

**EFFECTS OF DIFFERENT HARVEST START TIMES
ON LEAFY VEGETABLES (LETTUCE, PAK CHOI AND
ROCKET) IN A REAPING AND REGROWTH SYSTEM**

A thesis
submitted in partial fulfilment
of the requirements of the Degree of
Master of Agriculture Science

at

Lincoln University

by

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Lincoln University

2008

Abstract of a thesis submitted in partial fulfilment of the requirements for the Degree of M.Agr.Sc.

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Leafy vegetables, lettuce (*Lactuca sativa* L. cv. Green Oakleaf), pak choy (*Brassica sinensis* L. cv. Oriental Taisai) and rocket (*Eruca sativa* L.), were planted in an open field at Lincoln University on January 2005. Plants were harvested at 5 cm cutting height above the growing point with three different harvest start times, early start (ES), mid start (MS) and late start (LS) of harvest respectively. There were three harvests during the growing season with a 4-week interval between harvests.

Generally, lettuce produced significantly higher total FW/plant (208 g) than pak choy or rocket (123 and 102 g total FW/plant, respectively). Lettuce also produced significantly higher total FW/plant than pak choy or rocket in each treatment.

Lettuce produced significantly more total saleable leaf FW/plant in the ES, MS and LS treatment (137.5, 120.9 and 169.3 g FW/plant), compared with pak choy (52.9, 100 and 92 g FW/plant) or rocket (31.5, 92.2 and 56.4 g FW/plant). Pak choy produced higher total saleable leaf FW/plant than rocket in the ES and LS treatments, but a similar total saleable leaf FW/plant in the MS treatment.

The best time to start harvesting was the LS treatment for lettuce, while pak choy and rocket produced better yields in the MS and LS treatments.

Results for total DW/plant showed that different harvest start times did not affect the total DW/plant in lettuce. However, pak choy and rocket produced less total DW/plant in the ES treatment compared to the MS or LS treatments. This was due to a faster

recovery by lettuce. In addition, lettuce produced significantly higher DW/plant during regrowth at the second and third harvests than pak choi or rocket, even though it was significantly lower at the first harvest. It is likely that after harvesting greater carbohydrate reserves and greater remaining leaf area produced greater regrowth potential in lettuce. These results suggest that lettuce has the most regrowth potential, while rocket has more than pak choi in this reaping and regrowth system.

When plants were harvested at the same cutting level, lettuce had the most remaining leaf area of the three species. This remaining leaf area for lettuce could be another reason for faster recovery and more regrowth potential. More reserves and remaining leaf area may also be the reason for more regrowth potential in rocket compared to pak choi.

Another important reason for the better performance of lettuce was that temperatures during the growing season were in the range of optimum temperatures (12-21 °C), except for the regrowth between the second and third harvests in the LS. This relates to higher photosynthetic rates and in turn leads to faster recovery and regrowth.

Lettuce was the most suitable crop in the reaping and regrowth system in this experiment. However, rocket might also be appropriate for this system, particularly if the price is high enough to make it economically viable.

Keywords: leafy vegetable, reaping and regrowth, reserve, carbohydrate, remaining leaf area, thermal time.

Preface

To My Beloved Family

“Mother, father and sister, I am lucky of being one of our family.” Thank you for your support. I am also thanking Guolong Zhang.

Contents

	Page
Abstract.....	ii
Preface.....	iv
Contents.....	v
List of Tables.....	viii
List of Figures.....	x
1.0 Introduction.....	13
2.0 Literature Review.....	16
2.1 Introduction.....	16
2.2 Salad products.....	17
2.3 The reaping and regrowth system of production.....	17
2.4 The use of reaping and regrowth system in tea.....	20
2.5 The use of reaping and regrowth system in salad vegetables.....	20
2.6 Factors affecting regrowth.....	21
2.6.1 The effect of temperature on regrowth.....	21
2.6.2 The effects of light on regrowth.....	25
2.6.3 The effects of water stress on regrowth.....	29
2.6.4 The effects of plant residue on regrowth.....	31
2.7 The course of plant development.....	34
3.0 Materials and Methods.....	35
3.1 Materials.....	35
3.2 Experimental design.....	35
3.3 Sampling.....	36

3.4	Measurements.....	36
3.5	Statistical tests.....	37
4.0	Results.....	38
4.1	The daily mean temperature during the growing season.....	38
4.2	Total fresh and dry weight of lettuce, pak choi and rocket.....	40
4.3	Fresh weight per plant at each harvest after early, mid and late starts of harvest.....	44
4.4	Saleable leaf fresh weight per plant and percentages of saleable leaves at each harvest after early, mid and late starts of harvest.....	47
4.5	Dry weight per plant at each harvest after early, mid and late starts of harvest...53	
4.6	Leaf area index (LAI) and leaf number per plant (LN/plant) at each harvest after early, mid and late starts of harvest.....	59
4.7	Effects of thermal time on accumulated dry weight per plant and accumulated leaf number per plant of lettuce, pak choi and rocket during the growing season at early, mid and late starts of harvest.....	67
5.0	Discussion.....	71
5.1	Effects of different harvest start times on yield.....	71
5.2	Effects of different harvest start times on DW/plant at each harvest.....	75
5.3	Effects of different harvest start times on saleable leaves at each harvest.....	79
5.4	Effects of different harvest start time on plant development.....	80
5.4.1	Effects of different harvest start time on leaf area index at each harvest.....	80
5.4.2	Effects of different harvest start time on leaf number per plant at each harvest.....	84
5.5	The most suitable crop of lettuce, pak choi and rocket in the reaping and regrowth system.....	89
5.5.1	Comparisons between lettuce, pak choi and rocket in fresh weight per plant...89	
5.5.2	Comparisons between lettuce, pak choi and rocket in saleable leaf fresh weight per plant.....	89
5.5.3	Comparisons between lettuce, pak choi and rocket in regrowth potential (DW/plant).....	90

6.0	Conclusions.....	91
7.0	Recommendations for Further Research.....	92
8.0	Acknowledgements.....	93
9.0	References.....	94

List of Tables

	Page
Table 2.1. Examples of reaping and regrowth systems of production.....	19
Table 4.1. The maximum, minimum and mean temperatures in each month during the growing season from 7 th February to 27 th April in 2005.....	39
Table 4.2. The effect of different starts of harvest times on total fresh and dry yield (g/m ²) and total fresh and dry weight (g/plant) of lettuce, pak choi and rocket.....	40
Table 4.3. Total FW/plant of lettuce, pak choi and rocket either in an early, mid or late start of harvest (p<0.05, SEM=15.97).....	43
Table 4.4. Total saleable leaf fresh weight per plant (g FW/plant) of lettuce, pak choi and rocket either in an early, mid or late start of harvest (p<0.05, SEM=12.84).....	43
Table 4.5. Saleable leaf fresh weight per plant (g) of lettuce, pak choi and rocket harvested at three different times during the growing season after either early, mid or late start of harvest.....	47
Table 4.6. Percentages of saleable leaves of lettuce, pak choi and rocket harvested at three different times during the growing season after either early, mid or late start of harvest.....	48
Table 4.7. Percentages of saleable leaves of lettuce, pak choi and rocket at each harvest at either an early, mid or late start of harvest (p<0.001, SEM=2.891).....	49
Table 4.8. Dry weight per plant (g) of lettuce, pak choi and rocket harvested at three different times during the growing season after either early, mid or late start of harvest.....	53
Table 4.9. Leaf area index (LAI) of lettuce, pak choi and rocket harvested at three different times during the growing season after either early, mid or late start of harvest.....	59
Table 4.10. Leaf number per plant of lettuce, pak choi and rocket harvested at three different times during the growing season after either early, mid or late start of harvest.....	63
Table 4.11. The phyllochron of lettuce, pak choi and rocket over the growing season.....	69
Table 4.12. The phyllochrons of lettuce, pak choi and rocket at each harvest at either an early, mid or late start of harvest.....	69

Table 4.13. The thermal time experienced by lettuce, pak choi and rocket for each harvest with either an early, mid and late start of harvest (°Cd).....	70
Table 5.1 Description of acronyms used to represent each field-season combination and the symbols used in figures to represent each field-season-treatment combination (Brown et al., 2005).....	86

List of Figures

	Page
Figure 1.1. Vegetable exports between 1996 and 2007 (\$ million, fob) (HortResearch, 2007).....	13
Figure 2.1. Outline of the reaping and regrowth system of two plant types of Vegetables (Takagaki et al., 2003).....	18
Figure 2.2. Influence of temperature on the rates of gross photosynthesis, respiration and net photosynthesis (Hay and Walker, 1989).....	24
Figure 2.3. Ground cover percentage of lettuce as a function of the leaf area index (LAI). Symbols: observed data. Solid line: fitted logistic function over the two years ($y=99.38/(1+19.03 \exp(-0.772))$, $R^2=0.99$) (Beccafichi et al., 2003).....	26
Figure 2.4. Percentage intercepted photosynthetically active radiation (PAR) of lettuce in relation to leaf area index (LAI) over all the fertiliser-N rates and two years (●, 1997; ○, 1999) (Tei et al., 2003).....	27
Figure 2.5. Relation between cumulative dry weight (g m^{-2}) and intercepted photosynthetically active radiation (PAR) (MJ m^{-2}) in lettuce. Symbols: observed data. Solid line is the linear relationship over densities and years ($y=-1.82 + 2.71x$, $R^2=0.99$). The slope is the radiation use efficiency (g DWt/MJ PAR) (Beccafichi et al., 2003).....	27
Figure 2.6. Changes in total plant weight of tall fescue during a 20—day regrowth period after treatment (HC, high reserve carbohydrates; LC, low reserve carbohydrates; HL, high residual leaf area; and LL, low residual leaf area) (Booyesen and Nelson, 1975).....	33
Figure 2.7 Diagrammatic presentation of the course of development of cultivated angiosperms (Krug, 1997).....	34
Figure 4.1. Daily mean air temperature from 7 th January to 27 th April in 2005.....	38
Figure 4.2. The interaction of harvest start time and variety on total dry yield per m^2 (Bars: SEM=23.94).....	41
Figure 4.3. The interaction of harvest start time and variety on total dry weight per plant (Bars: SEM=0.96).....	42
Figure 4.4. Lettuce fresh weight per plant harvested three times after either an early, mid or late start of harvest (SEM=8.12).....	44
Figure 4.5. Pak choi fresh weight per plant harvested three times after either an	

early, mid or late start of harvest (SEM=8.12).....	45
Figure 4.6. Rocket fresh weight per plant harvested three times after either an early, mid or late start of harvest (SEM=8.12).....	46
Figure 4.7. Saleable leaf fresh weight per plant of lettuce harvested three times after either an early, mid or late start of harvest (SEM=8.06).....	50
Figure 4.8. Saleable leaf fresh weight per plant of pak choi harvested three times after either an early, mid or late start of harvest (SEM=8.06).....	51
Figure 4.9. Saleable leaf fresh weight per plant of rocket harvested three times after either an early, mid or late start of harvest (SEM=8.06).....	52
Figure 4.10. The interaction of harvest start time and variety on dry weight per plant at the first harvest (Bars: SEM=0.317).....	54
Figure 4.11. The interaction of harvest start time and variety on dry weight per plant at the third harvest (Bars: SEM=0.431).....	55
Figure 4.12. Dry weight per plant of lettuce harvested three times after either an early, mid or late start of harvest (SEM=0.565).....	56
Figure 4.13. Dry weight per plant of pak choi harvested three times after either an early, mid or late start of harvest (SEM=0.565).....	57
Figure 4.14. Dry weight per plant of rocket harvested three times after either an early, mid or late start of harvest (SEM=0.565).....	58
Figure 4.15. Leaf area index (LAI) of lettuce harvested three times after either an early, mid or late start of harvest (SEM=0.125).....	60
Figure 4.16. Leaf area index (LAI) of pak choi harvested three times after either an early, mid or late start of harvest (SEM=0.125).....	61
Figure 4.17. Leaf area index (LAI) of rocket harvested three times after either an early, mid or late start of harvest (SEM=0.125).....	62
Figure 4.18. Leaf number per plant (LN/plant) of lettuce harvested three times after either an early, mid or late start of harvest (SEM=3.59).....	64
Figure 4.19. Leaf number per plant (LN/plant) of pak choi harvested three times after either an early, mid or late start of harvest (SEM=3.59).....	65
Figure 4.20. Leaf number per plant (LN/plant) of rocket harvested three times after either an early, mid or late start of harvest (SEM=3.59).....	66
Figure 4.21. The effect of thermal time on accumulated dry weight per plant of lettuce, pak choi and rocket harvested three times at the early start, mid start and late start of harvest ($T_b=4\text{ }^\circ\text{C}$; Lettuce,	

$y=0.017x-8.9$ $R^2=0.95$; Pak Choi, $y=0.011x-2.85$ $R^2=0.77$;
 Rocket, $y=0.015x-5.8$ $R^2=0.86$).....67

Figure 4.22. The effect of thermal time on accumulated leaf number per plant (LN/plant) of lettuce, pak choi and rocket harvested three times at the early start, mid start and late start of harvest ($T_b=4$ °C; Lettuce, $y=0.116x-54.5$ $R^2=0.95$; Pak Choi, $y=0.038x-13.9$ $R^2=0.93$; Rocket, $y=0.131x-64.1$ $R^2=0.96$).....68

Figure 5.1. Total plant leaf area (TPLA) versus thermal time (TT) for five lines of sunflower (Chapman et al., 1993).....80

Figure 5.2. Average leaf initiation rate (LIR) versus average temperature from emergence to head visible for a series of monthly plantings of Sunfola68-2 at Toowoomba (○) and Biloela (●) (Chapman et al., 1993).....84

Figure 5.3. Main stem node appearance of re-growth ‘Grasslands Kaituna’ lucerne against thermal time (Tt) accumulated from 1 July for crops grown at Lincoln University, Canterbury, New Zealand (see Table 5.1 for symbols). Black arrows mark days of <0 °C frosts, grey arrows indicate start of flowering in two crops (Brown et al., 2005).....85

Figure 5.4. Leaf area index (LAI) in relation to the net number of leaves for regrowth ‘Grasslands Kaituna’ lucerne crops grown at Lincoln University, Canterbury, New Zealand. Note. ☉ = 28 September to 9 November, 2000 (659 stems/m²), ○ = 14 November to 27 December, 2000 (649 stems/m²), ▲ = 1 January to 9 February, 2001 (584 stems/m²), ▼ = 2 February to 14 March, 2001 (593 stems/m²). Linear regressions were fitted to open symbols for spring re-growth cycles with >2000 leaves m⁻² (.....), $a = 0.31(0.20)$, $b = 0.00017(0.00002)$, $R^2 = 0.92$. Closed symbols represent summer with the regression fitted to all values (---) $a = -0.10(0.24)$, $b = 0.00044(0.00004)$, $R^2 = 0.94$ (Brown et al., 2005).....87

1.0 Introduction

Fresh salads can make an important contribution to the human diet. A benefit obtained from eating raw salads is the vitamin content of fresh salad leaves. Vitamins A, B, C, D, and E can be found in varying amounts in many salad plants (Fogg, 1983). Over the last decade, an abundance of research has shown that diets, low in fat and rich in fiber (diets that typically include a liberal consumption of vegetables), are protective against many cancers and lessen the risk of coronary heart disease (Ryder, 1999; Szeto et al., 2001).

In European countries, in 2003, growers produced more than 4 million tonnes of vegetables. Lettuce is a major salad vegetable in every country (Perrier, 2004). In New Zealand, the fresh vegetable sector represents all vegetable crops including alliums, brassicas, leafy crops, roots and tubers, and stalks, vines, bulbs and herbs. In 2007, there were about 3,435 vegetable growers, planting about 55,357 ha, worth around 858.7 \$M and 566.2 \$M for the domestic and export market respectively. There were 306 lettuce growers planting about 1,207 ha in 2007, worth 39.1 \$M and 1.2 \$M for domestic and export market (HortResearch, 2007). The value of vegetable exports increased between 1996 and 2007 as shown in Figure 1.1.

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Figure 1.1. Vegetable exports between 1996 and 2007 (\$ million, fob) (HortResearch, 2007) on pp. 17.

Many supermarkets sell two types of salad vegetables. Firstly buyers can find unprocessed salad vegetables harvested from the field and put directly onto the shelves. These vegetables should be washed and cut before eating. The second type of salad products are the prepared, ready-to-eat, salad vegetables. These vegetables have been harvested, minimally processed, cut and packaged. In New Zealand, mixed and bagged salads, containing several ingredients, can be found in supermarkets. On the other hand, customers can buy well washed and mixed leafy vegetables from a “salad” box. Because of their convenience to the consumer, bagged prepared salads have had rapid year-to-year growth since they were introduced. In New Zealand in 2007, value of the processed vegetable was more than double (about 305.6 \$M) compared to the value in 1996 (about 150 \$M). About 54% of exported vegetables were processed in 2007 (Fig. 1.1). In the United Kingdom between 1995 and 2000, sales of salad vegetables increased from \$US 1,564 million to \$US 1,700 million. In this market sector, prepared salad sales rose from \$US 471 million to \$US 592 million during the same period of time, too (Mintel International group Ltd, 2002).

For some leafy salad vegetables, growers usually harvest the whole plant. The vegetable is sold with little or no processing. Growers maintain a supply of salad vegetables for sale at the market, by repeatedly sowing, growing and harvesting crops.

Alternatively, a reaping and regrowth (RR) system can be used. In this system plants can be cut above the growing point when they meet the market requirements or are ready to harvest. New leaves come up from the growing point in the next two or three days. Harvesting can be repeated when the leaves are ready. In an environment which can satisfy plants’ needs, harvest and regrowth can be practised several times. For example, leaves of lettuce (*Lactuca sativa* L.) and Pak Choi (*Brassica nappa* L.) are able to be produced by this method (Fogg, 1983; Takagaki et al., 2003).

The reaping and regrowth method leads to higher yields with earlier cropping, and less space is needed to produce the same amount of lettuce and Pak Choi. The method can save costs and labour, thus improving the profit. The method parallels the production of grass for animal feeding (Chestnutt, 1994; Beleskey and Fedders, 1995; Fisher and Dowdeswell, 1995).

The residual plant portion, after cutting, will affect the growth of the succeeding leaves (Takagaki et al., 2003). Environmental factors, such as temperature and light, are also important influences affecting regrowth after cutting.

In many instances, plant growth is closely related to the amount of thermal time experienced. Specifically, temperature regimes can affect particular forms of growth and development, for example, the flowering of biennial crops such as lettuce and Chinese cabbage. If the seedlings of lettuce and Chinese cabbage experience a cold period and then more moderate temperatures, rapid flowering or bolting may result.

Light provides energy for the photosynthetic chemical reactions occurring in green leaves. The light intensity and duration will affect dry matter accumulation by influencing photosynthetic activity. Daylength may also influence plant flowering. Exposure to “long days” will induce flowering of lettuce and Chinese cabbage plants that have previously experienced cold (Pressman and Shaked, 1988; Waycott, 1995).

This report presents an investigation on a reaping and regrowth method for producing leafy salad vegetable production under field conditions at Lincoln University, Canterbury, New Zealand. The reaping and regrowth system was used for producing lettuce, Pak Choi and rocket (*Eruca sativa* L.). Few reports of reaping and regrowth systems were found in New Zealand literature. This study was conducted to observe if the system is suitable for Canterbury conditions, and to observe some factors influencing the growth and yield of these three vegetables. The aims of this trial were to determine

- (1) the influence of initial plant size on subsequent production in a RR system;
- (2) the influence of temperature on plant regrowth;
- (3) the species most suited to the “reaping and regrowth” system.

2.0 Literature review

2.1 Introduction

Vegetables, rich in vitamin and fibre, are good for human health. Vegetable salads are popular because they contain more vitamins than cooked vegetables, and salads are easy to make. Also, salads taste delicious.

In recent years, the reaping and regrowth system has been introduced into leafy vegetable production (Maruo et al., 2003; Takagaki et al., 2003; Fogg, 1983). This production system is not new. It has been widely used in grass and tea production (Belesky and Fedders, 1995; Murtagh and Smith, 1996; Bore et al., 2003). In leafy vegetable production, the reaping and regrowth system has been shown to be suitable for leafy salad vegetables, such as lettuce, pak choi, jute (*Corchorus olitorius* L.), sweet basil (*Ocimum basilicum* L.), and Chinese kale (*Brassica oleracea* L.). Growers harvest many times during the crop lifetime. This method (reaping and regrowth) can improve the productivity of leafy vegetables and save time and costs (Maruo et al., 2003; Takagaki et al., 2003). It was shown that lettuce produced about 0.042 kg/m²/day at density of 10×10 cm in the reaping and regrowth system, while it produced under 0.02 kg/m²/day in conventional cultivation (Maruo et al. 2003).

In Japan a study about reaping and regrowth systems showed that the cutting height is important for growth rate and quality especially for shoot type vegetables (Maruo et al., 2003; Takagaki et al., 2003). However, reports about environmental and management effects on vegetable regrowth are not found in popular studies. This chapter reviews the influences of environmental factors and nutrition application on regrowth of leafy vegetables, and the physiological responses to environmental factors and nutrition.

2.2 Salad products

Green leafy salad vegetables in the market can be divided into two types—the whole plant and minimally processed vegetables. The minimally processed salad vegetables bring convenience to customers. Profits can be enhanced through creating convenience during processing providing more benefit to supermarkets and processing plants. The vegetables should be washed, simply cut and packed, ready to eat.

Single leafy vegetable salads are a type of minimally processed vegetable product. This kind of salad vegetable usually has smaller leaves. When these single leaves are reaped, it is not necessary to cut them. Before putting these single leaves onto shelves, a good simple wash is enough. For example, Maruo et al. (2003) pointed out that the products of leafy lettuce harvested in reaping and regrowth system could be distributed directly as cut-vegetables and packing work might also be simplified. In addition, they concluded that the shoot type salad vegetables (such as vegetable jute) can also be produced in this system.

As a kind of processed, ready to eat salad, mesclun or mixed salad can also be found in supermarkets. Mesclun is a salad mix of assorted small, young, salad leaves that may include lettuces, spinach (*Spinacia oleracea* L.), rocket, Swiss chard (*Beta vulgaris* subsp. *Cycla*), mustard (*Brassica Juncea* L.), endive (*Cichorium endivia* L.), dandelion (*Taraxacum officinale* L.) leaves, and/or other leafy vegetables. The name comes from Provençal (Southern France)—mescla, ‘to mix’—and literally means ‘mixture’. The seeds of different leafy vegetables are mixed and sown, and when the mixture of plants is ready to harvest, the leaves will be collected, washed and packed (Phillips and Harrison, 2005; Ryder, 1999).

2.3 The reaping and regrowth system of production

The reaping and regrowth system is a production system that uses the growth habits of those plants, which can regenerate leaves and/or shoots after reaping leaves or shoots. Many harvests can be obtained from one sowing time. For leaf type vegetables, plants

can reproduce leaves when the cutting level is above the growing point. For shoot type vegetables, if the shoots are harvested, new shoots and leaves can regrow from the side growing points (Fig. 2.1) (Maruo et al., 2003; Takagaki et al., 2003). Studies have shown that leaf lettuce (leafy vegetable) and vegetable jute (shoot vegetable) can be successfully produced using a reaping and regrowth system (Maruo et al., 2003).

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Figure 2.1. Outline of the reaping and regrowth system of two plant types of vegetables (Takagaki et al., 2003) on pp. 76.

The reaping and regrowth system is not only feasible for the production of leafy salad vegetables, but has also been used in tea and grass production (Belesky and Fedder, 1995; Fisher and Dowdeswell, 1995; Murtagh and Smith, 1996; Bore et al., 2003). In addition, the system can be applied to other species (Table 2.1).

Table 2.1. Examples of reaping and regrowth systems of production.

System descriptions	Plants used	Typical interval	Author
Croppicing	black locust (<i>Robinia pseudoacacia</i> L.), boxelder (<i>Acer negundo</i> L.), catalpa (<i>Catalpa ovata</i> L.), poplar/cottonwood (<i>Populus deltoides</i> L.)	1, 2 or 5 years	Facciotto et al., 2003; Geyer, 2006; Luxmoore, et al., 2008
Tea harvesting	Eucalyptus (<i>Eucalyptus pellita</i> L.) tea (<i>Camellia sinensis</i> L.)	45 or 90 days	Bore et al., 2003
Ratoon cropping	rice (<i>Oryza sativa</i> L.)	one season	Palchamy et al., 1995
	sorghum (<i>Sorghum bicolor</i> L.)	about 2 months	McCormick et al., 1995
Mesclun	various salad vegetables eg. Lettuce(<i>Lactuca sativa</i> L.), endive (<i>Cichorium endivia</i> L.)	once or twice weekly	Phillips and Harrison, 2005; Ryder, 1999
Vegetables	Amaranthus (<i>Amaranthus cruentus</i> L.), jute (<i>Corchorus olitorius</i> L.), sweet basil (<i>Ocimum basilicum</i> L.), lettuce(<i>Lactuca sativa</i> L.), pak choi (<i>Brassica campestris</i> L.), Chinese kale (<i>Brassica oleracea</i> L.), Indian spinach (<i>Beta vulgaris</i> L.)	1 to 3 weeks	Olufolaji and Tayo, 1989; Allemann et al., 1996; Maruo et al., 2003; Takagaki et al., 2003
Green forage	rape (<i>Brassica oleracea</i> L.), turnip (<i>Brassica rapa</i> L.), various pasture grasses, eg. Ryegrass (<i>Lolium perenne</i> L.), tall fescue (<i>Festuca arundinacea</i> L.), pearl millet (<i>Pennisetum americanum</i> L.),	6 to 12 weeks	Wiedenhoef and Barton, 1994)
Pasture	Rhodes grass (<i>Choris gayana</i> L.), lucerne (<i>Medicago sativa</i> L.), cooksfoot (<i>Dactylis glomerata</i> L.)	4 or 8 weeks	Belesky and Fedder, 1995; Turner et al., 2005; Marchione, 2004); Booysen and Nelson, 1975; Ferraris and Norman, 1976; Kigel and Dotan, 1982; Brown et al., 2005); Peri, et al., 2003

2.4 The use of reaping and regrowth system in tea

The reaping and regrowth system has been used in tea (*Camellia sinensis* L.). In China, tea farmers pick tea leaves or young shoots regularly. The picking time depends on the kind of tea that is going to be made, because different teas need different textures of leaves. For example, a tea may use young or old leaves. Bore et al. (2003) reported in a study on the 'effects of pruning time and resting period on total non-structural carbohydrates, regrowth and yield of tea (*Camellia sinensis* L.)'. Generally, total non-structural carbohydrate declined when trees were pruned at 61 cm height and then increased. In a rather different form of production, that of tea tree oil, the herbage is regularly cut and the harvested leaf and shoot is distilled for oil (Murtagh and Smith, 1996).

2.5 The use of reaping and regrowth system in salad vegetables

The reaping and regrowth system is also suitable for leafy and shoot type vegetables. Maruo et al. (2003) and Takagaki et al. (2003) reported the reaping and regrowth system is feasible for leaf vegetable production. They reported the system can reduce labour and other costs due to the high efficiency of harvest and a simplified packing process. In their studies, vegetable jute (*Corchorus olitorus* L.), sweet basil (*Ocimum basilicum* L.), lettuce (*Lactuca sativa* L.), pak choi (*Brassica campestris* L. chinesis group) and Chinese kale (*Brassica oleracea* L.) were included. Kasture et al. (2000) also used this method to research the response of levels of cutting on the growth of green leaves of Indian spinach (*Beta vulgaris* L.) of the cultivars All Green and Pusa Jyoti. Olufolaji and Tayo (1989) showed that the reaping and regrowth system was superior to a once only total harvest for amaranthus (*Amaranthus cruentus* L.). They showed the total numbers of leaves and branches of Amaranthus developed was greater, gaining a higher total fresh weight yield, and the total dry weight of various plant parts, and resulting in more profit at the optimum commercial stage. Amaranthus (*Amaranthus* spp.) is used for grain and as a vegetable. The leaves are high in protein, vitamins, and minerals (Omami, et al., 2006). Ryder (1979) noted the cutting back and regrowth method can be used for lettuce production. This reference indicates that the reaping and regrowth system has been used for salad vegetables for

a long period of time and that it is a successful production method for leafy salad vegetables.

2.6 Factors affecting regrowth

The factors that may influence plant regrowth can be divided into two categories under the terms—‘environmental’ and ‘management’ factors. The effects of temperature, radiation interception, water stress and nutrition (environmental factors) on regrowth of plants will be discussed in detail. The effects of plant size/plant residue and cutting intervals on crop and plant regrowth fall in the management category of factors.

2.6.1 The effect of temperature on regrowth

When plants of a leaf vegetable are cut back, new leaves or shoots start to regrow from the remaining growing points. Growth refers to the accumulation of biomass in the plant as a whole or in certain organs (Hodges, 1991). For leaf vegetables, growth is that accumulation of biomass in leaves. A primary factor affecting plant growth development is temperature, as modulated by other factors including daylength and vernalization (Hodges, 1991). The quantitative effects of temperature on plant growth have been studied intensively and extensively using the concept of thermal time. It is possible to calculate accumulated thermal time (degree days, °Cd), i.e. the total effective temperature to which any plant has been exposed (Wiggans, 1956; Jamieson et al., 1995, 1998; Jamieson and Munro, 1999; Slafer and Rawson, 1995).

The basic concept of thermal time is as follows. The phenological and growth processes proceed in direct relation to the accumulated temperature or thermal time experienced by the crop. Below a base temperature, no thermal time accumulates and crop growth or development rate ceases. The rate of thermal time accumulation and the crop growth and development rate increase with increasing temperature up to an optimum temperature (T_{op}) value or range of values (plateau). Above that temperature value or plateau the rates of thermal time accumulation and the crop growth and

development decrease with increase in temperature until no further accumulation occurs and crop development ceases (Hodges, 1991).

The base temperature (T_b) must be known when accumulated thermal time is going to be calculated. It is known that the base temperature is not a fixed value (Iwata, 1975). It may vary according to the external conditions, by the age of plants and by previous treatment. Slafer and Rawson (1995) stated that the base temperature and optimum temperature were different at the leaf appearance phase and the culm elongation stage for wheat. According to the relationship of temperature and the rate of development, the minimum, maximum and optimum temperature (T_{min} , T_{max} and T_{op}) can be obtained. The T_{min} , T_{max} and T_{op} are required to calculate thermal time. Although the base temperature changes according to different crops or growth stages, estimating the development of crops by the thermal time index—which is the total summation of the degree days above the base temperature to reach a particular stage of development, has usually been successful (Iwata, 1975). The degree days during a day are calculated by subtracting the base temperature from the daily mean temperature, as presented by the following formula:

$$\text{Degree days} = (T_{min} + T_{max})/2 - T_b \quad (1)$$

Where T_{min} , T_{max} and T_b mean minimum, maximum and base temperature respectively.

Using this general formula, the heat requirement for any developmental period can be calculated. Also, Iwata (1975) showed other formulas for calculating thermal time:

$$\text{Degree days} = [(T_{min} + (T_{max} - \text{degrees over optimum})]/2 - T_b \quad (2)$$

$$\text{Degree days} = (T_b + T_{min} \text{ above base} + T_{max})/2 - T_b \quad (3)$$

$$\text{Degree days} = [(T_b + T_{min} \text{ above base}) + (T_{max} - \text{degrees over optimum})]/2 - T_b \quad (4)$$

Iwata (1975) compared the coefficients of variation of the corrected indices calculated by formula 2 to that of formula 1, and those by formula 4 to that of formula 3. In the

comparisons of the coefficients of variation between with and without corrections for the optimum temperatures, it was found that the corrections decreased the variations of thermal time needed by some plant species.

Temperature and thermal time affect crop growth and development. The rate of leaf appearance in wheat depends on temperature (Jamieson et al., 1995). When the rate is expressed in thermal time based on air temperature, a marked contrast is apparent between autumn and spring sowings. This variation has often been attributed to a preconditioning response that determines the thermal phyllochron (thermal time to produce one leaf) at about the time of emergence, either directly through an effect of daylength or its rate of change. Jamieson et al. (1995) reported that there was a faster rate of leaf appearance per unit thermal time (based on air temperature) in spring than in autumn and winter sowings. The mean phyllochron (calculated as the reciprocal of the slope of the regression line for the first 8 leaves) of Avalon wheat was 93 °Cd for autumn and winter sowings and 72 °Cd for spring sowings.

Regrowth of leaf vegetables occurs above T_b and ceases at temperatures above T_{max} . The fastest growth rate occurs at T_{op} (Ferraris and Norman, 1976). Ferraris and Norman (1976) reported that there was a positive ($p < 0.01$) association between regrowth rate and temperature for pearl millet (*Pennisetum americanum* (L.) K. Schum) planted as forage in December in New South Wales, Australia. In 1985, Hill and Pearson studied regrowth responses of temperate grasses to different temperatures. This trial was conducted in glasshouses with day/night temperatures 15/10, 18/13, 21/16, 24/19 and 30/25 °C (12/12 h). Uxivex and Tama Italian ryegrass (*Lolium multiflorum* L.), prairie grass (*Bromus catharticus* L.) and fescue (*Festuca arundinacea* L.) were measured when defoliated every 4 or 8 weeks after 11 weeks of primary growth. It was reported that the rate of regrowth for prairie grass, Uxivex and Tama Italian ryegrass was at its highest in the low temperature regime of 15/10 °C, but the fescue experienced fastest growth in a day/night regime of 24/19 °C. Kallenbach et al. (1996) showed that regrowth of sainfoin (*Onobrychis viciifolia* Scop.), a cool-season, nonbloating, perennial legume, declined as metabolic rate increased with temperature. Because respiration increased with temperatures, this led to the reduction of net photosynthesis (Fig. 2.2) (Hay and Walker, 1989). Kallenbach et al. (1996) also pointed out that severe defoliation during periods of high temperatures

might cause plant death because high metabolic rates can not be supported by existing leaf area or taproot carbohydrates. Therefore, regrowth could differ among different temperatures.

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Figure 2.2. Influence of temperature on the rates of gross photosynthesis, respiration and net photosynthesis (Hay and Walker, 1989).

Hill and Pearson (1985) noted that regrowth of different species respond differently at the same temperature regimes. Differences in regrowth rates between prairie grass and ryegrasses became greater with temperature up to 24/19 °C. Prairie and Italian ryegrasses had higher regrowth rates than fescue at 15/10 °C, but had lower growth rates than fescue at 24/19 °C.

Moreover, plants at different growth development phases respond differently to varying temperatures. Hill and Pearson (1985) reported that reproductive development was earlier in plants at lower temperatures and did not occur in those grown at 24/19 and 30/25 °C.

Therefore, the literature shows first of all that temperature does affect regrowth of plants of grasses, and secondly that grasses have different patterns of regrowth. There are several studies about effects of temperature on pasture regrowth after cutting (Ferraris and Norman, 1976; Hill and Pearson, 1985; Kallenbach et al., 1996; Slack et al., 2000). Tobisa et al. (2003) showed higher regrowth of forage legume phasey bean (*Macroptilium lathyroides* L. Urb) at 25-30 °C than at 20 °C. In addition, studies showed that the regrowth of brassica forages followed the positive relationship between the accumulated yield and thermal time, in leafy turip (*B. rapa* L.), rape (*B. napus* L.) and Kale (*B. oleracea* L.) (Wiedenhoeft, 1993; Brown et al., 2007). However, references about the effects of temperature on regrowth of leafy salad vegetables such as lettuce and rocket are lacking. This study has examined the effects of varying seasonal temperature on salad vegetable regrowth.

2.6.2 The effects of light on regrowth

Solar radiation is energy from the sun. Portions of the solar radiation spectrum can be used to produce carbohydrates through the process of photosynthesis. In the process of photosynthesis, chlorophyll and other pigments in the choroplasts trap the energy of solar radiation and convert it into carbohydrate. Chlorophyll absorbs very strongly in the blue and red region of the radiation spectrum, and this region is labelled photosynthetically active radiation (PAR, $\text{Jm}^{-2} \text{s}^{-1}$) and includes wavelengths between 400 nm to 700 nm (Sinclair and Muchow, 1999).

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Figure 2.3. Ground cover percentage of lettuce as a function of the leaf area index (LAI). Symbols: observed data. Solid line: fitted logistic function over the two years ($y=99.38/(1+19.03 \exp(-0.772))$, $R^2=0.99$) (Beccafichi et al., 2003) on pp. 512.

Most solar radiation is absorbed by the crop canopy and in particular is intercepted by leaf blades. Figure 2.3 indicates the relationship between percentages of ground covered by lettuce leaves and leaf area index (Beccafichi et al., 2003). The amount of radiation intercepted is typically dependent on leaf area index (LAI) (Fig. 2.4) (Tei et al., 2003). However, leaf angle is also an important determinant of radiation interception. Beccafichi et al. (2003) reported that for lettuce (Janchen) a ceiling ground cover ratio was reached at about LAI 10 (Fig. 2.3). Tei et al. (2003) showed that there was a similar relationship between LAI and the percentage of intercepted PAR (Fig. 2.4).

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Figure 2.4. Percentage intercepted photosynthetically active radiation (PAR) of lettuce in relation to leaf area index (LAI) over all the fertiliser-N rates and two years (●, 1997; ○, 1999) (Tei et al., 2003) on pp.194.

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Figure 2.5. Relation between cumulative dry weight (g m^{-2}) and intercepted photosynthetically active radiation (PAR) (MJ m^{-2}) in lettuce. Symbols: observed data. Solid line is the linear relationship over densities and years ($y = -1.82 + 2.71x$, $R^2 = 0.99$). The slope is the radiation use efficiency (g DWt/MJ PAR) (Beccafichi et al., 2003) pp. 512.

Studies show that there is a linear relationship between dry matter and/or fresh leaf production and intercepted PAR in lettuce (Fig. 2.5) (Beccafichi et al., 2003; Caron et al., 2007; Tei et al., 2003). Thus, the accumulated dry matter weight is positively related to the amount of PAR intercepted.

In addition, net CO₂ assimilation is affected by the irradiance. Knight and Mitchell (1988) showed that net CO₂ assimilation was greater for plants of 'Waldmann's Green' leaf lettuce at 84% rather than 16% of the total irradiance (82 W m⁻²). Sanchez et al. (1989) also pointed out that the maximum net CO₂ assimilation rate for Crisphead lettuce decreased as the irradiance at which the plants were grown decreased. Continuous shading reduced lettuce growth generally due to the reduction in irradiance. Lettuce was most sensitive to reductions in irradiance when growth and development were most rapid (Sanchez et al., 1989).

LAI decreases immediately after plant tops and leaves are cut and removed. Cutting reduces intercepted radiation. With the recovery of LAI, intercepted PAR and dry matter production increase gradually. Nassiri and Elgersma (1998) studied the radiation interception and dry matter production during the regrowth phase in perennial ryegrass—white clover mixtures. They showed that LAI increased weekly in ryegrass and white clover in the harvestable herbage zone (above 5 cm from the ground) during each three week regrowth period. For white clover, the maximum rate of increase and the highest LAI (about 4) were reached in summer (July). They also reported that the percentage of intercepted radiation after cutting was 20—30% and increased to about 95% during each 3 week regrowth periods. Dry matter production increased weekly during regrowth in a pattern similar to that of the LAI recovery (Nassiri and Elgersma, 1998).

Bunnell et al. (2005) studied the daily light requirement of a 'TifEagle' Bermudagrass golf Green. Three levels of shade, none, low and high (0, 41, and 92%), were applied to mature TifEagle' Bermudagrass. When daily light integral was less than 32.6 mol m⁻²d⁻¹, percentage lateral regrowth (horizontal growth or recovery of plants) declined significantly.

High afternoon shade reduced TifEagle Bermudagrass TQ and percentage lateral regrowth by 17% compared with no afternoon shade. Morning high shade reduced percentage lateral regrowth by 11% compared with no morning shade. Overall, shade applications caused a more reduction to TifEagle Bermudagrass regrowth (Bunnell et al., 2005).

Furthermore, Bunnell et al. (2005) also studied the effect of sunlight hours on lateral regrowth of TifEagle Bermudagrass. Sunlight treatment durations were 12, 8 and 4 hours. The percentage of lateral regrowth was 65, 64 and 47% for the 12, 8 and 4 hours treatments respectively.

From the studies conducted by Bunnell et al. (2005) above, it is shown that irradiance levels during the regrowth phase can affect regrowth. Also, the amount of intercepted radiation during the regrowth stage does affect regrowth. For TifEagle Bermudagrass, there was a minimum daily light integral of $32.6 \text{ mol m}^{-2} \text{ d}^{-1}$. When the daily light integral was less than this, regrowth declined significantly.

2.6.3 The effects of water stress on regrowth

Plants depend on water for a wide range of functions. These include the followings:

- 1) Water is an essential constituent of all plants, sometimes comprising as much as 95% of total weight. When plant tissues fall below a certain water content, the tissues will die (Sutcliffe, 1969; Ehlers and Goss, 2003).

- 2) Water is a basic constituent of a single cell. There is a thin layer of water surrounding each cell and this permeates the micro-spaces between solid material in the cell wall, as a chemical agent or a solvent. Also, it can be a transport of salts and assimilates within the plant (Sutcliffe, 1969; Ehlers and Goss, 2003).

- 3) Water is a source of hydrogen atoms for the reduction of carbon dioxide in photosynthesis, and a production of respiration. Water participates directly in a number of chemical reactions occurring in protoplasm during the metabolic process as well (Sutcliffe, 1969; Ehlers and Goss, 2003).

In general, water is the most important factor affecting plant growth and yield. Water stress is experienced by plants when there has been a loss of water from their tissues, a condition typical of periods of water shortage (Ehlers and Goss, 2003). Begg and Turner (1976) stated that water stress could influence nearly all aspects of plant growth and development. Water stress can influence the rate of growth and development of plants.

Water stress can affect plant height and green leaf area. Water stress at any stage of the plant life cycle can affect the growth and yield of crops (Roy, 1985). Generally, the life cycle of cereal plants can be divided into three stages: vegetative (from germination to appearance of flower), flowering (from the appearance of flower to seed initiation), and seed filling (from grain filling to maturity) (Roy, 1985; Mogensen and Talukder, 1987; Nielsen and Nelson, 1998). For some crops, the vegetative stage can also be divided into tillering, booting etc. For example, ryegrass, wheat and rice have the stages of tillering and booting. For leafy salad vegetables, harvests usually happen during the vegetative stage.

Water deficits experienced during the vegetative phase have been shown to reduce plant height (Doss et al., 1974; Nielson and Nelson, 1998), and this reduction has been related to dry matter yield (Doss et al. 1974). This, of course, is related to yields in a reaping and regrowth system for leafy vegetables. Reduction in yield due to water stress is usually due to reduced LAI which causes reduced radiation interception.

Roy (1985) showed that drought at any phase of wheat development decreased the green surface area of main stems by 20—40%. The net growth rate per plant was lowered by about 60—80% of non-stressed plants. Consequently, dry matter growth was reduced to 75% of the well-watered control. Roy (1985) also pointed out that water stress at the vegetative stage reduced green leaf area.

For black bean, Nielsen and Nelson (1998) found that in 1996, the maximum leaf area of black bean, when water was withheld during seed filling, was nearly 2 times greater than the maximum leaf area for the treatment when water was withheld during vegetative stage. Plants in treatments where water was withheld early in the growth of plants, the vegetative phase, had lower leaf area indices than the other treatments.

Nielsen and Nelson (1998) also reported that no recovery of leaf area index happened with watering.

The yield components for leaf and shoot salad vegetables such as lettuce, pak choi, Chinese cabbage, rocket, etc., are the green leaves and/or shoots. Any reduction in green leaves and/or shoots means less economic yield. Coelho et al. (2005) investigated the influence of water stress on the marketable yield of American lettuce (*Lactuca sativa* cv Lucy Brown) grown under greenhouse conditions. There were four levels (25, 50, 75 and 100%) of Class A pan evaporation replenishment (PER). There was a positive relationship between fresh head weight and diameters and PER. The lowest fresh head weight and diameter was obtained at 25% PER. The highest marketable fresh head weight and diameter was obtained at 100% PER. It seems likely that water stress can also affect the regrowth of salad vegetables and reduce the recovery of green leaves and /or shoots after cutting.

Water stress has been shown to affect regrowth of plants. Volaire (1994) studied the effects of summer drought on the regrowth of cocksfoot (*Dactylis glomerata* L.). He showed that regrowth in autumn was reduced by severe drought in summer. Sheaffer et al. (1992) showed that when drought occurred during the regrowth period, forage yield of *P. arundinace*, *D. glomerata*, *B. inermis* , *P. pratense* was 33, 37, 24 and 34%, respectively, of the controls. Corresponding whole season yield of stressed grasses were 54, 60, 81 and 62% of the control plants that had not been drought affected.

2.6.4 The effects of plant residual dry matter on regrowth

Perennial pasture grasses provide for repetitive harvesting. Thus, the rate of regeneration of top growth between harvests is critical in determining seasonal yield. Carbohydrate for regrowth may be provided by current photosynthate or plant reserves, or both (Booyesen and Nelson, 1975). Since the harvested topgrowth is also the photosynthetic source, the more complete the harvest, the smaller the residual photosynthetic area. Under such conditions, plants become more dependent upon reserves for regrowth. Repeated use of reserves may in turn lead to a reduction of

plant vigour when the process is repeated before the reserves are again replenished (Booyesen and Nelson, 1975). Volaire (1994) also reported that intense defoliation of cocksfoot in spring caused the reduction of levels of carbohydrate reserves in autumn, leading to decrease of regrowth. Smith (1974) found that when timothy (*Phleum pratense* L.) was seriously defoliated (cut at 7.6 cm height without leaf blades), current photosynthate could not meet the growing needs and regrowth was retarded. Ward and Blaser (1961) suggested that under these conditions reserves were critical for tiller development and for rapid formation of new photosynthetic tissue. However, later in time, regrowth rate was more strongly related to leaf area and current photosynthate.

Wilson and Robson (1970) reported that weight of regrowth of ryegrass was similar to that of uncut plants unless plants were cut to less than 6 cm height. Under this level, carbohydrate levels in the stubble decreased after cutting and the reduction was directly associated with severity of topgrowth removal. Davies (1974) found that the subsequent tiller production and leaf appearance rate of ryegrass in regrowth was decreased if the remaining leaf area was decreased.

Booyesen and Nelson (1975) studied the influences of leaf area (HL, high residual leaf area; and LL, low residual leaf area) and carbohydrate reserves (HC, high reserve carbohydrates; LC, low reserve carbohydrates) on regrowth of tall fescue (*Festuca arundinacea* L. Alta) (Fig. 2.6). The HC/HL and LC/LL treatments presented the two extreme patterns of dry matter accumulation in which the energy sources (stored reserves and current photosynthate) were both most adequate and most limited, respectively. When two-thirds of the leaf area was left on the plants at day 0 (HL), the pattern of dry matter accumulation was not affected by the low carbohydrate level (LC). When all leaf blades (LL) were removed, the patterns of dry matter accumulation for HC and LC plants were similar during the first 10 days of regrowth, with only a slightly increased rate of accumulation during the following 10 days in HC plants over LC plants (Booyesen and Nelson, 1975). It shows cutting height and reserve carbohydrates can affect regrowth, and the cutting height is more important than the reserve of carbohydrates.

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Figure 2.6. Changes in total plant weight of tall fescue during a 20—day regrowth period after treatment (HC, high reserve carbohydrates; LC, low reserve carbohydrates; HL, high residual leaf area; and LL, low residual leaf area) (Booyesen and Nelson, 1975) on pp. 263.

In addition, Ferraris and Norman (1974) studied the factors affecting the regrowth of pearl millet (*Pennisetum americanum* L. K. Schum.) under 3-weekly cutting regimes, including three cutting heights (10, 30 and 50 cm). It showed that there was a positive ($p < 0.01$) relationship between regrowth over 3 weeks and the leaf area index of the stubble at the start of the regrowth period. Tobisa et al. (2003) also reported that higher regrowth of phasey bean (*Macroptilium lathyroides* L. Urb) at 15 cm cutting height than 7.5 cm cutting height, due to differences in the amount of storage nutrients available for regrowth.

The reserves of carbohydrate will be used for regrowth in Brassica. Van den Boogaard et al. (2001) studied the effect of defoliation on growth of cauliflower (*B. oleracea* L.). They found that concentrations of non-structural carbohydrates were reduced after defoliation, showing that reserves were mobilised to support regrowth. Jean et al. (1994) also reported that the non-structural carbohydrate content reduced

during regrowth period in forage rape (*B. napus* L.). Starch content, which is the largest pool of non-structural carbohydrate, decreased in leaves and roots from 187 and 497 mg/g DM in winter to 69 and 79 mg/g DM in the early regrowth period in spring, respectively.

2.7 The course of plant development

Krug (1997) studied the general pattern of the development of cultivated monocot and dicot plants shown as Fig. 2.7. Krug (1997) said that sowing is the beginning of the process, after which plants emerge, grow and develop vegetatively and reproductively. Plants may be harvested while still in the vegetative phase, e.g. salad vegetable lettuce, pak choi and rocket. According to Fig. 2.7, plants grow slowly in terms of “mass” around the emergence phase, and grow faster with increasing “mass” as time progresses. This is because of low LAI and poor radiation interception (Fig. 2.4) (Tei et al., 2003). In a reaping and regrowth system, when plants are harvested, it means a removal of the topgrowth, and plants have to regrow from residual biomass.

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Figure 2.7 Diagrammatic presentation of the course of development of cultivated angiosperms (Krug, 1997) on pp. 104.

3.0 Materials and Methods

The experimental plots were located at Lincoln University, Canterbury, New Zealand (latitude 43°38'S, longitude 172°28'E). The soil is classified as Templeton soil with 20 to 23 cm deep of topsoil. Topsoil texture is fine sandy loam (Cox, 1978). The climate is described as temperate and sub-humid with long-term annual mean rainfall 670±300 mm and annual potential evaporation of 1300 mm. Mean annual temperature is 11.4 °C, with mean monthly temperatures below 10 °C from May to September inclusive.

3.1 Materials

Three different salad vegetable crop plants were used in this experiment, Italian green oakleaf lettuce (*Lactuca sativa* L. cv. Green Oakleaf), Pak Choi (*Brassica sinensis* L. cv. Oriental Taisai) and the herb rocket, (*Eruca sativa* L.). The seeds were from Egmont Seed Company Ltd, New Plymouth, New Zealand. While the three vegetable crops are different species, throughout this thesis, the results will refer to these as varieties of leafy salad vegetables.

Lettuce, pak choi and rocket were sown on January 7th, 2005 and grown on in cell transplant trays. The seedling mixture included 60% of fine peat and 40% of 1-5 mm pumice. When 90% of the seedlings had four leaves fully expanded, plants were transplanted into the experimental plots. The crops were planted on February 3rd, 2005 and the last harvest was on April 27th, 2005.

3.2 Experimental design

The experiment was a completely randomized block design. It was a factorial combination of treatments, three Harvest start times (H) by three Varieties (V). Lettuce, pak choi and rocket, the three varieties were planted in plots of 4.2 m × 3 m.

The plant density was 20 cm × 20 cm with 40 plants per plot. Three treatments were applied: early start (ES) of harvest, mid start (ES) of harvest (7 days later than ES) and late start (LS) of harvest (7 days later than MS). The cutting height was 5 cm above the ground. There were two further harvests for each treatment after the start harvest. The cutting intervals were four weeks between harvests. Full fertilization and irrigation were applied. Nitrophoska (nitrogen 12%, phosphorus 10% and potassium 10%) was applied at 55 kg ha⁻¹. Water was supplied every day or every two days for 1—2 hours. There was no indication of water stress.

3.3 Sampling

Eighteen plants per plot were measured for leaf number per plant, fresh weight and dry weight per plant (g/plant). Five plants of each plot were randomly sampled at each harvest and leaf area index/plant and the percentage of saleable leaves was recorded.

3.4 Measurements

Fresh and dry weight

Fresh weight was measured immediately after harvesting. The samples were then dried at 55 °C in a forced air oven. After 48 hours, dry weight was measured.

Leaf number per plant, percentage of saleable leaves, saleable leaf fresh weight per plant and leaf area index

Leaves were counted from a sample of 18 plots. Five randomly sampled plants were used to determine the percentage of saleable leaves based in the saleable and unsaleable leaf number. Diseased leaves, off colour leaves and leaves less than 5 cm² were discarded as unsaleable leaves. Saleable leaf fresh weight per plant was calculated out with fresh weight per plant by percentages of saleable leaves. Leaf area index of five sampled plants was measured using a Li-Cor Model 3100 Area Meter machine (cm²).

Temperature

Temperature data was from the Broadfield meteorological station about 2 kilometres north of Lincoln University (°C). Thermal time (day degrees centigrade, DDC) was calculated using a base temperature of 4 °C for lettuce (Kristensen et al., 1987; Morgan, 1999), pak choi (Adams et al., 2005; Chen et al., 2005; Marshall and Squire, 1996) and rocket (Gómez-Campo, 1999).

3.5 Statistical tests

General ANOVA using Genstat (Snell and Simpson, 1991) software was used to analyse the total dry yield (g/m^2), total dry weight per plant (g/plant), total fresh yield (g/m^2), fresh weight per plant (FW/plant, g/plant), saleable leaf fresh weight per plant (saleable leaf FW/plant, g), percentages of saleable leaves (%), leaf number per plant (LN/plant) and leaf area index (LAI) at the first and second harvests. A REML analysis was applied at the third harvest for the measurements above, and FW/plant, saleable leaf FW/plant, DW/plant, percentages of saleable leaves, LN/plant and LAI at each harvest because data was lost due to hail damage. Mean separation was through the use of standard errors of the means (SEM).

4.0 Results

4.1 The daily mean temperature during the growing season

The daily mean air temperatures are shown in Figure 4.1. The long-term mean temperature of the growing season was 15 °C. The highest daily maximum was 32 °C on 15th January 2005. The lowest daily minimum was 0.4 °C on 26th April 2005. Table 4.1 indicates the maximum, minimum and mean temperatures in each month during the growing season from 7th February to 27th April.

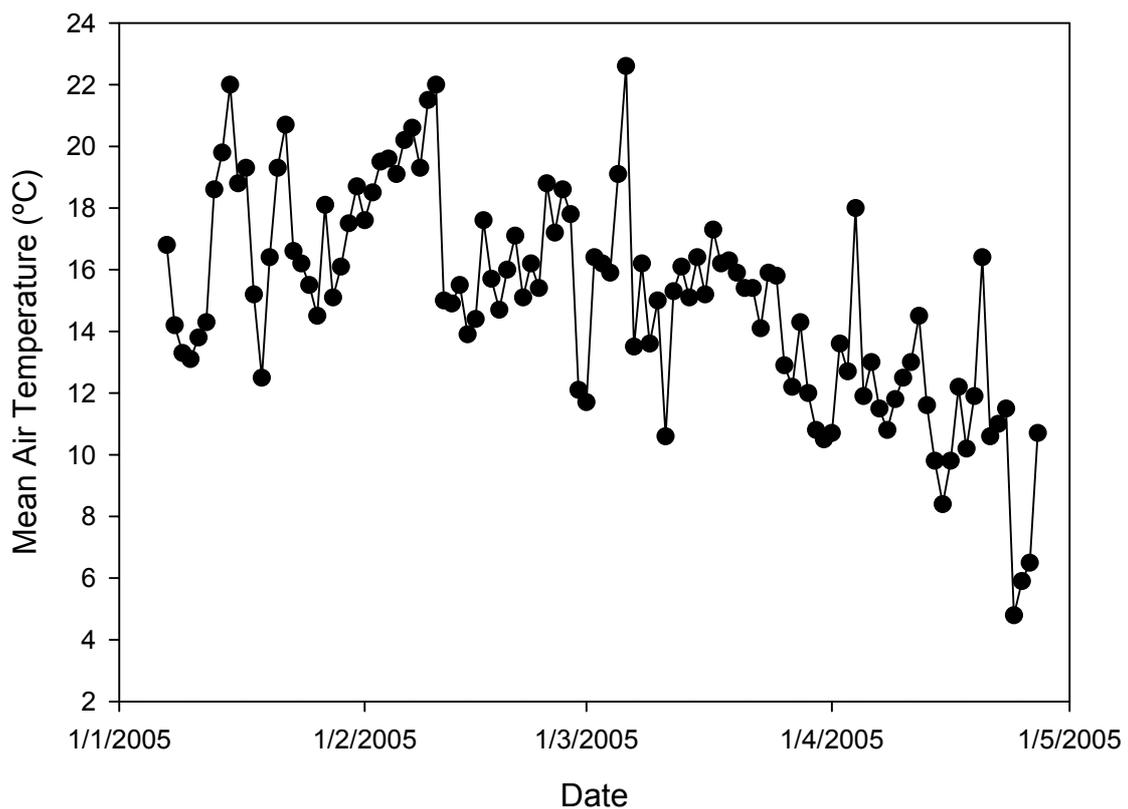


Figure 4.1. Daily mean air temperature from 7th January to 27th April in 2005.

Table 4.1. The maximum, minimum and mean temperatures in each month during the growing season from 7th February to 27th April in 2005.

Month	Maximum (°C)	Minimum (°C)	Mean (°C)
Jan.	22.2	11.6	16.7
Feb.	23.4	12.7	17.3
Mar.	19.9	10.5	15.0
Apr.	16.5	6.3	11.3

4.2 Total fresh, dry weight and saleable leaf fresh weight of lettuce, pak choi and rocket

The total yields (g/m^2) and total weights (g/plant) are shown in Table 4.2. Plants were harvested at three different start times, early start (ES), mid start (MS) and late start (LS). An early start to harvest gave decreased total fresh yields compared to the two later harvest starts. However, there was no effect on dry yields. Fresh weights of MS and LS mean of 158 g/plant were higher than the ES (117 g/plant). Again dry weight was not affected by harvest start time.

Table 4.2. The effect of different starts of harvest times on total fresh and dry yield (g/m^2) and total fresh and dry weight (g/plant) of lettuce, pak choi and rocket.

	Total fresh yield (g/m^2)	Total dry yield (g/m^2)	Total fresh weight (g/plant)	Total dry weight (g/plant)
Harvest start time (H)				
early	2924	241.9	117	9.7
mid	3911	283.7	157	11.3
late	3963	275.9	159	11.4
Significance	$p=0.005$	NS	$p=0.005$	NS
SEM*	229.4	13.8	9.2	0.55
Variety (V)				
lettuce	5185	286.8	208	11.5
pak choi	3075	229.4	123	9.2
rocket	2538	285.3	102	11.4
Significance	$p<0.001$	$p=0.009$	$p<0.001$	$p=0.009$
SEM	229.4	13.8	9.2	0.55
cv%	22.1	17.9	22.2	17.9
Significant interaction	Nil	H×V	Nil	H×V

*: SEM, standard error of mean.

Among the three varieties, lettuce produced the highest fresh yield (5185 g/m^2) and fresh weight (208 g/plant) (Table 4.2). Pak choi produced 3075 g/m^2 and 123 g/plant , while rocket produced 2538 g/m^2 and 102 g/plant . There was no significant interaction of harvest start and variety on fresh yield or fresh weight per plant.

The total dry yield (g/m^2) and total dry weight were not affected by harvest start time. Pak choi produced the lowest dry yield and dry weight at 229.4 g/m^2 and 9.2 g/plant .

There was no difference in yield between lettuce and rocket. Both the interactions of harvest start time and variety on total dry yield and total dry weight were significant (Table 4.2).

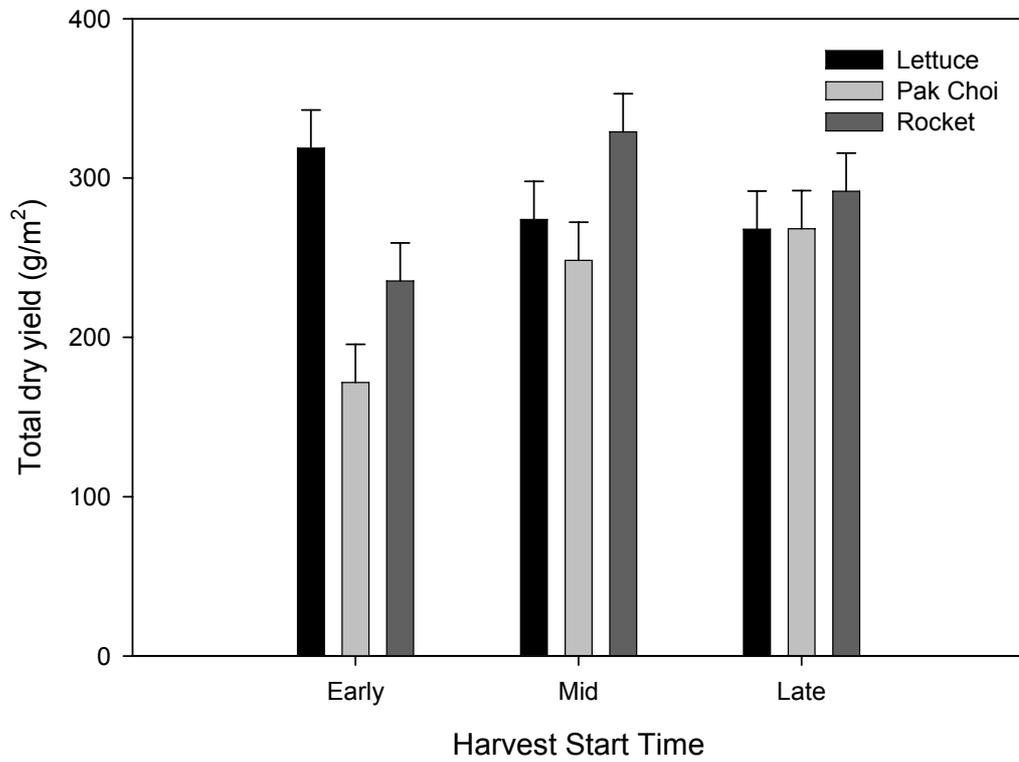


Figure 4.2. The interaction of harvest start time and variety on total dry yield per m² (Bars: SEM=23.94).

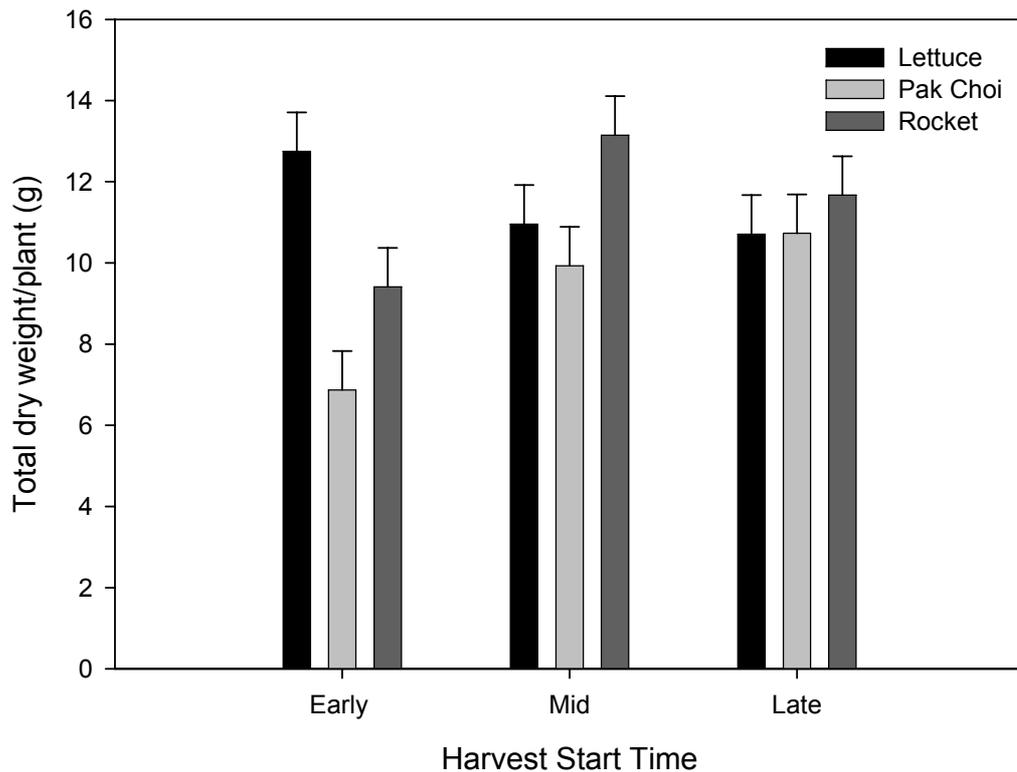


Figure 4.3. The interaction of harvest start time and variety on total dry weight per plant (Bars: SEM=0.96).

The significant interaction on total dry yield and total dry weight per plant (Fig. 4.2 and 4.3) showed that while lettuce was not affected very much by different start times, pak choi and rocket yielded less when the harvest start was early.

Lettuce produced significantly ($p < 0.05$) more total FW/plant than pak choi and rocket in each treatment (Table 4.3). Pak choi produced significantly higher total FW/plant than rocket in the LS treatment, while in the ES and MS treatments they produced the similar total FW/plant. Lettuce plants produced higher total FW/plant in the LS (240.2 g) than in the ES and MS (191.9 and 190.9 g FW/plant). Pak choi produced higher total FW/plant in the MS and LS (143.4 and 141.2 g FW/plant) compared with the ES (84.4 g FW/plant). The total FW/plant of rocket was significantly ($p < 0.05$) different from each other between treatments.

Table 4.3. Total FW/plant (g) of lettuce, pak choi and rocket either in an early, mid or late start of harvest ($p < 0.05$, SEM=15.97).

Harvest Start Time	Lettuce	Pak Choi	Rocket
ES	191.9 aa	84.4 ab	74.5 ab
MS	190.9 aa	143.4 bb	135.8 bb
LS	240.2 ba	141.2 bb	94.2 cc

The first letter equals significance between harvest start times and the second letter equals significance between species.

Table 4.4 shows that lettuce produced the highest total saleable leaf FW/plant in each treatment among the three crops ($p < 0.05$). Pak choi produced higher total saleable leaf FW/plant than rocket in the ES and LS treatments. Compared between treatments, lettuce produced the highest total saleable leaf FW/plant in the LS (169.3 g), while rocket was in the MS (92.2 g). Pak choi produced similar total saleable FW/plant in the MS and LS (100 and 92 g FW/plant), higher than in the ES (52.9 g FW/plant).

Table 4.4. Total saleable leaf fresh weight per plant (g FW/plant) of lettuce, pak choi and rocket either in an early, mid or late start of harvest ($p < 0.05$, SEM=12.84).

Harvest Start Time	Lettuce	Pak Choi	Rocket
ES	137.5 aa	52.9 ab	31.5 ac
MS	120.9 ba	100.0 bb	92.2 bb
LS	169.3 ca	92.0 bb	56.4 cc

The first letter equals significance between harvest start times and the second letter equals significance between species.

4.3 Fresh weight per plant at each harvest after early, mid and late starts of harvest

As shown in Figure 4.4, the ES resulted in increasing fresh weight per plant of lettuce over the three harvests (3.9 g/plant, 78.9 g/plant and 109.1 g/plant for harvest 1, 2 and 3 respectively), while the MS and LS harvests produced the highest fresh weight per plant at the second harvest (125.3 and 182.0 g), and then decreased at the third harvest (56.9 and 6.5 g). FW/plant at the first harvest was 8.7 and 51.7 g in the MS and LS treatments.

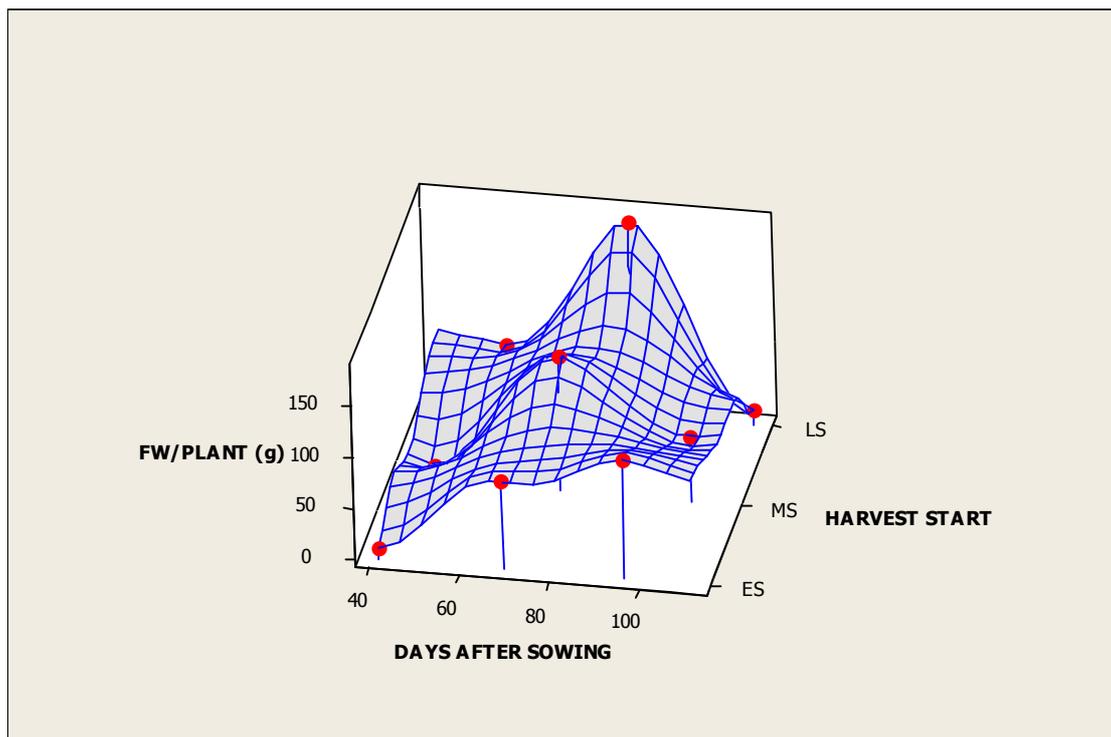


Figure 4.4. Lettuce fresh weight per plant harvested three times after either an early, mid or late start of harvest (SEM=8.12).

For pak choi (Fig. 4.5), FW/plant increased at the second harvest (53.5 and 76.1 g) from the first harvest (14.3 and 56 g FW/plant), and decreased at the third harvest (16.7 and 11.4 g FW/plant) in the ES and MS. The LS produced the highest FW/plant at the first harvest (77.4 g), and then FW/plant decreased constantly at the second (55.4 g) and third (8.4 g) harvests.

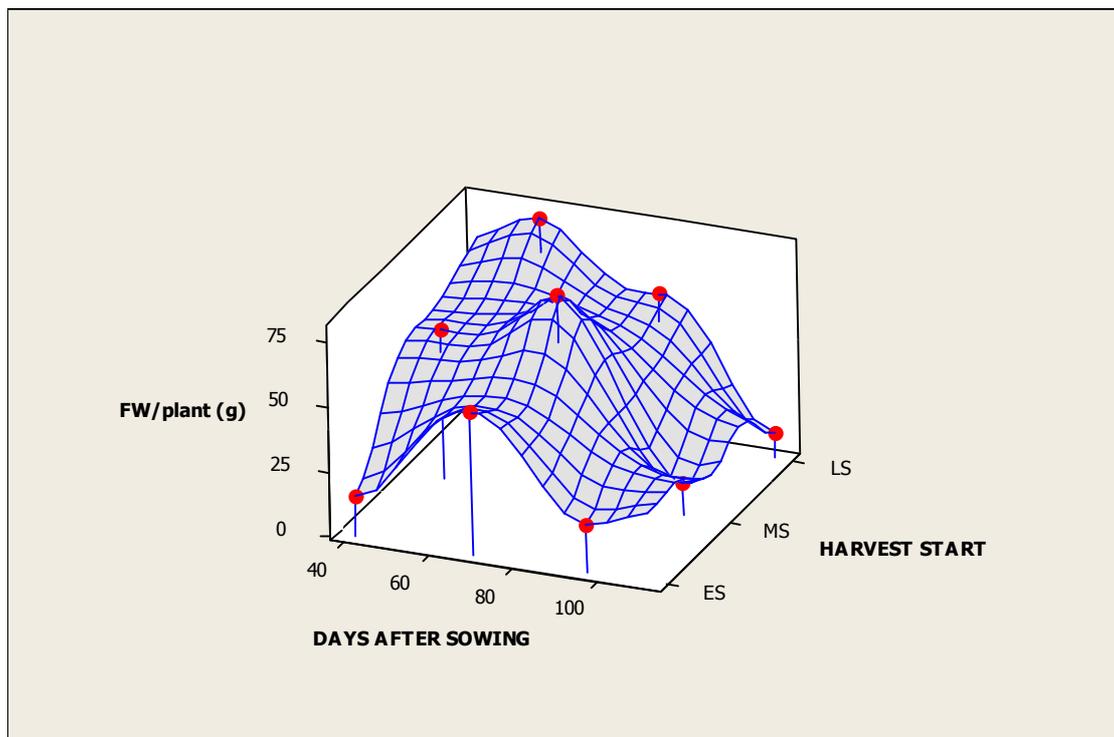


Figure 4.5. Pak choi fresh weight per plant harvested three times after either an early, mid or late start of harvest (SEM=8.12).

For rocket (Fig. 4.6), FW/plant of ES and MS was highest at the second harvest (36.2 and 81.7 g), and reduced at the third harvest (31.9 and 16.2 g). Rocket produced 6.4 and 37.9 g FW/plant at the first harvest in the ES and MS. FW/plant of the LS decreased constantly following the harvesting times, 49.6 g for the first harvest, 36.4 g for the second harvest and 8.3 g for the third harvest.

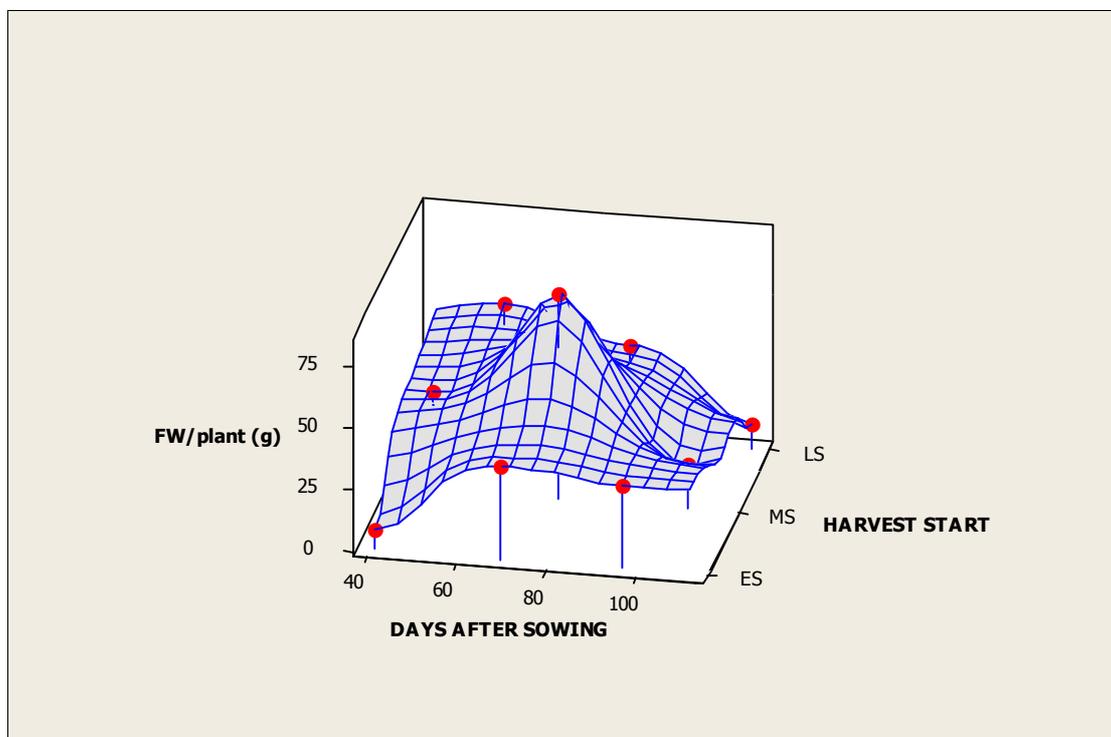


Figure 4.6. Rocket fresh weight per plant harvested three times after either an early, mid or late start of harvest (SEM=8.12).

4.4 Saleable leaf fresh weight per plant and percentages of saleable leaves at each harvest after early, mid and late starts of harvest

Saleable leaf fresh weight per plant at each harvest is indicated in Table 4.5. At the first harvest, LS produced the highest saleable leaf fresh weight per plant (38.6 g), while the ES and MS plants produced 6.3 and 25.5 g/plant. At the second harvest, saleable leaf FW/plant was 38.9 g for ES, 66.0 g for MS and 67.3 g for LS. At the third harvest, the ES produced the highest saleable leaf FW/plant, 28.7g. The MS produced 13.0 g/plant, and there were no saleable leaves for the LS.

For varieties of lettuce, pak choi and rocket, pak choi produced the highest saleable leaf FW/plant (36.4 g) at the first harvest, while lettuce produced 11.6 g/plant and rocket produced 22.3 g/plant. At the second harvest, lettuce produced 90.3 g saleable leaf FW/plant, while pak choi and rocket produced 45.2 and 36.7 g/plant. At the third harvest, lettuce produced 40.6 g saleable leaf FW/plant. Pak choi and rocket produced almost no saleable leaf FW/plant.

Table 4.5. Saleable leaf fresh weight per plant (g) of lettuce, pak choi and rocket harvested at three different times during the growing season after either early, mid or late start of harvest.

	Harvest 1	Harvest 2	Harvest 3
Harvest start time (H)			
early	6.3	38.9	28.7
mid	25.5	66.0	13.0
late	38.6	67.3	*
Significance	p<0.001	p=0.01	p<0.001
SEM	1.81	6.86	NA
Variety (V)			
lettuce	11.6	90.3	40.6
pak choi	36.4	45.2	0
rocket	22.3	36.7	1.0
Significance	p<0.001	p<0.001	p<0.001
SEM	1.81	6.86	NA
cv%	26.8	41.4	NA
Significant interaction	H×V	H×V	H×V

*: data lost due to hail storm.

As shown in Table 4.6, at the first harvest, ES had the highest percentage of saleable leaves (76%), while the MS and LS had 72% and 64% respectively. At the second harvest, MS had the highest percentage of saleable leaves (78%), while both ES and LS were 67%. At the third harvest, ES produced the highest saleable percentage of leaves, 28%. MS was 23%, while LS produced no saleable leaves.

Table 4.6. Percentages of saleable leaves of lettuce, pak choi and rocket harvested at three different times during the growing season after either early, mid or late start of harvest.

	Harvest 1 (%)	Harvest 2 (%)	Harvest 3 (%)
Harvest start time (H)			
early	76	67	28
mid	72	78	23
late	64	67	*
Significance	p<0.001	p<0.001	p=0.046
SEM	1.23	1.88	NA
Variety (V)			
lettuce	62	74	48
pak choi	75	72	0
rocket	74	66	3
Significance	p<0.001	p=0.012	p<0.001
SEM	1.23	1.88	NA
cv%	6.1	9.2	NA
Significant interaction	H×V	H×V	Nil

*: data lost due to hail storm.

For varieties (Table 4.6), pak choi had the highest percentage of saleable leaves (75%), while lettuce and rocket were 62% and 24% at the first harvest. At the second harvest, lettuce produced more percentage of saleable leaves (74%) than pak choi (72%) and rocket (66%). At the third harvest, 48% of lettuce leaves was saleable, while pak choi and rocket had nearly no saleable leaves.

Table 4.7 indicates the percentages of saleable leaves at each harvest in all treatments. The percentages of saleable leaves in lettuce decreased significantly ($p < 0.001$) with repeat harvests. At each harvest, lettuce in the ES produced more percentages of saleable leaves.

For pak choi, the percentages were almost the same at the first and second harvests in the ES and MS treatments. However, leaves were not saleable at the third harvest in the ES and MS. At the first and second harvests, plants in the LS produced lower percentages of saleable leaves compared with the ES and MS.

The change of percentages of saleable leaves in rocket was similar to lettuce. However, plants of rocket produced the highest percentages of saleable leaves in the MS than the ES and LS at the second harvest, and the leaves were not saleable at the third harvest in the MS treatment.

Table 4.7. Percentages of saleable leaves of lettuce, pak choi and rocket at each harvest at either an early, mid or late start of harvest ($p < 0.001$, SEM=2.891).

Harvest Start Time	H1 (%)	H2 (%)	H3 (%)
		Lettuce	
ES	67.6 aa	64.1 ab	75.8 ac
MS	66.1 aa	79.5 bb	67.6 bc
LS	51.0 ba	78.4 bb	*
		Pak Choi	
ES	77.2 aa	78.1 aa	0 ab
MS	77.5 aa	74.0 ba	0 ab
LS	71.4 ba	65.0 cb	*
		Rocket	
ES	81.9 aa	59.8 ab	7.7 ac
MS	71.5 ba	79.3 bb	0 bc
LS	69.3 ba	58.6 ab	*

*: data lost due to hail storm; the first letter equals significance between harvest start times and the second letter equals significance between species.

In Figure 4.7, saleable leaf fresh weight per plant of lettuce is shown at each harvest after the three different starts of harvest. Saleable leaf FW/plant of ES increased constantly among the three harvests, 2.7 g for the first harvest, 51.7 g for the second harvest and 83.1 g for the third harvest. The MS and LS produced the highest saleable leaf FW/plant at the second harvest (76.2 g and 142.8 g respectively), saleable leaf FW/plant was lower at the first harvest (5.8 g for MS and 26.4 g for LS) than the third harvest (38.8 g for MS), but saleable leaf FW/plant in the LS was lost due to hail storm.

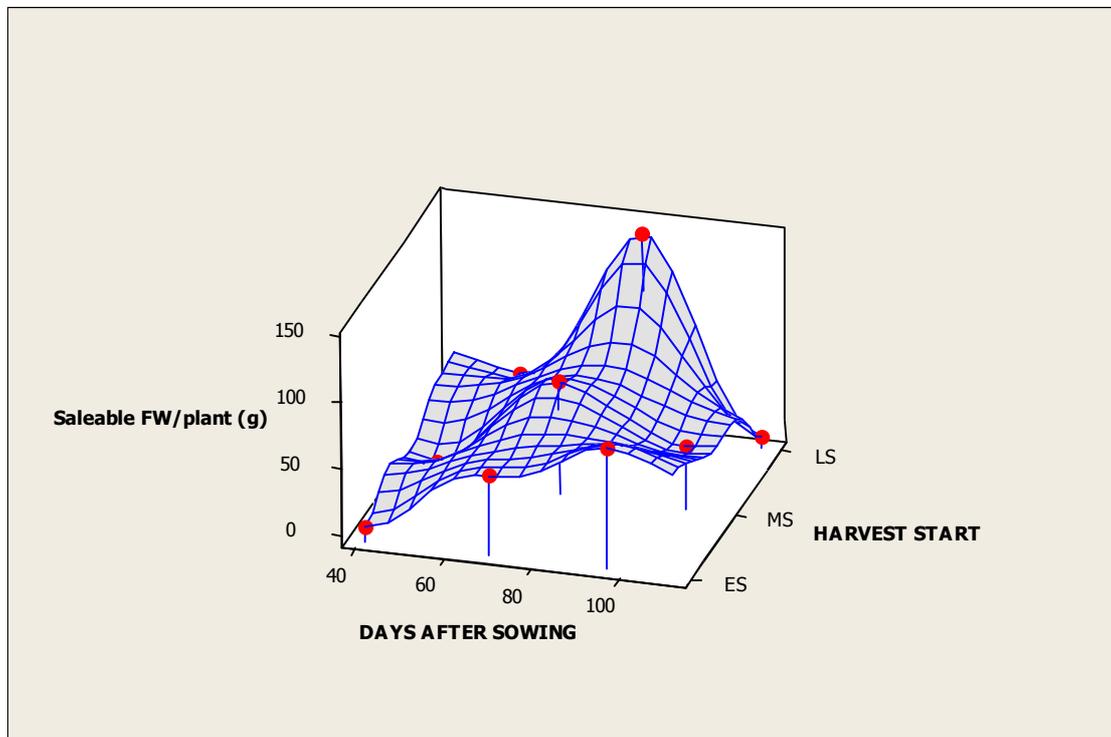


Figure 4.7. Saleable leaf fresh weight per plant of lettuce harvested three times after either an early, mid or late start of harvest (SEM=8.06).

For pak choi (Fig. 4.8), the ES and MS produced the highest saleable leaf FW/plant at the second harvest (41.9 and 56.6 g respectively), and there was no saleable leaf FW/plant at the third harvest. Saleable leaf FW/plant of the LS reduced constantly among the three harvests, 54.8, 37.1 g and no saleable (due to hail storm) leaves for the first, second and third harvests respectively.

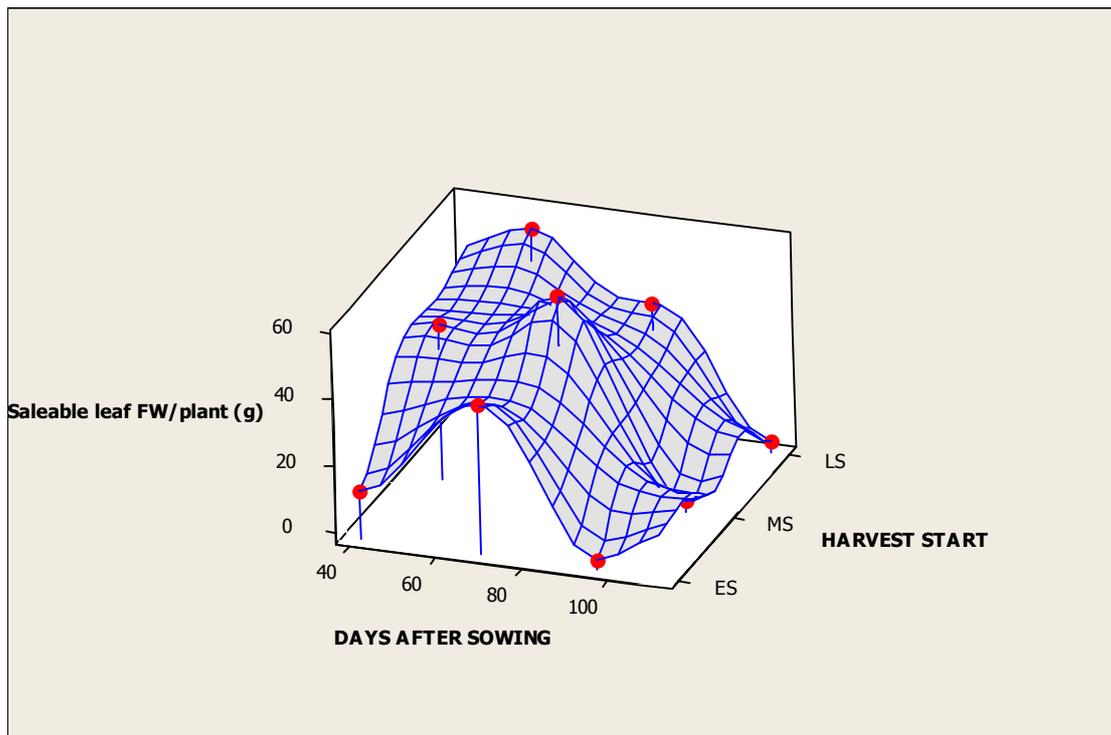


Figure 4.8. Saleable leaf fresh weight per plant of pak choi harvested three times after either an early, mid or late start of harvest (SEM=8.06).

For rocket (Fig. 4.9), the ES and MS produced the highest saleable leaf FW/plant at the second harvest (23.1 and 65.1 g), and this decreased to 3.1 g for ES and 0 g for MS at the third harvest. Saleable leaf FW/plant of the LS decreased constantly with the delay of harvest start time, 34.5, 22.0 and 0 (due to hail storm) for the first, second and third harvests respectively.

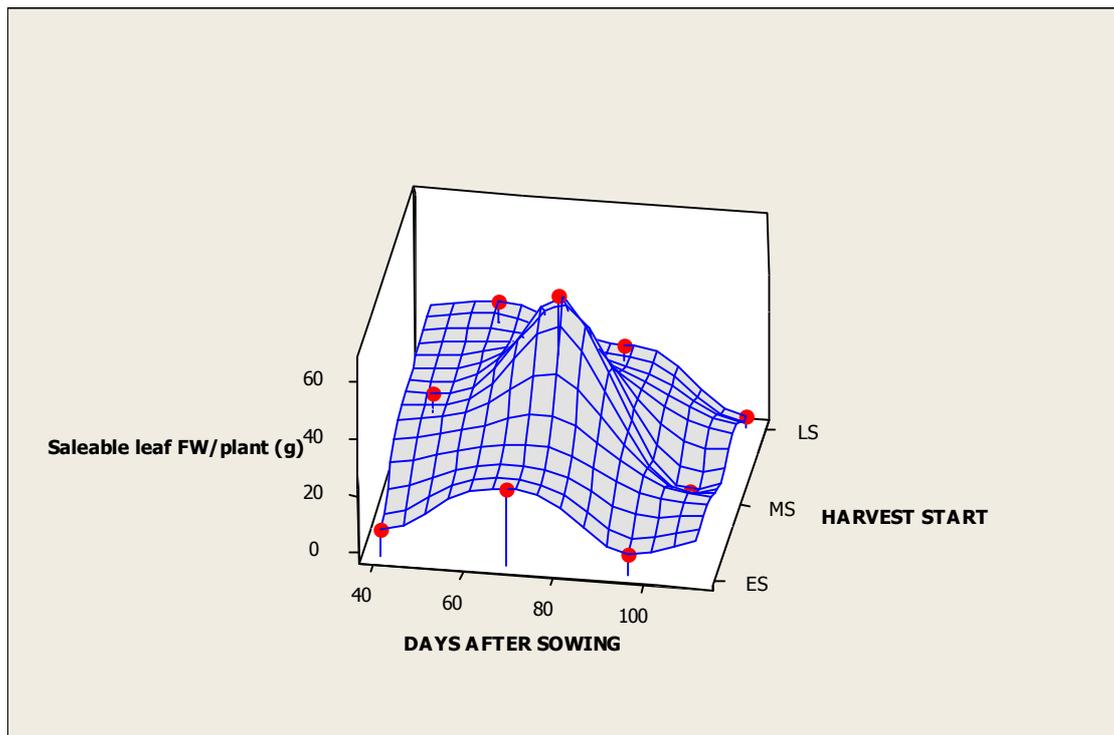


Figure 4.9. Saleable leaf fresh weight per plant of rocket harvested three times after either an early, mid or late start of harvest (SEM=8.06).

4.5 Dry weight per plant at each harvest after early, mid and late starts of harvest

Dry weight per plant of lettuce, pak choi and rocket at each harvest in the three different harvest starts are shown in Table 4.8. At the first harvest, delaying harvest start time resulted in significantly higher DW/plant ($p < 0.001$). At the second harvest, DW/plant of the ES, MS and LS were similar ranging from 5.0 to 5.7 g DW/plant. At the third harvest, the delay of harvest start time caused significantly lower DW/plant ($p < 0.001$).

At each harvest, the DW/plant of lettuce, pak choi and rocket were significantly different between each other. Lettuce produced lower DW/plant (1.7 g) at Harvest 1, and higher DW/plant (6.2 g and 3.6 g) at Harvest 2 and 3 than pak choi and rocket. Pak choi produced higher DW/plant at Harvest 1 (3.9 g), but lower DW/plant (4.1 and 1.1 g) at Harvest 2 and 3 than rocket (3.6, 5.7 and 2.2 g DW/plant for Harvest 1, 2 and 3 respectively).

Table 4.8 Dry weight per plant (g) of lettuce, pak choi and rocket harvested at three different times during the growing season after either early, mid or late start of harvest.

	Harvest 1	Harvest 2	Harvest 3
Harvest start time (H)			
early	0.8	5.3	3.5
mid	3.3	5.7	2.3
late	5.1	5.0	0.98
Significance	$p < 0.001$	$p = 0.550$	$p < 0.001$
SEM	0.18	0.47	0.25
Variety (V)			
lettuce	1.7	6.2	3.6
pak choi	3.9	4.1	1.1
rocket	3.6	5.7	2.2
Significance	$p < 0.001$	$p = 0.013$	$p < 0.001$
SEM	0.18	0.47	0.25
cv%	20.6	30.8	37.8
Significant interaction	H×V	Nil	H×V

Figure 4.10 shows that for each variety, plants produced higher DW/plant in the later starts of harvest at the first harvest. In the ES, pak choi produced higher DW/plant (1.3 g) than lettuce (0.42 g) at the first harvest. In the MS and LS treatments, both pak choi and rocket produced significantly higher DW/plant than lettuce ($p<0.01$).

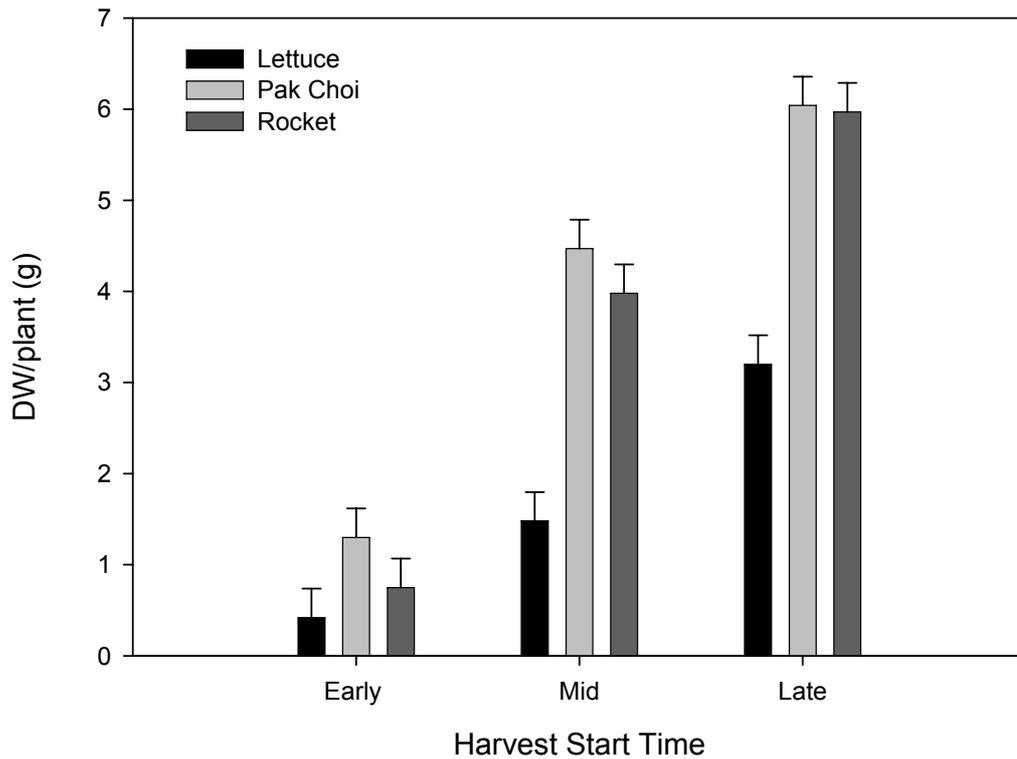


Figure 4.10. The interaction of harvest start time and variety on dry weight per plant at the first harvest (Bars: SEM=0.317).

The interaction of harvest start time and variety on dry weight per plant at the third harvest is indicated in Figure 4.11. DW/plant of lettuce and rocket decreased significantly as the harvest start time was delayed. However, pak choi produced the similar DW/plant in the ES, MS and LS treatments.

In ES and MS, DW/plant of lettuce, pak choi and rocket were significantly different between each other ($p < 0.01$). However, lettuce, pak choi and rocket yielded similar DW/plant in the LS.

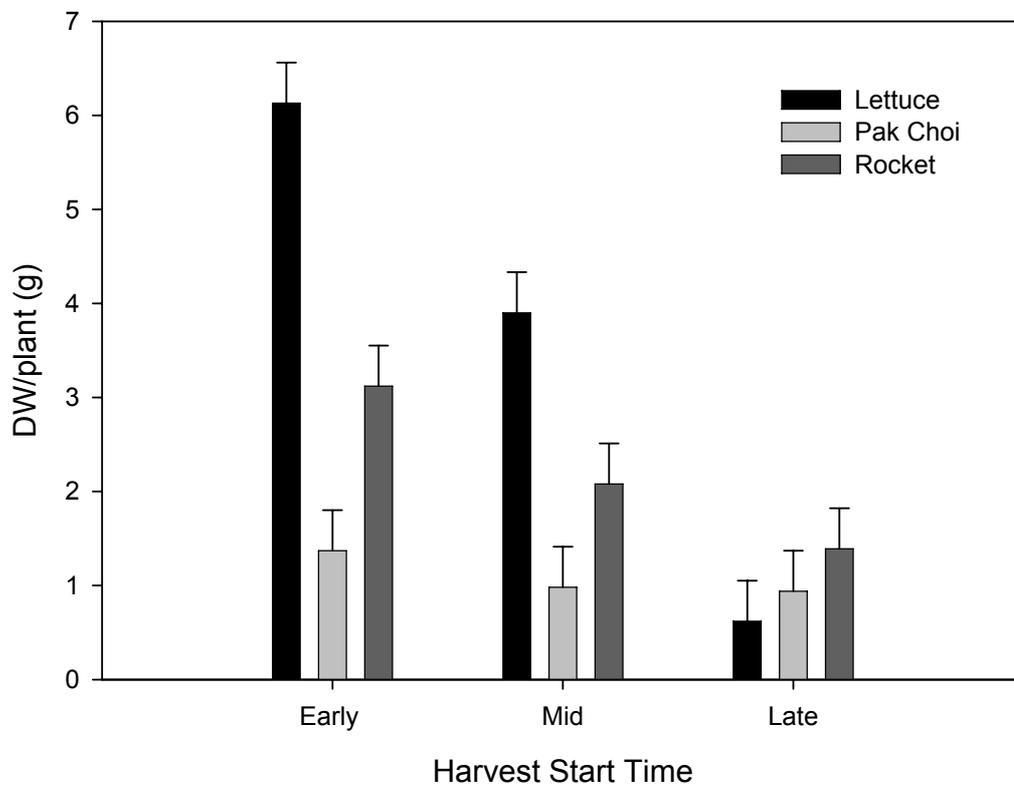


Figure 4.11. The interaction of harvest start time and variety on dry weight per plant at the third harvest (Bars: SEM=0.431).

Lettuce plants produced higher DW/plant in the later starts of harvest at the first harvest, 0.42, 1.48 and 3.2 g DW/plant for the ES, MS and LS respectively (Figure 4.12). In the ES, DW/plant of lettuce increased significantly from 0.42 g DW/plant at the first harvest to 6.2 g DW/plant at the second harvest ($p < 0.001$), and then levelled off at 6.1 g DW/plant at the third harvest. In the MS and LS, lettuce DW/plant were higher at the second harvest than at the first harvest, but lower at the third harvest compared with the second harvest, especially for the third harvest in the LS (0.62 g DW/plant). Lettuce produced the highest DW/plant (6.9 g) at the second harvest in the LS.

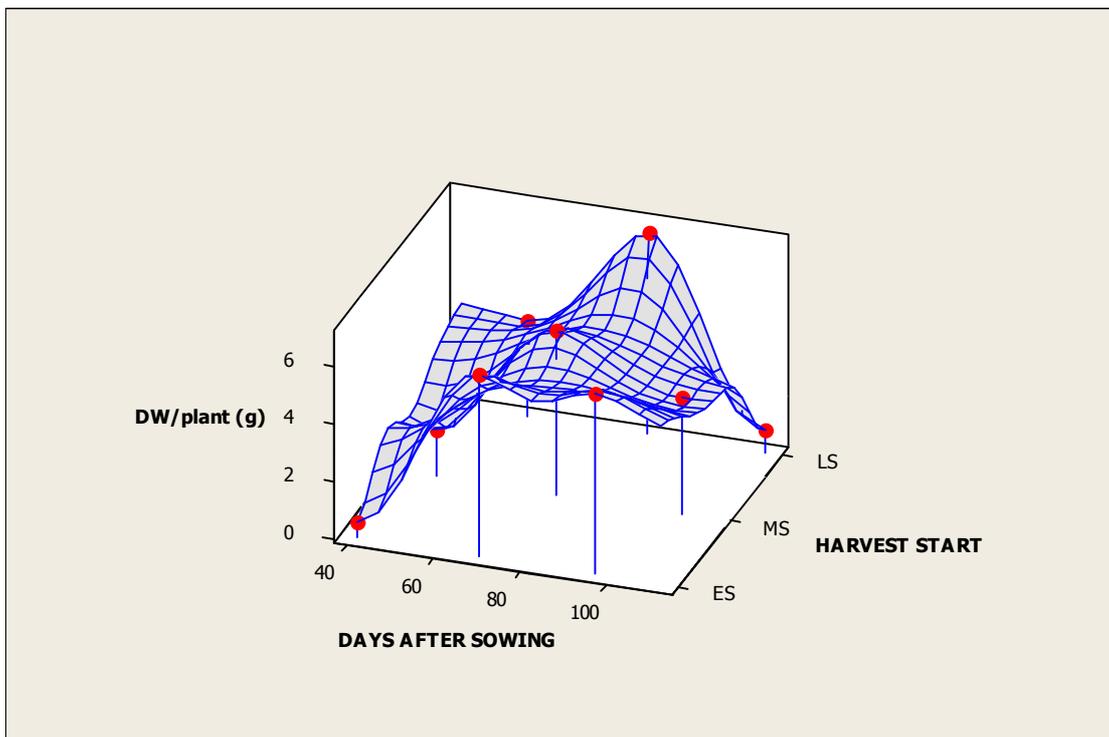


Figure 4.12 Dry weight per plant of lettuce harvested three times after either an early, mid or late start of harvest (SEM=0.565).

Figure 4.13 shows pak choi DW/plant at each harvest in the ES, MS and LS. It indicates that plants produced significantly ($p < 0.001$) higher DW/plant in the later starts of harvest at the first harvest (1.3, 4.5 and 6.0 g DW/plant for the ES, MS and LS, respectively). In the ES treatment, DW/plant of pak choi increased at the second harvest (4.2 g) compared with the first harvest (1.3 g), and then decreased at the third harvest (1.37 g). In the MS, pak choi produced the similar DW/plant at the first and second harvests (4.47 and 4.48 g), but much lower DW/plant (0.98 g) at the third harvest. In the LS, DW/plant of pak choi decreased constantly among the three harvests, 6.0, 3.75 and 0.94 g DW/plant at the first, second and third harvest. Pak choi produced the highest DW/plant at the first harvest in the LS treatment.

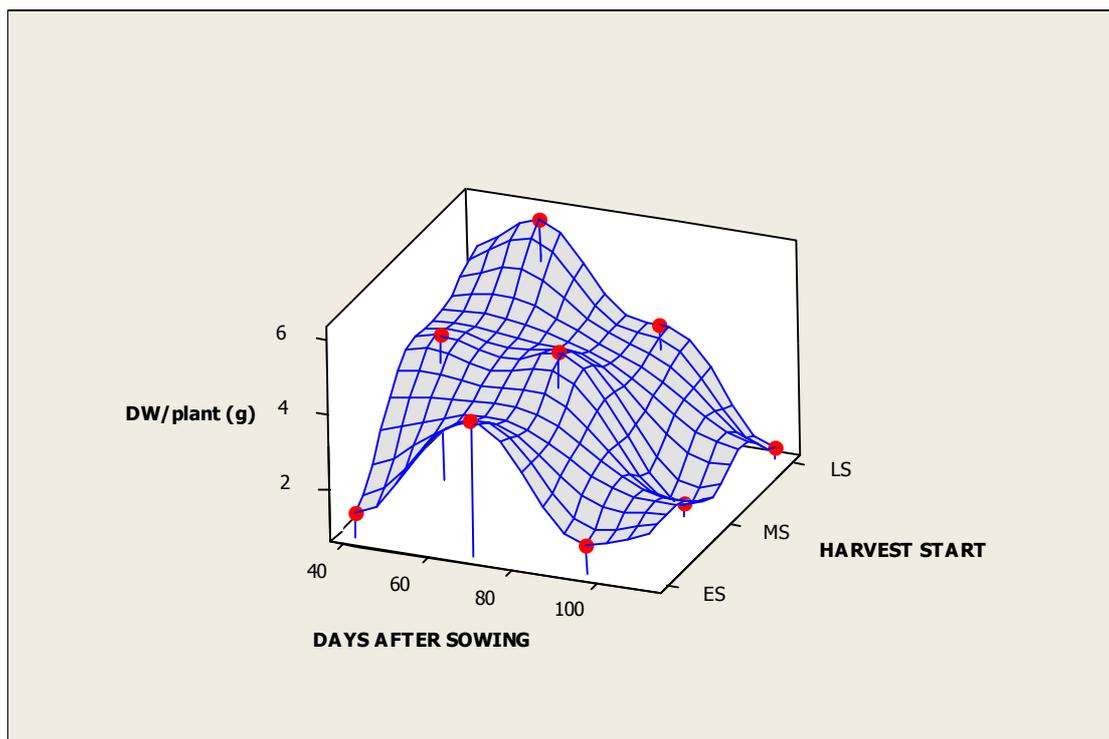


Figure 4.13 Dry weight per plant of pak choi harvested three times after either an early, mid or late start of harvest (SEM=0.565).

In Figure 4.14, rocket plants also produced significantly higher DW/plant in the later starts of harvest at the first harvest ($p < 0.001$), 0.75, 3.98 and 5.97 g DW/plant for the ES, MS and LS respectively. DW/plant of rocket increased significantly ($p < 0.001$) at the second harvest in the ES and MS (5.6 and 7.1 g DW/plant), and then decreased at the third harvest (3.1 and 2.1 g DW/plant for the ES and MS respectively). In the LS treatment, rocket DW/plant declined significantly ($p < 0.001$) and constantly, 5.97, 4.3 and 1.4 g DW/plant for the first, second and third harvests.

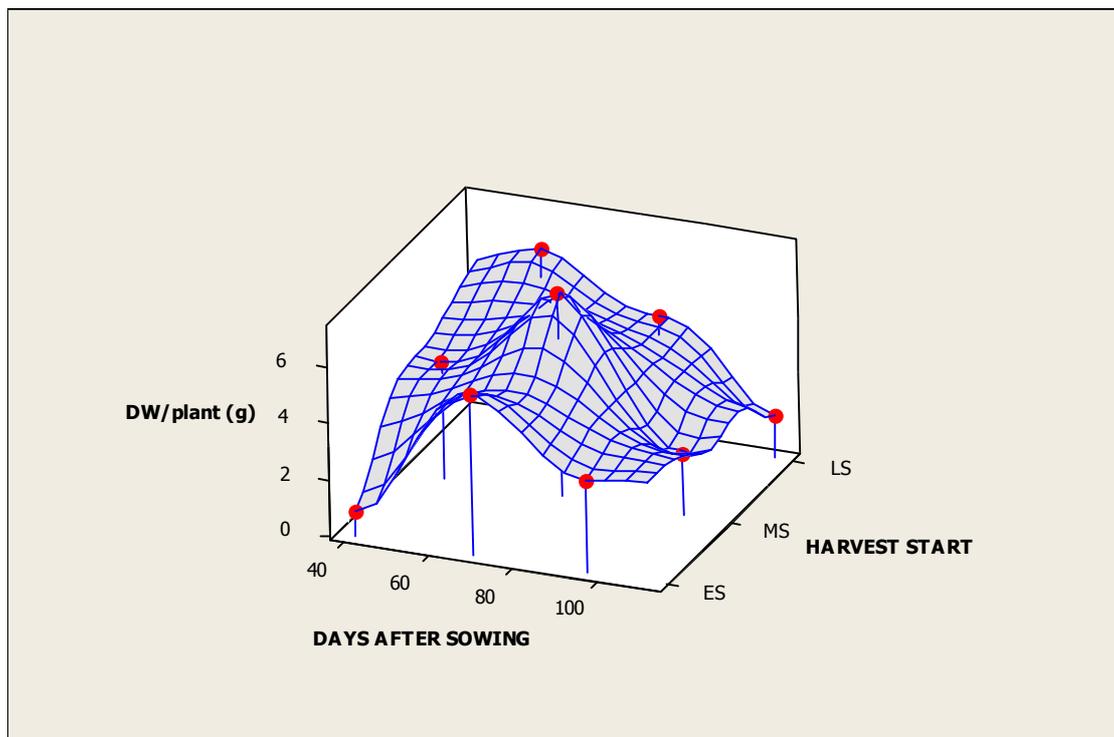


Figure 4.14 Dry weight per plant of rocket harvested three times after either an early, mid or late start of harvest (SEM=0.565).

4.6 Leaf area index (LAI) and leaf number per plant (LN/plant) at each harvest after early, mid and late starts of harvest

Table 4.9 shows LAI of lettuce, pak choi and rocket at harvest 1, 2 and 3 at the ES, MS and LS harvests. At harvest 1, an early start of harvest resulted in less LAI. Harvest start time affected LAI significantly ($p < 0.001$). Lettuce had less LAI than pak choi and rocket.

At harvest 2, the three different harvest starts did not affect LAI very much. Lettuce produced higher LAI (1.56) than pak choi and rocket (0.6 and 0.62 respectively).

At harvest 3, an early start of harvest led to increasing of LAI significantly ($p < 0.001$). Also, lettuce produced higher LAI (0.7) than pak choi and rocket (0.26 for both).

The interaction of harvest start time and variety affected LAI of lettuce, pak choi and rocket significantly at harvest 1, 2 and 3 (Table 4.9).

Table 4.9 Leaf are index (LAI) of lettuce, pak choi and rocket harvested at three different times during the growing season after either early, mid or late start of harvest.

	Harvest 1	Harvest 2	Harvest 3
Harvest start time (H)			
early	0.12	0.74	0.83
mid	0.38	0.99	0.40
late	0.67	1.05	*
Significance	$p < 0.001$	NS	$p < 0.001$
SEM	0.03	0.11	0.08
Variety (V)			
lettuce	0.30	1.56	1.28
pak choi	0.43	0.60	0.26
rocket	0.43	0.62	0.26
Significance	$p = 0.008$	$p < 0.001$	$p < 0.001$
SEM	0.03	0.11	NA
cv%	26.9	40.5	NA
Significant interaction	H×V	H×V	H×V

*: data lost due to hail storm.

Figure 4.15 shows that LAI of lettuce in the ES treatment increased constantly during the three harvests, 0.17, 1.22 and 1.43 for the first, second and third harvests respectively. In the MS and LS treatments, LAI of lettuce increased at the second harvest (1.36 and 2.09 for the MS and LS) from the first harvest (0.17 and 0.66 for the MS and LS), and decreased at the third harvest (0.68 and 0 for the MS and LS). The data was lost at the third harvest in the LS treatment because of hail storm.

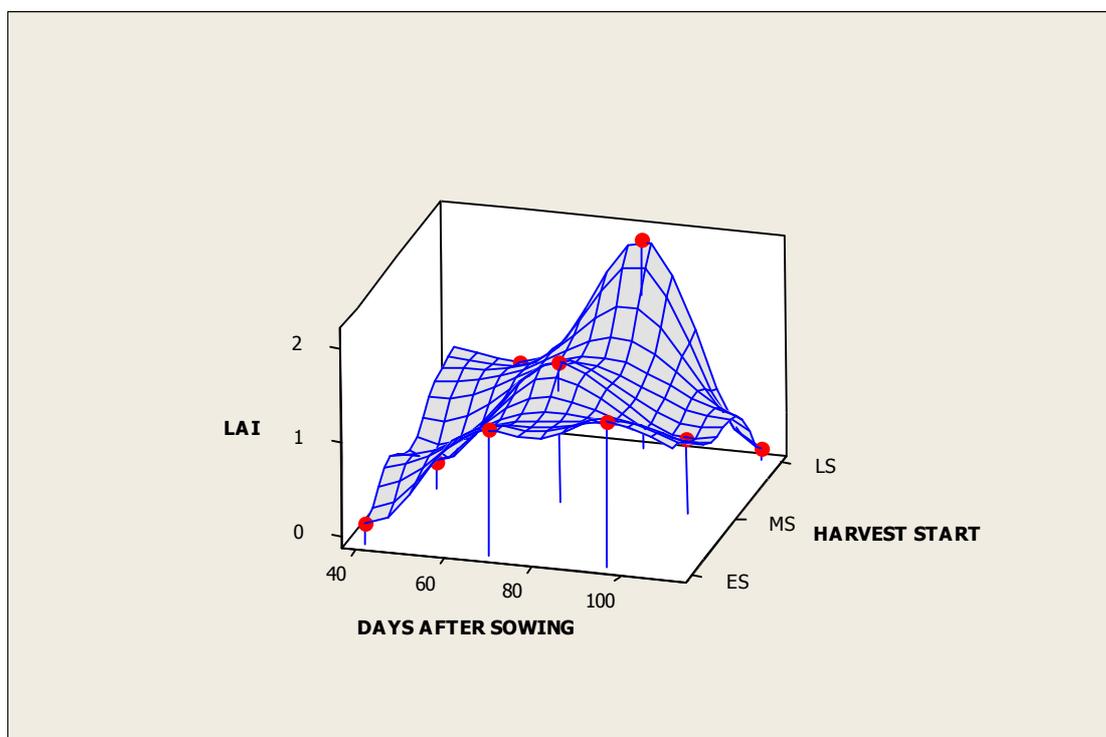


Figure 4.15 Leaf area index (LAI) of lettuce harvested three times after either an early, mid or late start of harvest (SEM=0.125).

For pak choi (Fig. 4.16), LAI in the ES treatment increased at the second harvest (0.54) from the first harvest (0.17), and then levelled off at the third harvest (0.53). In the MS treatment, LAI increased at the second harvest and decreased at the third harvest and decreased at the third harvest (0.5, 0.71 and 0.25 for the first, second and third harvests respectively). In the LS, LAI of pak choi decreased at the second harvest (0.55) from the first harvest (0.63). The third harvest was lost due to hail.

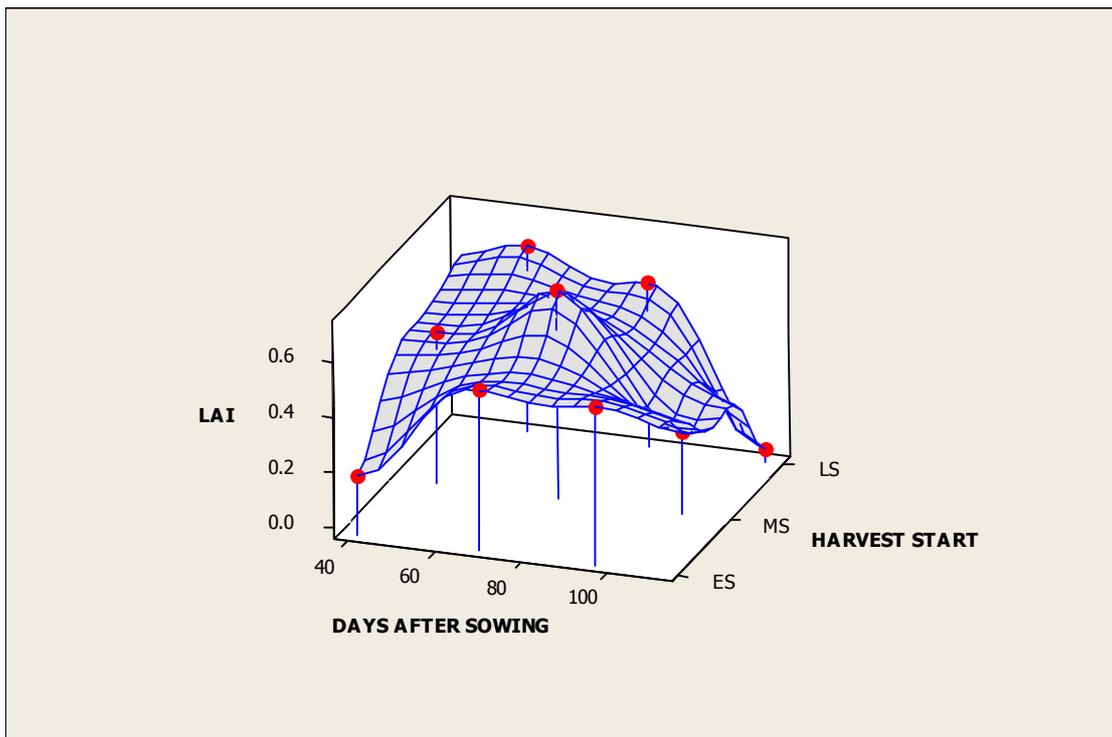


Figure 4.16 Leaf area index (LAI) of pak choi harvested three times after either an early, mid or late start of harvest (SEM=0.125).

For rocket (Fig. 4.17), LAI increased constantly in the ES during the three harvests (0.1, 0.45 and 0.53 for the first, second and third harvests). However, it decreased constantly in the LS, 0.71, 0.51 and 0 (data lost) for the first, second and third harvests respectively. In the MS treatment, LAI increased at the second harvest, and decreased at the third harvest (0.48, 0.89 and 0.26 for the first, second and third harvests, respectively).

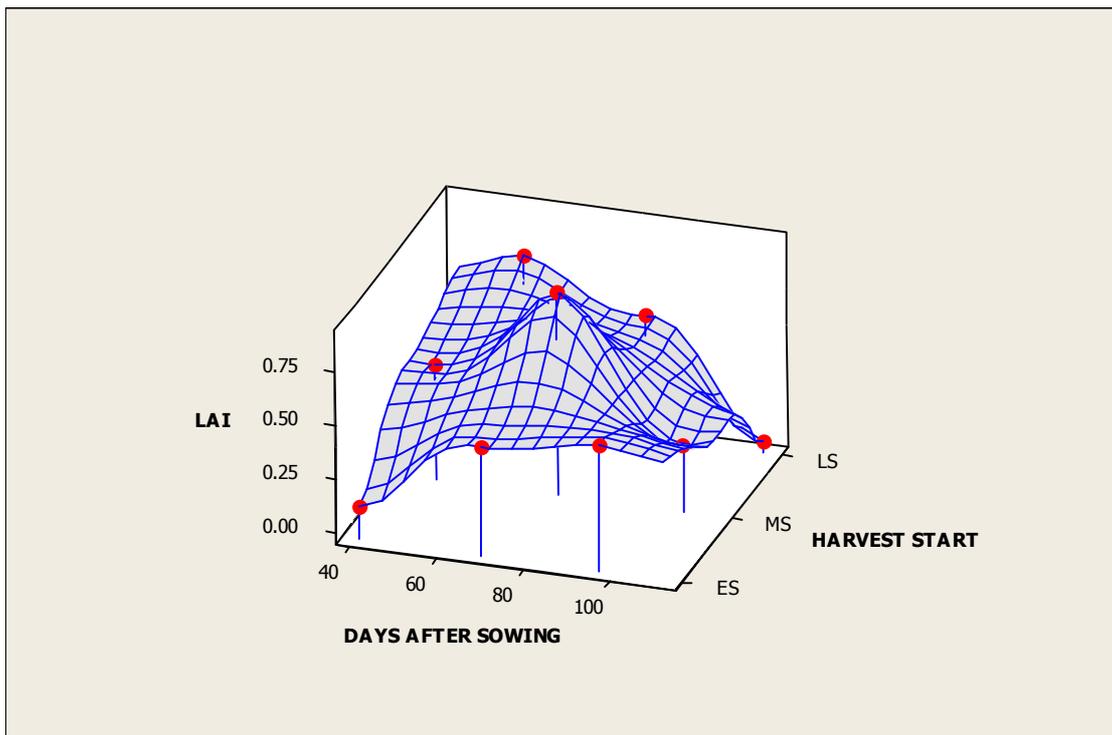


Figure 4.17 Leaf area index (LAI) of rocket harvested three times after either an early, mid or late start of harvest (SEM=0.125).

Leaf number per plant (LN/plant) of the three different harvest start times at each harvest is shown in Table 4.10. At harvest 1, a later start of harvest resulted in increasing numbers of leaves per plant, 8.8, 14.4 and 24.4 for ES, MS and LS respectively. Rocket produced the highest LN/plant (19.8) of the three varieties. Lettuce produced higher LN/plant (18.3) than pak choi (9.4).

At harvest 2, a later start of harvest also resulted in increasing of LN/plant, 25.1, 30.5 and 32.2 for ES, MS and LS respectively. Pak choi produced fewer leaves per plant (12.0) than lettuce (38.2) and rocket (37.6).

At harvest 3, different harvest start times did not affect LN/plant. Rocket produced the highest LN/plant (26.9). Lettuce produced more leaves per plant (20.9) than pak choi (6.4).

The interaction of harvest start time and variety affected LN/plant of lettuce, pak choi and rocket significantly at harvest 1, 2 and 3 (Table 4.10).

Table 4.10. Leaf number per plant of lettuce, pak choi and rocket harvested at three different times during the growing season after either early, mid or late start of harvest.

	Harvest 1	Harvest 2	Harvest 3
Harvest start time (H)			
early	8.8	25.1	30.1
mid	14.4	30.5	24.0
late	24.4	32.2	*
Significance	p<0.001	p=0.002	NS
SEM	0.5	1.3	2.1
Variety (V)			
lettuce	18.3	38.2	20.9
pak choi	9.4	12.0	6.4
rocket	19.8	37.6	26.9
Significance	p<0.001	p<0.001	p<0.001
SEM	0.5	1.3	NA
cv%	11.0	15.3	NA
Significant interaction	H×V	H×V	H×V

*: data lost due to hail storm.

In Figure 4.18, LN/plant of lettuce increased at the ES and MS harvests from 9.6 and 12.1 for ES and MS at the first harvest to 37.7 and 35.5 for ES and MS at the second harvest, and then decreased to 34.1 and 28.5 for ES and MS at the third harvest. In the LS treatment, LN/plant increased at the second harvest (33.4, 41.3 for harvest 1 and 2 respectively). The data was lost at the third harvest in the LS because of hail damage.

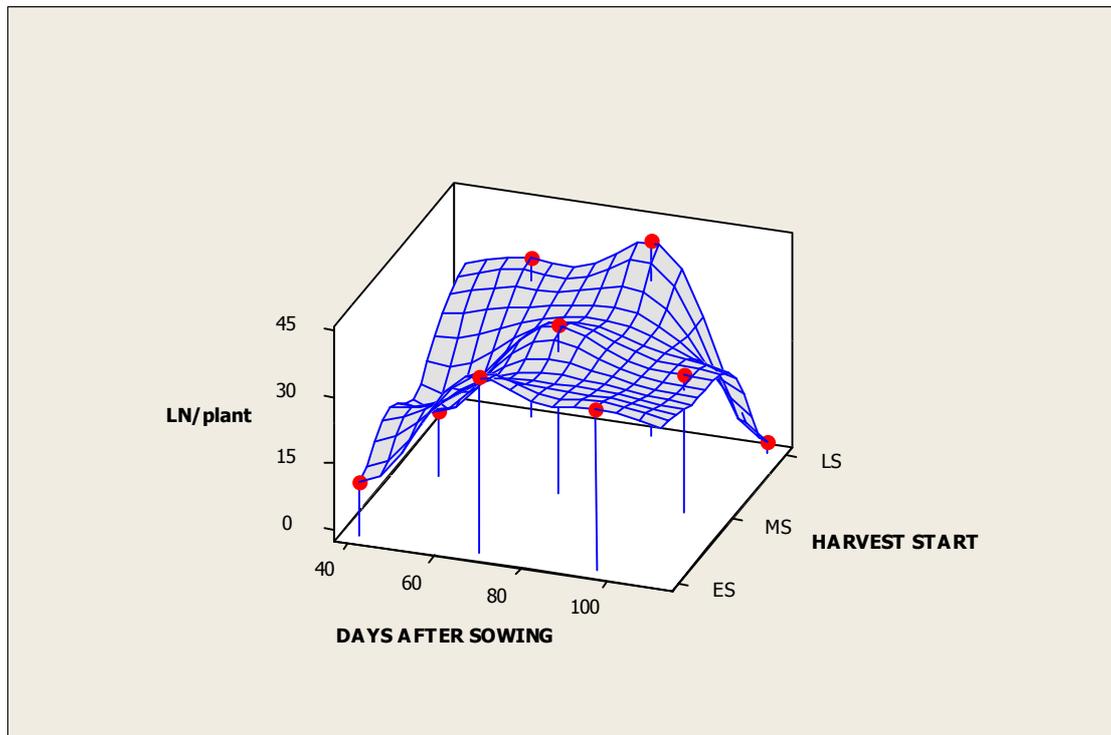


Figure 4.18. Leaf number per plant (LN/plant) of lettuce harvested three times after either an early, mid or late start of harvest (SEM=3.59).

LN/plant of pak choi (Figure 4.19) increased at the second harvest, and decreased at the third harvest for all three different harvest starts. The LN/plant was 8.2, 10.5 and 9.4 for the ES, 10.5, 13.4 and 9.8 for the MS, and 9.6, 12 and 0 (data lost due to hail damage) for the LS at harvest 1, 2 and 3 respectively.

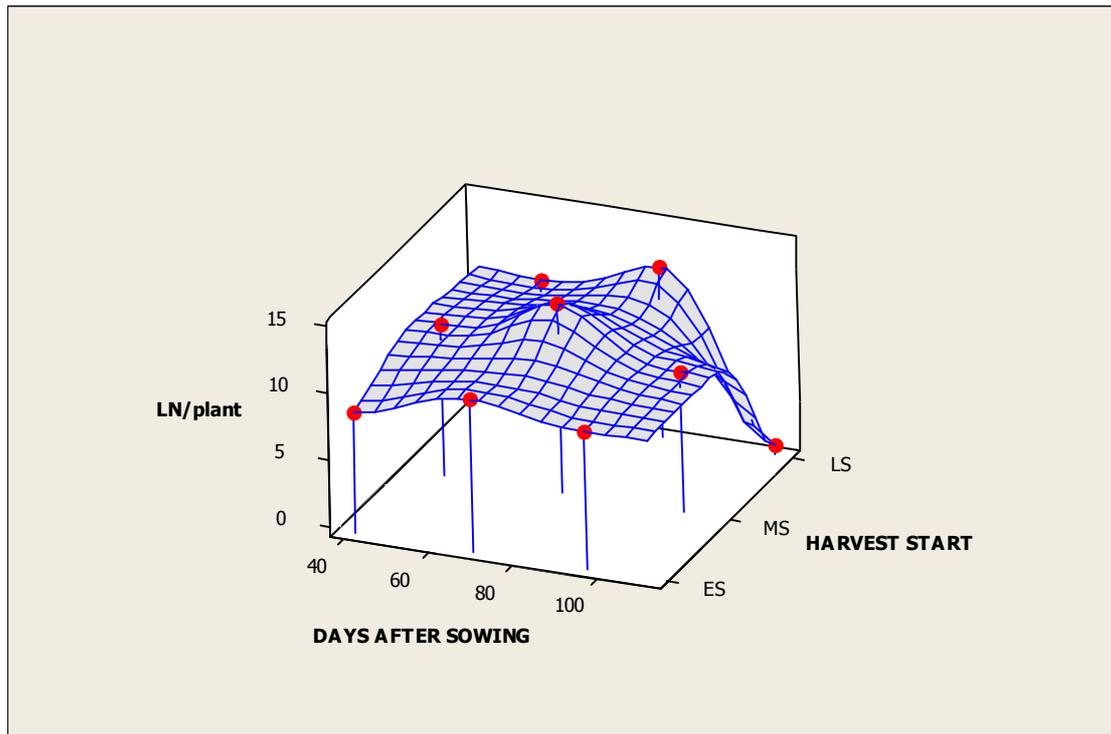


Figure 4.19. Leaf number per plant (LN/plant) of pak choi harvested three times after either an early, mid or late start of harvest (SEM=3.59).

In Figure 4.20, LN/plant of rocket is shown at three different starts of harvest over three harvests. Rocket LN/plant increased constantly for the ES and LS harvests, 8.6, 26.9 and 46.7 for harvest 1, 2 and 3 respectively at the ES, and 30.1, 43.4 and 0 (data lost due to hail damage) for harvest 1, 2 and 3 respectively at the LS. For the MS, LN/plant of rocket increased from 20.6 at harvest 1 to 42.6 at harvest 2, and then decreased to 33.8 at harvest 3.

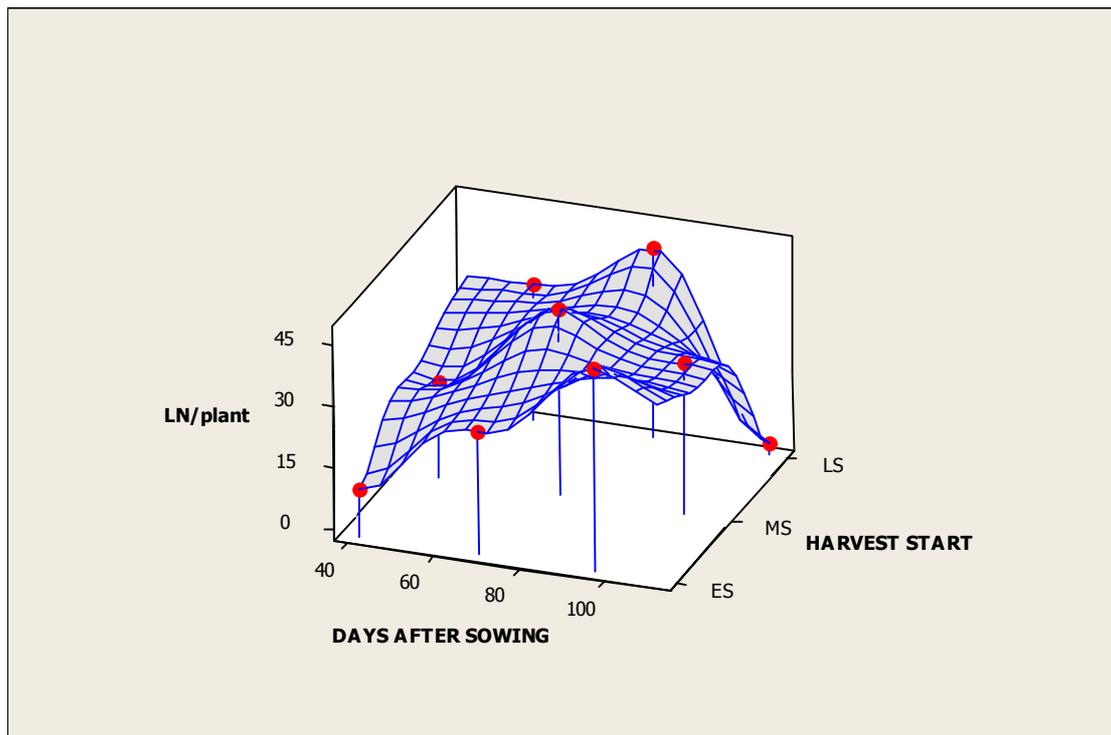


Figure 4.20. Leaf number per plant (LN/plant) of rocket harvested three times after either an early, mid or late start of harvest (SEM=3.59).

4.7 Effects of thermal time on accumulated dry weight per plant and accumulated leaf number per plant of lettuce, pak choi and rocket during the growing season at early, mid and late starts of harvest

Figure 4.21 shows the effect of thermal time on accumulated dry weight per plant of lettuce, pak choi and rocket at different starts of harvest. There was a positive linear relationship between accumulated DW/plant and thermal time for all three varieties. The growth rates (g accumulated DW/°Cd) of lettuce, pak choi and rocket were not different from each other significantly (grand mean of 0.014 g/°Cd).

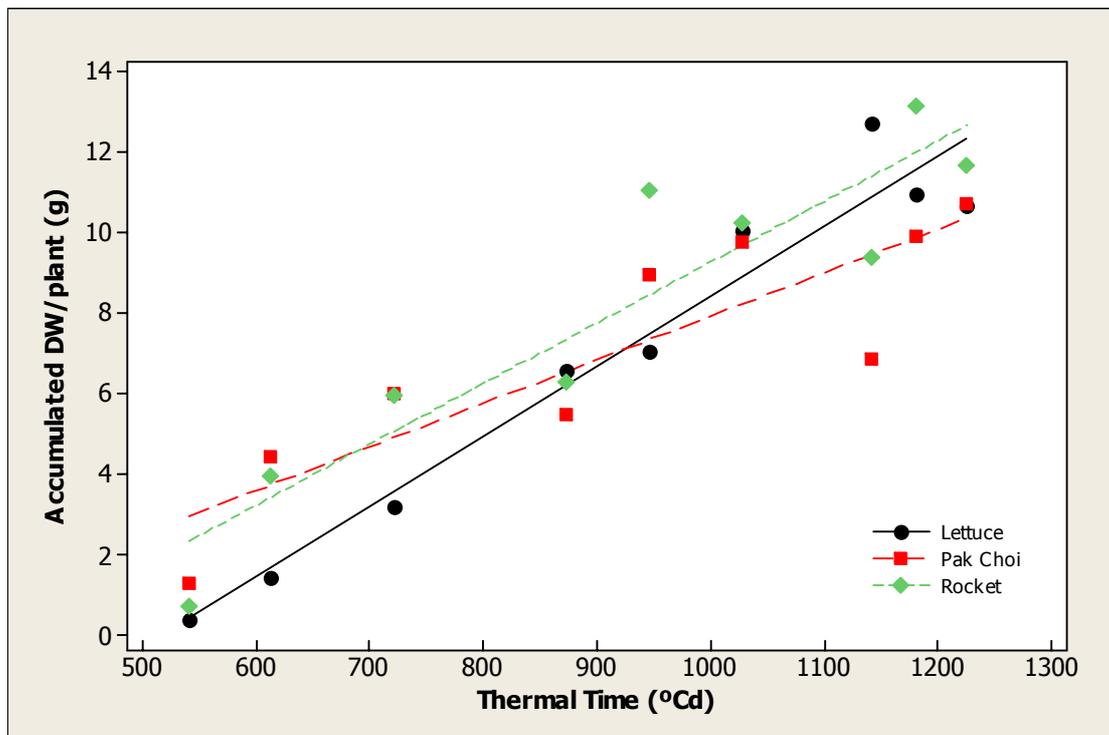


Figure 4.21. The effect of thermal time on accumulated dry weight per plant of lettuce, pak choi and rocket harvested three times at the early start, mid start and late start of harvest ($T_b=4$ °C; Lettuce, $y=0.017x-8.9$ $R^2=0.95$; Pak Choi, $y=0.011x-2.85$ $R^2=0.77$; Rocket, $y=0.015x-5.8$ $R^2=0.86$).

In Figure 4.22, it shows the effect of thermal time on accumulated LN/plant of lettuce, pak choi and rocket. There was a positive linear relationship between accumulated LN/plant and thermal time for each variety. Lettuce and rocket had the fastest development rate (0.116 and 0.131 leaves/°Cd) than pak choi (0.038 leaves/°Cd). There were significant differences in development rate (leaves/°Cd) between lettuce and pak choi, and between rocket and pak choi ($p < 0.001$). The phyllochron was shown in Table 4.11 for lettuce, pak choi and rocket in the ES, MS and LS during the growing season.

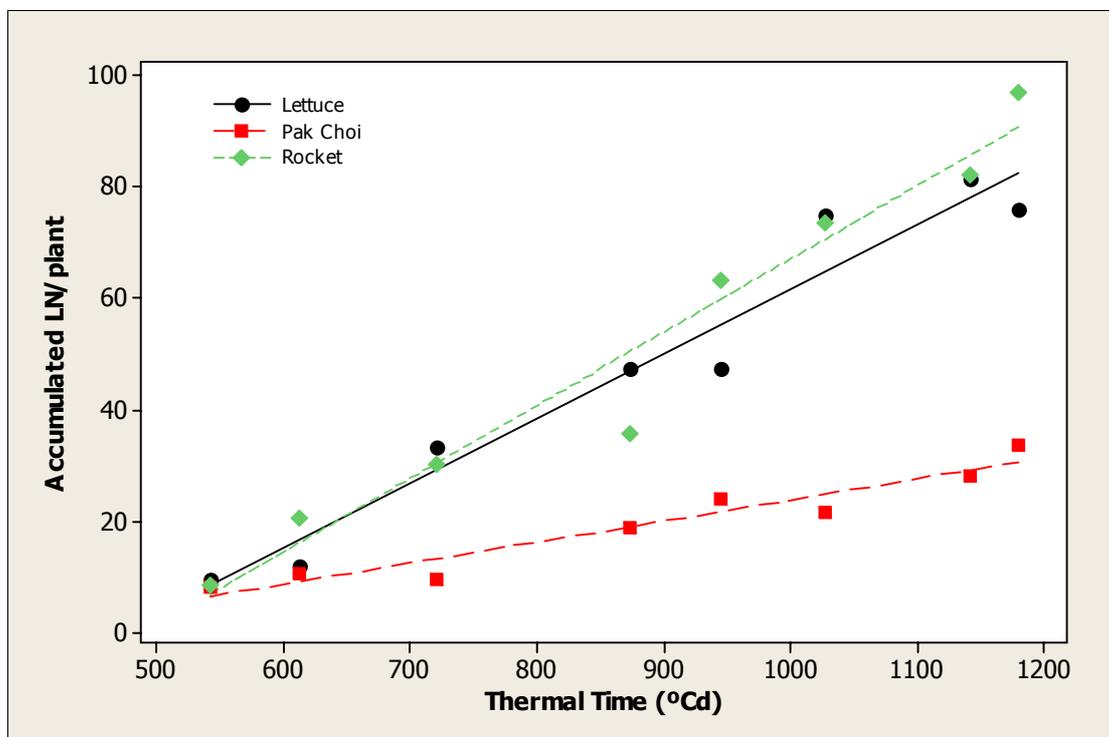


Figure 4.22. The effect of thermal time on accumulated leaf number per plant (LN/plant) of lettuce, pak choi and rocket harvested three times at the early start, mid start and late start of harvest ($T_b = 4\text{ °C}$; Lettuce, $y = 0.116x - 54.5$ $R^2 = 0.95$; Pak Choi, $y = 0.038x - 13.9$ $R^2 = 0.93$; Rocket, $y = 0.131x - 64.1$ $R^2 = 0.96$).

Table 4.11. The phyllochron of lettuce, pak choi and rocket over the growing season.

	Lettuce	Pak Choi	Rocket
Phyllochron (°Cd)	8.6	26.3	7.6

Compared between harvests, Table 4.12 shows that the phyllochron decreased with the harvest times in each treatment for lettuce, pak choi and rocket. The phyllochron of lettuce was smaller (21.6 °Cd/leaf) in the LS than the ES and MS (56.4 and 50.6 °Cd/leaf) at the first harvest. Pak choi needed more thermal time to produce one leaf in the LS at the first harvest (75.1 °Cd/leaf), and in the ES at the second and third harvests (31.6 and 28.6 °Cd/leaf), compared with the other two treatments respectively. It is shown that the phyllochron of rocket was larger at the first harvest (63 °Cd/leaf) and second (12.3 °Cd/leaf) harvests in the ES treatment than the MS and LS treatments (Table 4.12).

Table 4.12. The phyllochrons (°Cd/leaf) of lettuce, pak choi and rocket at each harvest at either an early, mid or late start of harvest.

Harvest Start Time	H1	H2	H3
	Lettuce		
ES	56.4	8.8	7.9
MS	50.6	9.4	8.2
LS	21.6	7.4	*
	Pak Choi		
ES	66.0	31.6	28.6
MS	58.3	24.8	23.9
LS	75.1	25.7	*
	Rocket		
ES	63.0	12.3	5.8
MS	29.7	7.8	6.9
LS	23.9	7.1	*

*: data lost due to hail storm.

Table 4.13 indicates the thermal time experienced by plants from sowing to the first harvest and during regrowth between the harvests. For the first harvest, thermal time increased with the delay of harvest start time. However, it was reversed for the third harvest. For the second harvest, thermal time of the ES and MS were almost the same (331.6 and 333.3 °Cd), but the LS experience less thermal time (307.6°Cd).

Table 4.13. The thermal time experienced by lettuce, pak choi and rocket for each harvest with either an early, mid and late start of harvest (°Cd).

Harvest Start Time	sowing→H1	H1→H2	H2→H3
ES	541.6	331.6	268.6
MS	612.4	333.3	234.4
LS	720.6	307.6	197.3

5.0 Discussion

5.1 Effects of different harvest start times on yield

The total dry yield and total dry weight of lettuce were not affected by different harvest start times. However, the interaction between harvest start time and variety showed that pak choi and rocket in the- ES treatment produced less total dry yield and weight than in the MS and LS treatments (Figure 4.2 and 4.3). The higher production from lettuce means that this species recovered more quickly.

One reason for the faster recovery of lettuce after the first harvest in the ES treatment could be the plant reserves. When the plants were harvested, roots and part of leaves and petals were left behind. This provides a carbohydrate reserve to stimulate regrowth. As lettuce, pak choi and rocket had the similar growth rates (grand mean 0.014 g accumulated DW/°Cd) (Fig. 4.21) and experienced the same thermal time (due to sowing at the same time and growing in the same conditions), the three varieties should produce the same level of DW at the first harvest in the ES, assuming similar base temperatures. However, lettuce produced less DW/plant (1.7 g) at the first harvest than pak choi (3.9 g DW/plant) and rocket (3.6 g DW/plant) significantly ($p < 0.001$) (Table 4.5). Thus, more carbohydrates may have been deposited in the root system of lettuce after the first harvest in the ES treatment compared to pak choi and rocket (Qin et al., 2002).

Qin et al. (2002) said that the ratio of root/shoot DW decreased significantly from about 0.38 to 0.2 ($p < 0.05$) with the increasing number of days growing at 20 °C root-zone temperature in the early period of growth stage. However, Qin et al. (2002) also showed that root dry weights of Butterhead lettuce were at the same level in the early growth stage at a root-zone temperature 20 °C, and leaf dry weights increased with the days growing the same conditions and period of time. These results shown by Qin et al. (2002) indicated that lettuce seemed to partition more photosynthate to the root system in the early period of growth. This means that as much as 38% of lettuce dry

matter could be reserved in the root system in the early periods of growth stage. Increased reserves in the root, therefore, may be the reason for the lower DW/plant at the first harvest, but higher DW/plant at the second harvest.

Booyesen and Nelson (1975) found that carbohydrates for regrowth may be provided by current photosynthate or/and plant reserves in grass. They also said that under the condition of heavy topgrowth removal, the first new leaves generated depended on plant reserves. Wilson and Robson (1970) and Ward and Blaster (1961) also showed the same result. Therefore, it is possible for a plant to produce several new leaves quickly by using reserves. Once, new photosynthetic leaf area is formed, regrowth rate is strongly related to leaf area and current photosynthate supply (Booyesen and Nelson, 1975; Ward and Blaster, 1961). Because the cutting level was 5 cm above the growing point, lettuce, pak choi and rocket were severely defoliated. Plant recovery was dependent on reserves at the start of regrowth. Therefore, more reserves for lettuce in the ES may be the reason for the faster recovery in lettuce.

Van den Boogaard et al. (2001) said that non-structural carbohydrate (sugar and starch) concentrations in cauliflower (*Brassica oleracea* L. var. *botrytis*) were reduced after defoliation, showing that reserves were mobilised to support regrowth. Jean et al. (1994) also studied the changes in the non-structural carbohydrate content during growth periods in forage rape (*Brassica napus* L.). They reported that the non-structural carbohydrate content in leaves and roots decreased significantly in the early growth period after winter, from 187 and 497 mg/g DM to 69 and 79 mg/g DM respectively. The reserves were used for plant regrowth of new leaves. Similar results were observed previously (Avice et al., 1997; Cralle and Bovey, 1996; Oesterheld and McNaughton, 1988).

Another reason for the faster recovery of lettuce could be more photosynthetic leaf area. The lettuce in this experiment had oak leaf shaped leaves. Pak choi's leaf was a big, long petal with a wide blade. Rocket's leaf shape was branched into several small leaflets. When plants were cut at 5 cm above the growing point, part of the remaining lettuce leaf area was left. However, most of pak choi photosynthetic leaf area was removed, leaving two or three small curved and tight leaves. The remaining photosynthetic leaf area of rocket was somewhere between lettuce and pak choi.

Results in Figures 4.15, 4.16 and 4.17 show that lettuce usually produced higher LAI at each harvest in different harvest start treatments, suggesting that there might be more remaining leaf area for lettuce compared with pak choi and rocket. More photosynthetic leaf area means greater radiation interception and more photosynthate (Nassiri and Elgersma, 1998). Therefore, lettuce probably had more carbohydrates for the start of regrowth, resulting in faster recovery.

Van den Boogaard et al. (2001) also said the relative growth rate of cauliflower plants increased after defoliation. Oosterheld and McNaughton (1988, 1991) and Oosterheld (1992) reported the same result of increased relative growth rates in *Themeda triandra*, *Briza subaristata* and *Stipa baviensis* after defoliation or grazing. This higher relative growth rate after defoliation resulted at least partly from a higher net assimilation rate (Oosterheld and McNaughton, 1991). The higher net assimilation rate may result from a higher photosynthetic rate (Evans, 1991; Lovett and Tobiessen, 1993; Ovaska et al., 1992).

The higher photosynthetic area for lettuce after harvest and higher photosynthetic rate could result in faster regrowth of plants. In addition, Oosterheld and McNaughton (1991) and Oosterheld (1992) showed that the restoration of the relationship between leaf area and plant weight resulted partly from a larger allocation of assimilates to the leaves, and partly from an increase in leaf area. It may be possible that root growth was decreased after defoliation, because assimilates will be used preferentially for leaf area growth. Lambers et al. (1995) discussed that roots only received assimilate that were left by sinks, i.e. young leaves are mainly sinks, and old leaves are sources. Thus, root growth would decrease after defoliation, due to more assimilates for regrowth of the leaf area (Eissenstat and Duncan, 1992; Bassman and Zwier, 1993), until plants restore the ratio between shoot and roots (Reich et al., 1993).

In addition, a lower base temperature for lettuce could be another reason for faster recovery than pak choi and rocket. In this experiment, the base temperature used for calculating thermal time was 4 °C for all three varieties. However, there is the possibility of a lower base temperature for lettuce. Lettuce can start to grow at temperature as low as 3 °C (Morgan, 1999). In this situation, lettuce would experience

more thermal time than pak choi and rocket. Plant growth rates were closely related to thermal time, and lettuce may have recovered more quickly.

Another possible reason for the faster recovery of lettuce could be that lettuce has a lower optimum temperature than does pak choi or rocket. Lettuce, pak choi and rocket are all cool season crops, and produce better quality plants in cool conditions. A repeat experiment was conducted in February and harvesting started in March. However, the second experiment was harvested only twice due to very slow growth rates, caused by low temperature and frost. From the comparison between the two repeated experiments, it was observed that plants which experienced lower temperatures in the second experiment produced better quality leaves. Morgan (1999) proved that lettuce would produce better quality plants in the cooler conditions of winter and spring. Morgan (1999) also said the optimum temperatures of lettuce were 12 to 21 °C. The optimum temperatures of pak choi were not found directly. Leng et al. (2002) reported that the optimum temperature of rapeseed (*Brassica napus* L.) were 20 to 25 °C. Because pak choi belongs to the Brassica, the optimum temperatures for pak choi may be similar to the rapeseed. Unfortunately the optimum temperatures of rocket are not available in the literature. According to the total yield and plant weights in this experiment, it is suggested that the optimum temperatures of rocket might be higher than lettuce, but lower than pak choi (Fig. 4.2 and 4.3).

The mean temperatures were 16.7, 17.3, 15 and 11.3 °C for January, February, March and April respectively. The minimum and maximum daily mean temperatures ranged from 10.5 to 23.4 °C in these three months (Table 4.1 and Fig. 4.1). This indicates that lettuce should have the fastest growth rates in January, February and March, because lettuce experienced optimum temperatures. For pak choi and rocket, or at least for pak choi, there were only 7 days mean temperatures in the optimum range of 20 to 25 °C. Since, plants have the highest rate of net photosynthesis in the optimum temperature (Hay and Walker, 1989), lettuce grew faster than pak choi and rocket, leading to faster recovery.

5.2 Effects of different harvest start times on DW/plant at each harvest

Generally, delaying harvest start time resulted in a higher DW/plant at the first harvest (Table 4.8). Lettuce, pak choi and rocket all had similar results (Fig. 4.10). This was due to more thermal time experienced by plants with the delayed harvest start times, e.g. 541.6, 612.4 and 720.6 °Cd for the ES, MS and LS at the first harvest, respectively (Table 4.10). There was a positive relationship between accumulated dry weight and thermal time as shown in Figure 4.18. Weidenhoeft (1993) and Brown et al. (2007) also concluded that forage brassica species (rape, turnip, leafy turnip and kale) produced higher regrowth yield with higher thermal time and warmer conditions. Extensive studies on plant growth and thermal time have shown similar results (Madariaga and Knott, 1951; Wiggans, 1956; Iwata, 1975; Jamieson et al., 1995, 1998; Jamieson and Munro, 1999; Slafer and Rawson, 1995).

For lettuce (Fig. 4.12), at the second harvest, the ES produced higher DW/plant than the MS. However, the ES and MS experienced almost the same amount of thermal time, 331.6 and 333.3 °Cd (Table 4.9). There may be two reasons for this result. Leaf cutting stress may affect plant growth. When plants were harvested in the ES, they were very small, with only about 9 leaves (Fig. 4.18). Thus, little leaf dry weight was removed, only 0.42 g DW/plant at the first harvest. Plants of the MS treatment were larger, about 12 leaves were present at the first harvest. When leaves were removed, reserves in the plant residual were used for new leaf growth, and more current photosynthates were partitioned into the leaves (Booyesen and Nelson, 1975; van den Boogaard et al., 2001).

The other reason why the ES produced higher DW/plant than the MS could be that during the interval between the first and second harvests, the lettuce plants of the ES experienced more days of optimum temperatures than the MS. This means that plants in the ES may have had higher photosynthetic rates, leading to more DW/plant at the second harvest.

Again, the LS produced higher DW/plant than the ES and MS. However, plants of the LS experienced less thermal time (307.6 °Cd) than the other start times. There were

33.4 leaves per plant in the LS at the first harvest. Therefore, more reserves and photosynthetic leaf area were left in the plant residue, compared to the ES and MS. This means that in the early regrowth period of the LS there were more carbohydrates and current photosynthate for new leaf growth. Thus, the photosynthetic leaf area can be established more quickly in the LS treatment after the first harvest (Booyesen and Nelson, 1975; van den Boogaard et al., 2001).

As described above, the delay of harvest start time resulted in larger plants. Larger plants mean larger root systems and more and bigger leaves. This results in more carbohydrate and photosynthetic leaf area left for plant regrowth. Carbohydrate for regrowth may be provided by current photosynthate or plant reserves, or both (Booyesen and Nelson, 1975).

Booyesen and Nelson (1975) studied the influences of leaf area (HL, high residual leaf area; and LL, low residual leaf area) and carbohydrate reserves (HC, high reserve carbohydrates; LC, low reserve carbohydrates) on regrowth of tall fescue (*Festuca arundinacea* L. Alta) (Fig. 2.7). The HC/HL and LC/LL treatments presented the two extreme patterns of dry matter accumulation in which the energy sources (stored reserves and current photosynthate) were both most adequate and most limited, respectively. When two-thirds of the leaf area was left on the plants at day 0 (HL), the pattern of dry matter accumulation was not affected by the low carbohydrate level (LC). When all leaf blades (LL) were removed, the patterns of dry matter accumulation for HC and LC plants were similar during the first 10 days of regrowth, with only a slightly increased rate of accumulation during the following 10 days in HC plants over LC plants (Booyesen and Nelson, 1975). It shows reserve carbohydrates and photosynthetic leaf area can affect regrowth, and the cutting height is more important than the reserve carbohydrate reserve.

Tobisa et al. (2003) also reported higher regrowth of phasey bean (*Macroptilium lathyroides* L. Urb) at 15 cm cutting height than 7.5 cm cutting height, due to differences in the amount of storage nutrients available for regrowth.

At the third harvest, the ES plants produced the highest DW/plant and the LS plants produced the least. The reduced DW/plant with the delayed harvest start corresponded

to a reduced thermal time, 268.6 and 197.3 °Cd (Table 4.13). Lettuce plants in the ES produced higher DW/plant than the MS and LS, due to higher regrowth rate (0.023 g DW/°Cd) at the third harvest. This was faster than the growth rate during the entire growing season (Fig. 4.21). The ES plants were larger because it was warmer when plants were harvested from the ES harvest compared to the MS and LS at the third harvest. The regrowth rate in the LS was very slow (0.003 g DW/°Cd), because the temperatures were very low ranging from 6.3 to 16.5 °C. The mean temperature was 11.3 °C (Fig. 4.1 and Table 4.9). It has been shown that temperature was the main driver of primary leaf appearance (Hodges, 1991). Wiedenhoeft (1993) found that brassica crops of forage rape (*Brassica napus* L.), turnip (*Brassica rapa* L.) and a hybrid leafy turnip (*Brassica rapa* × *Brassica pekinensis* L.) produced more yield when they experienced warmer temperatures during regrowth.

Another reason for higher regrowth rate in the ES plants could be due to more reserves. However, the reserves may not be useful for regrowth in the LS treatment, due to low temperatures or vigour loss. Repeated use of reserves may in turn lead to a reduction of plant vigour when the process is repeated before the reserves are again replenished (Booyesen and Nelson, 1975).

For pak choi (Fig. 4.13), plants in the MS produced significantly higher DW/plant than the LS ($p < 0.001$). Between the first and second harvests, the MS experienced more thermal time than the LS, while the thermal times for the ES and MS were almost the same (Table 4.13). Although there was no significant difference between the ES and MS at the second harvest, the ES produced less DW/plant (4.2 g) than the MS (4.48 g). The regrowth rates for the ES, MS and LS were 0.013, 0.013 and 0.012 g DW/°Cd, similar to the growth rate of the whole growing season (0.011 g DW/°Cd) (Fig. 4.21). This suggests that pak choi regrowth was strictly related to the thermal time experienced during the growing interval, and reserves had little effect on the regrowth at the different harvest starts.

At the third harvest, plants of the ES, MS and LS produced the similar DW/plant, even though the thermal time declined with the delayed harvest start time. Pak choi had little ability to regrow after the second harvest.

For rocket (Fig. 4.14), the pattern of regrowth was similar to lettuce. However, at the second harvest, the MS plants produced the highest DW/plant (7.1 g), and had the highest regrowth rate (0.021 g DW/°Cd). Thermal time may therefore be more important for rocket regrowth, rather than reserves (Fig. 4.14 and Table 4.10). The MS experienced more thermal time (333.3 °Cd) than the LS (307.6 °Cd), and had more reserves and remaining photosynthetic leaf area than the ES.

For the second regrowth period, the ES plants produced higher DW/plant because of higher temperatures during the regrowth period than the MS and LS (Wiedenhoeft, 1993). Also, reduced plant vigour may be one reason for lower DW/plant at the third harvest in the LS treatment (Booyesen and Nelson, 1975).

At the third harvest, lettuce produced higher DW/plant than pak choi and rocket in the ES and MS treatments (Fig. 4.14). The possible reason for this may be that in the early growth stages, more photosynthates were partitioned to the root system for lettuce. Lower DW/plant at the first harvest for lettuce suggests this was the case (Fig. 4.10). Stewart and Moorhead (2004) studied the suitability of radish (*Raphanus sativa* L.) and cabbage (*Brassica oleracea* L.) for multiple grazing, and concluded that radish could have two more harvests than cabbage. The partitioning of more assimilates into the root system in the early growth stages, which can contribute to a lower leaf yield at the first grazing, might be responsible for resilience and persistence during later grazings. Therefore, more reserves in the root system in the early growth may be the cause of higher DW/plant at the third harvest in the ES and MS.

5.3 Effects of different harvest start times on saleable leaves at each harvest

In this experiment, saleable leaf FW/plant was calculated as: FW/plant times the percentage of saleable leaves at each harvest. The percentage of saleable leaves was calculated based on leaf number, because most unsaleable leaves were too small, the actual weight of unsaleable leaves was minimal. For this reason, it is assumed that leaf FW/plant was the same as saleable leaf FW/plant.

Usually, leaves were unsaleable because they were small (less than 5 cm²), or not green. For lettuce, the main reason for reduced percentages of saleable leaves was smaller leaf size. When plants were cut at 5 cm height above the growing point, the tips of unexpanded inner leaves were harvested, and they were usually less than 5 cm². For pak choi and rocket, the colour change from green to yellow and/or purple was the main reason for unsaleable leaves.

Lettuce plants in the LS treatment produced the highest saleable leaf FW/plant (142.8 g) at the second harvest (Fig. 4.7). This is because lettuce produced the highest FW/plant (182 g) (Fig. 4.4) and a high percentage of saleable leaves (78.4%) (Table 4.5). Pak choi produced the highest saleable leaf FW/plant at the first harvest in the LS treatment, while rocket produced the highest saleable leaf FW/plant at the second harvest in the MS treatment.

There was a great difference between lettuce and the other two at the third harvest. Lettuce produced saleable leaves at the third harvest in the ES and MS treatment. If there had been no hail storm, fresh leaves in the LS treatment would have been saleable although FW/plant was very low (5.6 g) (Fig. 4.4). The saleable leaf FW/plant at the third harvest was the second highest in the ES (Fig. 4.7). However, pak choi and rocket were not saleable at the third harvest in all treatments because of the leaf colour change and the hail damage.

5.4 Effects of different harvest start time on plant development

In this study, lettuce, pak choi and rocket were harvested at three different harvest start times, ES, MS and LS respectively. The plant sizes were different at the first harvest in the three treatments, leading to various levels of reserves and different remaining photosynthetic leaf areas. In this experiment, the influence of water stress and nitrogen were not considered, because levels of these important plant requirements were optimised. Therefore, the effects of temperature, reserves and/or remaining photosynthetic leaf area will be discussed.

5.4.1 Effects of different harvest start time on leaf area index at each harvest

For all three varieties, LAI increased with a delay of harvest start time at the first harvest. Plants in the delayed harvest start had experienced more thermal time at the first harvest, and this resulted in greater LAI (Fig. 4.15, 4.16, 4.17 and 5.1). Birch et al. (2003), Chapman et al. (1993) and Díaz-Ambrona et al. (1998) have shown similar relationships.

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Figure 5.1 Total plant leaf area (TPLA) versus thermal time (TT) for five lines of sunflower (Chapman et al., 1993) on pp.105.

However, at the second harvest, plants produced higher LAI, although they experienced less thermal time. For example, lettuce plants in the LS had a higher LAI (2.09) of harvested leaves than in the ES and MS at the second harvest (Fig. 4.15), but they experienced less thermal time (307.6 °Cd) (Table 4.10). Because there was no effect of water or nitrogen on leaf growth in this study, plant carbohydrate reserves and more remaining photosynthetic leaf area could be responsible for this result.

The remaining assimilates in plant residues have been shown to be remobilised to regrow new leaves after harvest (Booyesen and Nelson, 1975; Cralle and Bovey, 1996; Jean et al., 1993; Oosterheld and McNaughton, 1988; Smith, 1974; Tobisa et al., 2003; Ward and Blaser, 1961; Wilson and Robson, 1970), especially for severe topgrowth removal. Under these conditions, the first few leaves were dependent on reserves because the current photosynthate assimilated by remaining green leaves may not be sufficient to support leaf regrowth (Booyesen and Nelson, 1975; Davis, 1974; Smith, 1974; Volaire, 1994; Ward and Blaser, 1961; Wilson and Robson, 1970). The more available reserves, the faster the first few leaves can be established in the early period of regrowth. In turn, more current photosynthates can be provided for plant regrowth. In this experiment, plants in the later harvest start treatment were larger, and carried more reserves after harvest than did the earlier harvest start treatments.

When plants were harvested at 5 cm height above the growing point, the larger lettuce plants in the LS treatment had more remaining photosynthetic leaf area. Thus, more current photosynthates could be provided in the early period of regrowth in the LS treatment (Davis, 1974; Ferraris and Norman, 1974; Smith, 1974; Ward and Blaser, 1961). In addition, plants after defoliation have been shown to have higher photosynthetic rates (Evans, 1991; Lovett and Tobiessen, 1993; Ovaska et al., 1992), leading to higher relative growth rate (van den Boogaard et al., 2001). This means that even more current photosynthates for regrowth were available in the LS treatment compared with the ES and MS treatment. Furthermore, a higher portion of assimilates were partitioned into leaves rather than roots after defoliation during regrowth (Bassman and Zwier, 1993; Eissenstat and Duncan, 1992; Oosterheld, 1992; Oosterheld and McNaughton, 1991), until the ratio between shoot and root was restored (Reich et al., 1993). Therefore, it is concluded that more remaining

photosynthetic leaf area of lettuce in the LS, relating to higher photosynthetic rates and higher portion of assimilates partitioned into leaves after defoliation, can result in a higher LAI during regrowth compared with plants in the ES and MS, even though the ES and MS experienced more thermal time (Table 4.13).

At the second harvest, lettuce produced higher LAI in the MS than in the ES (Fig. 4.15), although they experienced the similar thermal time (331.6 and 333.3 °Cd for the ES and MS) during regrowth (Table 4.13). This could have resulted from more reserves and photosynthetic leaf area after the first harvest in the MS than the ES, because of larger plant size in the later harvest start treatment.

However, it is expected that remaining photosynthetic leaf area of pak choi had little effect on regrowth. During the experiment, it was observed that little photosynthetic leaf area remained for pak choi after cutting at 5cm height above the growing point because of the long petal with a large leaf blade. It suggests that there may be little or no difference in the remaining green leaves between different harvest start treatments after defoliation. Therefore, it would be reasonable to assume that the effect of the remaining photosynthetic leaf area on regrowth is minimal for pak choi.

Plants of pak choi and rocket in the MS treatment produced higher LAI than in the ES and LS treatments (Fig. 4.16 and 4.17). This was due to higher thermal time in the MS than the LS (Table 4.11), and more reserves and/or remaining photosynthetic leaf area than the ES after the first harvest. Moreover, plants of pak choi and rocket in the ES and LS produced similar LAI values at the second harvest. This may be due to plants in the ES experiencing more thermal time (331.6 °Cd) than the LS (307.6 °Cd), however, the ES had less reserves and/or remaining photosynthetic leaf area for regrowth compared with the LS.

Furthermore, plants of all three varieties in the ES treatment produced higher or similar LAI at the third harvest compared with the second harvest (Fig. 4.15, 4.16 and 4.17), while they experienced less thermal time during regrowth after the second harvest (268.6 °Cd) than after the first harvest (331.6 °Cd). This can also be explained by more reserves and/or more remaining leaf area for regrowth after the second harvest compared with the regrowth after the first harvest.

At the third harvest, the LAI decreased as the harvest start time was delayed for all three crops (Fig. 4.15, 4.16 and 4.17). The LAI of the LS at the third harvest was lost due to the hail storm. However, according to the relationship between the LAI and thermal time (Fig. 5.1), and the thermal time experienced during regrowth between the second and third harvests (Table 4.11), the LAI of the LS should be lower than the MS at the third harvest.

A number of researchers have shown that decreases in LAI can occur with delayed harvest start time (Birch et al., 2003; Chapman et al., 1993; Díaz-Ambrona et al., 1998), because temperature is the main driver of primary leaf appearance (Hodges, 1991). The lower temperatures also affect leaf expansion because they result in lower photosynthetic rates causing reduced assimilation (Fig. 2.2) (Hay and Walker, 1989; Valentine and Kemp, 2007). The reduced assimilations will limit leaf expansion (Robertson et al., 2002). Thermal time during regrowth between the second and third harvests was 268.6, 234.4 and 197.3 °Cd for the ES, MS and LS respectively. This shows that temperature for the ES was higher than the MS and LS during regrowth (Fig. 4.1). Therefore, the LAI at the third harvest decreased with the delayed harvest start.

During autumn, assimilates can be preferentially partitioned into roots rather than shoots (Teixeira et al., 2007). This causes lower leaf growth, and in turn leads to lower LAI. Thus, this may be another possible reason for lower LAI in the MS compared with the ES at the third harvest.

5.4.2 Effects of different harvest start time on leaf number per plant at each harvest

The ability to form or reform a canopy of leaves after sowing or defoliation depends on the rate of new leaf appearance (Moot et al., 2007). In addition, primary leaf appearance is driven mainly by temperature (Hodges, 1991). Chapman et al. (1993) indicated that the leaf initiation rate was linearly related to the average temperature (Fig. 5.2). This means plants in warmer environment initiate more leaves.

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Figure 5.2 Average leaf initiation rate (LIR) versus average temperature from emergence to head visible for a series of monthly plantings of Sunfola68-2 at Toowoomba (○) and Biloela (●) (Chapman et al., 1993) on pp. 107.

In this study, there was a positive linear relationship between the accumulated LN/plant and thermal time (Fig. 4.22). The phyllochrons of lettuce, pak choi and rocket (8.6, 26.3 and 7.6 °Cd/leaf respectively) suggest that temperature was a main driver of leaf appearance (Hodges, 1991; Moot et al., 2007). Ruiters (1986), Hay and Kemp (1992) and Díaz-Ambrona et al. (1998) showed the same relationship between leaf number and thermal time, proving that temperature was the main factor influencing leaf number during plant growth. Furthermore, Brown et al. (2005)

indicated a positively linear relationship between the main stem nodes and accumulated thermal time during regrowth in lucerne (Fig. 5.3). This suggests that even during the regrowth temperature is still the main driver of primary leaf appearance, influencing leaf number per plant (Brown et al., 2005; Hodges, 1991; Moot et al., 2007).

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Figure 5.3 Main stem node appearance of re-growth 'Grasslands Kaituna' lucerne against thermal time (Tt) accumulated from 1 July for crops grown at Lincoln University, Canterbury, New Zealand (see Table 5.1 for symbols). Black arrows mark days of <0 °C frosts, grey arrows indicate start of flowering in two crops (Brown et al., 2005) on pp. 353.

Table 5.1 Description of acronyms used to represent each field-season combination and the symbols used in figures to represent each field-season-treatment combination (Brown et al., 2005) on pp. 350.

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In this experiment, LN/plant at the third harvest in the LS was lost due to hail damage. However, they were calculated using the relationship between thermal time and leaf number (Table 4.11 and 4.13). Thus, the LN/plant at the third harvest in the LS treatment would have been 22.9, 7.5 and 26.0 for lettuce, pak choi and rocket.

Results showed that LN/plant at the first harvest of lettuce and rocket increased as the harvest start was delayed. Because they were sown on the same day, plants in the delayed harvest start treatment experienced more thermal time and more days for growth.

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Figure 5.4. Leaf area index (LAI) in relation to the net number of leaves for regrowth 'Grasslands Kaituna' lucerne crops grown at Lincoln University, Canterbury, New Zealand. Note. \odot = 28 September to 9 November, 2000 (659 stems/m²), \circ = 14 November to 27 December, 2000 (649 stems/m²), \blacktriangle = 1 January to 9 February, 2001 (584 stems/m²), \blacktriangledown = 2 February to 14 March, 2001 (593 stems/m²). Linear regressions were fitted to open symbols for spring re-growth cycles with >2000 leaves m⁻² (.....), $a = 0.31(0.20)$, $b = 0.00017(0.00002)$, $R^2 = 0.92$. Closed symbols represent summer with the regression fitted to all values (---) $a = -0.10(0.24)$, $b = 0.00044(0.00004)$, $R^2 = 0.94$ (Brown et al., 2005) pp. 355.

The LN/plant at the third harvest decreased as the harvest start was delayed for lettuce and rocket (Fig. 4.18 and 4.20). This is because thermal time decreased with the delayed harvest start (Table 4.13). The intervals for regrowth in each treatment were 4 weeks. Therefore, plants in the ES experienced warmer temperatures than the MS and LS during regrowth between the second and third harvests, leading to higher LN/plant. This suggests the relationship between leaf initiation rate and average temperature shown in Figure 5.2.

However, at the second harvest, the LN/plant in the LS treatment for lettuce and rocket were higher than the ES and MS treatments, while the thermal time in the LS was lower than the ES and MS. This means that the phyllochron in the LS was smaller than the ES and MS at the second harvest for lettuce and rocket (Table 4.12).

The reason for this result was at least partly due to the plant branching. During the growing season, branching was observed in all crops. It was easy to find new leaves branching from the main leaves in pak choi and rocket in the field. The branching of lettuce was found during counting leaf numbers after harvest. New sub-leaflets were seen between main leaves. The branch leaves were usually small in size and not saleable. However, they did increase leaf number per plant, resulting in lower phyllochron.

For pak choi, LN/plant was similar to one another at the first harvest in the ES, MS and LS treatments (Fig. 4.19). The phyllochron in the LS was higher than the ES and MS (Table 4.12). This suggests that as thermal time increased with the delayed harvest start time at the first harvest LN/plant did not increase, but the leaf size did increase for pak choi. The higher LN/plant was at the second harvest in the MS (13.4) compared with the ES and LS. The phyllochron at the second harvest in the MS was lower than the ES and LS, because of the higher thermal time experienced by the MS.

The phyllochrons at the third harvest were lower than the second harvest in the ES and MS respectively (Table 4.12). However, the thermal time in regrowth was lower for the third harvest compared with the second harvest (Table 4.13). These results again may be due to branching and smaller leaf size, as branching increases leaf number and decreases phyllochron, and the lower temperatures limit leaf expansion (Hodges, 1991; Robertson et al., 2002).

The different harvest start times did not affect the main LN/plant, which is driven by temperature (Brown et al., 2005; Hodges, 1991; Moot et al., 2007). However, it may affect plant branching that could increase LN/plant. Therefore, different harvest start time may cause an increase in LN/plant indirectly by influencing branching.

5.5 The most suitable crop for the reaping and regrowth system

5.5.1 Comparisons between lettuce, pak choi and rocket in fresh weight per plant

In this study, lettuce produced higher total FW/plant (208 g) than pak choi (123 g) and rocket (102 g) using a reaping and regrowth system (Table 4.2). Lettuce produced the highest total fresh weight at the first harvest (Fig. 4.4, 4.5 and 4.6), although pak choi produced the most DW/plant (Table 4.8). As discussed, earlier lettuce was probably partitioning more dry matter below ground early on. However, by the second and third harvests, lettuce was considerably more productive than pak choi or rocket. There is no comparison between the third harvests in different harvest start treatments because of the hail storm. Therefore, lettuce produced higher total FW/plant than pak choi and rocket in either ES, MS or LS treatment (Table 4.3).

5.5.2 Comparisons between lettuce, pak choi and rocket in saleable leaf fresh weight per plant

The saleable leaf FW/plant of lettuce at the first harvest in the MS and LS (5.8 and 26.4 g) were lower than those of pak choi (43.4 and 54.8 g saleable leaf FW/plant) and rocket (27.2 and 34.5 g saleable leaf FW/plant). However, lettuce produced higher saleable leaf FW/plant at the second harvest (51.7, 70.2 and 142.8 g saleable FW/plant for the ES, MS and LS) than pak choi (41.9, 56.6 and 54.8 g saleable leaf FW/plant for the ES, MS and LS). Lettuce also produced 83.1 and 38.8 g saleable leaf FW/plant in the ES and MS at the third harvest, while pak choi were not saleable, and rocket produced much lower saleable leaf FW/plant (3.1 g) in the ES and no saleable leaves in the MS at the third harvest. (Fig. 4.7, 4.8 and 4.9).

Total saleable leaf fresh weight per plant calculated from all harvests showed that lettuce produced the highest total saleable leaf FW/plant in each treatment (Table 4.4).

5.5.3 Comparisons between lettuce, pak choi and rocket in regrowth potential (DW/plant)

Lettuce produced higher DW/plant at the second and third harvest (6.2 and 3.6 g DW/plant) than pak choi (4.1 and 1.1 g DW/plant) and rocket (5.7 and 2.2 g DW/plant), even though it produced lower DW/plant (1.7 g) at the first harvest (Table 4.5). This suggests that lettuce has higher regrowth ability than pak choi and rocket.

In addition, both lettuce and rocket produced reasonable DW/plant at the second and third harvests in all treatments. However, pak choi produced much lower DW/plant at the third harvest (Fig. 4.12, 4.13 and 4.14). It seems that pak choi could only produce one reasonable yield at the second harvest in each treatment during this experiment, while lettuce and rocket were able to regrow twice in the growing season. Thus, lettuce and rocket have a higher regrowth potential than pak choi.

In conclusion, lettuce produced the highest FW/plant and saleable leaf FW/plant. Also, lettuce had higher regrowth ability than pak choi and rocket. Therefore, lettuce is the most suitable crop in the reaping and regrowth system in this study. However, rocket might also be appropriate for this system, particularly if the price is high enough to make it economically viable.

6.0 Conclusions

- A larger plant size at harvest start resulted in higher total yield. This was probably because more reserves of carbohydrate were present to stimulate regeneration of new leaves.
- During regrowth, plants showed a positive linear relationship between accumulated dry weight and thermal time.
- Harvesting caused plant branching, leading to an increase in leaf number and decrease in leaf size.
- Lettuce was the most suitable crop in the reaping and regrowth system in this study. This was because lettuce was less affected by different harvest start times, and produced more fresh weight and saleable leaf fresh weight than pak choi and rocket. Lettuce had more regrowth potential, resulting in more potential harvests and faster recovery.
- Rocket might also be appropriate for this system, particularly if the price is high enough to make it economically viable.

7.0 Recommendations for Further Research

- In further studies of factors affecting plant regrowth in the reaping and regrowth system, root DW should be measured. With root DW and shoot/root ratio, the deposition and usage of reserves before harvest and during regrowth can be studied.
- Further research into the effect of cutting severity (different cutting heights) on plant regrowth needs to be conducted.
- Further study on the influence of harvesting times and cutting intervals on the vigour for plant regrowth needs to be conducted.
- More species, such as endive (*Cichorium endive* L.) and chicory (*Cichorium intybus* L.); different varieties of lettuce and pak choi need to be used to find the suitable species and/or varieties in the reaping and regrowth system.
- The value of sales for lettuce, pak choi and rocket should be studied in the reaping and regrowth system.

8.0 Acknowledgements

I am thanking all of the people who helped me during this study. I do appreciate it. I have to mention my supervisor Bruce McKenzie, Mike Morley-Bunker and Richard Sedcole who helped me design my experiment, analyse data and write this thesis. Especially, I will present my special appreciation to Bruce. “Bruce! You are a good person, good doctor and good friend!”

Also, I will thank Long Cheng who supports me mentally. Again, I thank all people who helped me and who I have come to know at Lincoln University. I had a nice experience of studying overseas because of you.

9.0 References

- Adams, C, Scott, W. R., Wilson, D. R. and Purves, L. (2005). Dry matter accumulation and phenological development for four Brassica cultivars sown in Canterbury. *Proceeding of the Agronomy Society of New Zealand*, 35, 1-18.
- Allemann, J., Heever, E. V. D. and Vijoën, J. (1996). Evaluation of Amaranthus as a possible vegetable crop. *Applied Plant Science*, 10(1), 1-4.
- Avice, J. C., Lemaire, G., Ourry, A. and Boucaud, J. (1997). Effects of the previous shoot removal frequency on subsequent shoot regrowth in two *Medicago sativa* L. cultivars. *Plant and Soil*, 188, 189-198.
- Basse, H., Glaschke, B., Drouzy, J., Trébuchet, G., Haigh, J. C., Watts, L. E. and Huyskes, J. A. (1960). Descriptions of varieties. In C. M. Rodenbury (Ed.), *Varieties of lettuce: an international monograph* (pp. 148). Wageningen: Instituut voor de Veredeling van Tuinbouwgewassen.
- Bassman, J. H., Zwier, J. C. (1993). Effect of partial defoliation on growth and carbon exchange of two clones of young *Populus trichocarpa* Torr. and Gray. *Forest Science*, 39, 419-431.
- Beccafichi, C., Benincasa, P., Guiducci, M. and Tei, F. (2003). Effect of crop density on growth and light interception in greenhouse lettuce. *Acta Horticulturae*, 614, 507-513.
- Begg, J. E. and Turner, N.C. (1976). Crop water deficits. *Advances in Agronomy*, 28, 161-217.
- Belesky, D. P. (2006). Regrowth interval influences productivity, botanical composition, and nutritive value of old world bluestem and perennial ryegrass swards. *Agronomy Journal*, 98, 270-279.
- Belesky, D. P. and Fedders, J. M. (1995). Warm-season grass productivity and growth rate as influenced by canopy management. *Agronomy Journal*, 87, 42-48.
- Booyesen, P. deV. and Nelson, C. J. (1975). Leaf area and carbohydrate reserves in regrowth of tall fescue. *Crop Science*, 15, 262-266.
- Bore, J. K., Isutsa, D. K., Itulya, F. M. and Ng'etich, W. K. (2003). Effects of pruning time and resting period on total non-structural carbohydrates, regrowth and yield of tea (*Camellia sinensis* L.). *Journal of horticultural Science & Biotechnology*,

78, 272-277.

- Brown, H. E., Maley, S. and Wilson, D. R. (2007). Investigations of alternative kale management: production, regrowth and quality from different sowing and defoliation dates. *Proceedings of the New Zealand Grassland Association*, 69, 29-33.
- Brown, H. E., Moot, D. J. and Teixeira, E. I. (2005). The components of lucerne (*Medicago sativa*) leaf area index respond to temperature and photoperiod in a temperate environment. *European Journal of Agronomy*, 23, 348-358.
- Bunnell B. T., McCarty, L. B. and Bridges, Jr. W. C. (2005). 'TifEagle' bermudagrass response to growth factors and mowing height when grown at various hours of sunlight. *Crop Science*, 45, 575-581.
- Bunnell B. T., McCarty, L. B., Faust, J. E., Bridges, Jr. W. C. and Rajapakse, N. C. (2005). quantifying a daily light integral requirement of a 'TifEagle' Bermudagrass Golf Green. *Crop Science*, 45, 569-574.
- Caron, B. O., Manfron, P. A., Lucio, A. D., Schmidt, D., Medeiros, S. L. P., Bonnacarrere, R. A. G. and Dourado-Neto, D. (2007). Equations to estimate shoot phytomass of lettuce. *Ciencia Rural*, 37(5), 1248-1254
- Chapman, S. C., Hammer, G. L. and Palta, J. A. (1993). Predicting leaf area development of sunflower. *Field Crops Research*, 34, 101-112.
- Chen, C., Jackson, G., Neill, K., Wichman, D., Johnson, G. and Johnson, D. (2005). Determining the feasibility of early seeding canola in the Northern Great Plains. *Agronomy Journal*, 97, 1252-1262.
- Chestnutt, D. M. B. (1994). Effect of early season sward management on sward quality and lamb liveweight gain during autumn. *Grass and Forage Science*, 49, 405-413.
- Coelho, A. F. S., Gomes, É. P., Sousa, A. P. and Glória, M. B. A. (2005). Effect of irrigation level on yield and bioactive amine content of American lettuce. *Journal of the Science of Food and Agriculture*, 85, 1026-1032.
- Cox, J. E. (1978). Soils and agriculture of part Papanui County, Canterbury. *New Zealand Soil Bureau Bulletin no. 34. D.S.I.R.*, Wellington, New Zealand.
- Cralle, H. T. and Bovey, R. W. (1992). Total nonstructural carbohydrates and regrowth in honey mesquite (*Prosopis glandulosa*) following hand defoliation or clopyralid treatment. *Weed Science*, 44, 566-569.
- Daise, A. (1974). Leaf tissue remaining after cutting and regrowth in perennial

- ryegrass. *The Journal of Agricultural Science*, 82, 165-172.
- Davies, A. (1974). Leaf tissue remaining after cutting and regrowth in perennial ryegrass. *Journal of Agricultural Science*, 82(1), 165-172.
- Díaz-Ambrona, C. H., Tarquis, A. M. and Inés Mínguez, M. (1998). Faba bean canopy modelling with a parametric open L-system: a comparison with the Monsi and Saeki Model. *Field Crops Research*, 58, 1-13.
- Dixon, G. R. (2007). Breeding, genetics and models. In G. R. Dixon (Ed.), *Vegetable brassicas and related crucifers* (pp. 35-72). UK: CABI.
- Doss, B. D., Pearson, R. W., and Roger, H. T. (1974). Effect of soil water stress at various growth stages on soybean yield. *Agronomy Journal*, 66, 297-299.
- Eissenstat, D. M. and Duncan, L.W. (1992). Root growth and carbohydrate responses in bearing citrus trees following partial canopy removal. *Tree Physiology*, 10(3), 245-257.
- Ehlers, W. and Goss, M. (2003). *Water Dynamics in plant production*. UK: CAB.
- Evans, A. S. (1991). Whole-plant responses of *Brassica campestris* (Cruciferae) to altered sink-source relations. *American Journal of Botany*, 78, 394-400.
- Facciotto, G., Zenone, T. and Sperandio, G. (2003). Returns from biomass crops uncertain without aid. *Informatore Agrario*, 59(10), 91-93.
- Ferraris, R. and Norman, M. J. T. (1976). Factors affecting the regrowth of *Pennisetum americanum* under frequent defoliation. *Australian Journal of Agricultural Research*, 27, 365-371.
- Fisher, G. E. J. and Dowdeswell, A. M. (1995). The effects of regrowth and maintenance height on a grass sward with a high density of tiller. *Grass and Forage Science*, 51, 464-468.
- Fogg, H. G. W. (1983). *Salad crops all year round*. UK: Newton Abbot.
- Geyer, W. A. (2006). Biomass production in the Central Great Plains USA under various coppice conditions. *Biomass and Bioenergy*, 30(8/9), 778-783.
- Gómez-Campo, C. (1999). Taxonomy. In C. Gómez-Campo (Ed.), *Biology of Brassica Coenospecies*. New York: Elsevier.
- Hay, R. K. M. and Kemp, D. R. (1992). The predicting of leaf canopy expansion in the leek from a simple model dependent on primordial development. *Annals of Applied Biology*, 120, 537-545.
- Hay, R. K. M. and Walker, A. J. (1989). *An introduction to the physiology of crop yield*. Harlow, Essex, England : Longman Scientific & Technical.

- Hill, M. J. and Pearson, C. J. (1985). Primary growth and regrowth responses of temperate grasses to different temperatures and cutting frequencies. *Australian Journal of Agricultural Research*, 36, 25-34.
- Hirata, M. Kanemaru, E. and Tobisa, M. (2006). Patch choice by cattle grazing tropical grass swards: A preliminary study. *Applied Animal Behaviour Science*, 97, 134-144.
- Hodges, T. (1991). *Predicting Crop Phenology*. Boston, USA: CRC Press.
- HortResearch. (2007). *Fresh facts: New Zealand Horticulture 2007*. Auckland, New Zealand: HortResearch.
- Iwata, F. (1975). Heat unit concept of crop maturity. In U. S. Gupta (Ed.), *Physiological aspects of dryland farming* (pp. 351-370). New Delhi: Oxford and IBH Publishing Co.
- Jamieson, P. D., Brooking, I. R., Porter, J. R. and Wilson, D. R. (1995). Prediction of Leaf appearance in wheat: a question of temperature. *Field Crops Research*, 41, 35-44.
- Jamieson, P. D., Semenov, M. A., Brooking, I. R. and Francis, G. S. (1998). *Sirius*: a mechanistic model of wheat response to environmental variation. *European Journal of Agronomy*, 8, 161-179.
- Jamieson, P. D. and Munro, C. A. (1999). A simple method for the phenological evaluation of new cereal cultivars. *Proceeding of the Agronomy Society of New Zealand*, 29, 63-68.
- Jean, H. Y., Kim, T. H., Kim, B. H. and Kang, W. S. (1994). Changes in the non-structural carbohydrate content during growth period in forage rape. *Journal of the Korean Society of Grassland Science*, 14(4), 331-338.
- Kallenbach, R. L., Matches, A. G. and Mahan, J. R. (1996). Sainfoin regrowth declines as metabolic rate increases with temperatures. *Crop Science*, 36, 91-97.
- Kasture, V. M., Chauhan, P. S., Patil, V. N., Shivankar, R. S. and Wankhede, K. N. (2000). Effect of cutting on the vegetative growth of Indian spinach (*Beta vulgaris* L.). *Research on Crops*, 1(3), 416-417.
- Kigel J. and Dotan A. (1982). Effect of different durations of water withholding on regrowth potential and non-structural carbohydrate content in rhodes grass (*Chloris gayana* Kunth). *Australian Journal of Plant Physiology*, 9, 113-120.
- Knight, S. L. and Mitchell, C. A. (1988). Growth and yield characteristics of 'Waldmann's Green' leaf lettuce under different photon fluxes from metal halide

- or incandescent + fluorescent radiation. *Scientia Horticulturae*, 35, 51-61.
- Kristensen, S., Friis, E., Henriksen, K. and Mikkelsen, S. A. (1987). Application of temperature sums in the timing of production of crisp lettuce. *Acta Horticulturae*, 198, 217-225.
- Krug, H. (1997). Environmental influences on development, growth and yield. In H. C. Wien (Ed.), *The physiology of vegetable crops* (pp. 101-180). New York: CAB International.
- Lambers, H., van den Boogaard, R., Veneklaas, E. J. and Villar, R. (1995). Effects of global environmental change on carbon partitioning in vegetative plants of *Triticum aestivum* and closely related *Aegilops* species. *Global Change and Biology*, 1, 397-406.
- Leng, S., Xia, J., Hu, Z. and Chen, X. (2002). Studies on photosynthetic characteristics of the leaves of rapeseed (*Brassica napus*) seedlings. *Chinese Journal of Oil Crop Sciences*, 24(4), 10-18.
- Linnemann, A. R., Louwen, J. M., Straver, G. H. M. B. and Westphal, E. (1986). Influence of nitrogen on sown and ratooned upland kangkong (*Ipomoea aquatica* Forsk.) at two planting densities. *Netherlands Journal of Agricultural Science*, 34, 15-23.
- Lorenz, H. P. and Wiebe, H. J. (1980). Effect of temperature on photosynthesis of lettuce adapted to different light and temperature conditions. *Scientia Horticulturae*, 13, 115-123.
- Lovett, G. M. and Tobiessen, P. (1993). Carbon and nitrogen assimilation in red oaks (*Quercus rubra* L.) subject to defoliation and nitrogen stress. *Tree Physiology*, 12, 259-269.
- Luxmoore, R. J., Tharp, M. L. and Post, W. M. (2008). Simulated biomass and soil carbon of loblolly pine and cottonwood plantations across a thermal gradient in southeastern United States. *Forest Ecology and Management*, 254(2), 291-299.
- Marchione, V. (2004). Influence of two irrigation regimes on the growth rate and aesthetic parameters of different tall fescue and perennial ryegrass cultivars in southern Italy. *Acta Horticulturae*, 661, 145-152.
- Marshall, B. and Squire, G. R. (1996). Non-linearity in rate-temperature relations of germination in oilseed rape. *Journal of Experimental Botany*, 47(302), 1369-1375.
- Maruo, T., Akimoto, S., Wada, N., Tto, M., Takagaki, M. and Shinahara, Y. (2003).

- New leaf vegetable production system using automatic reaping harvester and rail system. *Acta Horticulturae*, 620, 63-70.
- Matsui, T., Eguchi, H. and Mori, K. (1981). Mathematical model of flower stalk development. In N. S. Talekar & T. D. (Eds.), *Chinese cabbage: proceedings of the first international symposium* (pp. 235-244). Taiwan: AVRDC Publication.
- McCormick, M. E., Morris, D. R., Ackerson, B. A. and Blouin, D. C. (1995). Ratoon cropping forage sorghum for silage: yield, fermentation, and nutrition. *Agronomy Journal*, 87(5), 952-957.
- Mckenzie, B. A. and Hill, G. D. (1990). Growth, yield and water use of lentils (*Lens culinaris*) in Canterbury, New Zealand. *Journal of Agricultural Science*, 114, 309-320.
- Mintel International Group (2002). *Country report, 2002*.
- Mogensen, V. O. and Talukder, M. S. V. (1987). Grain yield of spring wheat in relation to water stress. II. Growth rate of grains during drought. *Cereal Research Communications*, 15(4), 247-253.
- Moot, D. J., Matthew, C. and Kemp, P. D. (2007). Growth of pastures and supplementary crops. In P. V. Rattray, I. M. Brookes and A. M. Nicol (Eds.), *New Zealand Society of Animal Production Occasional Publication No. 14 : Pasture and Supplements for Grazing Animals* (pp. 13-22). Hamilton, New Zealand: New Zealand Society of Animal Production.
- Morgan, L. (1999). Introduction. *Hydroponic lettuce production*. Australia: Casper Publications Pty Ltd.
- Murtagh, G. J. and Smith, G. R. (1996). Month of harvest and yield components of tea tree. II. Oil concentration, composition, and yield. *Australian Journal of Agricultural Research*, 47(5), 817-827.
- Nassiri, M. and Elgersma, A. (1998). Competition in perennial ryegrass-white clover mixtures under cutting. 2. leaf characteristics, light interception and dry-matter production during regrowth. *Grass and Forage Science*, 53, 367-379.
- Nielsen, D. C. and Nelson, N. O. (1998). Black bean sensitivity to water stress at various growth stages. *Crop Science*, 38(2), 422-427.
- Oosterheld, M. (1992). Effect of defoliation intensity on aboveground and belowground relative growth rates. *Oecologia*, 92, 313-316.
- Oosterheld, M. and McNaughton, S. J. (1988). Intraspecific variation in the response of *Themeda triandra* to defoliation: the effect of time of recovery and growth

- rates on compensatory growth. *Oecologia*, 77, 181-186.
- Oosterheld, M. and McNaughton, S. J. (1991). Effect of stress and time for recovery on the amount of compensatory growth after grazing. *Oecologia*, 85, 305-313.
- Olufolaji, A. O. and Tayo, A. O. (1989). Performance of four morphotypes of *Amaranthus cruentus* L. under two harvesting methods. *Tropical Agriculture*, 66(3), 273-276.
- Omami, E. N., Hammes, P. S. and Robbertse, P. J. (2006). Differences in salinity tolerance for growth and water-use efficiency in some amaranth (*Amaranthus* spp.) genotypes. *New Zealand Journal of Crop and Horticultural Science*, 34, 11-22.
- Ovaska, J., Walls, M. and Mutikainen, P. (1992). Changes in leaf gas exchange properties of cloned *Betula oerdula* saplings after partial defoliation. *Journal of Experimental Botany*, 43, 1301-1307.
- Palchamy, A., Purushothaman, S. and Rajagopal, A. (1995). Ratoon cropping in rice for better water resource management in river command area in Tamil Nadu. *Madras Agricultural Journal*, 82(1), 33-36.
- Peri, P. L., Moot, D. J., McNeil, D. L. and Lucas, R. J. (2003). Modelling net photosynthetic rate of field-grown cocksfoot leaves to account for regrowth duration. *New Zealand Journal of Agricultural Research*, 46, 105-115.
- Perrier, L. (2004). Salad production and trade in Spain and other European countries. *Infos Ctifl*, 205, 21-24.
- Phillips, C. A. and Harrison, M. A. (2005). Comparison of the microflora on organically and conventionally grown spring mix from a California processor. *Journal of Food Protection*, 68(6), 1143-1146.
- Pressman, E. and Shaked, R. (1988). Bolting and flowering of Chinese cabbage as affected by the intersivity and source of supplementary light. *Scientia Horticulturae*, 34, 177-181.
- Qin, L., He, J. and Lee, S. K. (2002). Reponse of lettuce (*Lactuca sativa* L.) growth to reciprocal root-zone temperature (RZT) transfer at different growth stages. *Journal of horticultural Science and Biotechnology*, 77(6), 683-690.
- Rajin, M., Mckenzie, B. A. and Hill, G. D. (2003). Water-use efficiency and effect of water deficits on crop growth and yield of kabuli chichpea (*Cicer arietinum* L.) in a cool-temperate subhumid climate. *Journal of Agricultural Science*, 141, 285-301.

- Reich, P. B., Walters, M. B., Krause, S. C., Vanderklein, D. W., Raffa, K. F. and Tabone, T. (1993). Growth, nutrition and gas exchange of *Pinus resinosa* following artificial defoliation. *Trees: structure and function*, 7(2), 67-77.
- Robertson, M. J., Carberry, P. S., Huth, N. I., Turpin, J. E., Probert, M. E., Poulton, P. L., Bell, M., Wright, G. C., Yeates, S. J. and Brinsmead, R. B. (2002). Simulation of growth and development of diverse legume species in APSIM. *Australian Journal of Agricultural Research*, 53, 429-446.
- Roy, S. K. (1985). *Environmental control of tillering and yield of wheat*. PhD thesis, Lincoln College, University of Canterbury, New Zealand.
- Ruiter, J. M. (1986). The effects of temperature and photoperiod on onion bulb growth and development. *Proceedings Agronomy Society of New Zealand*, 16, 93-100.
- Ryder, E. J. (1979). *Leafy salad vegetables*. Westport, Connecticut: The Publishing Company, INC.
- Ryder, E. J. (1999). Introduction to the crops. In E. J. Ryder (Ed.), *Lettuce, endive and chicory* (pp. 1-27). New York: CABI.
- Sanchez, C. A., Allen, R. J. and Schaffer, B. (1989). Growth and yield of crisphead lettuce under various shade conditions. *Journal of the American Society for Horticultural Science*, 114(6), 884-890.
- Sheaffer, C. C., Peterson, P. R., Hall, M. H. and Stordahl, J. B. (1992). Drought effects on yield and quality of perennial grasses in the north central United States. *Journal of Production Agriculture*, 5(4), 556-561.
- Sinclair, T. R. and Muchow, R. C. (1999). Occam's Razor, radiation-use efficiency, and vapor pressure deficit. *Field Crops Research*, 62(2/3), 239-243.
- Slack, K., Fullkerson, W. J. and Scott, J. M. (2000). Regrowth of prairie grass (*Bomus willdenowii* Kunth) and perennial ryegrass (*Lolium perenne* L.) in response to temperature and defoliation. *Australian Journal of Agricultural Science*, 51, 555-561.
- Slafer, G. A. and Rawson, H. M. (1995). Rates and cardinal temperatures for processes of development in wheat: effects of temperature and thermal amplitude. *Australian Journal of Plant Physiology*, 22, 913-926.
- Smith, D. (1974). Growth and development of timothy tillers as influenced by level of carbohydrate reserves and leaf area. *Annals of Botany*, 38, 595-606.
- Snell, E. J. and Simpson, H. R. (1991). *Applied statistics: a handbook of Genstat*

- analyses*. New York: Chapman and Hall.
- Sutcliffe, J. (1969). *Plants and water*. Edward Arnold Ltd., London.
- Szeto, Y. T., Chung, W. Y. and Benzie, I. F. F. (2001). The ferric reducing (antioxidant) power (FRAP) assay, and antioxidants in the Chinese diet and population. *Micronutrients and health: molecular biological mechanisms*, 2001, 12-16.
- Takagaki, T., Amuka, S., Maruo, T., Sukprakan, S. and Shinohara, Y. (2003). Application of reaping method for harvesting leafy vegetables grown in capillary Hydroponic system. *Acta Horticulturae*, 620, 71-76.
- Tei, F., Benincasa, P. and Guiducci, M. (2003). Critical nitrogen concentration in lettuce. *Acta Horticulturae*, 627, 187-194.
- Teixeira, E. I., Moot, D. J. and Mickelbart, M. V. (2007). Seasonal patterns of root C and N reserves of lucerne crops (*Medicago sativa* L.) grown in a temperate climate were affected by defoliation regime. *European Journal of Agronomy*, 26(1), 10-20.
- Tobisa, M., Tajiri, K., Murakami, K., Shimojo, M. and Masuda, Y. (2003). Effects of growth temperature and cutting height on regrowth of tropical forage legume phasey bean (*Macroptilium lathyroides* L. Urb). *Grassland Science*, 49(2), 149-157.
- Turner, L. R., Donaphy, D. J., Lane, P. A. and Rawnsley, R. P. (2006). Effect of defoliation management, based on leaf stage, on perennial ryegrass (*Lolium perenne* L.), prairie grass (*Bromus willdenowii* Kunth.) and cocksfoot (*Dactylis glomerata* L.) under dryland conditions. 2. Nutritive value. *Grass and Forage Science*, 61, 175-181.
- Valentine, I. and Kemp, P. D. (2007). Pasture and supplement resources. In P. V. Rattray, I. M. Brookes and A. M. Nicol (Eds.), *New Zealand Society of Animal Production Occasional Publication No. 14 : Pasture and Supplements for Grazing Animals* (pp. 3-11). Hamilton, New Zealand: New Zealand Society of Animal Production.
- van den Boogaard, R., Grevsen, K. and Thorup-Kristensen, K. (2001). Effects of defoliation on growth of cauliflower. *Scientia Horticulturae*, 91, 1-16.
- Volaire, F. (1994). Effects of summer drought and spring defoliation on carbohydrate reserves, persistence and recovery of two populations of cocksfoot (*Dactylis glomerata*) in a Mediterranean environment. *Journal of Agricultural Science*,

122(2), 207-215.

- Ward, G. Y. and Blaster, R. E. (1961). Carbohydrate reserves and leaf area in regrowth of orchardgrass. *Crop Science*, 1, 366-370.
- Waycott, W. (1995). Photoperiodic response of genetically diverse lettuce accessions. *Journal of the American Society for Horticultural Science*, 120(3), 460-467.
- Wiedenhoef, M. H. (1993). Management and environment effects on dry matter yield of three *Brassica* species. *Agronomy Journal*, 85, 549-553.
- Wiedenhoef, M. H. and Barton, B. A. (1994). Management and environment effects on *Brassica* forage quality. *Agronomy Journal*, 86, 227-232.
- Wiggan, S. C. (1956). The effect of seasonal temperatures on maturity of oats planted at different dates. *Agronomy Journal*, 48, 21-25.
- Wilson, D. B. and Robson, M. J. (1970). Regrowth of S24 ryegrass and its relation to yield measurement of grazed swards. *Journal of the British Grassland Society*, 25, 220-227.