susceptible plants. Symptoms usually appear within 2-5 days of spraying. Best results will be obtained in condition which favour rapid plant growth. It has no activity through the soil and no chemical residues remain in the soil to affect subsequent crops. In sunlight bentazone undergoes oxidation and dimerization with loss of SO_2. It mixes readily with water and is often used in combination with other herbicides. In NSW and Queensland, soybeans are tolerant to bentazone at all stages of growth; temporary mild scorch may occur but this will not affect yield. For best results it should be applied when weeds are small and actively growing (Swarbick, 1976).

Chloroxuron (Tenoran) - a substituted urea and a selective herbicide for the control of annual broadleaf weeds and some grasses in soybeans, carrots, peas, parsnips, strawberries and ornamentals. It is best applied early post-emergence to a fine seedbed. It has a short residual soil life. It is not appreciably translocated following foliar application but strongly absorbed by roots and transported to leaves. Chloroxuron is often used to control mosses in amenity and sports turf. Soils high in clay content or organic matter are strongly adsorbent (O'Connor, 1990).

Clopyralid (Versatill) - a substituted pyridine for the control of Californian thistle, yarrow, clovers and many flat weeds in some crops, turf, forestry and pre-cultivation. It may be used selectively in asparagus, beets, cereals, forage brassicas, radiata pine, shelter and ornamental trees and turf. Clopyralid is really absorbed by leaves, stems and roots in susceptible plants and translocated in the plant to interfere with cell elongation and other vital processes (O'Connor, 1990).

Dalapon (Icipon) - an organochlorine used as a selective systemic herbicide for control of annual and perennial grasses (including couch grass) in orchards, tobacco, sunflower, soybean, and potatoes. It is most effective as a foliage spray although there is absorption by plant roots and acts by precipitation of protein which interferes with production of pantothenic acid. It acts best when grass is growing vigorously and before seeds start to develop. It is slow in action and may take several weeks to achieve maximum effect (Swarbick, 1976 ; O'Connor, 1990).

Haloxyfop (Gallant) - selectively controls grass in nurseries, orchards, and in most broadleaf crops. It is a carboxylic acid derivative and the addition of crop oil improves its activity on grasses. Gallant contains 100g/l haloxyfop in a form of an emulsifiable concentrate. It is one of the most recently developed translocated herbicides for the selective control of grasses in dicotyledon crops (O'Connor, 1990; Harrington, 1992).

Ioxynil (Totril) - a hydroxybenzonitrile for the control of a wide range of broadleaf weeds in garlic, onions, established and newly sown fine turf grasses. For most effective weed control with this chemical, it is essential to spray when the majority of weeds are small. It is absorbed into the plant via leaves and stems but there is very little translocation. Ioxynil does not persist in the soil. The upright waxy foliage of garlic and onions allows them to tolerate ioxynil.

MCPA - belongs to the phenoxyacetic group of herbicides and provides control of a wide range of herbaceous dicotyledonous weeds in grass crops. It is mainly used for control of broadleaf weeds in pasture and most selective lawn herbicides are also based around MCPA. MCPA is also used extensively for weed control in cereals. MCPA is available in New Zealand only as a salt formulation, and it remains active in the soil for no more than a week after application. Phenoxyacetic herbicides are only very weakly adsorbed by soil particles but are readily deactivated by soil micro organisms (Harrington, 1992).

MCPB - a phenoxybutyric herbicide used for selective weed control in some legume crops. To be successful it should be applied to weeds at the seedling stage, so it tends to be used for weed control in young pastures, because any weeds that are causing problems in pasture during the first few months are likely to be seedlings and therefore susceptible to MCPB (Harrington, 1992).

Methabenzthiazuron (Tribunil) - a substituted urea which is a selective herbicide for broadleaf weed controls in vegetables and some cereals. It has both knockdown plus soil residual action to control germinating weeds. Best results are obtained from application to actively growing weeds. Methabenzthiazuron is absorbed through both the foliage and roots, and its residual activity controls subsequent weed germination (O'Connor, 1990).

4.4 MATERIALS AND METHODS

4.4.1 Objectives

The main objective of this research programme was to assess the tolerance of *Tropaeolum majus* (cv. Choice Mixed) to various herbicides and so identify herbicides suitable to assist with commercial seed production of this species. A suitable herbicide would prevent the growth of unwanted vegetation without causing injury to the crop. The herbicide screening programme consisted of two main experiments:

a. Soil applied herbicide trial

b. Foliage applied herbicide trial

4.4.2 Soil applied herbicide trials

The main aims of these experiments were:

a. To assess the tolerance of nasturtium to various soil applied herbicides

b. To assess whether the tolerance of nasturtium to these herbicides was influenced by the potting medium

Assessment of soil applied herbicides consisted of a preliminary screening trial and successful herbicides from that trial were further tested in a second trial.

4.4.2.1 Preliminary trial

4.4.2.1.1 Procedure

In the first trial, 11 pre-emergence herbicides were tested on *T. majus* plants grown in pots.

The experiment was conducted at the Seed Technology Centre, Massey University. The seed lot used for this experiment was the same as that used in the density trial (Chapter 2). Plants were grown in 300 ml plastic pots each with drainage holes in their base. Silt loam soil from adjacent to the field density plots was used as the media (details of soil analysis appear in Appendix 2.1). Four seeds were sown into each pot approximately 2 to 3 cm deep and the surface gently tamped flat. In this preliminary screening trial a total of 11 herbicides was screened, and each treatment was replicated 6 times. The details of the herbicides and their respective application rates are given in Table 4.1.

Table 4.1 The treatments used in the preliminary soil-applied herbicide trial.

TREATMENT Common name	Trade name	RATE (kg ai/ha)
Trifluralin	Treflan	0.8
Chlorpropham	Chloro-IPC	3.2
Alachlor	Shell Alachlor	2.0
Metribuzin	Sencor	0.9
Oxyfluorfen	Goal	0.72
Diuron	Karmex	1.6
Simazine	Gesatop	1.0
Oryzalin	Surflan	3.0
Oxadiazon	Foresite	1.6
Terbacil	Sinbar	1.6
Chlormethazole	Probe	1
Untreated	-	-

The sowing date for the preliminary trial was 10th December 1991 and treatments were applied 2 days later except for trifluralin (a pre-sowing herbicide), which was mixed with the media before seeds were sown. The six pots to be sprayed in each treatment were placed under a pendulum sprayer specially designed for spraying pots (Harrington pers. comm.). It consisted of a miniature compressed air sprayer mounted as a pendulum and equipped to spray pots beneath the centre of its arc of swing (Day *et al.*, 1963). Herbicides were applied in water at 215 l/ha and a spray pressure of 2.0 bar (200 kPa). Plate 4.1 shows the pendulum sprayer in operation. The sprayed pots were then transferred to a standing-out area and were watered daily by hand. The weather conditions closely resembled that in the field density trial, and details are presented in Appendix 2.3.

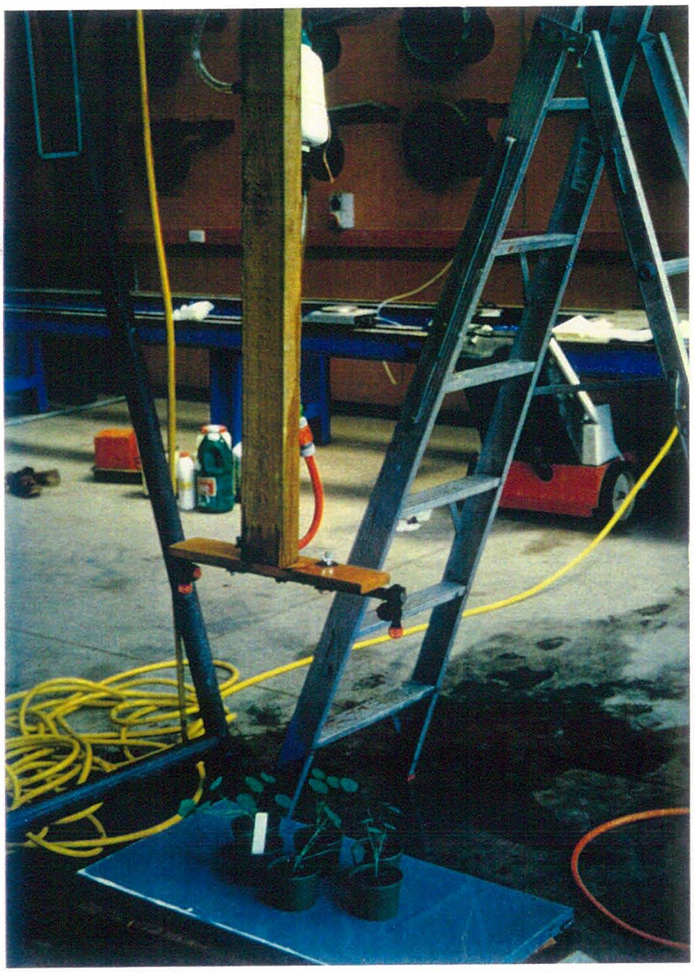


Plate 4.1 Pendulum sprayer design for pots spray.

4.4.2.1.2 Assessments

Seedlings emerged 8 days after spraying, then each pot was thinned to 1 plant per pot 5 days after emergence and herbicidal activity was assessed. The assessment was done 4 weeks after seedlings had emerged by close visual inspection of each plant. A scoring system was used to quantify the phytotoxicity of plants to herbicides. Assessment was done by vigour scores using a scale from 0 (=least) to 10 (=most vigorous growth). Low vigour meant poor tolerance of herbicides, while the most vigorous plants were highly tolerant. The vigour scoring was mainly on observation of symptoms such as stunting of growth, distortion, necrosis, chlorosis of foliage and stem weakening leading to collapse. A score of 0 was given to pots in which no seedlings successfully emerged, 1 to seedlings which germinated but died down completely and 10 signified that leaves were brightly green, the plant looked unaffected by the herbicide and there was no leaf necrosis or growth stunting. Intermediate scores depended on plant appearance and the extent of growth inhibition.

4.4.2.2 Second soil applied herbicide trial

4.4.2.2.1 Procedure

The second experiment was conducted in early February 1992 using a similar procedure to that in the preliminary trial except fewer herbicides were used in this experiment. Six pre-emergence herbicides that look promising from the preliminary screening were reassessed using two different types of growing media. One medium was soil from field plots and the second medium was a mixture of clean river sand and potting mix mixed by volume 2 to 1 respectively. The potting mix used was a mixture of 50% peat, 40% pumice and sand, 10% Nitrogen stabilized bark, dolomite, agricultural lime, super phosphate, P.G mix, terrazole (soil fungicide) and 100 day controlled release Nutricote. Each treatment was applied to six pots of soil and six pots of potting mix. The details of the applied herbicides and their respective rates are listed in Table 4.2.

Table 4.2 Treatments used in the second soil-applied herbicide screening experiment.

TREATMENTS Common name	Trade Name	APPLICATION RATE kg ai/ha
Oryzalin	Surflan	3.0
Trifluralin	Treflan	0.8
Chlorpropham	Chloro-IPC	3.2
Oxadiazon	Foresite	1.6
Alachlor	Shell Alachlor	2.0
Oxyfluorfen	Goal	0.72
Untreated	Control	-

The sowing date for the main trial was 8th February 1992 and treatments were applied 2 days after sowing with the exception of trifluralin as in the preliminary trial. Herbicides were applied in water at a volume equivalent to 371 l/ha and a spray pressure of 2 bar (200 kPa). The sprayed pots were then transferred to a glasshouse, watered by hand for the first two days and then switched to an automatic sub-irrigation system. The temperature was maintained at an average of 25°C during the day and 10°C at night.

4.4.2.2.2 Assessments

Seedlings emerged 6 days after spraying, the number of seedlings that emerged from each pot was recorded and then each pot was thinned to one plant per pot 5 days after emergence and then the extent of damage to each plant was assessed at regular intervals. The first assessment was on 26th February 1992 and further assessments were conducted every 3 weeks after this date, with a close visual inspection being made of each plant. The scoring system for quantifying the phytotoxicity of the herbicides was similar to that in the preliminary screening except that scoring occurred every 3 weeks and the final scoring was made on 20th May 1992, 15 weeks after first assessment. The following measurements were also made on 21st May 1992:

a. main stem length and number of nodes
b. leaf number (old and green) and their corresponding fresh and dry weight
c. flower number (including floral buds, wilted and senesced flowers)
d. total plant fresh and dry weight of stem and leaf components

Dry weight was determined by drying plants to a constant weight for 3 days at 80°C.

4.4.3 Foliage applied herbicide trial

4.4.3.1 Procedure

The foliage applied herbicide trial was conducted in a glasshouse at the Seed Technology Centre, Massey University. *Tropaeolum majus* seeds were first sown into 300 ml pots as for the soil applied herbicide trial except the only media used was the 2:1 sand/peat mixture. Seedlings were allowed to grow in the glasshouse for 4 weeks and thinned to 1 plant per pot 3 weeks after planting. Treatments were applied 4 weeks after planting using the same technique as for the soil applied herbicide trial except that herbicides were applied in 479 l/ha water. Spraying was conducted on 6th January 1992 with 10 herbicide treatments and an untreated control, and each was replicated six times. The details of each treatment and applied rates are given in Table 4.3.

The sprayed plants were transferred to the glasshouse at the Seed Technology Centre and allowed to grow with daily overhead watering. A thermohydrograph was placed in the glasshouse to record the air temperature and relative humidity during the growth period.

4.4.3.2 Assessments

Assessment of the foliage applied herbicides trial used the vigour scoring method and a final assessment on vegetative and reproductive yields as in the second soil applied herbicide trial. The vigour scoring used a scale from 1 (=least) to 10 (=most vigorous growth). A score of 1 was given to seedlings completely killed by the treatment and 10 signified no phytotoxic effects from the treatment. Scoring occurred at regular intervals with the first assessment being carried out one week after spraying and subsequent assessments occurring every three weeks. Final assessment was carried on 17^{th} May 1992. The type of damage symptoms were recorded in the first assessment. Total plant dry weight, main stem length, number of flowers and number of nodes were recorded.

Table 4.3 Post-emergence herbicides and their respective rates.

TREATMENTS	APPLICATION RATES	
Common Name	Trade Name	kg ai/ha
Chloroxuron	Tenoran	4.0
Haloxyfop	Gallant	0.30
Ioxynil	Totril	0.67
MCPB	IWD MCPB	1.6
MCPA	IWD MCPA	1.5
Clopyralid	Versatill	0.30
Asulam	Asulox	1.6
Dalapon	Icipon	4.4
Bentazon	Basagran	1.4
Methabenzthiazuron	Tribunil	1.4
Untreated	-	-

4.4.4 Statistical analysis

Data analysis for all herbicide experiments involved the calculation of means for each treatment, then an analysis of variance (ANOVA) was conducted on the means. The vigour scoring data had a rectangular distribution. For the ANOVA to be valid, probit transformation of the score data was needed to produce a normal distribution of the data. The Student Newman Keuls (SNK) multiple range test was used to separate those treatment means which were significantly different.

4.5 RESULTS

4.5.1 Soil application trial

4.5.1.1 Preliminary trial

Results from the preliminary trial showed that five herbicide treatments caused an unacceptable level of crop damage (Figure 4.2). Six herbicides caused no significant difference from untreated plants in terms of damage symptoms and thus appeared worthy of further testing. Chlormethazole, simazine, metribuzin, diuron and terbacil caused significant levels of damage to nasturtium in this preliminary screening and so were not included in the second trial.

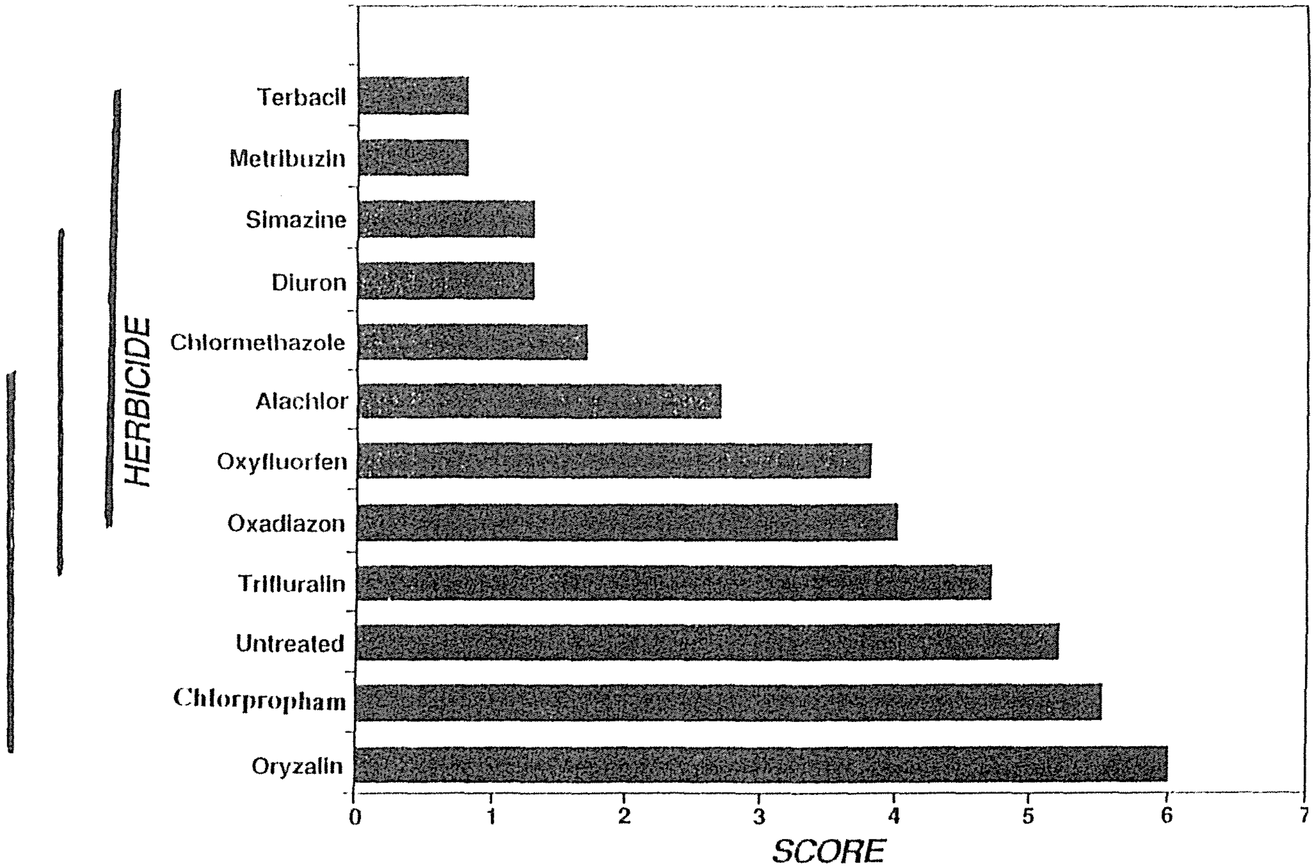


Figure 4.2 The tolerance of pot sown *Tropaeolum majus* (cv. Choice Mixed) to some soil applied herbicides as assessed 4 weeks after seedling emergence. Scores ranged from 0 (total death) to 10 (very healthy). Treatments joined by vertical bars are not significantly different ($P<0.05$).

4.5.1.2 Results (second experiment)

When the six most promising herbicides from the preliminary experiment were tested again for selectivity to germinating nasturtium seedlings, tolerance was found to differ significantly for several of the herbicides depending on the type of growing medium (Table 4.1). When grown in soil, two herbicides, oxadiazon and oxyfluorfen, caused unacceptable levels of damage in nasturtium (Figure 4.3). Oryzalin and chlorpropham were the least damaging and treated plants were not significantly different ($P<0.05$) from untreated plants. Oxyfluorfen only checked crop plants initially but killed them completely by the final harvest. Trifluralin and alachlor caused some damage in the first 3 weeks but treated plants recovered later and were similar to untreated plants by the final harvest.

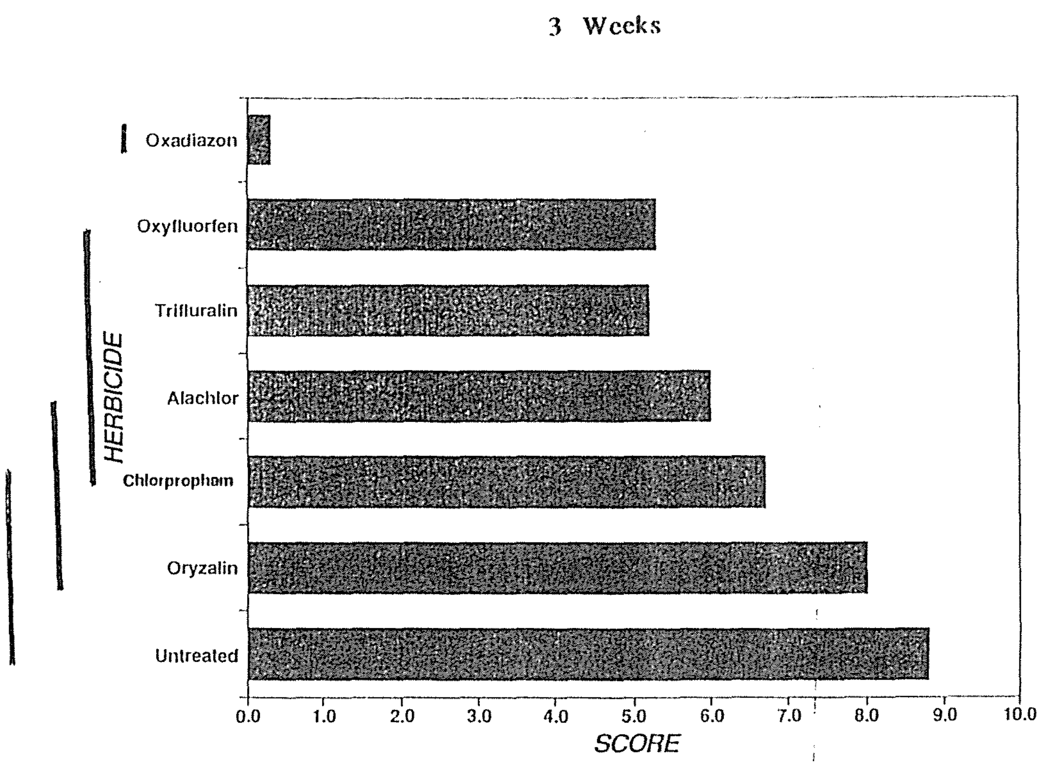
Chlorpropham and oryzalin were also well tolerated by nasturtium plants grown in the peat/sand mixture (Figure 4.4). The other four herbicides caused same initial damage to crop plants in the initial weeks after application, but all treated plants growing in this medium had recovered well by the time of the final harvest.

To summarise the data from the vigour scores, oxadiazon and oxyfluorfen at rates of 1.6 and 0.72 kg ai/ha respectively caused severe damage, but this only occurred in plants growing in soil. The other four herbicides were generally well tolerated by nasturtiums apart from some initial check in growth. Oxadiazon and oxyfluorfen were much less damaging to plants in the sand/peat media.

Table 4.4 Tolerance scores for garden nasturtium plants which germinated in pots containing either soil (S) or a peat/sand mixture (M) treated with soil-applied herbicides on 10th February 1992. Scores ranged from 0 (totally dead) to 10 (very healthy). Scores within columns for the same growing medium with the same letter are not significantly different (P=0.05).

Weeks After Application

TREATMENT		3	6	9	12	15
Trifluralin	S	5.2c	8.5a	8.3a	8.2a	7.7a
	M	3.7b	6.8b	7.3c	7.3abc	7.3b
Oxadiazon	S	0.3d	1.2b	0.8b	0.8b	0.7b
	M	3.8b	7.2b	7.5bc	7.8abc	7.2b
Oxyfluorfen	S	5.3c	2.3b	2.2b	1.5b	1.3b
	M	4.7b	7.3b	7.2c	7.2c	7.7b
Alachlor	S	6.0bc	6.8a	8.3a	8.3a	8.3a
	M	5.0b	5.0b	7.5bc	7.8bc	7.3b
Chlorpropham	S	6.7abc	8.2a	8.2a	8.2a	8.0a
	M	9.8a	9.8a	8.5abc	8.3c	8.0ab
Oryzalin	S	9.8ab	8.7a	8.8a	8.2a	8.3a
	M	10.0a	9.8a	9.7ab	9.3ab	9.0ab
Untreated	S	8.8a	9.3a	9.2a	9.2a	9.0a
	M	10.0a	10.0a	9.8a	9.5a	9.3a



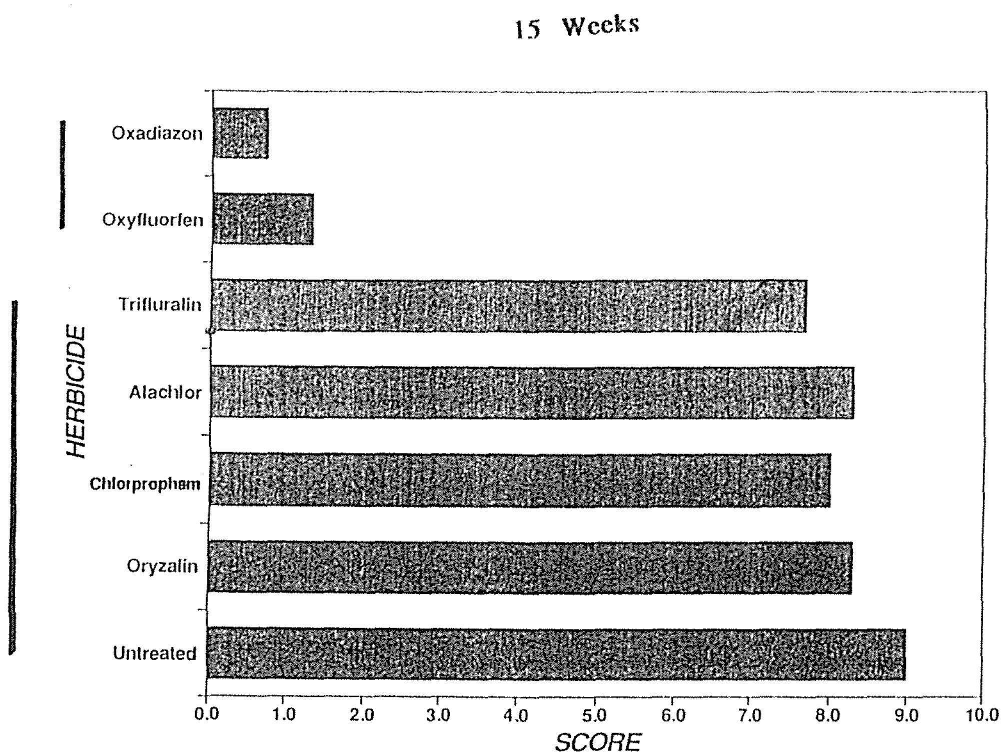
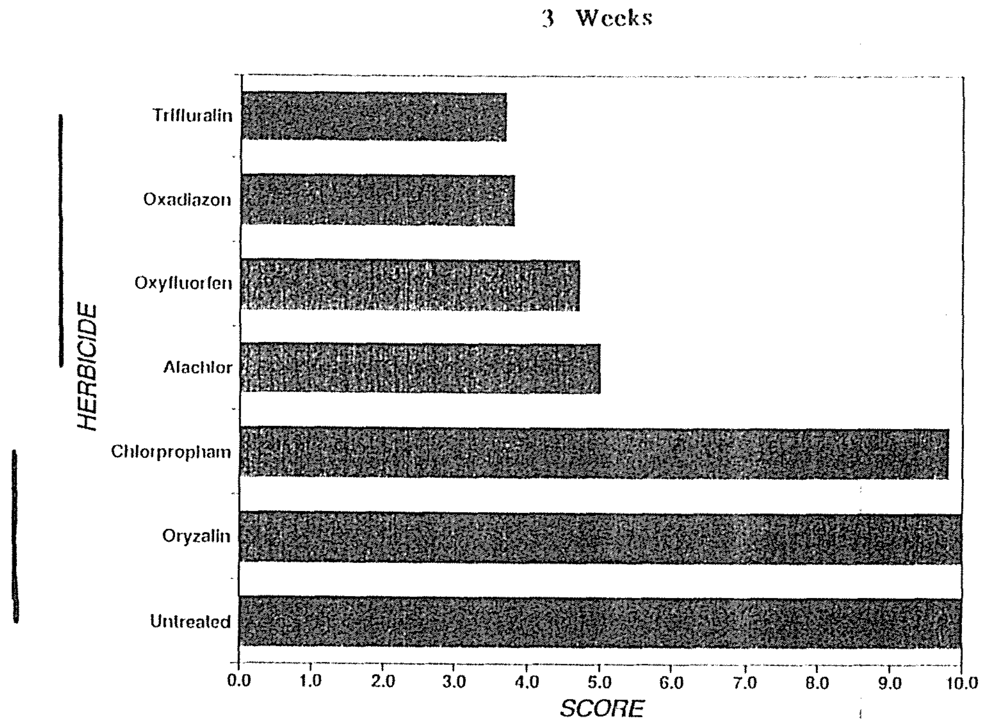


Figure 4.3 Tolerance scores for soil sown *Tropaeolum majus* (cv. Choice Mixed) to some soil applied herbicides as assessed at 3 and 15 weeks after seedling emergence. Scores ranged form 0 (total death) to 10 (very healthy). Treatments joined by vertical bars are not significantly different (P<0.05).



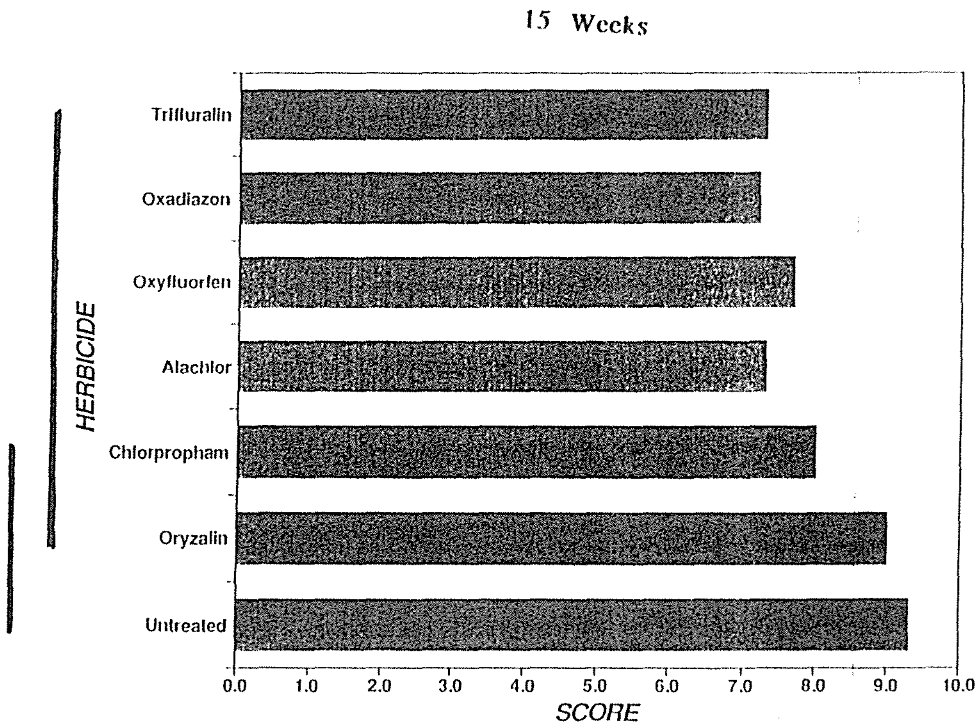


Figure 4.4 Tolerance of nasturtium (cv. Choice Mixed) grown in sand/peat mixture pots to some soil applied herbicides as assessed respectively at 3 and 15 weeks after seedling emergence. Scores ranged from 0 (total death) to 10 (very healthy). Treatments joined by vertical bars are not significantly different ($P<0.05$).

The effects of the soil-applied herbicides on the parameters measured in treated plants 15 weeks after application are shown in Table 4.5. Generally these parameters reflected the same results obtained from the vigour scoring. Oxyfluorfen and oxadiazon caused the most adverse effects on flowering in plants grown in soil (Figure 4.5). In the sand/peat mix, oxadiazon, trifluralin and alachlor caused significant reductions in the number of flowers produced. As with the vigour scores and flower production, oxyfluorfen and oxadiazon treated plants had significantly lower ($P<0.05$) dry weights than plants from most after treatments. While in the soil mix, alachlor, trifluralin, oxadiazon and oxyfluorfen all caused a significant reduction in shoot and root dry weight.

Table 4.5 Effects of soil herbicides on shoot and leaf dry weights (TDW), number of flowers (FL), main stem length (SL), total dry non-photosynthetic leaf number (OL), and the number of photosynthetic leaves (GL) of nasturtium (cv. Choice Mixed) measured at final assessment, 15 weeks after sowing. Scores ranged form 0 (totally dead) to 10 (very healthy). Scores within columns for the same growing medium with the same letter are not significantly different (P=0.05).

Herbicide		FL	SL (cm)	TDW (g)	OL	GL
Trifluralin	S	4.5a	23.8a	1.01a	15.8a	5.5ab
	M	2.0ab	10.5b	0.83bc	12.7ab	5.3a
Oxadiazon	S	0.5b	2.7c	0.18c	2.2c	1.0b
	M	2.7ab	14.5ab	0.77bc	12.2ab	6.3a
Oxyfluorfen	S	0.8b	3.3c	0.18c	2.8c	2.0b
	M	4.8a	17.0ab	0.83bc	12.0ab	6.8a
Alachlor	S	2.3ab	14.8ab	0.91a	9.0abc	7.3a
	M	0.8b	9.5b	0.4c	9.0b	5.7a
Chlorpropham	S	4.2a	13.8ab	0.93a	12.7ab	6.7a
	M	5.2a	18.8a	1.38ab	15.7a	8.0a
Oryzalin	S	2.0ab	9.0b	0.57ab	4.8bc	5.0ab
	M	4.8a	18.7a	1.18ab	17.8a	6.8a
Untreated	S	2.3ab	11ab	0.58ab	9.6abc	4.2ab
	M	5.0a	21.2a	1.63a	14.8ab	8.0a

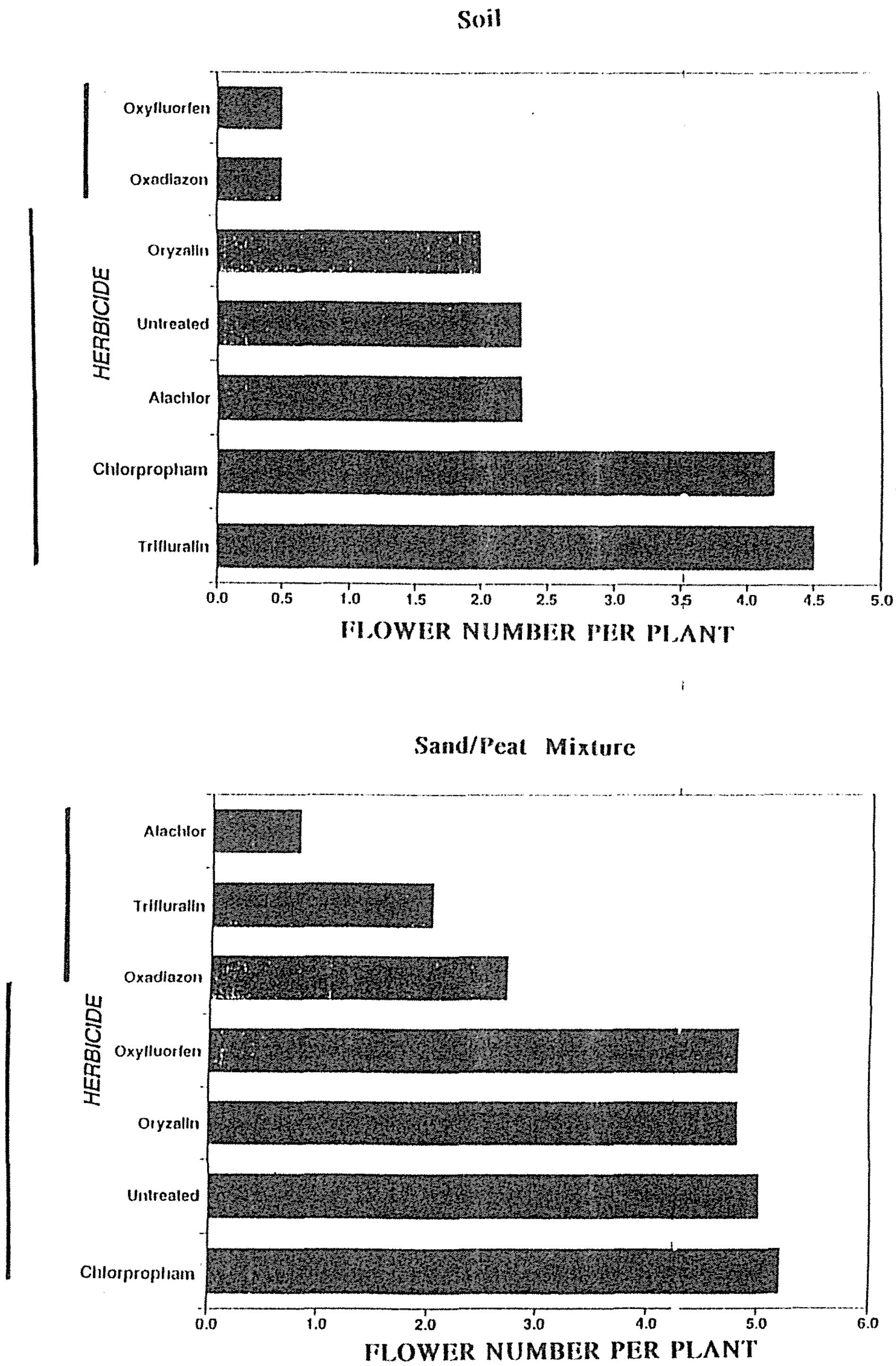
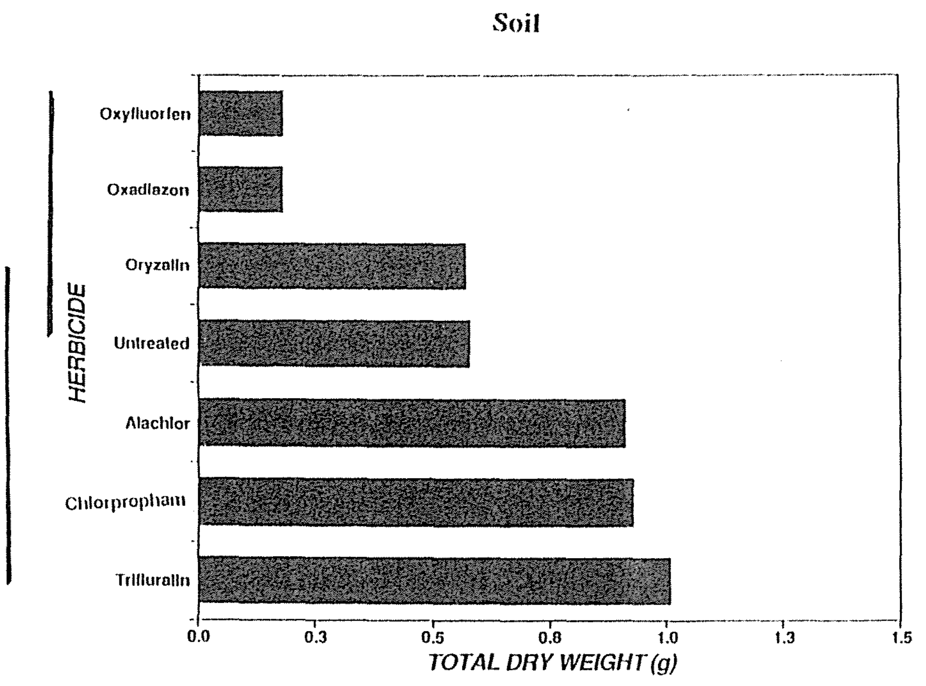


Figure 4.5 Effects of soil applied herbicides on flower number (FL) in *T. majus* (cv. Choice Mixed) at final harvest for soil grown and sand/peat media. Scores ranged from 0 (total death) to 10 (very healthy). Treatments joined by vertical bars are not significantly different ($P<0.05$).



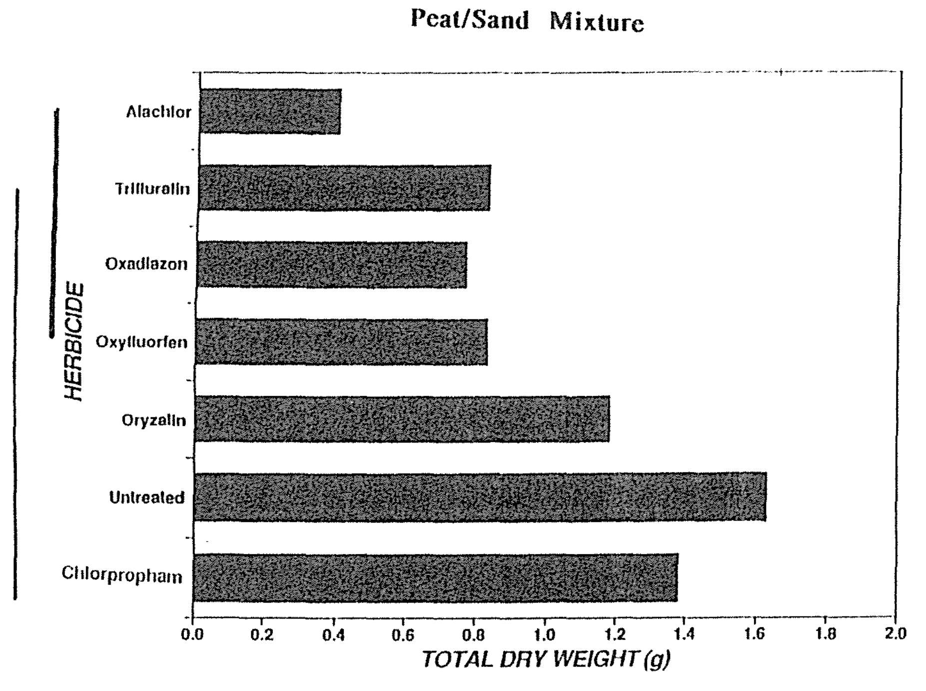
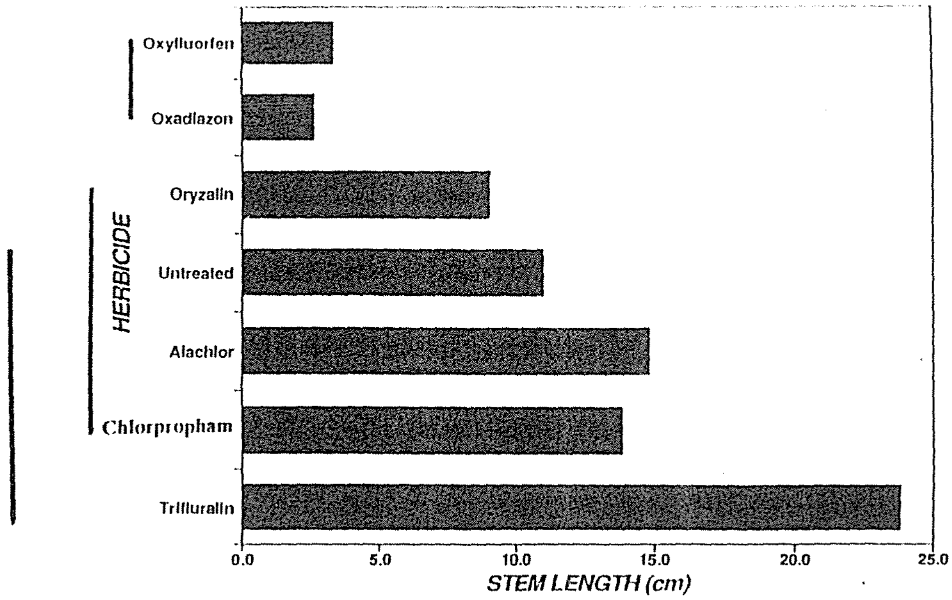


Figure 4.6 Effects of soil applied herbicides on leaf and shoot dry weights of soil and sand/peat grown nasturtium (cv. Choice Mixed) at 15 weeks after seedling emergence. Scores ranged form 0 (totally dead) to 10 (very healthy). Treatments joined by vertical bars are not significantly different ($P<0.05$).

Soil



Peat/Sand Mixture

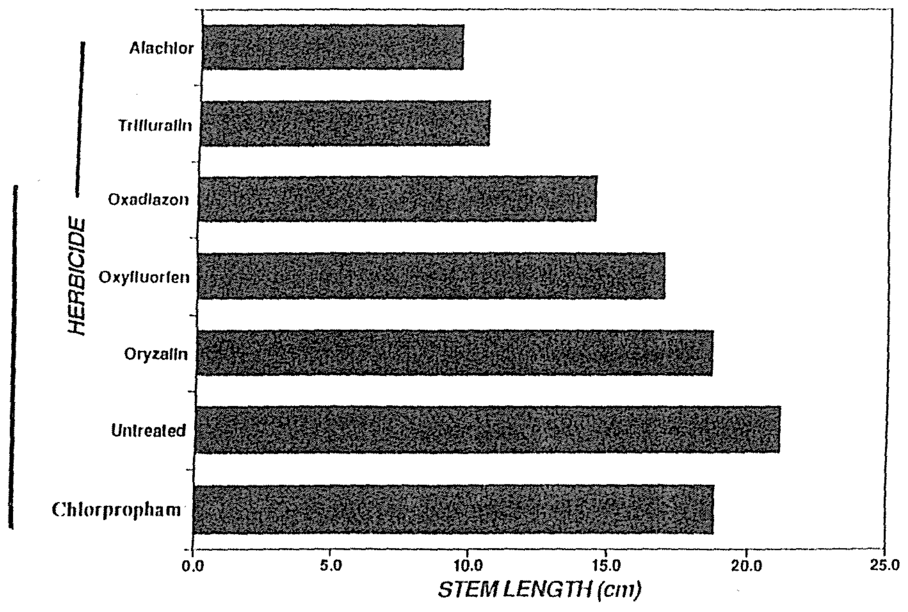


Figure 4.7 Length of main stems for both soil and sand/peat mixture grown of *T. majus* (cv. Choice Mixed) treated with soil applied herbicides at 15 weeks after spraying. Scores ranged from 0 (total death) to 10 (very healthy). Treatments joined by vertical bars are not significantly different ($P < 0.05$).

4.5.2 Foliage applied herbicide trial

The tolerance scores for herbicides applied at the 5-7 leaf stage to nasturtium plants are summarised in Table 4.5, and results for the first and final assessment are also presented in Figure 4.8. Initially MCPB, Ioxynil and MCPA were the most damaging treatments. The most noticeable injury was observed in plants treated with MCPA and MCPB, with stem distortion and weakening causing plants to lose rigidity and collapse. MCPA also caused chlorosis in sprayed leaves. Ioxynil caused the most damage to leaves, resulting in heavy necrosis, rapid desiccation and weakening of stems which collapsed the soil surface. Methabenzthiazuron, Clopyralid, Chloroxuron and Bentazone caused significantly less damage to nasturtiums than MCPA, MCPB or Ioxynil. The main symptoms were wilting and yellowing leaves. Haloxyfop and Asulam were even less damaging, causing only some yellowing of leaves. Dalapon did not affect nasturtiums at all and was not significantly different to the untreated control.

Ioxynil was still the most damaging treatment when plants were assessed 15 weeks after application, by which time all treated plants had died (Figure 4.8). The effects of MCPA, Clopyralid and Bentazone also still very noticeable, with many crop plants almost dead in these treatments. However plants which had been treated with Methabenzthiazuron, Chloroxuron, Haloxyfop, Asulam and MCPB had recovered from initial damage. Even though to be significantly different to untreated but at acceptable damage levels.

The effects of post-emergence herbicides on various parameters measured at the final assessment 15 weeks after application are given in Table 4.4. Ioxynil, MCPA and Dalapon caused a significant reduction in flower numbers (Figure 4.10). The rest of the treatments showed no significant effects on flowering, though they all resulted in less flowers than untreated plants. Apart from the obvious effect of Ioxynil on plant dry weight, Bentazone, MCPA and Chloroxuron also caused a significant ($P=0.05$) reduction in plant dry weight and node numbers. The plant dry weight for the rest of the treatments was not significantly different from untreated plants.

Table 4.6 Summary of tolerance scores for garden nasturtium plants (cv. Choice Mixed) grown in pots containing soil with foliar applied herbicides at the 5-7 leaf stage in pot glasshouse sown nasturtiums : mean weekly scores for January-May 1992. Scores ranged from 0 (totally dead) to 10 (very healthy). Scores within columns for the same growing medium with the same letter are not significantly different (P=0.05).

Weeks After Application

TREATMENT	1	4	7	10	13
Untreated	10.0a	9.8a	10.0a	9.0a	8.8a
Dalapon	9.5a	8.3b	7.5b	7.3b	7.5b
Asulam	7.2b	6.8bc	7.8b	8.0ab	7.8ab
Haloxyfop	6.3bc	6.7bcd	7.3b	7.0b	7.5b
Bentazone	5.5c	4.7e	2.0d	2.3d	3.2c
Chloroxuron	5.5c	6.7bcd	7.3b	7.2b	7.0b
Clopyralid	5.3c	5.0de	4.2c	3.8c	3.7c
Tribunil	5.3c	7.0bc	8.3b	7.8ab	7.5b
MCPA	2.8d	4.0e	4.5c	4.2c	4.2c
Ioxynil	2.7d	2.2f	1.0d	1.0e	1.0d
MCPB	2.7d	5.3cde	8.0b	8.2ab	7.8ab

Table 4.7 Effects of foliar applied herbicides on number of flowers (FN), main stem length (SL), total dry weight (TDW), and number of nodes (N) recorded at final assessment, 16 weeks after spraying. Scores ranged from 0 (totally dead) to 10 (very healthy). Scores within columns for the same growing medium with the same letter are not significantly different (P=0.05).

TREATMENT	FN	SL	TDW	N
Untreated	3.3a	127.7a	2.74a	31.8ab
Dalapon	0.5b	119.7a	2.02ab	33.0ab
Asulam	2.0ab	76.0ab	1.61ab	31.7ab
Haloxyfop	2.0ab	141.2a	2.48ab	36.5a
Bentazone	0.7ab	25.33ab	1.2b	29.0ab
Chloroxuron	1.0ab	61.5ab	1.27b	29.0b
Clopyralid	1.2ab	151.7a	1.72ab	40.2a
Tribunil	2.7ab	123.7a	2.12ab	34.3ab
MCPA	0.3b	69.0ab	1.21b	31.7ab
Ioxynil	0.0c	0.0c	0.0c	0.0c
MCPB	1.2ab	146.0a	2.48ab	36.0a

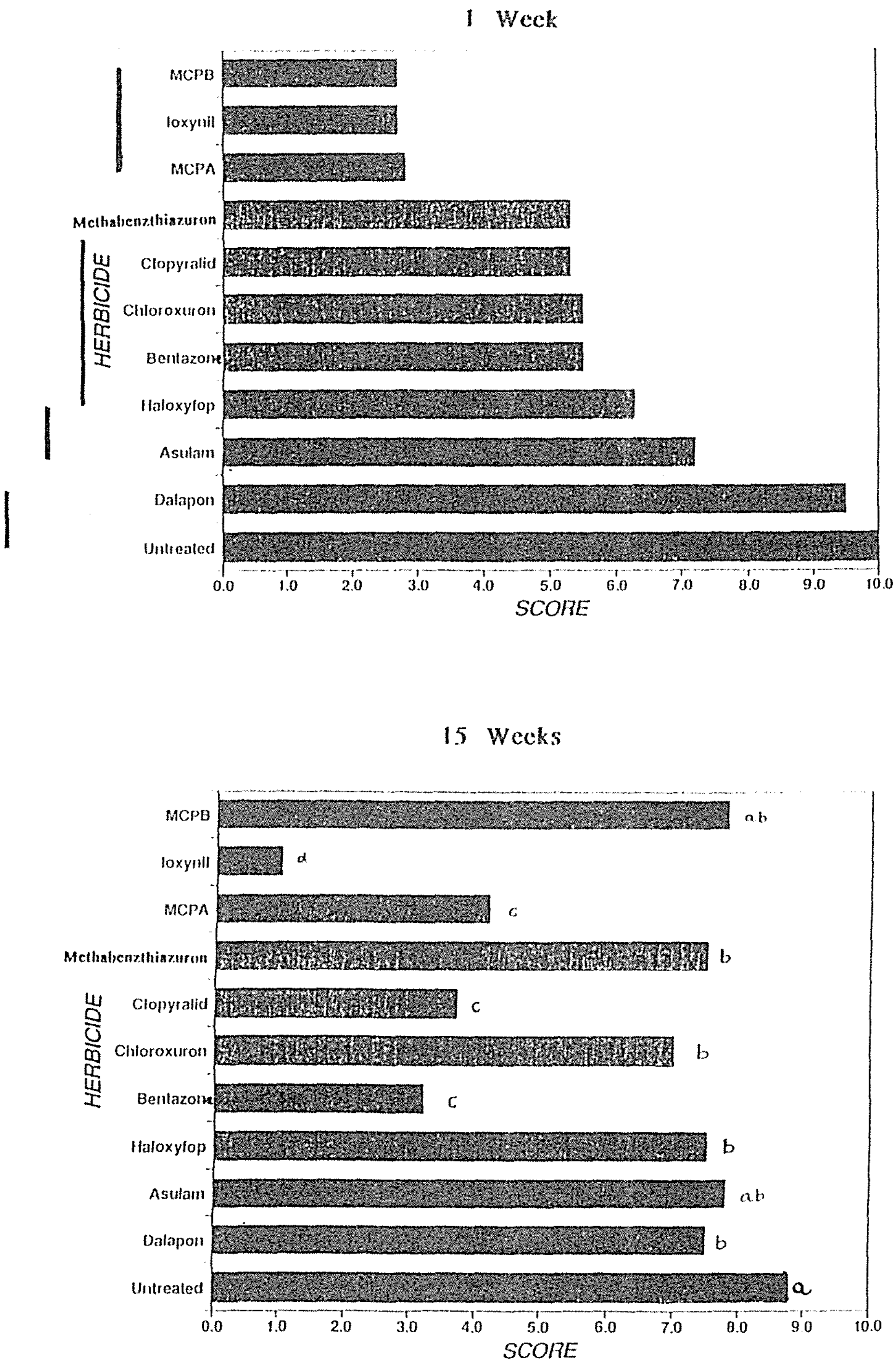


Figure 4.8 Tolerance scores of *T. majus* (cv. Choice Mixed) 1 and 15 weeks after treatment with foliar-applied herbicides. Scores ranged from 0 (total death) to 10 (very healthy). Treatments joined by vertical bars are not significantly different (P<0.05).

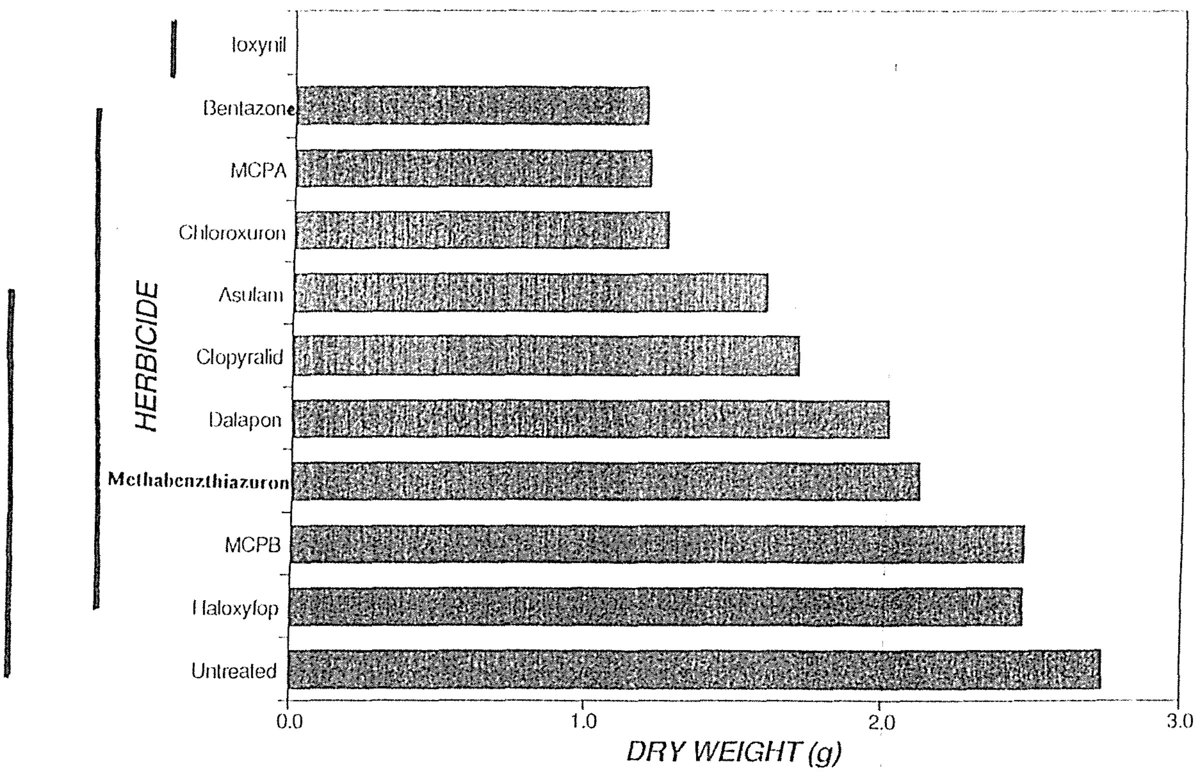


Figure 4.9 Total plant dry weight for *T. majus* at final assessment (cv. Choice Mixed) for foliar-applied herbicides to 5-7 leaf stages seedlings. Scores ranged form 0 (total death) to 10 (very healthy). Treatments joined by vertical bars are not significantly different (P<0.05).

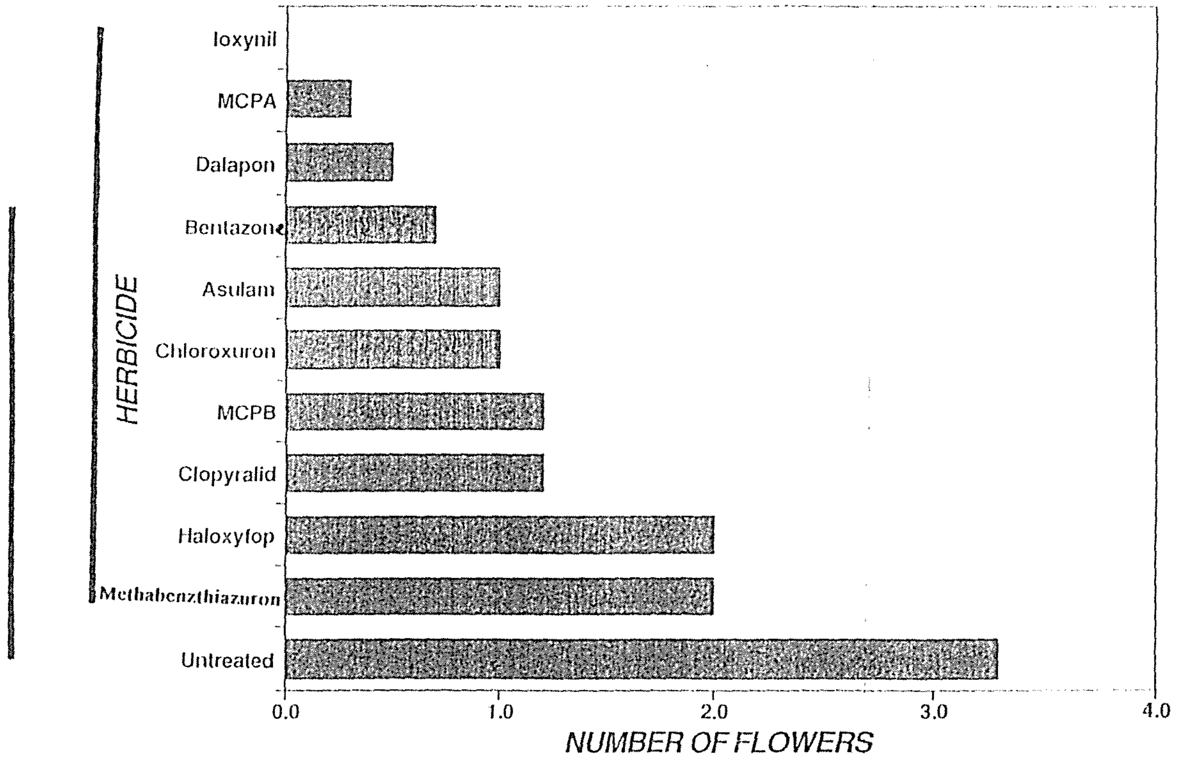


Figure 4.10 Effects of foliage applied herbicide on flower number for *T. majus* (cv. Choice Mixed) at final harvest. Scores ranged from 0 (total death) to 10 (very healthy). Treatments joined by vertical bars are not significantly different ($P < 0.05$).

4.6 DISCUSSION AND CONCLUSION

Evaluation of the activity of various herbicides on *Tropaeolum majus* must take into account possible toxicity both from foliage and root uptake. Because of the lack of information about selective herbicides suitable for use on nasturtiums, pot trials are a useful way to screen the selectivity of a large numbers of both soil and foliar-applied herbicides that might be safe to the crop. This method also requires much less land than plot experiments.

Interpretation of the results must of course take into account a number of factors such as dose of herbicide required for weed control, timing of application, acceptability of crop damage and for sand culture tests, soil availability, mobility and persistence. Phytotoxicity of treatments was recorded mainly as vigour scores, plant dry weights, and number of flowers. The number of flowers provided the best prediction of potential seed yield as the lack of pollinating agents in the glasshouse limited further seed development.

4.6.1 Soil applied herbicides for direct sown nasturtium

The preliminary trial with soil-applied herbicides resulted in elimination of Chlormethazole, Simazine, Metribuzin, Diuron and Terbacil from further evaluation due to their significantly adverse effect on germinating nasturtiums.

Results from both trials showed that pre-emergence applications of oryzalin, trifluralin, chlorpropham and alachlor caused little damage to nasturtium seedlings.

However oxyfluorfen and oxadiazon applied at a rate of 0.72 and 1.6 kg ai/ha respectively caused severe damage to nasturtium seedlings grown in soil but caused minimal damage to plants grown in a peat/sand mixture. Lamont and O'Connell (1986) showed that oxyfluorfen produced severe leaf scorching within 3 days of its application in species of aster (*Aster chinensis*), zinnia (*Zinnia elegans*), helichrysum (*Helichrysum brackteatum*), gysophila (*Gysophila elegans*) but not carnation (*Dianthus caryophyllous*), and that shoot dry weights of these scorched plants, except chrysanthemum (*Chrysanthemum morifolium*) at rate of (rates - 2 l ai/ha) were significantly lower ($P<0.05$) than control plants. Oxadiazon also produced obvious scorching in all species except carnation. Aster, chrysanthemum and gysophila recovered but zinnia was significantly reduced ($P<0.05$). The greatest damage of nasturtiums by these two chemicals when grown in soil may be related to their respective properties. Both are contact herbicides with medium-long residual life in soils low in organic matter (O'Connor, 1990). They are best applied to bare moist soil and to be effective as a residual treatment, they must cover the soil surface in an uninterrupted layer. Emerging weeds contact the chemical layer as they break the soil surface and chemical is taken up by the emerging shoot. The difference in texture between the soil and sand/peat mixture may explain the differences in results with these two herbicides. The soil probably had more micropores, increasing the capillary action which carried moisture to the surface and maintained the active chemical layer to allow effective control. In the peat/sand mixture, a loose structure with larger soil macropores may have reduced the capillary action, allowing the surface to dry out and therefore reducing the effectiveness of the herbicides.

Trifluralin applied at 0.8 kg ai/ha and alachlor at 2 kg ai/ha showed significant ($P<0.05$) effects on crop vigour only at the early stages after emergence, total dry weight and flower number in the soil pots but a significant reduction in total dry weights and flower numbers ($P < 0.05$) in sand/peat pots. Chlorpropham and Oryzalin were the best treatments, causing no significant decrease in crop vigour, dry weight or flower number.

Trifluralin, Alachlor and Oxiadiazon caused significant reduction in flower numbers only for plants grown in peat/sand mixture the but not the vigour scores ($P > 0.05$) and soil pots. They also caused significant reduction in stem length in peat/sand mixture. Effect of weeds present at untreated soil pots caused a significant reduction in dry weight and stem length. In the soil applied herbicides used, the most promising ones were chlorporpham, oryzalin, trifluralin and alachlor. These are recommended for further field trials as they appear not to be phytotoxic. Oxadiazon has also shown obvious scorching in a range of species except carnation. Aster, chrysanthemum and gysophila recovered but zinnia was significantly reduced ($P < 0.05$). The greatest damage of nasturtiums by these two chemicals when grown in soil may be related to their respective properties. Both are contact herbicides with medium-long residual life in soils low in organic matter (O'Connor, 1990). They are best applied to bare moist soil and to be effective as a residual treatment, they must cover the soil surface in an uninterrupted layer. Emerging weeds contact the chemical layer as they break the soil surface and chemical is taken up by the emerging shoot. The difference in texture between the soil and sand/peat mixture may explain the differences in results with these two herbicides. The soil probably had more micropores, increasing the capillary action which carried moisture to the surface and maintained the active chemical layer to allow effective control. In the peat/sand mixture, a loose structure with larger soil macropores may have reduced the capillary action, allowing the surface to dry out and therefore reducing the effectiveness of the herbicides.

These herbicides are recommended for further field trials, however, since they appeared not to be phytotoxic to nasturtiums. Even though some of these herbicides had a significant effect on flower number in the sand/peat mix results from the soil pots will probably give a better prediction of their effect on seed yield in the field. Trifluralin and Oryzalin are two of the top three herbicides recommended for use in ornamentals (based on price, weed control and registration) (Molinar, 1987). Both control many grasses and broadleaved weeds successfully. Oryzalin however has an advantage in terms of management because watering is not necessary for up to 3 weeks after application and it can provide effective residual control activity up to 8 months depending on the rate. Trifluralin, however provides residual weed control for 4-6 months and is registered for a large number of ornamental species. Duzmal (1989) showed that trifluralin applied at 3-4 kg ai/ha can maximize seed yield in *Antirrhinum majus, C. chinesis* and *Zinnia elegans*. Alachlor use for successful pre-emergence weed control of grasses in sunflower up to 94% without damaging to crop at a rate of 3 l/ha (Durigan and Motta, 1989) and also in to red pepper (Stater *et al.*, 1991). Chlorpropham can be successfully used for selective control of grasses, dock seedlings, chickweed and a wide range of other weed species in daffodils and tulips at rates of 6-11 litres/ha in 200 l of water/ha (O'Connor, 1990).

4.6.2 Herbicides for post-emergence weed control

The evaluation of some post-emergence or foliage applied herbicides on *Tropaeolum majus* in this experiment showed variation in plant response to the different treatments. Ioxynil applied at a rate of 0.67 kg ai/ha was the most damaging to nasturtiums, causing plants to die. This generally confirms the fact that ioxynil is specifically useful for broadleaf weed control in monocotyledonous crops such as garlic and onions (Alirzaev, 1989 ; O'Connor, 1990). MCPA, Bentazone, and Clopyralid applied at rates of 1.5, 1.4 and 0.3 kg ai/ha respectively also caused significant levels of damage to nasturtiums though less than with Ioxynil. These herbicides are also commonly used for broadleaved weeds control in grasses and monocotyledons seed crops (O'Connor, 1990).

Methabenthiazuron and Haloxyfop applied at 1.4 and 0.3 kg ai/ha respectively caused a slight reduction in plant vigour tolerance but did not affect final dry weight and flower number. Chloroxuron (4 kg ai/ha) also reduced vigour tolerance slightly but resulted in a significant reduction in final plant dry weight. MCPB caused severe damage initially but treated plants recovered and there was no effect on the final vigour score, dry weight or flower number. Dalapon at a rate of 4.4. kg ai/ha also showed no effects on vigour tolerance or dry weight but significantly caused a reduction in flower numbers produced. Asulam at 1.6 kg ai/ha caused no significant reduction ($P>0.05$) on final nasturtium dry weight or flower numbers though vigour was reduced for some the first four weeks after application.

One important aspect of proper management of a commercial seed crop is the cost of production. By looking at the respective costs of the more promising herbicides, growers can determine the cheapest herbicides for weed control, though this also depends on the type of weeds present and plant growth stage. Table 4.5 shows the cost per hectare using the tested application rates for the various herbicides which looked promising from these experiments.

Table 4.8 The relative costs of herbicides recommended to be safe for selective weed control in nasturtiums (cv. Choice Mixed).

HERBICIDE	TRADE NAME	RATE l/ha	COST $/ha
Soil-Applied			
Chlorpropham	Chloro-IPC	8	145.30
Alachlor	Shell Alachlor	4	59.54
Orzyalin	Surflan	4	147.90
Trifluralin	Treflan	2	19.78
Foliage-Applied			
Asulam	Asulox	4	86.00
Haloxyfop	Gallant	3	108.10
Methabenzthiazuron	Tribunil	2	110.55
MCPB	IWD MCPB	4	30.30
*Chloroxuron	Tenoran	8	

*- herbicide no longer available on market

While definite recommendations can not be made without further field testing the findings of this research do provide some useful leads. It is suggested that growers should design a weed control programme for nasturtiums using cost/benefit analysis.

For example, cheapest pre-emergence weed control can be achieved using trifluralin or/and alachlor both of which control a wide range of annual grasses and broadleaf weeds during establishment of nasturtiums. For post-emergence weed control MCPB can be effective in controlling broadleaf weeds, haloxyfop for grass weeds control and asulox for spot spraying of docks or bracken. From observation in the field density trial nasturtiums are very quick to establish, vigorous early growth enabling the plant to develop a well spread canopy suppressing most late developing weeds. It is only during crop establishment that weed control is critical so most weed control strategy should depend on successful pre-emergence soil-applied herbicides, with foliar-applied herbicides being applied later if needed.

In conclusion, on direct sown crops, nasturtium showed high tolerance to trifluralin, chlorpropham, alachlor and oryzalin. None of these pre-emergence herbicides reduced nasturtium emergence, growth or seed yield. From the foliar applied herbicides used in this study asulam, haloxyfop, MCPB and methabenzthiazuron were all shown to be safe post-emergence herbicides on nasturtiums.

CHAPTER 5

GENERAL DISCUSSION AND CONCLUSION

Nasturtium is a relatively new flower crop to New Zealand but rather popular in South America and highly valued for its showy foliage and flowers, and ease of culture (Rowell, 1986), main growth features are its rapid establishment and vigorous trailing ability along with a long flowering season. It is a crop which can be used both as an ornamental and vegetable plant (Macoboy, 1986). An understanding of plant development and the effects of environment are both important for successful seed production (Langer, 1984). There have been very few publication on flower crop seed production most of which have been dominated with the production of high quality plants at specified growth stages such as vigorous seedlings for the nursery trade (Mastalerz and Holcomb, 1985), prolific flowering for pot plants (Boodley, 1981) and large flowers of high quality and long vaselife for cutting, (Larson, 1980). The information obtained in this study are intended to be of agronomic and hopefully of economic value to nasturtium seed production as there is no detailed work on seed production, particularly in relation to plant density and herbicide usage for weed control in this species.

The information on effect of plant density on vegetative growth and reproductive development, seed yield and quality in *Tropaeolum majus* cv. Choice Mixed grown under field conditions are presented in Chapter 2.

The effect of plant population density on plant structure, vegetative morphology and seed yield was strikingly. From the field experiment increasing density from 3 to 45 plants per m^2 reduced total plant dry weight, leaf area, leaf dry weight, leaf number, number of secondary and tertiary branches, and flower number per plant. However, when yields were converted to a unit area basis these parameters showed no significant difference at this wide range of different plant densities. The most distinctive effect of competition on plant morphology was showed by the restriction of secondary branch development at 45 pl/m^2 as a direct result of competition. Plants grown at low density (3 pl/m^2) showed the greatest branch development with higher numbers and length of secondary branches, and maximum leaf number per plant followed by increased leaf area and subsequently plant dry weight.

In nasturtiums different seed yields per plant between densities were due to differences in plant branching capacity. At the lowest density (3 pl/m^2) of cv. Choice Mixed had about 7 secondary branches and 65 tertiary branches producing a maximum seed yield of 61.9 g/pl at 40 days after peak flowering. At the highest density planting (45 pl/m^2) only 7 total branches were produced and maximum yield at 40 days after peak flowering was only 3.98 grams per plant. So, increasing plant density resulted in decreased seed yield per plant. Despite this seed yield per unit area was similar at all densities. This is contrast to density effects reported in other plants such as marigold (Bhati and Chitkara, 1988), carrot (Hiller and Kelly, 1985) and cowpea (Kwapata and Hall, 1990) in which high density planting yield per unit area was higher than at lower densities. In flowering pot plants and cut flower crops there are many reports of the effects of plant spacing on growth and yield for flowering production. For example, in marigold (*Tagetes erecta*) flower yield per plant was highest at a wide spacing (50cm x 50cm) but yield per unit area was highest at closer spacing (40cm x 40cm). Armitage (1987) also reported that plant density had a major effect on some field-grown perennial crops (Achillia Coronation Gold, *Physostegia virginiana* L., seed yield was strikingly. From the field experiment increasing density from 3 to 45 plants per m^2 reduced total plant dry weight, leaf area, leaf dry weight, leaf number, number of secondary and tertiary branches, and flower number per plant. However, when yields were converted to a unit area basis these parameters showed no significant difference at this wide range of different plant densities. The most distinctive effect of competition on plant morphology was showed by the restriction of secondary branch development at 45 pl/m^2 as a direct result of competition. Plants grown at low density (3 pl/m^2) showed the greatest branch development with higher numbers and length of secondary branches, and maximum leaf number per plant followed by increased leaf area and subsequently plant dry weight.

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The protracted flowering pattern and subsequent seed shattering which occurs in *Tropaeolum majus* identified by Boulton (1986) is the major obstacle to recovering high seed yield. In seed production practice these aspects make the precise determination of the correct time to harvest the crop an important management decision to achieve maximum harvestable seed. It seems logical that more informative on seed yield components could assist in determining a suitable index for deciding information on changes in yield components during the six month flowering period.

The results presented clearly show that the number of flowers has the greatest single influence on seed yield in *Tropaeolum majus* since the greatest fluctuation occurs in this components during the whole flowering period. Other seed yield components showed comparatively little change, and remained relatively constant throughout. This suggests that the number of flowers could well be used as a guideline for deciding optimum harvest timing.

Sequential flowering in nasturtiums caused seed yield to be spread over a long period. Each harvest may reduce seed yield because of the presence of immature seeds and seeds of different maturity stage. Protracted flowering is created by the continuous shoot growth of main stems and their respective lateral branches with a sequential development of flowers and seeds along the shoot. So, production of new nodes in branch development is a continuous process which sustains the lengthy flowering period. For this reason, the manipulation of branches and shoot status seems to be a realistic approach in attempting to improve seed production in nasturtium.

The seed development study (Chapter 3) showed that approximately 30 to 40 days are required from blooming for nasturtium flowers to develop into mature seeds ready for harvesting. It is recognised that highest maximum seed yield recovery in the field for once over harvest could be achieved about 35 to 45 days after maximum flowers are observed. Harvesting before this stage results in lower seed yield and a higher proportion of immature seeds. Later harvesting reduces seed yield due to extensive seed shedding. Seeds achieved physiological maturity at 40-50 days after pollination and shed at a very high seed moisture content of 78-80%. Maximum germinability was achieved at 30 DAP while seed viability reached a maximum at 40-50 DAP. Post harvest dormancy occurred in seed at maturity resulting in a drop in laboratory germination percentage.

Weeds are always present in nasturtium crops and often reduce yield substantially in terms of seed production. The lack of any selective herbicide recommendation on chemical weed control in nasturtiums suggested the need to evaluate a range of soil and foliar applied herbicide in the glasshouse (Chapter 4) to assess the tolerance of nasturtium to herbicide. Four pre-emergence chemicals, chlorpropham (3.2 kg ai/ha), alachlor (2 kg ai/ha), oryzalin (3 kg ai/ha) and trifluralin (0.8 kg ai/ha) were considered to be most successful and are recommended for direct sown nasturtium crops. Nasturtium seedlings were most resistant to the application of asulam (1.6 kg ai/ha), haloxyfop (0.3 kg ai/ha), methabenzthiazuron (1.4 kg ai/ha) and MCPB (1.6 kg ai/ha).

5.1 Possibility for producing *Tropaeolum majus* in New Zealand

The findings from this study suggest that *Tropaeolum majus* could be grown for seed in New Zealand in the summer season or later frost free areas. Seed yield can obviously be increased through suitable management but information is still scarce, and more research is required. Nasturtium could be best direct sown into the field providing the seedbed was well prepared (Chapter 2) and effective weed control is maintained either by hand weeding or by selective herbicides (Chapter 4), particularly during the establishment phase 4 to 6 weeks after sowing.

Nasturtium grows well in warm temperature areas and is a crop with a high 'ease of management' requiring little or no fertilizer or irrigation in most situations. The best time to sow would be from late October to early November. Seedling emergence occurs 10-14 days after sowing; floral bud initiation at 55 days after sowing; and flowering commences at 65 days after sowing to reach peak flowering around late January to early February.

Correct harvest time is still a problem due to seed shedding and if machine harvesting is desired this obviously requires further research. However, as a guideline, seeds may be harvested 30-39 days after peak flowering (for cv. Choice Mixed) before seeds start shedding.

Recommendations of optimum plant density for seed production from a commercial point of view would be based on the cost of production associated with each density. Using this criterion a low plant density of 3 pl/m^2 provided the most economic returns, with less seeds being used to produce maximum yield even though weeds at establishment phase would be a problem due to wider spacing. At high densities, plants rapidly form canopies which smother and control upcoming weeds effectively. In terms of the cost of extra seeds used for similar returns however, a combination of low density (3 pl/m^2) with selective herbicides applied pre-emergence would be more economic than using high density plantings of 45 pl/m^2 without herbicides. For example, 3 pl/m^2 equals 30000 pl/ha compared to 45 pl/m^2 with a total of 450000 pl/ha (a 15-fold difference). The high cost of seeds (approximately 10c each) at increasing plant density far outweighs the cost of herbicides needed at lower densities. The present study has therefore lead to a recommendation for *Tropaeolum majus* seed production in New Zealand which is to sow at a density of 3 pl/m^2 combined with pre-emergence weed control using trifluralin (0.8 kg ai/ha) or alachlor (2 kg ai/ha) plus post-emergence application of MCPB (1.6 kg ai/ha) or asulam (1.6 kg ai/ha) if needed. This recommendation has an associate seed and herbicide cost structure of $/ha compared with $/ha at a high density of 45 pl/m^2:

a. Low density + Herbicides

30000 pl/ha x 10c per seed + trifluralin ($19.80) = $3019

b. High density - Herbicides

450000 pl/ha x 10c per seed = $45000

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APPENDICES

Appendix 2.1 Soil test results (Fertilizer & Lime Research Centre, Massey University, New Zealand).

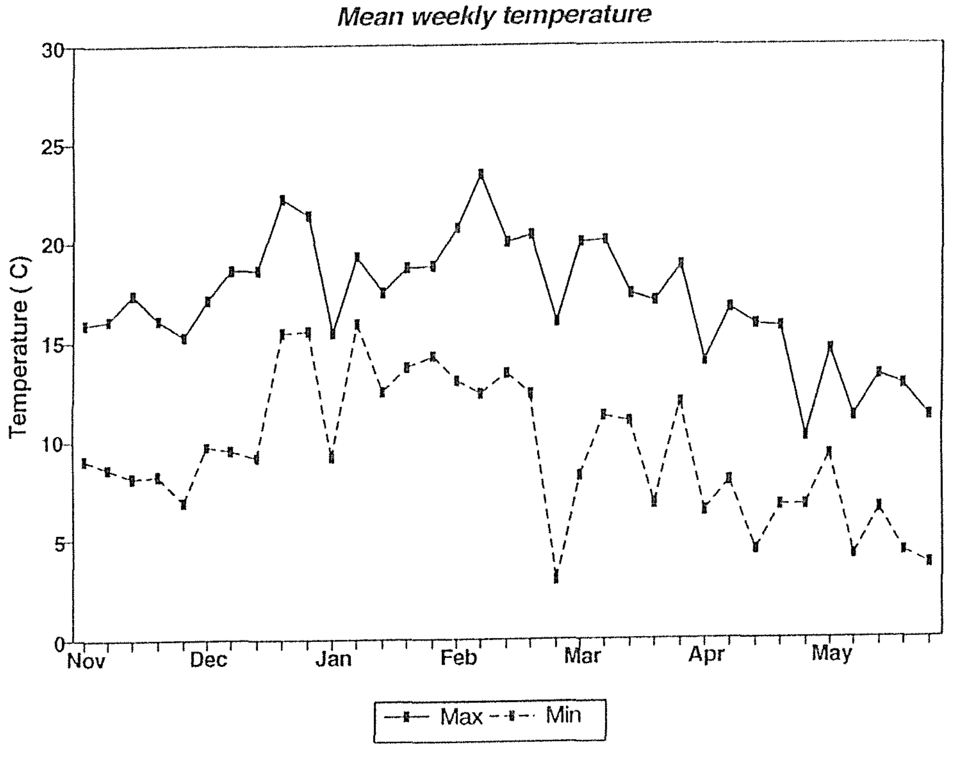
Element	Figure Obtained
	6.7
Olsen P	51
SO_4	9.5
Exchange K	0.37
Exchange Ca	14.1
Exchange Mg	0.61
Exchange Na	0.32
CEC	17

Phosphate and sulphate values are expressed as micrograms per gram (air-dry). Exchangeable cations and CEC values are expressed as meq/100 grams (air-dry).

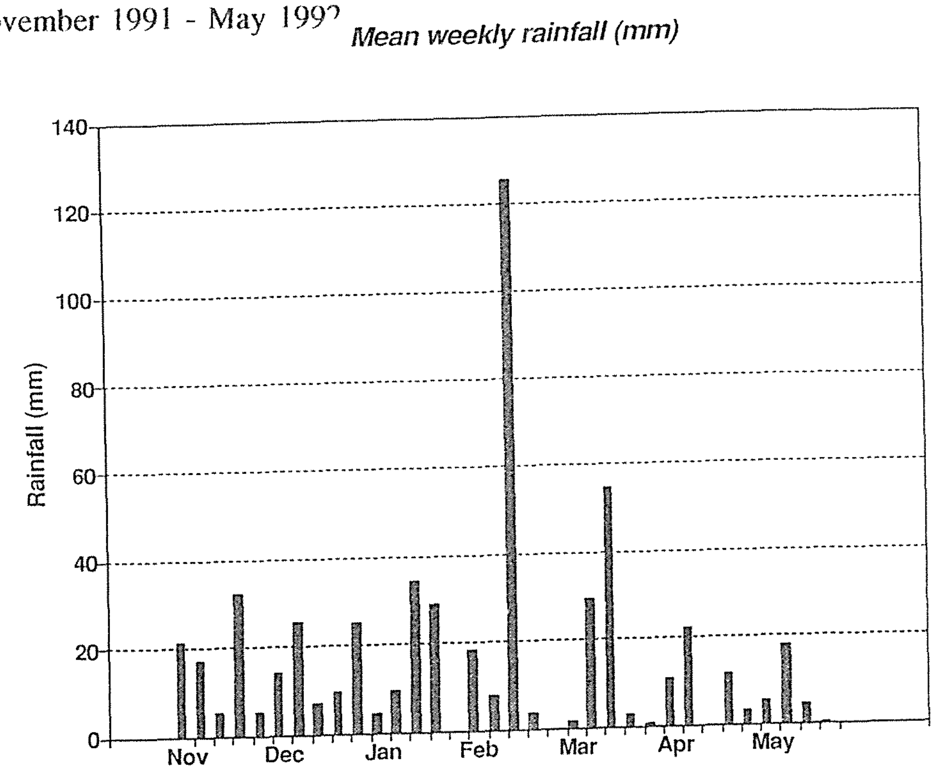
Appendix 2.2 Description of Tokomaru silt loam soil (Cowie, 1978). Soils and Agriculture of Kairanga Country, North Island, New Zealand. **NZ. Soil Bureau Bulletin** 33:92.

Tokomaru silt loam soil is a moderately leached and moderately acid soil, classified as a yellow grey earth (Typic fragiaquaf) derived from a parent material of lightly consolidated siltstone or fine sandstone (Late tertiary or Pleistocene in age). It is composed of a 15-20 cm deep grey, friable topsoil and a 15-20 cm deep pale yellow firm subsoil with a yellowish brown compact third horizon.

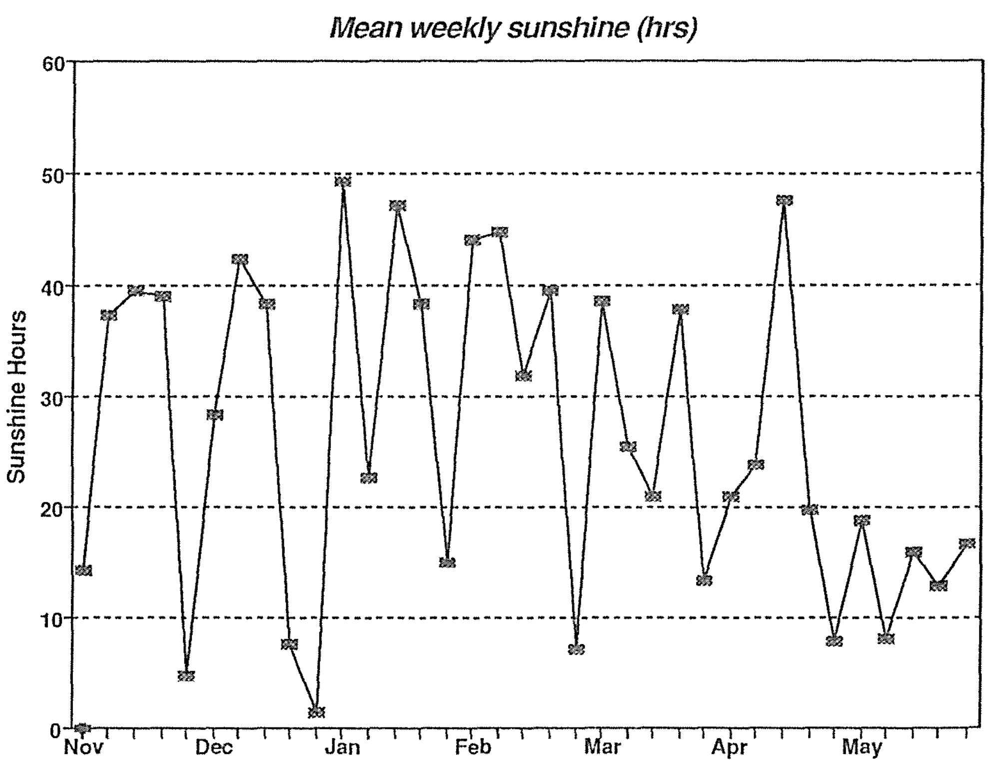
Appendix 2.3 Weekly temperature at Palmerston North, New Zealand during November 1991 - May 1992.



Appendix 2.4 Mean weekly rainfall at Palmerston North, New Zealand during November 1991 - May 1992



Appendix 2.5 Mean weekly sunshine period at Palmerston North, New Zealand during November 1991 - May 1992.



Appendix 3.1 Seed development data summary.

Stage	1	2	3	4	5	6
DAP	10	20	30	40	50	60
100 SFW (g)	26.8	40.6	49.8	66.4	66.2	60.1
100 SDW (g)	3.06	6.20	9.08	14.4	14.7	14.7
% SMC	88.6	84.7	81.7	78.3	77.8	75.5
% Germination	0	2	64	9	2	0
% Viability	0	8	72	91	92	92
% Fresh Ungerm.	0	0	28	83	88	91
% TZ Viability	0	13.3	83	88.3	93.3	93.3