

**Growth and development of ‘Pasja’ and kale crops grown
with two methods and four rates of phosphorus (P)
application.**

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Abstract of a thesis submitted in partial fulfilment of the
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*‘Pasja’ (*Brassica campestris x napus*) and kale (*Brassica oleracea* var. *acephala* L.) were grown at Lincoln, Canterbury, New Zealand in 2008 with different levels of phosphorus (P) fertiliser. Banded or broadcast P fertiliser was applied at 0, 20, 40 and 60 kg P/ha at establishment. Total dry matter (DM) production, the proportion of the leaf and stem and leaf area development were measured over time and related to the biophysical environment.

For ‘Pasja’, final DM increased with P rate from 3730 kg DM/ha to ~4900 kg DM/ha at 60 kg P/ha. For kale the increase was from 8710 kg DM/ha for the control to ~11000 kg DM/ha for all P treatments. The leaf to stem ratio declined from 22-31 at 17 days after emergence to 10.4 at the final harvest for ‘Pasja’, which meant the crop was effectively made up mainly of leaf (~90%). The ratio for kale declined from 2.7 at 24 days after emergence to 0.64 at the final harvest. The leaf to stem ratio for both species did not respond to either the method of application or rate of P. Seedling DM accumulation increased with applied P over the first 10 to 17 DAE for ‘Pasja’ and kale respectively. The crops went from shoot growth priority to root growth.

The phyllochron of both species was unaffected by P application but responded linearly to the temperature above 0°C. For ‘Pasja’ the phyllochron was 60 °Cd compared with 109 °Cd for kale. As a consequence ‘Pasja’ developed its canopy and reached critical leaf area index (LAI_{crit}) earlier than kale.

Leaf area index (LAI) for the control crops of both species was lower than for P fertiliser treatments with a maximum of 3.6 for ‘Pasja’ and 3.8 for kale. There was no difference in leaf area indices among the P fertiliser treatments for ‘Pasja’, while kale LAI differed with the rate of P application up to 40 kg P/ha.

Total accumulated intercepted solar radiation (RI_{cum}) was 8 and 11% greater for ‘Pasja’ and kale crops respectively when P was applied compared with the control. Thus, the difference in total dry matter yield due to P application was attributed to the difference in RI_{cum} . Neither the method of application or rate of P applied affected the radiation use efficiency (RUE) of either crop. For ‘Pasja’ the RUE was 1.1 g DM/MJ PAR and for kale 1.33 g DM/MJ PAR.

Based on this research, it was concluded that P application increased RI_{cum} as a result of increased LAI. The difference in total DM yield was attributed to differences in RI_{cum} .

It is recommended that farmers growing ‘Pasja’ and kale under similar conditions to this experiment should apply 40 kg P/ha for ‘Pasja’ and band 20 kg P/ha for kale.

*‘Pasja’ is considered both as a species and cultivar in this document as it marketed as such in New Zealand. Technically ‘Pasja’ is a leaf turnip.

Keywords: *Brassica campestris* L., *Brassica oleracea acephala* L., critical leaf area index, DM accumulation, extinction coefficient, leaf area index, leaf to stem ratio, method of application, phyllochron, radiation use efficiency, solar radiation.

Contents

Topic	Page
Abstract	iii
Contents	v
List of Tables	x
List of Figures	xii
Equations	xv
Plates	xvi
Appendices	xvii

Chapter 1: General introduction 1

1.1 Aims and objectives	2
1.1.1 Thesis structure	2

Chapter 2: Review of Literature

2.1 Introduction	3
2.2. Phosphorus requirements and placement	4
2.2.1 Soil phosphorus	4
2.2.2 Soil loss of P (P fixation)	5
2.2.2.1 Factors influencing soil loss of P	5
2.2.2.1.1 Soil chemical composition and mineralogy	5
2.2.2.1.2 Soil pH	6
2.2.2.1.3 Time of reaction	6
2.2.2.2 Phosphorus retention test	7
2.2.3 Brassica crops' P requirements	7
2.2.3.1 Effects of P on brassica establishment	7
2.2.3.1.1 Fertiliser toxicity	8
2.2.3.2 Effects of P on brassica growth	10
2.2.4 Phosphorus fertiliser placement	11
2.2.4.1 Broadcasting	12
2.2.4.2 Banding	12
Summary	14

2.3 Temperature and light relationship	15
2.3.1 Thermal time and leaf appearance	15
2.3.2 Thermal time	16
2.3.3 Leaf appearance	17
2.3.4 Leaf expansion and leaf area index	20
2.3.4.1. Leaf expansion	20
2.3.4.2. Leaf area index	22
2.3.5 Leaf senescence	25
2.3.6 Light interception and yield	26
2.3.6.1 Dry matter production	28
Summary	30
Conclusion	31

Chapter 3: Methods and materials

3.1 Treatments and experimental design	32
3.1.1 Soil and land preparation	32
3.1.2 Seed treatments and insect control	33
3.1.3 Weed control	34
3.2 Measurements	
3.2.1 Seedling emergence	35
3.2.2 Dry matter (DM)	35
3.2.2.1. Seedling DM accumulation and partitioning	35
3.2.2.2 DM production	35
3.2.3 Canopy development and radiation interception	37
3.2.3.1 Leaf appearance arte	37
3.2.3.2 Leaf area	38
3.2.3.3 Radiation interception	39
3.2.4 Data analysis	39
3.2.5 Meteorological data	40

Chapter 4: Yield, leaf and stem partitioning in ‘Pasja’ and kale

4.1 Introduction	42
4.1.1 Plant establishment	42
4.2 Final ‘Pasja’ dry matter (DM) yield	42
4.3 Seasonal DM accumulation	43
4.3.1 ‘Pasja’ Seedling DM accumulation	44
4.3.2 ‘Pasja’ crop DM accumulation	46
4.3.3 Pasja leaf and stem partitioning	48
4.4 Thermal time and DM	49
4.4.1 ‘Pasja’ DM accumulation	49
4.5 Kale DM accumulation	50
4.5.1 Final DM yield	50
4.5.2. Seasonal DM accumulation	51
4.5.2.1 Kale seedlings DM accumulation	51
4.5.2.2 Kale crop DM accumulation	53
4.5.2.3 Kale leaf and stem partitioning	55
4.6 Thermal time and DM	56
4.6.1 Kale DM accumulation	56
4.7 Discussion of DM results	58
4.7.1 Method of P application	58
4.7.2 Effects of rate of P application on ‘Pasja’ and kale DM accumulation	58
4.7.2.1 ‘Pasja’ DM accumulation	58
4.7.2.2 Kale DM accumulation	60
Conclusion	62

Chapter 5: Leaf appearance, leaf area index (LAI), solar radiation interception (RI) and radiation use efficiency (RUE) in ‘Pasja’ and kale crops grown with different rates of phosphorus.

5.1 Introduction	63
5.2 Leaf appearance rate	64
5.2.1 Analysis of ‘Pasja’ leaf appearance	64
5.3 Leaf area index (LAI) and radiation interception (RI)	66
5.3.1 ‘Pasja’ leaf area index (LAI)	66

5.3.2 ‘Pasja’ radiation interception	68
5.3.3 ‘Pasja’ extinction coefficient (k)	70
5.3.4 ‘Pasja’ leaf area index, percentage radiation interception and accumulated intercepted radiation	70
5.4 ‘Pasja’ radiation use efficiency (RUE)	72
5.5 Analysis of kale leaf appearance	73
5.5.2 Kale leaf area index (LAI) and Radiation interception (RI)	75
5.5.2.1 Kale leaf area index	75
5.5.2.2 Kale radiation interception	77
5.5.2.3 Kale extinction coefficient (k)	78
5.5.2.4 Kale leaf area index, percentage radiation interception and accumulated intercepted radiation	79
5.6 Kale RUE	80
5.7 Discussion of leaf development and radiation interception results	81
5.7.1 Method of P application	81
5.7.2 Base temperature	81
5.7.3 Effects of the rate of P application on ‘Pasja’ leaf development, solar radiation interception and use efficiency	81
5.7.3.1 Leaf appearance rate	81
5.7.3.2 Leaf area index (LAI) and radiation interception (RI)	82
5.7.4 Effects of the rate of P application on kale leaf development, solar radiation interception and use efficiency	84
5.7.4.1 Leaf appearance rate	84
5.7.4.2 Leaf area index (LAI) and radiation interception (RI)	85
Conclusion	87
 Chapter 6: General discussion and conclusions	 88
6.1 Agronomic implications	88
6.1.1 Method of application	88
6.1.2 Rate of application	89
6.1.3 Leaf development, light interception and radiation use efficiency	90
6.2 Practical implications to New Zealand farmers	90

Recommendations	93
Conclusions	94
Acknowledgements	95
References	96
Appendices	105

List of Tables	Page
Table 2.1: Effects of P fertiliser type on brassica crop final plant population, plant weight and yield (Hayward & Scott, 1993)	9
Table 2.2: The effect of sowing date on the extension of the second and sixth leaf of three cultivars of <i>B. campestris</i> L. sown on two dates in Canterbury (Adopted from Collie, 1997)	21
Table 2.3: Mean LAI and radiation transmission at given heights in kale, measured by a solarimeter (Adapted from Monteith 1965)	24
Table 2.4: LAI _{crit} and extinction coefficients (k) different crops and pasture species (Adapted from Hay & Walker, 1989; McKenzie <i>et al.</i> 1999)	27
Table 3.1: Average soil test results and optimum quick test for pasture growth (McLaren & Cameron, 1996)	33
Table 4.1: Final dry matter yield (kg/ha) and leaf to stem ratio on the 20 th of March for 'Pasja' sown with different methods of application and rates of phosphorus, at Lincoln in 2008.	43
Table 4.2: Shoot to root ratio and total DM accumulation for 'Pasja', 3 & 10 days after emergence (DAE), sown with different methods of application and rates of phosphorus, at Lincoln in 2008.	45
Table 4.3: Weighted mean absolute growth rate (WMAGR), maximum crop growth rate (C _{max}), time to reach 50% of total dry matter (M) and duration of exponential growth phase (DUR) for 'Pasja' sown with different methods of application and rates of phosphorus, at Lincoln in 2008.	47
Table 4.4: Total DM and leaf: stem ratio on 6 th May (final harvest) for kale sown with different methods of application and rates of phosphorus, at Lincoln in 2008.	50
Table 4.5: Shoot and root dry matter accumulation for kale, 10 & 17 days after emergence (DAE), when sown at different methods of application and rates of phosphorus, at Lincoln in 2008.	52
Table 4.6: Weighted mean absolute growth rate (WMAGR), maximum crop growth rate (C _{max}), time to reach 50% of TDM (M) and duration of exponential growth phase (DUR) for kale sown with different methods of application and rates of phosphorus, at Lincoln in 2008.	54

Table 4.7: Total DM and leaf to stem on 29 th January (first harvest) for kale sown with different methods of application and rates of phosphorus, at Lincoln in 2008.	55
Table 5.1: Weighted mean absolute leaf area expansion rate (LAER), maximum leaf area index (max LAI), maximum leaf area expansion rate (C_{max}), time to reach 50% of max LAI (M) and duration of exponential leaf area expansion phase (DUR) for 'Pasja' sown with different methods of application and rates of phosphorus, at Lincoln in 2008.	67
Table 5.2: Leaf area index (LAI), percentage interception of radiation (%RI) and accumulated intercepted radiation (RI_{cum}) for 'Pasja', 38 & 59 days after emergence when sown with different methods of application and rates of phosphorus, at Lincoln in 2008.	71
Table 5.3: Weighted mean absolute leaf area expansion rate (LAER), maximum leaf area index (max LAI), maximum leaf area expansion rate (C_{max}), time to reach 50% of max LAI (M) and duration of exponential leaf area expansion phase (DUR) for kale sown with different methods of application and rates of phosphorus, at Lincoln in 2008.	76
Table 5.4: Leaf area index (LAI), percentage interception of radiation (%RI) and accumulated intercepted radiation (RI_{cum}) for kale, at 52 and 73 days after emergence when sown with different methods of application and rates of phosphorus, at Lincoln in 2008.	79
Table 6.1: Long term regional and the current season thermal time means from 17/12/1971 to 31/05/2000, at $T_b=0^{\circ}C$. (Based on mean temperature from NIWA)	91

List of Figures	Page
Figure 2.1: Soil pH (McLaren & Cameron, 1996)	6
Figure 2.2: ‘Pasja’ dry matter responses to application of N and P fertilizers (first harvest) at low P and moderate N site (Lake Ferry) (Wilson <i>et al.</i> 2006)	10
Figure 2.3: Leaf appearance in thermal time for (a) ‘Pasja’ and (b) kale. (Wilson <i>et al.</i> 2004).	18
Figure 2.4: Plant leaf accumulation of three cultivars of <i>Brassica campestris</i> L. over four sowing dates (Collie, 1997)	19
Figure 2.5: Final leaf number for four <i>Brassica</i> species from five planting dates (19, 29 October, 8, 28 November, and 9 December) (Nanda <i>et al.</i> 1995)	20
Figure 2.6: Profiles of area per leaf against leaf position from the base of the plant (leaf 1) for each of the four <i>Brassica</i> species (a) and for <i>B. napus</i> L at planting dates 1, 3 and 5) (Nanda <i>et al.</i> 1995)	23
Figure 2.7: Expansion of individual leaves in thermal time from emergence of kale. (Wilson <i>et al.</i> 2004)	25
Figure 3.1: Weather data from 1 December 2007 to 31 May 2008; long term average (●) and experimental period (monthly) totals (□).	41
Figure 4.1: ‘Pasja’ dry matter (DM) accumulation over 73 days after emergence at 0 kg P/ha (●); 20 kg P/ha (▽); 40 kg P/ha (■) or 60 kg P/ha (◇). Bars represent the least significant difference ($LSD_{p<0.05}$). (See Table 4.3 for variables derived from the logistic curves). Solid lines represent quadrat (0.5 m ²) sampling and dashed lines represent seedling sampling (See Sections 3.2.2.1 & 3.2.4).	46
Figure 4.2 ‘Pasja’ leaf and stem (●) DM accumulation over the season. Leaf DM at different rates of P (0 kg P/ha (▼); 20 kg P/ha (□); 40 kg P/ha (◆) or 60 kg P/ha (Δ)	48
Figure 4.3: ‘Pasja’ DM accumulation as influenced by thermal time ($T_b = 0^{\circ}\text{C}$), at 0 kg P/ha (▲) and mean P fertiliser (■).	49

- Figure 4.4: Kale dry matter (DM) accumulation over 122 days after emergence at 0 kg P/ha (●); 20 kg P/ha (▼); 40 kg P/ha (■) or 60 kg P/ha (◆). Bars represent the least significant difference ($LSD_{p<0.05}$). (See Table 4.7 for variables derived from the logistic curves). Solid lines represent quadrat (0.5 m²) sampling and dashed lines represent seedling sampling (See Section 3.2.2.1 & 3.2.4). 53
- Figure 4.5: Kale DM accumulation as influenced by thermal time ($T_b = 0^\circ\text{C}$), at 0 kg P/ha (◆) and mean P fertiliser (●). 57
- Figure 5.1: The number of leaves on the main stem for ‘Pasja’ plotted against (a) time after emergence (DAE) and (b) thermal time (Tt) at Lincoln in 2008. Lines are fitted to the mean of all data from crops grown with different methods of application and rates of phosphorus. 65
- Figure 5.2: ‘Pasja’ leaf area index accumulation over 66 days, at 0 kg P/ha (●); 20 kg P/ha (○); 40 kg P/ha (▼) or 60 kg P/ha (▽). Bars are levels of significance ($LSD_{(p<0.05)}$) (See Table 5.1 for variables derived from the fitted logistic curves and Table 5.2 for the critical LAI (LAI_{crit}), percentage interception of radiation and accumulation of radiation). Solid lines represent quadrat (0.5 m²) sampling and dotted lines represent seedling sampling (See Section 3.2.2.1) 66
- Figure 5.3: The interception of incident PAR by ‘Pasja’ canopies of differing leaf area index. The different symbols show the different P rates, 0 kg P/ha (●); 20 kg P/ha (○); 40 kg P/ha (▼) or 60 kg P/ha (▽). (See Equation 5.1 for details) 69
- Figure 5.4: Natural logarithm of radiation transmission against LAI for ‘Pasja’ at different rates of P, 0 kg P/ha (●); 20 kg P/ha (○); 40 kg P/ha (▼) or 60 kg P/ha (▽), when grown at Lincoln in 2008. ($Y=0.77x$) 77 69
- Figure 5.5: ‘Pasja’ total dry matter against RI_{cum} for different P rates, 0 kg P/ha (●); 20 kg P/ha (○); 40 kg P/ha (▼) and 60 kg P/ha (▽), when grown at Lincoln in 2008. ($Y=1.1x$). 72
- Figure 5.6: The number of leaves on the main stem for kale plotted against (a) days after emergence (DAE) and (b) thermal time (Tt) at Lincoln in 2008. Lines are fitted to the mean of all data, from crops sown with

different methods of application and rates of phosphorus. 74

Figure 5.7: Kale leaf area index accumulation over 122 days at 0 kg P/ha (●); 20 kg P/ha (○); 40 kg P/ha (▼) or 60 kg P/ha (▽). Bars are levels of significance ($LSD_{(p<0.05)}$) (See Table 5.3 for variables derived from the fitted logistic curves and Table 5.4 for the critical LAI (LAI_{crit}), percentage interception of radiation and accumulation of radiation). Solid lines represent quadrat (0.5 m^2) sampling and dotted lines represent seedling sampling (See Section 3.2.2.1). 75

Figure 5.8: The interception of incident PAR by kale canopies of differing leaf area index. The different symbols show the different P rates (0 kg P/ha (●); 20 kg P/ha (○); 40 kg P/ha (▼) or 60 kg P/ha (▽). (See Equation 5.1 for details) 77

Figure 5.9: Natural logarithm of radiation transmission against LAI for kale at different rates of P (0 kg P/ha (●); 20 kg P/ha (○); 40 kg P/ha (▼) or 60 kg P/ha (▽), when grown at Lincoln in 2008. ($Y=0.9x$). 78

Figure 5.10: Kale radiation use efficiency under different P rates (0 kg P/ha (●); 20 kg P/ha (○); 40 kg P/ha (▼) and 60 kg P/ha (▽), for crops grown at Lincoln in 2008. ($Y=1.33x$). 80

Equations	Page
Equation 2.1	16
Equation 2.2	26
Equation 3.1	36
Equation 3.2	36
Equation 3.3	36
Equation 3.4	37
Equation 3.5	37
Equation 3.6	37
Equation 3.7	37
Equation 3.8	37
Equation 3.9	37
Equation 3.10	38
Equation 3.11	39
Equation 3.12	39
Equation 3.13	40
Equation 5.1	69

Plates	Page
Plate 3.1: Leaf minor maggot (<i>Liriomyza brassicae</i>) damage on ‘Pasja’ crop	34
Plate 3.2: ‘Pasja’ plants marked for leaf appearance count (Note: bamboo flags to mark the plants and red paint to mark every 5 th leaf on each of the 10 chosen plants)	38

Appendices	Page
2.1: Phosphorus retention by topsoils of New Zealand soil orders (Adapted from McLaren & Cameron, 1996).	105
3.1: Soil test results	106
4.1: Final leaf and stem DM yield (kg/ha) for ‘Pasja’ and kale sown with different methods of application and rates of phosphorus, at Lincoln in 2008.	108
4.2: Initial leaf and stem DM yield (kg/ha) for ‘Pasja’ and kale sown with different methods of application and rates of phosphorus, at Lincoln in 2008.	109
4.3 Shoot to root dry matter (DM) accumulation for ‘Pasja’, 3 & 10 days after emergence (DAE) and kale at 10 and 17 DAE, sown with different methods of application and rates of phosphorus, at Lincoln in 2008.	110
5.2: The regression of R^2 values against base temperature for (a) ‘Pasja’ and (b) kale crops, for determination of the most appropriate base temperature.	111

Chapter 1: General introduction

Brassica crops are grown in diverse climates and soil fertility situations (Wilson *et al.* 2006). They have large nutrient requirements and respond to fertiliser applications (Wallace, 1946; Toosey, 1972), especially phosphorus (P) (Wilson *et al.* 2006) when Olsen P levels are less than 20 mg /kg soil (White *et al.* 1999). The New Zealand climate and soil diversity makes it difficult to specify optimum management (Wilson *et al.* 2006) such as fertiliser requirements. However, yield is greatly enhanced when a starter P fertiliser of about 50 kg P /ha is applied at sowing (Moot *et al.* 2007), but the rate depends on the initial Olsen P value. Claridge (1972) reported that P is needed at seedling establishment, as it is important in root development.

Phosphorus deficiency leads to early senescence of older leaves and stunting of new leaves (Moot *et al.* 2007). This results in reduced forage dry matter (DM) yield, which is important for crops like ‘Pasja’ and kale. Although brassica crops respond to P fertiliser, Wilson *et al.* (2006) found that ‘Pasja’ and kale have different abilities to utilise both fertiliser and soil P (Section 2.2.3.2), hence the need for a greater understanding of how the method and rate of application affect yield and its components.

Excessive amounts of P can lead to toxicity especially if in contact with the seed or seedling roots (Tisdale *et al.* 1985; Section 2.2.3.1.1). Phosphorus is a major farm cost accounting for about 20% of the expenditure on lowland dairy farms (Moot *et al.* 2007). Thus, to control this expenditure, an understanding of optimum application rates, timing and placement of P fertilisers (Lewis, 1941) is desirable. Phosphorus is also highly immobile in soils (Akhter, *et al.* 2007) and can be rapidly fixed onto soil surfaces (McLaren & Cameron, 1996) which means there is a need for appropriate methods of application and rates that ensure P is readily available to the plants.

Two methods of P fertiliser application are banding and broadcasting (Lewis, 1941; Tisdale *et al.* 1985). Some research has shown that banding is more efficient than broadcasting, especially if fertiliser is applied at sowing (Wilson *et al.* 2006) but some results have been inconsistent.

‘Pasja’ and kale are mainly used for supplementation of poor pasture growth in dry summers or in cold winters respectively (de Ruiter *et al.* 2007; Moot *et al.* 2007; Valentine & Kemp, 2007). These crops are also used in rotation with pasture

and cereals, to control problem pests and weeds (de Ruiter *et al.* 2007), while at the same time providing feed to animals.

‘Pasja’ produces a small bulb and swollen tap root (White *et al.* 1999) which provides multiple growing points. These growing points allow ‘Pasja’ crops to be grazed several times at 6-8 week intervals. ‘Pasja’ is usually sown in spring for summer and/or autumn feeding or late summer for autumn and/or early winter feeding.

Kale crops produce large stems that are of low quality and are protein deficient (Charlton & Stewart, 2003). Animals often reject the stems. Kale has good tolerance to drought and is winter-active and can therefore be used for both summer and winter feed.

1.1 Aims and objectives

The inconsistency of results in the literature on the influence of the method and rate of P application on growth and development of brassica crops led to the present study.

The overall aim was to determine the effect of method of application and rate of P on establishment of ‘Pasja’ and kale crops.

The specific objectives were to determine the effect of 0, 20, 40, and 60 kg P/ha and the effect of banding or broadcasting P on the growth and development of ‘Pasja’ and kale.

1.1.1 Thesis structure

This thesis is presented in six chapters. Chapter 2 reviews literature for both ‘Pasja’ and kale, where the effects of both soil and fertiliser P on growth and development are outlined. Chapter 3 outlines the details of the experiment and measurements taken. Chapter 4 describes total crop yield and dry matter partitioning responses of ‘Pasja’ and kale to applied P. Analyses in Chapter 5 focuses on leaf development and RI_{cum} . Radiation use efficiency and leaf extinction coefficient are also described. Chapter 6 provides a general discussion of the practical implications of the results of the current experiment and discusses the potential for further studies.

Chapter 2. Review of Literature

2.1 Introduction

There are many factors that influence brassica crop establishment. These include sowing methods (Wallace, 1946; Claridge, 1972; Evans, 1972), seed size and sowing depth (Lamp, 1962; Stewart, 2002), sowing time (Stephen, 1976; Harper & Compton, 1980; Collie & McKenzie, 1998), irrigation and fertilisation (Claridge, 1972), weeds (Meeklah, 1970), pests (Lowe, 1956; Harrison, 1970; Addison & Welsh, 1994) and diseases (Stewart & Charlton, 2003). This thesis focuses solely on the effect of P nutrition on brassica crop establishment and subsequent growth and development. Other factors were controlled as much as possible during the experiment.

A key to 'Pasja' and kale production is P management (Wilson *et al.* 2006), in terms of method of application and rate of P (Tisdale *et al.* 1985). Phosphorus fertilizer can easily be lost in the soil (McLaren & Cameron, 1996) through fixation. This means the rate of application should not exceed plant requirements. Phosphorus can be applied in a band or broadcast at establishment. Early research showed that banding gave superior results (Lewis and Strickland, 1944) and optimum rate to be 50-60 kg P/ha (Jung *et al.* 1984; Wilson *et al.* 2006) on soils with Olsen P levels lower than 12 mg/kg soil.

Within a season crop production is mainly determined by its ability to intercept available solar radiation and convert it into useful forms of energy. Monteith (1977) stated that crop biomass is the product of accumulated intercepted solar radiation (RI_{cum} ; MJ/m²) and the efficiency with which it is used to produce biomass, described as radiation use efficiency (RUE; g DM/ MJ PAR). Leaf appearance and leaf expansion rate are the predominant factors that influence plant growth, because they determine the amount of solar radiation intercepted by the crop. For maximum radiation interception, there is a need for a large disease-free leaf area to be established early in the season and plants to maintain a critical leaf area index (LAI_{crit}) for as long as possible.

In this chapter previous research on effects of P on crop production is examined. The first part describes the soil-P relationship, crop P requirements and placement. Crop responses to the environment are then discussed with special reference to leaf development, radiation interception and use efficiency, as these form a useful basis for explaining these yield responses.

2.2 Phosphorus requirements and placement

2.2.1 Soil phosphorus

Phosphorus is regarded as one of the key nutrients for the successful growth of all plants (McLaren & Cameron, 1996) and is important for brassica crops which are used in New Zealand winter and for supplementary animal feeding (de Ruiter *et al.* 2007; Valentine & Kemp, 2007). Jarvis *et al.* (2002) stated that New Zealand soils are deficient in P to achieve desired rates of crop production and hence there is a need to apply mineral P fertiliser. Phosphorus exists in very low concentrations in soil solution, ranging from 0.02 to 0.15%, while plants contain 0.1-0.5% in dry matter (McLaren & Cameron, 1996). According to Quin & Scobie (1985), without fertiliser New Zealand pastoral farming would be ~25% of current production. The same authors stated that P accounts for ~75% of the cost of all fertilisers used in New Zealand, while fertiliser accounts for ~19% of the total farm production.

Unlike nitrogen, P is not replaced into the soil from the atmosphere (Abrahamson & Darkey, 1988). The only natural source on site is from the gradual weathering of parent material. Thus, the main source of P available to plants is from mineral fertiliser. Losses of P from the soil-plant system can be classified as above ground (loss through animals) and below ground (soil P loss). Only below ground soil P loss (fixation) will be discussed in this review.

Soil P fixation depends on soil chemical composition and mineralogy, soil pH and time of reaction (McLaren & Cameron, 1996). Phosphorus is readily available at pH 6-7 (Figure 2.1), but is retained by aluminium (Al) and iron (Fe) oxides (Saunders, 1959) in acidic soils and by calcium (Ca) and magnesium (Mg) in alkaline soils. Leaching of P is negligible from New Zealand soils (Nguyen & Goh, 1992) except in very coarse textured soils and under high rainfall and/or irrigation.

New Zealand soils vary considerably in P requirements, particularly for the establishment of brassica crops (Wilson *et al.* 2006), with low rates needed in brown grey earths and dry yellow grey earths and higher rates in wet yellow grey earths (Appendix 2.1; Syers, 1974).

2.2.2 Soil P fixation

When P fertilisers are applied to soils and are dissolved by soil water, reactions occur among the P, soil constituents and the non-P fertiliser components. These remove P from the solution phase and render the P less soluble and less available to plants (Sample *et al.* 1980). This reversion to plant unavailable forms of P has been known traditionally as P fixation, but in recent years the term soil loss of P has been used to describe this phenomenon (McLaren & Cameron, 1996). Soil loss of P is mainly due to immobilisation (Abrahamson & Darkey, 1988) and to a lesser extent leaching of P (Quin & Scobie, 1985; McLaren & Cameron, 1996). Immobilisation is the reversion of relatively soluble and plant available P forms to unavailable forms.

According to McLaren & Cameron (1996) less than 50% of applied P fertiliser is taken up by the plants in the first year following application and the rest is fixed in the soil. The soil loss of P is dependent on soil type and average rainfall of the area. For example, soil loss of P is low from brown grey earth and recent soils such as Templeton silt loams, receiving less than 1000 mm rainfall per year compared with yellow brown pumice and loam soils receiving more than 1000 mm rainfall per year. This fixation of P in non labile forms is the main cause of P immobilisation and hence unavailability in the soil.

2.2.2.1 Factors influencing soil loss of P.

According to McLaren & Cameron (1996), the main factors that influence soil loss of P are chemical composition and mineralogy, soil pH and time of reaction.

2.2.2.1.1 Soil chemical composition and mineralogy

The presence of calcium carbonate and oxides of iron and aluminium (Samples *et al.* 1980) play a key role in P retention in soils. Less crystalline and more amorphous colloids are able to fix larger amounts of P, than the strongly crystalline oxides of iron and aluminium (McLaren & Cameron, 1996). Samples *et al.* (1980) suggested that P is precipitated as Ca-, Fe-, or Al- phosphates or is chemically bonded to these cations at the surface of soil minerals. The ability of the cations to fix P is a function of soil pH (Figure 2.1). Phosphorus can also be rendered permanently unavailable through occlusion (McLaren & Cameron, 1996), whereby the P ions diffuse into the soil mineral or are incorporated into developing coatings of oxides of Fe and Al.

Saunders (1965) concluded that P retention in New Zealand topsoil was clearly related to the nature of parent material and degree of weathering of the soil profile. It was lowest in weakly weathered semi-arid and Pallic soils. Phosphorus retention is also related to high content of the amorphous clay allophane and associated amorphous oxides of Fe and Al (Appendix 2.1). Parfitt (1980) stated that the active Al pool in yellow brown loam soils arises from the presence of the clay mineral allophane, which is responsible for much of the P loss on these soils. The estimated soil loss of P could be up to 50% within one year which is agronomically significant.

2.2.2.1.2 Soil pH

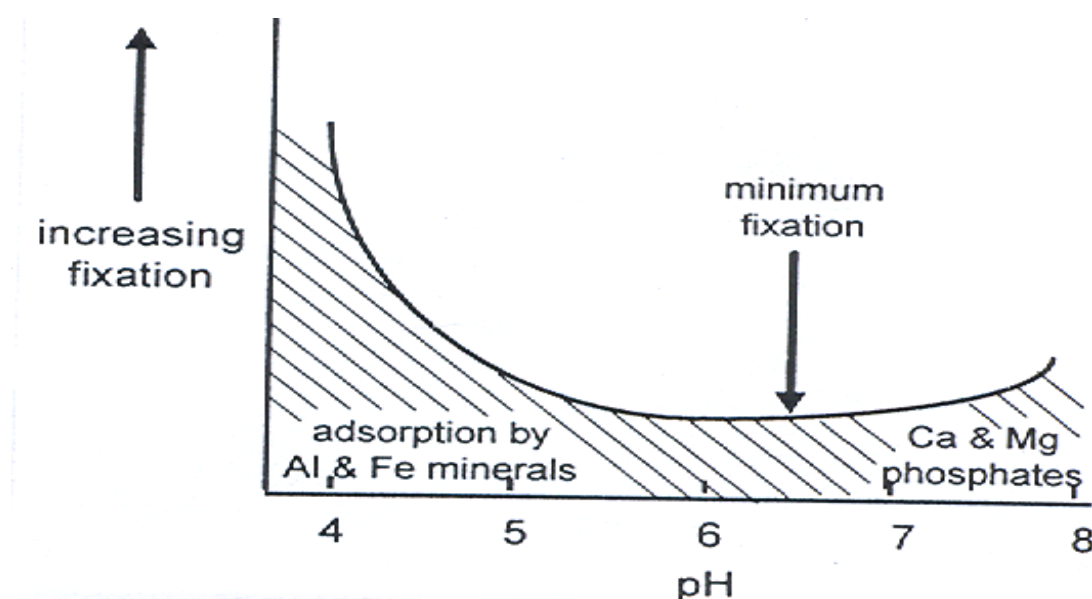


Figure 2.1: Effects of soil pH on P fixation by soils (Reproduced by permission of Oxford University Press Australia from *Soil Science (2d ed)* by McLaren & Cameron © Oxford University Press, www.oup.com.au).

Figure 2.1 shows that readily available P (minimum fixation) is between pH 6-7. Under acid conditions, fixation is mainly a result of adsorption by colloidal Fe and Al materials, while in alkaline conditions, by Ca and Mg compounds. This means the additions of lime to acidic soils, improves availability of soil P.

2.2.2.1.3 Time of reaction

The conversion of labile to non-labile (stable) P forms (McLaren & Cameron, 1996) is an extremely slow process and can take years. This means when soluble P is added

to a soil with low fixing capacities, in the short and medium terms a large proportion of the added P will be available for plant uptake.

2.2.2.2 Phosphorus retention test

In New Zealand, soil capacity to fix P is determined by a P retention test (McLaren & Cameron, 1996) and soils are divided into low, medium and high P retention categories (Appendix 2.1). Soils with high P retention capacities are developed from volcanic ash, andesitic rock and basalt (During, 1984). These soils reduce availability of P rapidly. Soils derived from young pumiceous ash are of medium to low P retention and recent and greywacke soils are low P retention soils (Appendix 2.1).

2.2.3 Phosphorus requirements of Brassica crops

2.2.3.1 Effects of P on brassica establishment

In New Zealand, brassica crops are grown on soils of diverse fertility status (Wallace, 1946; Toosey, 1972) and respond to fertiliser application, especially P (McLeod, 1965; Wilson *et al.* 2006), when Olsen P levels are less than 20 mg /kg soil (White *et al.* 1999). Yield is greatly enhanced when a starter fertiliser of about 50 kg P /ha is applied at sowing (Moot *et al.* 2007) but the actual rates depend on initial Olsen P levels. Tisdale *et al.* (1985) suggested that P fertiliser should be placed near the plants.

In a commercial farming situation, it is usually the less productive pastures that are often sown out into brassica crops, which are in less than optimal conditions. McLeod (1965) showed that kale consistently produced higher yields when P was applied. Under no P, establishment was slow and the resultant crop stunted.

Brassica crop production is also limited by nitrogen (N) and micro elements boron (B) and molybdenum (Mo) (Hayward and Scott, 1993; White *et al.* 1999). Nitrogen should be applied when the brassica crops follow cereals (Davies, 1970), but may not be necessary after a high producing pasture, with high returns from animal urine and dung. The main source of N is mineralisation of organic matter (White *et al.* 1999), but economic responses to N are obtained on low fertility soils or with a second successive brassica crop.

Wilson *et al.* (2006) found that yield of 'Pasja' and kale responded strongly to N and P (Figure 2.2). Jung *et al.* (1984) reported a linear response on yield of turnips (*Brassica campestris* L.) and rape (*Brassica napus*), to P at 60 and 90 day harvests,

respectively. Turnip DM yield did not respond to P application after 60 days. Rape yield at no N and no P did not increase after 60 days, whereas at 132 kg N /ha and 60 kg P /ha, yield increased by between 33% and 50%, between the 60 and 90 day harvests. These authors also showed that brassica crops did not respond to higher rates of P (>60 kg P /ha), while Wilson *et al.* (2006) found the maximum rate was related to the Olsen P level and did not exceed 50 kg P /ha.

According to Davies (1970) and Claridge (1972) P is needed at seedling establishment. Seeds can be pelleted with reverted super phosphate but only small amounts required. McLeod (1965) found that rape sown without P suffers an initial check in growth, but recovers with time. Kale, swedes (*Brassica napus* spp. *napobrassica*) and turnips sown without P will be slow to establish, remain retarded in growth and fail to properly bulb for the latter two. Where Mo is deficient, molybdate phosphate can be used. Borated reverted super is recommended where brown heart is common, such as many Southland soils and on most pumice soils (White *et al.* 1999). Research has shown little response to potassium (K) (Davies, 1970) unless on peaty soils which have no K in parent material.

2.2.3.1.1 Fertiliser toxicity

Without a small seed box many internal force feed drills are not capable of sowing conventional rates of brassica seeds which may be as low as 1 kg /ha. For this reason farmers must resort to mixing brassica seed with fertiliser to achieve reasonable seed distribution.

Brassica seeds are highly sensitive to germination injury from soluble fertilisers (Carter, 1967; Davies, 1970; Hayward and Scott, 1993), but this is a function of fertiliser type (Table 2.1), placement and soil moisture content. According to Carter (1967) and Davies (1970) superphosphate fertilisers with high fluoride content and urea with buiret should never be mixed with seeds before sowing. Ammonia vapour from nitrogenous fertilisers is also highly toxic to germinating seeds.

Two ways in which fertilisers reduce germination and hence establishment are direct toxic effects due to chemical substances such as fluoride, buiret and ammonia (Carter, 1967) and the osmotic effect resulting from high salt concentration. Greater damage occurs at low moisture levels (Carter, 1967), probably due to the combined effects of higher toxic ions and higher osmotic pressure. Lewis (1941) found that

drilling P fertiliser in contact with kale seeds impaired germination and at times killed young seedlings. The toxic effects were reduced by significant rainfall or irrigation soon after sowing, which removed soluble salts from the germination zone.

Table 2.1: Effects of P fertiliser type on brassica crop final plant population, plant weight and yield (Adapted from Hayward & Scott, 1993).

Fertiliser	Plants /m ²	Weight / plant (g)	Yield (t DM /ha)
Control	26.2 _a	25.0 _b	6.5 _{ab}
Lime reverted super	26.4 _a	38.0 _{ab}	10.0 _a
Superphosphate	26.2 _a	33.0 _{ab}	8.4 _{ab}
Longlife	28.0 _a	30.0 _{ab}	8.3 _{ab}
M.A.P	20.7 _{ab}	38.0 _{ab}	8.0 _{ab}
Nitrogen super	18.6 _{ab}	45.0 _a	8.2 _{ab}
D.A.P	22.5 _{ab}	39.0 _{ab}	8.6 _{ab}
Cropmaster 20	13.9 _b	34.0 _{ab}	4.1 _b

¹Means with the same letters as subscripts within columns are not significantly different at $\alpha=0.05$.

Table 2.1 shows that there was no significant difference in brassica establishment among P fertilisers which do not contain N and also among those that contained N, but there was a significant difference between the two groups of fertilisers. This could be attributed to the release of ammonia (NH₃) gas in the latter group, which is highly toxic to germinating seeds (Carter, 1967).

Table 2.1 also shows that sowing brassica crops with 'Cropmaster 20' (20% N) fertiliser severely reduced emergence to about half that of seed sown with lime reverted or long life fertilisers. Reduced emergence is probably due to the hygroscopic ammonium sulphate contained in the fertiliser, drawing water away from the seed thus preventing germination; and post germination drawing water from the seedling resulting in desiccation.

Broadcasting fertiliser can reduce the risk of germination injury as soluble fertilisers such as ammonium sulphate and 'Cropmaster 20', are not concentrated near the seed (Claridge, 1972; Hayward & Scott, 1993). Hayward & Scott (1993) showed that mixing of N fertiliser with seed reduced germination (Table 2.1), and hence is not

advisable. Conventional ridgers allow the placement of fertilisers beneath the seed, hence reducing seed damage (Claridge, 1972; Section 2.2.4). Brassica crops are the most sensitive followed by legumes (intermediate) then grasses (Carter, 1967).

2.2.3.2 Effects of P on brassica growth

According to Wilson *et al.* (2006), fertiliser management is an important aspect of growing high yielding forage brassica crops. Different crops have different fertiliser requirements depending on soil fertility status and expected yields. The key drivers of soil fertility for crop production in general are nitrogen (N) and phosphorus (P) (Moot *et al.* 2007; Figure 2.2), with leafy brassica crops responding strongly, especially after cereals (Wrightson Seeds, 2007).

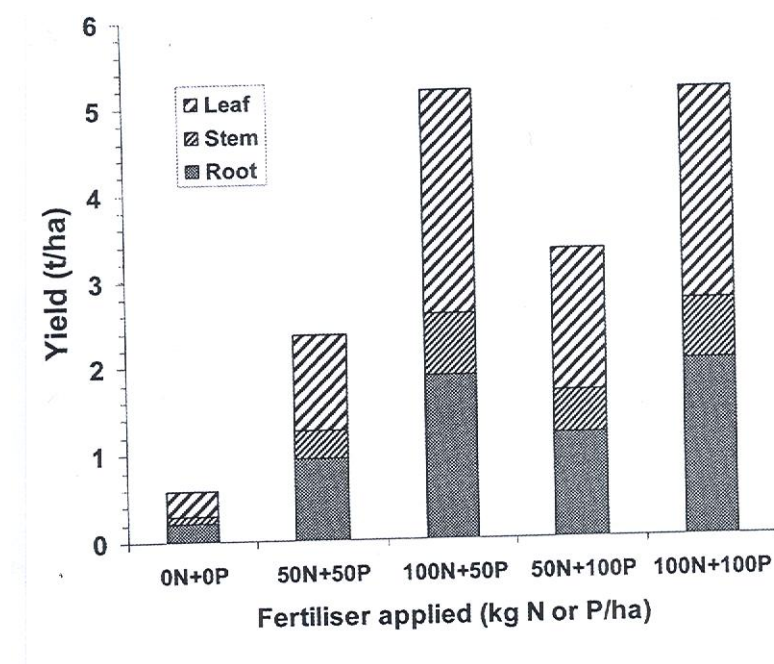


Figure 2.2: ‘Pasja’ dry matter responses to application of N and P fertilisers (first harvest) at low P and moderate N site (Lake Ferry) (Wilson *et al.* 2006)

Figure 2.2 shows that there was very low yield with no fertiliser applied, with initial Olsen P of 5.4 mg /L and available N status of 100 kg N /ha (Wilson *et al.* 2006). Yield components responded to P application rates up to 50 kg P /ha, while root and leaf yield responded to N rates up to 100 kg N /ha.

Phosphorus plays a pivotal structural and regulatory role in plant growth, photosynthesis, energy conservation, carbon metabolism and enzyme function

(Akhter *et al.* 2007; Moot *et al.* 2007). Brassica yield responds strongly to phosphorus, with an 18 t /ha kale crop requiring about 50 kg P /ha (Wilson *et al.* 2006). Claridge (1972) stated that kale is a gross feeder and produces exceptionally heavy yields under conditions of high fertility and optimum rainfall. Wilson *et al.* (2006) found that 'Pasja' and kale had similar, intermediate values of the parameter that defines the amount of P they need to access, but were different in their ability to utilize fertilizer P. Kale utilised P efficiently regardless of whether it was banded or broadcast. Kale utilised fertiliser P three times more than soil P. 'Pasja' was only half as efficient at utilizing fertiliser P and 40% less efficient at utilizing soil P.

Phosphorus is a major farm cost (Quin & Scobie, 1985; Moot *et al.* 2007), accounting for about 20% of the expenditure on lowland dairy farms. This reinforces the need for optimum timing and placement of P fertiliser. Traditionally it was assumed that uniform distribution of fertiliser over the soil surface would suffice (Lewis, 1941), but current knowledge on behaviour of nutrients especially P in soils (Tisdale *et al.* 1985; McLaren & Cameron, 1996) has shown this may not always be the case.

2.2.4 Phosphorus fertiliser placement

Tisdale *et al.* (1985) stated that correct placement was important as it increased efficiency of P use from emergence to maturity, prevents seed and seedling injury and should be of convenience to the farmer in terms of saving labour need and cost, timeliness and speed of operation. The rate and distance of P movement in soils is limited (Tisdale *et al.* (1985) and this depends on soil type and moisture.

Two methods of P fertiliser application are banding and broadcasting (Lewis, 1941; Tisdale *et al.* 1985). There are many variations to banding and broadcasting. The variations depend on machinery used, whether fertilizer is applied before or after sowing and the type of nutrient applied. Research has shown that banding is more efficient than broadcasting (Lewis and Strickland, 1944). Lewis and Strickland (1944) found that band fertiliser application gave twice as much yield of grain and straw in cereals as broadcasting. Lewis (1941) found that P fertilisers are more effective in drills than when broadcast, although this will depend on soil type and P fixation.

2.2.4.1 Broadcasting

Tisdale *et al.* (1985) defined broadcasting as fertilizer applied uniformly over the field before sowing and either soil incorporated by tillage or left on the surface under no till system or perennial forages. Broadcasting requires large amounts of fertilizer to build up soil nutrients. Hayward and Scott (1993) found that broadcasting different P fertilizers did not improve brassica establishment compared with banding. They also found that broadcasting P fertilisers, containing N, led to improved establishment but not individual plant weight and yield. This can be attributed to the even distribution of ammonia (NH₃) gas (Tisdale *et al.* 1985), resulting in less damage to seed (Carter, 1967; Section 2.2.3.1.1). Wilson *et al.* (2006) found that 'Pasja' used P seven times less efficiently when broadcast than banded. This could be attributed to its feeble root system compared with kale and hence limited ability to access evenly spread P.

2.2.4.2 Banding

Banding is the application of fertilisers in 'rows', below or to the side of the plant rows (Tisdale *et al.* 1985), usually at planting. Banding needs special equipment and careful calibration, compared with broadcasting. Hayward and Scott (1993) found that banding of superphosphate significantly improved establishment, probably due to improved P availability (Carter, 1967; Moot *et al.* 2007), close but not in contact with roots. Sowing kale and swede seeds in contact with the fertilisers severely reduces establishment (Carter, 1967), as they are very sensitive at germination. Banding reduces contact between P fertilizer and soils, thus reduces P fixation (Tisdale *et al.* 1985). This increases the amount of available P and gives early stimulation to seedlings, resulting in earlier and greater leaf appearance and expansion (Section 2.3.4).

Banding is more advantageous to crops with limited root systems such as 'Pasja' and those with shorter growing periods (Tisdale *et al.* 1985). Lewis (1941) stated that the effectiveness of P banding depended on fertilizer placement, either below or to the side of the seeds. It was effective when placed close to, but not in contact with the seeds, and to the side rather than below for brassica crops. This is probably because primary roots grow downwards and come into contact with a high concentration of the fertilizer likely to cause damage. When fertilizer is placed to one side only secondary roots can access it during the delicate early growing periods. One

of the attributes of the 'Cross Slot' drill (McKenzie *et al*, 1999) is that it places fertiliser below and to one side of the seed.

Summary

One of the key factors involved in 'Pasja' and kale production is P management both in terms of rate and method of application. This is because the two crops have different efficiencies of P utilisation (Wilson *et al.* 2006) and because of the high cost of P fertiliser in relation to total farm expenditure (Moot *et al.* 2007). The fact that P can easily be lost in the soil (McLaren & Cameron, 1996) through fixation means rate of application should not exceed plant requirements. Phosphorus can be band applied or broadcast, depending on crop growth stage, with the former method suited to application at sowing. Limited research has shown banding to give superior results (Lewis and Strickland, 1944) and optimum rate to be 50-60 kg P /ha (Jung *et al.* 1984; Wilson *et al.* 2006). For these reasons method and rate of P application were one of the key aspects investigated in the present study using 'Pasja' and kale which have feeble and vigorous root systems respectively. The impacts of applied fertiliser on crop growth and development will then determine the yield potential.

2.3 Temperature and light relationship

2.3.1 Thermal time and leaf appearance

The ability to form leaves after sowing or grazing, and time interval between the appearances of successive leaves on the main stem is closely linked to the formation of new nodes at the stem apex (Moot *et al.* 2007). This is defined as the phyllochron (Gallagher, 1979) which is quantified by thermal time. Phyllochron is controlled by temperature (both air and soil), depending on the position of the stem apex and leaf extension zone. There is little evidence to suggest that other factors such as solar radiation, nutrient status and water supply have an important influence on leaf appearance rates (Terry *et al.* 1983; Hay and Walker, 1989; Morrison & McVetty, 1991) within their normal field ranges, provided other growth factors are not limiting (Morrison & McVetty, 1991).

Adams *et al.* (2005) found mean base temperature for leaf appearance of kale, rape and turnips was 4 °C and the phyllochron was 64.5 °Cd for ‘Gruner’ kale, 67.5 °C for ‘Kestrel’ kale and 61.3 °Cd for ‘Goliath’ rape. Morrison & McVetty (1991) found that the phyllochron of rape was 46 °Cd, above a base temperature of 5°C.

Cao & Moss (1989) found that the phyllochron in wheat (*Triticum aestivum* L.) and barley (*Hordeum vulgare* L.) increased exponentially with increasing temperature; averaging 57.2 ± 5.2 °Cd at 7.5 °C compared with 116.2 ± 7.1 °Cd at 25 °C. This shows that as the temperature increases, more thermal energy is needed to produce a leaf and the thermal efficiency (leaves / °Cd) decreases. This could be the reason why phyllochron varies with sowing date and latitude. Cao & Moss (1989) also showed that phyllochron decreased with increasing daylength, from 92.4 ± 4.5 °Cd to 64.5 ± 5 °Cd at 8 and 24 hour daylength respectively. However Jamieson *et al.* (1995) found a phyllochron of 93 °Cd for autumn and winter sown wheat compared with 72 °Cd for spring sown wheat. This indicated a faster rate of leaf appearance per unit thermal time in the warmer spring than in the cooler autumn / winter period. This was attributed to the fact that soil temperature warms up faster than air, and soil temperature controls development as the apex of wheat is underground until about the time the last two leaves emerge. This led Jamieson *et al.* (1995) to conclude that the discrepancies in published results may be due to the position of measuring temperature, as the shoot apex in cereals remains below or near the soil surface until stem elongation.

2.3.2 Thermal time (Tt)

Morrison *et al.* (1989) stated that numerous models have been proposed to describe the phenological development of plants as a function of environmental variables, to try and overcome the inadequacies of calendar days in predicting crop development. One such model is thermal time (Tt) also known as heat units or growing degree days (GDD), which is accumulated heat available for crop growth.

Thermal time can be used to represent the accumulated heat that is available for crop growth (Morrison *et al.* 1989; Mackenzie *et al.* 1999). Moot *et al.* (2007) noted that the accuracy of Tt predication for crops recognises the change in location of growing point and measurements are switched between soil and air temperature. The Tt concept is important in terms of establishment and leaf appearance and as a result, energy capture and DM production. The thermal time model is represented by Equation 2.1 (Morrison *et al.* 1989; Morrison & McVetty, 1991):

$$\sum_{s_1}^{s_n} Tm - Tb \text{ ----- Equation 2.1.}$$

Where Tm is mean daily temperature and

Tb is the baseline temperature, below which development ceases.

s_1 & s_n are different crop growth stages.

Morrison *et al.* (1989) found a base temperature for leaf appearance of ‘Westar’ summer rape (*Brassica napus* L.) to be 5°C. This was comparable to a mean of 4°C reported by Adams *et al.* (2005) for kale, rape and turnips. The optimum temperature range for germination was between 10 °C and 30 °C (White *et al.* 1999) with little, if any germination at <5 °C and >40 °C. Cool soil temperature and variable soil water availability limit seed germination causing erratic seedling emergence and subsequent growth.

Scott & Pollock (2004) ran a simulation model using thermal time and yield relationship, assuming brassica crops accumulate 1000 kg DM/ha /100 °Cd and found that delaying emergence from 1 December to 15 January resulted in loss of production by 30%, under Invercargill conditions. Adams *et al.* (2005) found that DM production of kale and turnips increased by 1100 kg DM/ha for every 100 °Cd, using

a base temperature of 4 °C. Moot *et al.* (2007) stated that plant species that are traditionally considered ‘slow’ to establish have a high Tt requirement for emergence, such as cocksfoot (*Dactylis glomerata* L.) (Tt=250 °Cd) compared to those that are ‘fast’ to establish like perennial ryegrass (*Lolium perenne* L.) (Tt=99 °Cd). Thermal time is not a direct driver of plant growth (Adams, 2004) but influences the rate of leaf appearance and expansion (Collie & McKenzie, 1998), which in turn influence light interception (the main driver of growth) and photosynthetic rate.

2.3.3 Leaf appearance

Leaf appearance and expansion rate are the predominant factors that influence plant growth (Sivakumar & Virmani, 1984) as leaf area per unit ground area determines the percentage of solar radiation intercepted. Nanda *et al.* (1995) and Collie, (1997) showed that the number of leaves on a plant is highly correlated to sowing date (Figure 2.5, 2.4), with early sown crops producing more leaves than late sown crops. This is in agreement with findings by Adams *et al.* (2005) that number of leaves per plant differed with sowing date and cultivar, with the number of leaves accumulating linearly with days after sowing for kale. This shows the dependence of leaf appearance to accumulated temperature and daylength (Gallagher, 1979; Cao & Moss, 1989).

Various studies have established a linear relationship between number of leaves per stem and accumulated temperature (°Cd); wheat (Gallagher, 1979); corn (*Zea mays* L.) (Warrington & Kanemasu, 1983); summer rape (Morrison & McVetty, 1991); brassicas (Nanda *et al.* 1995) and ‘Pasja’ and kale (Wilson *et al.* 2004).

Figure 2.3 shows that for both ‘Pasja’ and kale, leaf appearance responded linearly to thermal time. Figure 2.3 also shows that ‘Pasja’ produced leaves and therefore developed a full canopy faster than kale. Wilson *et al.* (2004) found that the mean leaf appearance rate for ‘Pasja’ was 0.016 leaves per °Cd compared with 0.009 leaves per °Cd for kale. This represents a leaf appearance rate for kale of just over half the rate of ‘Pasja’ (Figure 2.3), that is a phyllochron of about 62 °Cd for ‘Pasja’ and 110 °Cd for kale.

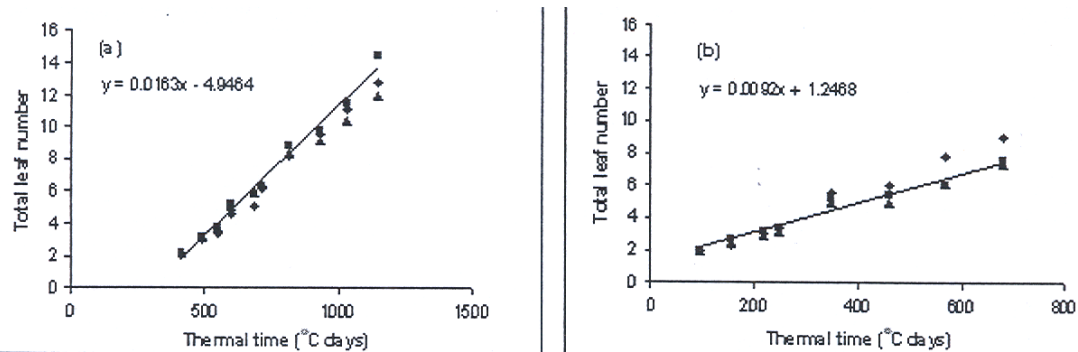


Figure 2.3: Leaf appearance in thermal time for (a) 'Pasja' and (b) kale (Wilson *et al.* 2004). * Data is from three sowing dates and the fitted line is for a medium plant population.

Warrington & Kanemasu (1983) and Cao & Moss (1989) found a constant leaf appearance rate for corn and wheat respectively for the first 12 leaves and rate increased thereafter. This was attributed to rapid stem elongation and the fact that upper stem leaves are smaller and require less time to expand. This was in agreement with findings by Nanda *et al.* (1995) for brassica crops where upper leaves emerged 33 and 48% faster than lower leaves for the last two sowing dates (28 November & 9 December) respectively in *B. napus*. Rate of leaf appearance increased with temperature (Cao & Moss, 1989) until an optimum is reached. Cao & Moss (1989) also found that leaf appearance increased non-linearly with increasing daylength, varying from 0.163 ± 0.008 leaves per day at 8 hours to 0.234 ± 0.018 leaves per day at 24 hour daylength.

Collie (1997) found that leaf appearance rate for turnips ranged from 0.346 leaves per day in early sown plants (11 January) to 0.177 leaves per day for the late sown plant (25 March) (Figure 2.4). This clearly shows the dependence of leaf numbers on Tt.

Figure 2.4 also shows that total number of leaves per plant is highly correlated to temperature, with the earlier sown turnips achieving maximum number of leaves quickly. As the leaf appearance rate is driven by temperature only (Jameison *et al.* 1995) it should be the same across different temperature ranges observed for different sowing times. The different leaf appearance rates shown in Figure 2.4 suggest that the base temperature is above zero. This conclusion is supported by studies done by Morrison *et al.* (1989) on rape ($T_b=5^{\circ}\text{C}$) and Adams (2004) on turnips, kale and rape cultivars ($T_b=4^{\circ}\text{C}$).

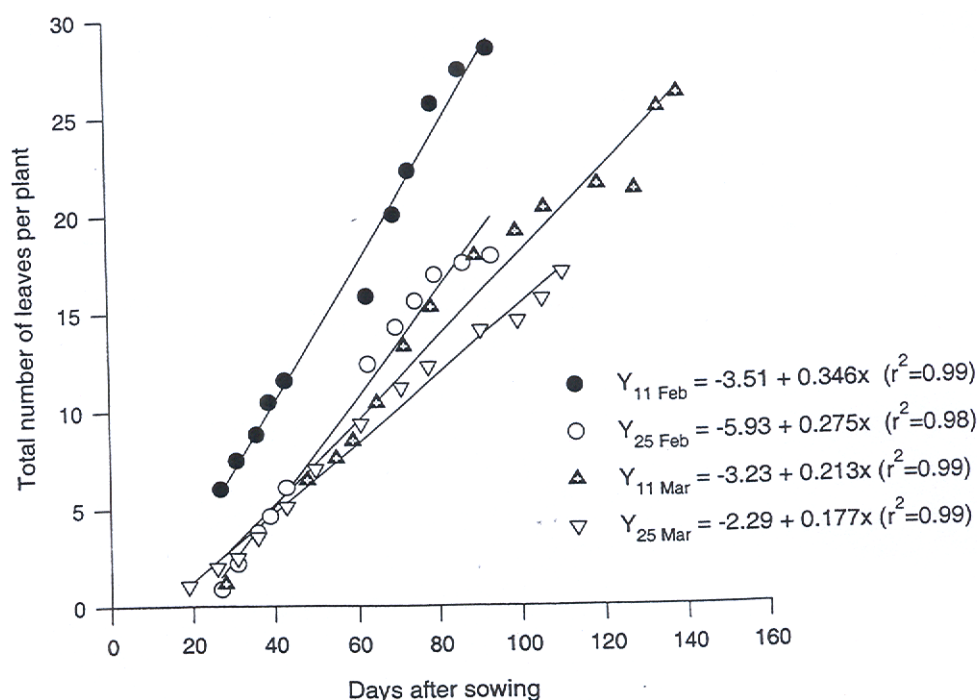


Figure 2.4: Plant leaf accumulation of three cultivars of *Brassica campestris* L. over four sowing dates (Collie, 1997).

Data from Figure 2.4 was used to calculate the phyllochron assuming a base temperature above 0 °C and rates of appearance obtained were 35.7, 43.5, 41.7 and 47.6 °Cd per leaf for the sowing dates 11 February, 35 February, 11 March and 25 March respectively. These results show that leaf appearance and consequently canopy closure is dependent on sowing date which affects the length of growing period. The average rate of leaf initiation in turnips was 0.025 leaves per day (40 °Cd per leaf) which was different to the 60 °Cd ($T_b=0^\circ\text{C}$) reported by Nanda *et al.* (1995). The difference could be due to different base temperatures used in these studies. Nanda *et al.* (1995) also reported longer phyllochrons for *B. juncea* (64.9 °Cd), *B. napus* (82.9 °C) and *B. carinata* (63.7 °Cd).

Nanda *et al.* (1995) found that duration of leaf appearance varies with sowing time (hence temperature) from 10.8 days (planting date 1) to 22 days (planting date 5) (Figure 2.5). Photoperiod changed from 11.3 to 10.2 hours and mean temperature from 24 to 15 °C between these two sowing dates. This delay in leaf appearance was equivalent to 1.35 days for each 1°C fall in mean temperature.

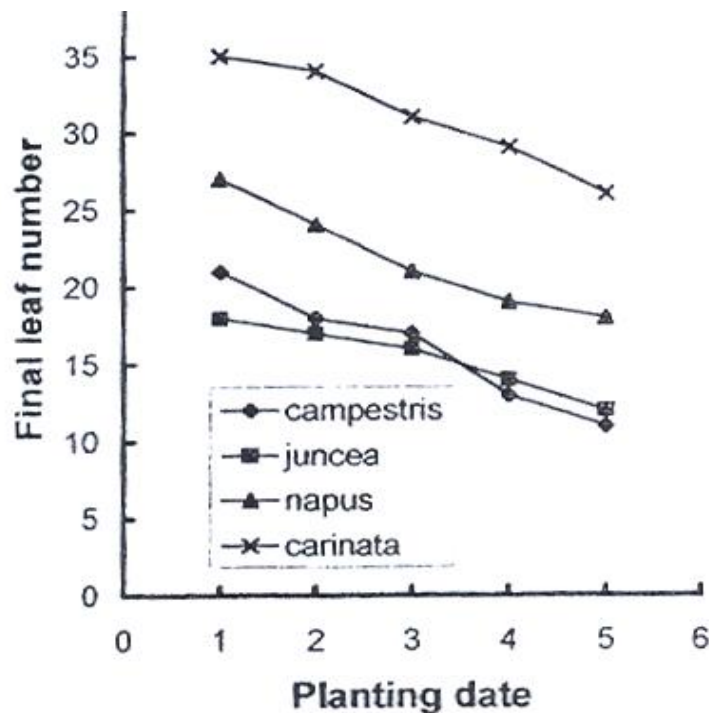


Figure 2.5: Final leaf number for four *Brassica* species from five planting dates (19, 29 October, 8, 28 November, and 9 December) (Nanda *et al.* 1995).

Fig 2.5 shows that the final number of leaves on the stem was species dependent and was reduced with delayed sowing under lengthening daylength and lowering temperature. This could be attributed to the reduction in temperature. The changes in Figure 2.5 could also be a result of environmental parameters influencing plants changing from vegetative to reproductive phase. This caused cessation of leaf appearance. Temperature and photoperiod have great influence through vernalisation. The prediction of phenological development hinges on the rate of leaf appearance and final meristem leaf number (Jamieson *et al.* 1995). Miglietta (1989) concluded that vernalisation and photoperiod influence time of flowering by their effect on the final leaf number on the meristem.

2.3.4. Leaf expansion and leaf area index (LAI)

2.3.4.1 Leaf expansion

Both leaf expansion and senescence also depend on temperature (Monteith, 1977). The rate of canopy expansion is a function of leaf appearance and senescence, tillering rate and duration of expansion (Terry *et al.* 1983). According to Nanda *et al.* (1996) phenological development in brassica species is altered primarily by

photoperiod, with a general shortening of phases as daylength increases. Some brassicas also respond to increased temperature (Morrison *et al.* 1989). Leaf area production is associated with phenological development (Nanda *et al.* 1995) with late floral bud appearance resulting in more and larger upper leaves.

Hay & Walker (1989) stated that the rate of leaf expansion decreased after leaf unfolding or emergence and the later phases of growth determined rate of increase of photosynthetic leaf area. Dale and Milthorpe (1983) estimated that phases after appearance account for 80% of total growth in length, 95% of dry weight and >99% of blade area, and hence are important in crop physiology. The size of the leaf at any time is genetically determined (Hay and Walker, 1989) and governed by ontogeny and environmental factors such as temperature, water, nutrient supply (Terry *et al.* 1983) and irradiance. Successive leaves on plants change in size and shape (Dale and Milthorpe, 1983; Collie, 1997) getting larger up to a certain node beyond which size decrease progressively (Figure 2.6a; Tables 2.2 & 2.3).

Table 2.2: The effect of sowing date on the extension of the second and sixth leaf of three cultivars of *B. campestris* L. sown on two dates in Canterbury (Adapted from Collie, 1997)

Sowing date	Leaf length	WMAGR ¹		Duration		Max. GR ²	
	(mm)	mm /d	mm °Cd	Days	°Cd	mm /d	mm °Cd
Leaf 2							
11 February	131.4	5.4 _a ³	0.4	25.3	350.0	8.7 _a	0.6 _a
27 March	105.3	3.3 _b	0.5	32.3	297.6	4.7 _b	0.8 _a
LSD	ns	0.9	ns	ns	ns	0.3	ns
Leaf 6							
11 February	378.5	12.7 _a	1.0 _a	30.2 _b	374.9	18.7 _a	1.5 _a
27 March	242.7	6.3 _b	0.8 _b	38.2 _a	318.4	9.1 _b	1.3 _b
LSD	49.7	1.2	0.11	6.2	ns	1.69	0.13

¹Mean weighted growth rate.

²Maximum extension rate.

³Means with the same letters as subscripts within columns are not significantly different at $\alpha=0.05$.

Table 2.2 shows that sowing date had a significant effect on expansion of leaves. Earlier sown plants (11 February) had a shorter duration of leaf expansion than late sown crops, 25.3 days compared with 32.3 for leaf 2 and 30.2 compared with 38.2 for leaf 6. The maximum rate of extension also showed the same trend, as the late sown crops had maximum leaf extension rate of 53% of that measured for the earlier sowing. Table 2.2 also shows the effect was greater with higher order leaves.

For 'Pasja' and kale, air temperature is important in determining leaf size. Wilson *et al.* (2004) found that leaf area in 'Pasja' and kale depended on leaf position up the plant, population and size of cohort (in kale). The same authors also found that leaf size increased from leaf 1 to about leaf 12 and thereafter became constant for both 'Pasja' and kale. Maximum leaf sizes in kale range from 0.05 m² for large cohorts at low population to 0.01 m² for small cohorts at high populations. Monteith & Elston (1983) stated that duration of leaf expansion is much less variable and more closely related to temperature, than the rate of expansion which is more sensitive to variation in soil water and nutrient supply especially nitrogen.

2.3.4.2. Leaf area index (LAI)

Leaf area index (LAI) is the surface area of the leaf canopy per unit of ground area (Watson, 1958) and is the net result of leaf production and senescence (Monteith, 1977). Area of a leaf is part of a progression of areas established in preceding leaves (Nanda *et al.* (1995). Leaf area depends on biophysical factors such as soil water, nutrient supply, temperature and diseases (Terry *et al.* 1983) as they affect leaf size, appearance and persistence. Water stress has been shown to slow down leaf extension rates (Gallagher & Biscoe, 1978). Leaf area increases with successive leaves (Fig 2.6a) reaching a peak in the leaf emerging at time of floral initiation. At higher positions leaf area declines (Figure 2.6a; Table 2.3). Leaf area is important in determining yield through radiation interception (Monteith, 1977) and biomass production (Watson, 1958; Nanda *et al.* 1995). The determination of leaf area and hence canopy development is more complex in kale (Wilson *et al.* 2004) as plants germinate and emerge over a substantial period.

Figure 2.6a also shows that the area per leaf increased with successive leaves, reaching a peak and then declining. The main determinant of the peak reached is time of floral initiation. Nanda *et al.* (1995) found that each successive leaf after leaf 3 had

a leaf area approximately 80 cm² larger than the preceding leaf provided there was no floral initiation.

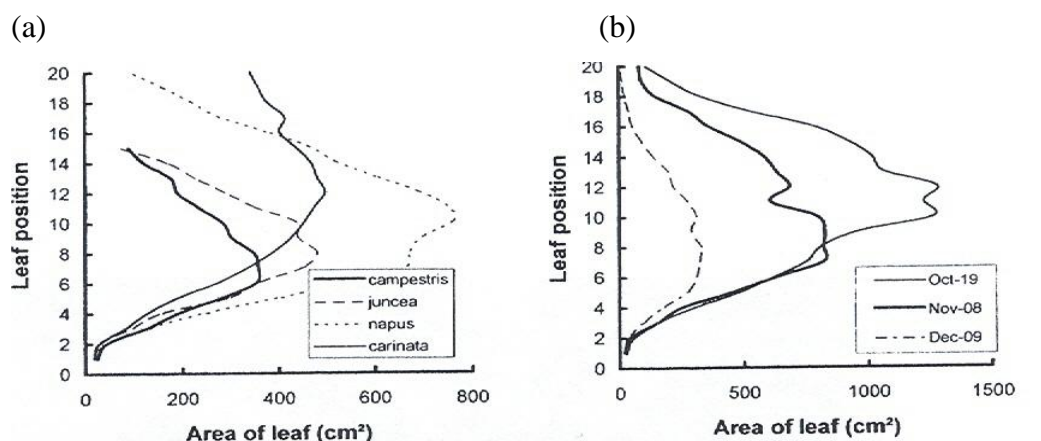


Figure 2.6: Profiles of area per leaf against leaf position from the base of the plant (leaf 1) for each of the four *Brassica* species (a) and for *B. napus* at planting dates 1, 3 and 5 (b) (Nanda *et al.* 1995).

Figure 2.6b shows the effect of planting date on leaf area, with largest leaves produced from the first planting and the smallest leaves from the latest planting. This agrees with work by Collie & Mackenzie (1998) where the last sowing date did not produce a full canopy.

Leaf area development depends on temperature (Hay & Walker, 1989) as it controls rate of leaf production and duration of expansion. It also depends on soil nitrogen status as it affects leaf size, longevity, branching and duration of branching. In dicotyledonous plants like brassica crops the relevant temperature is air temperature (Hay & Walker, 1989) while for grasses, soil temperature is more accurate as their growing points are closer to the ground.

The LAI at which 95% of the incoming radiation is intercepted is defined as the critical leaf area index (LAI_{crit}) (Moot *et al.* 2007). Collie & Mackenzie (1998) found the LAI_{crit} of turnips varied from 3 to 5.5 depending on sowing date, with a mean value of 4. This was in agreement with Gallagher & Biscoe (1978) who reported that for most crops the LAI_{crit} is between 4 & 5. Monteith (1981) reported that for most crops the LAI_{crit} range from 4 to 6 and Watson (1958) found that the LAI_{crit} for kale ranged from 3 to 5. Collie & Mackenzie (1998) also found that the time to LAI_{crit} was dependent on sowing date; with the early sowing achieving LAI_{crit} in 58 days compared with 82 days for the second last sowing (25 March) and the last

sowing failing to close the canopy. This means the last sowing never achieved maximum radiation interception.

Table 2.3: Mean leaf area indices (LAI) and radiation transmission at given heights in kale measured by a solar meter (Adapted from Monteith 1965).

Height (cm)	LAI	Height (cm)	Transmission
105 - 100	0.1	122	1.00
100 - 70	3.8	90	0.38
70 - 50	1.4	72	0.11
50 - 30	0.6	52	0.06
30 - 00	0.1	20	0.03

Table 2.3 shows that at establishment and during early growth, kale like most crops has a low LAI and hence is inefficient at intercepting radiation. The situation changes as more leaves appear and expand and the crop attained the LAI_{crit} at 70-100 cm height. According to Terry *et al.* (1983) irradiance may lead to a faster growth rate and expansion of total leaf surface due to the faster production of new leaves and rapid expansion of individual leaves (Dale & Milthorpe, 1983).

Wilson *et al.* (2004) used the concept of Tt to measure and model leaf expansion for kale. These authors defined the pattern of leaf expansion by a dimensionless “shape” factor (Figure 2.7) and fitted lines to data to represent leaf positions or different plant populations. They concluded that the maximum area per leaf depended on leaf position up the plant, plant population and size of cohort (Figure 2.7).

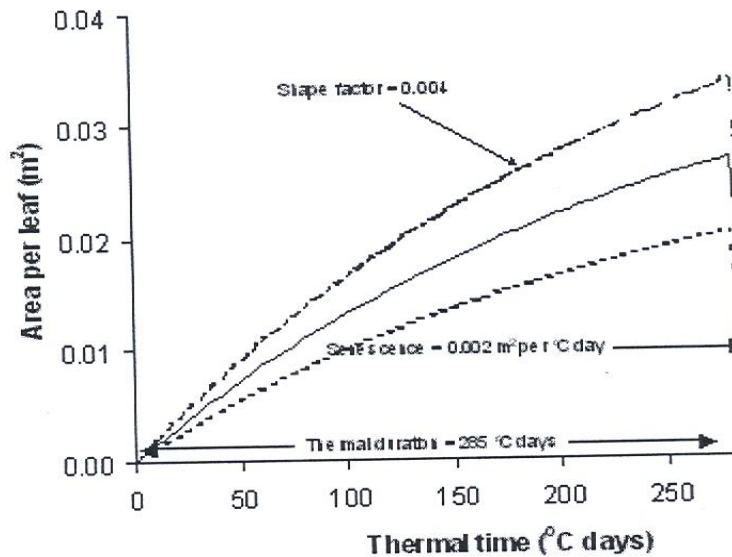


Figure 2.7: Expansion of individual leaves in thermal time (Tt) from emergence of kale (top line is for leaf number 12 and above or plant population of 70/m², while the bottom line is for leaf 1 to 12 and plant populations of 120/m²) (From Wilson *et al.* 2004).

Figure 2.7 also shows that at both 120/m² and 70/m² thermal duration to maximum area of each leaf was 285 °Cd for kale.

2.3.5 Leaf senescence

Zyskowski *et al.* (2004) stated that leaf senescence starts at about the time of canopy closure and Hay & Walker (1989) reported that leaf senescence can be accelerated by a range of environmental factors such as water and mineral stress, extremes of temperature and wind and also pests and diseases. Most crop species show sequential leaf senescence (Hay & Walker, 1989) with the oldest leaves senescing first. This is a result of competition between newly-expanded and older leaves for solar radiation, minerals and assimilates. As a consequence leaves begin to senesce according to age. Brassicas, especially those for winter consumption (e.g. kale) which are usually sown in summer and are sometimes consumed late winter or even spring (Stephen, 1976), are exposed to a drop in both temperature and radiation resulting in considerable loss of leaves. Kale leaves senesce at a constant rate in Tt of 0.002 m² / °Cd (Figure 2.7).

Adams *et al.* (2005) found a linear relationship when leaf senescence was expressed against Tt, with ‘Grunner’ and ‘Kestrel’ kale senescencing at 93 °Cd and 99 °Cd respectively, at a base temperature of 4°C. The rate of acceleration was however enhanced by low temperature and aphid attack, which reduced radiation interception.

2.3.6. Light interception and yield.

Solar radiation is the principal source of energy for plant biomass synthesis (Monteith, 1977). The portion of the solar spectrum important to plants for photosynthesis is the photosynthetically active radiation (PAR) (Moot *et al.* 2007) which is within the wavelength of 400-700 nm. The rate of plant growth is limited by a number of factors, among them the amount and quality of intercepted radiation (Sivakumar & Virmani, 1984) and the efficiency of utilization of the intercepted radiation (RUE). These two factors are dependent on environmental factors such as temperature, water and crop husbandry (Terry *et al.* 1983).

Radiation interception is a product of the fraction of intercepted light and total incident radiation (Szeicz, 1974; Zyskowski *et al.* 2004). Radiation interception represents the radiation spectrum that is actually intercepted by the plant and used for driving photosynthesis (Monteith, 1977). It is the most variable factor affecting crop production. The amounts of DM produced by various crops like sugar beet (*Beta vulgaris* L.) (Monteith, 1977) and barley (Gallagher and Biscoe, 1978) has been shown to be positively related to the amount of intercepted PAR. Gallagher and Biscoe (1978) found that the amount of radiation intercepted depends on LAI. In the early part of the season, when LAI is small, crop photosynthesis saturates at very low irradiances and hence total dry matter (DM) produced per unit absorbed radiation will be low. Monteith (1981) reported that DM production in temperate crops is generally proportional to the total amount of PAR intercepted, irrespective of irradiance. This is because most of these crops generally do not get light saturated. The relationship between incoming radiant energy and crop growth can be summarised by Equation 2.2 (Mackenzie *et al.* 1999):

$$Y = Q \times I \times E \times HI \text{ ----- Equation 2.2}$$

Where Y=crop yield,

Q=irradiance (Wm^{-2})

I=fraction of Q intercepted by the crop

E=efficiency of conversion of intercepted radiation into DM

HI=how much of TDM is partitioned into economic yield.

Mackenzie *et al.* (1999) stated that the most important and easily influenced factor affecting yield was the fraction of Q intercepted by the crop (I). This could be achieved by agronomic management practices that maximise LAI and its duration such as manipulating sowing time, plant density, geometry, soil nutrient and water availability and minimising the presence of pests and diseases. This is important to maintain the green area at or above LAI_{crit}. The rate of leaf growth and timing of senescence determined crop yield by determining the duration of maximum light interception.

The efficiency of crop canopy photosynthesis is less after ear emergency (Monteith, 1981) as no new leaves are produced and photosynthetic activity of existing leaves declines with age. The respiration per unit of assimilation tends to increase after anthesis which also reduces DM production from crop photosynthesis.

The LAI_{crit} is a function of extinction coefficient (k) (Table 2.4) which is a measure of the effectiveness with which a given leaf intercepts and absorbs radiation. Values of 'k' range from 1, for crops with predominantly prostrate leaves (planophile) to less than 0.3 for exceptionally erect foliage (erectophile) (Monteith, 1981).

Table 2.4: Critical leaf area indices and extinction coefficients (k) for different crops and pasture species (Adapted from Hay & Walker, 1989; McKenzie *et al.* 1999).

	LAI _{crit}	k
Lentils	7	0.27
Perennial ryegrass	4-6	0.4-0.5
Barley	4-5	0.5-0.7
Turnips	3.5	0.85
White clover	3	0.9-1.0
Kale (at maturity)	3-5	≥ 0.8

Table 2.4 shows that LAI_{crit} decreases with increasing k. According to Sinclair & Muchow (1999) plants with high k values intercept more radiation at LAI_{crit} of ≤ 4, while more erect leaves (low k) intercept more radiation above LAI_{crit} of 4. Hay and Walker (1989) noted that for ryegrass, a combination of low leaf area in the top strata of the canopy and low k (Table 2.4) results in less mutual shading and more efficient radiation interception. This is in contrast to clovers, where the top layers of the

canopy make up a large proportion of the total leaf area and leaves are disposed in a near horizontal plane (Table 2.4; $k=0.9-1.0$). This means for crops with a large k value like clovers, turnips and kale, most of the radiation is intercepted at the top of the canopy and hence photosynthesis is distributed over a small area of the leaf (Hay and Walker, 1989). In this case the upper leaves easily get light saturated (Watson, 1958; Monteith, 1981) resulting in reduced efficiency. Wilson *et al.* (2004) found that cumulative radiation interception in both 'Pasja' and kale (except for kale at low population) is not very sensitive to the value of k because the leaf canopies develop quickly to full interceptance.

Monteith (1977) reported that the relationship between crop growth rate and extinction coefficient changes with LAI. When LAI is smaller than the critical value, more horizontal leaves intercept more light than vertical ones with the same LAI. This means that just after emergence and during early growth, crops with more horizontal leaves intercept more radiation and grow faster than those with erect leaves. This scenario changes as plants continue to grow and LAI exceeds the critical value because there will be less mutual shading of leaves and lower leaves continue to get light. Their canopy does not get saturated, resulting in production of more DM.

2.3.6.1 DM production

The rate of biomass production can be predicted accurately if LAI of a crop is known (Gallagher & Biscoe, 1978). This is because during the early part of the growing season, the growth rate in many crops is directly related to radiation intercepted by the leaf surface (Gallagher, 1979) and the total DM produced is almost proportional to the radiation they intercept (Monteith, 1977).

Monteith (1977) proposed that growth of a plant is controlled by the amount of radiation intercepted by leaf surfaces and the efficiency of its utilization. In non-limiting conditions (Hay & Walker, 1989) variations in yield have been attributed to the amount of radiation intercepted rather than the efficiency of utilization. High growth rates are anticipated for crops which, at appropriate plant density show ontogenetic changes from a seedling planophile to a more mature erectophile architecture (Hay & Walker, 1989) which is the basic development pattern of many temperate grasses. Watson (1958) found total DM production varied through changes either in size of the photosynthetic system or its activity and length of growing period during which photosynthesis continued. As LAI varies with environmental conditions

(Terry *et al.* 1983), this means photosynthetic capacity of a crop and hence dry matter is also variable. Nanda *et al.* (1995) stated that LAI determines percentage (%) PAR intercepted by a crop and has a predominant influence on growth and DM production.

Gallagher & Biscoe (1978) reported that the important variables controlling the conversion of intercepted radiation to DM were the changes in photosynthesis with irradiance and temperature and the fraction of CO₂ fixed by photosynthesis that is respired. Studies in cereals between start of rapid growth and ear emergence have shown that photosynthesis increases linearly with irradiance (Monteith, 1981) until light saturation. Collie & McKenzie (1998) attributed high growth rate and DM production in the early sown turnips to a combination of long duration and high percentage of PAR. This resulted in greater amounts of intercepted PAR. They also noted that monthly radiation receipts declined with delayed sowing and the total level of PAR intercepted at each sowing date declined. This led to reduced DM produced.

Summary

Leaf appearance, expansion and interception of radiation are the predominant factors influencing plant growth. Although leaf appearance rate for brassica crops is linear to T_t , Adams (2004) found that it differed with sowing date and was dependent on temperature. Research has shown that early sown crops have faster leaf appearance rates (Collie & McKenzie, 1998) compared with late sown crops. Time of sowing should be based on T_t as the greater the time the crop is in the ground, the greater will be the dry matter produced.

Leaf area index determines the amount of light intercepted by the crop. The amount of light intercepted and its efficiency of utilisation influences dry matter production. For maximum radiation interception, there is need for a large disease-free leaf area to be established early in the season and plants maximize the duration above a LAI_{crit} .

Conclusion

- Phosphorus can be broadcast or band applied.
- Brassicas are responsive to P at rates up to 50 kg P/ha and N at rates up to 100 kg N/ha; however the actual rates depend on initial Olsen P level and available N respectively. Phosphorus should be applied at sowing. Care should be taken not to apply excess N and S as they cause animal health problems such as S-methyl cysteine sulphoxide (SMCO).
- Time of sowing should be based on thermal time rather than calendar days so as to be applicable to different areas and periods.
- Leaf appearance and expansion are the predominant factors influencing plant growth.
- Leaf area index determines the amount of light intercepted by the crop.

Chapter 3: Materials and Methods

The experiment was situated at Crop and Food Research Ltd, Canterbury, New Zealand, latitude 43°39', altitude 14 m, and average rainfall 640 mm (Fletcher & Moot, 2007).

3.1 Treatments and Experimental Design

The design was a split plot randomised complete block, replicated three times. The treatments were two brassica species ('Pasja' leaf turnip and 'Regal' kale) as the main plots and a factorial combination of two methods of application and four rates of P as the sub plots. Both species were sown on 17 December 2007.

Triple superphosphate (TSP; P=20.5%) at 0, 20, 40 and 60 kg P /ha was applied either broadcast by hand before sowing or banded below the seed at sowing with an Øyjoord drill. Nitrogen was applied three weeks after emergence at a rate of 100 kg N/ha for 'Pasja'. Nitrogen for the kale crop was split applied, three weeks after emergence at 150 kg N/ha and at nine weeks after emergence at 100 kg N/ha.

Main plots were 14 m long by 16.8 m (8 plots x 2.1 m) wide, separated from each other by 3 m gaps of bare ground to counter edge effect caused by greatly different crop heights. Each plot was one drill width (2.1 m), 14 rows at 150 mm interrow spacing. There was a 300 mm gap between the plots. The area had previously been under maize (*Zea mays* L.) in 2004 and pasture thereafter.

3.1.1 Soils and land preparation

The site was situated on a moderately deep Templeton silt loam soil (McLaren & Cameron, 1996). A soil test to 150 mm depth was taken from all 48 plots individually on 5 December 2008. The mean result is presented in Table 3.1 with individual plot data in Appendix 3.1.

Table 3.1: Average soil test results and optimum quick test for pasture growth for a Templeton silt loam soil at Crop and Food Research Ltd, Lincoln on 5 December 2008 and the optimum nutrient requirements (McLaren & Cameron, 1996).

	pH	Olsen P	Potassium	Calcium	Magnesium	Available N
Results ¹	6.1	13.3	0.35	8.0	0.6	76.0
Optimum	5.8-6	20-25	5-7	4-10	8-10	300

¹Average values from the 48 plots, soil analysis results (see Appendix 3.1)

The soils are classified as Pallic soil (Typic immature) (Webb *et al.* 2000), soil taxonomy; Udic or Typic Haplustepts and are moderately well drained.

Soil preparation consisted of conventional cultivation after deep ploughing. Seed was drilled using a 14 row Øyjoord drill in 15 cm rows at ~20 mm depth (Lamp, 1962). Sowing rate was 4 kg/ ha of viable seed for both species adjusted for germination test results (80% for ‘Pasja’ and 85% for kale).

3.1.2. Seed treatments and insect control

Seeds were treated with ‘Superstrike’, which contains a systemic insecticide to control springtails (*Bourletiella* species) (Salmon & Dumbleton, 2006). Diazinon (a.i. diazinon EC @ 800 g/L) at 1.0 L/ha, pre emergence and four weeks after sowing was also applied to guard against springtails and white butterfly larvae. Karate (a.i. lambda-cyhalothrin @ 250g/L) at 0.04 L/ha, contact at 0.075 L/ ha and Lorsban (a.i. chlorpyrifos @ 500 g/L) at 1.0 L/ha were applied to the ‘Pasja’ crop on 18 February 2008 (~6 weeks after emergence) to what was thought to be a mosaic virus infection (Plate 3.1)



Plate 3.1: Leaf miner maggot damage (*Liriomyza brassicae*) on 'Pasja' crop. (Picture was taken on 20 February).

This was later identified as leaf miner maggot damage (*Liriomyza brassicae*) (Harvey, 2006). It was also noted that the same plants had minor grey leaf spot fungus (*Alternaria brassicae*), downy mildew (*Perenospora parasitica*) and white rust fungus (*Albugo candida*) infection. After application no further pest or disease control was required.

3.1.3 Weed control

Herbicide 'Radiate' (a.i. picloran @ 150 g/L & clopyralid @ 225g/L as soluble concentrates) at 0.35 L/ha and 'Uptake' oil at 0.5 L/ha was applied 4 weeks after sowing, when 'Pasja' had at least four true leaves and kale had at least two true leaves, to control fathen (*Chenopodium album L.*) and nodding thistles (*Carduus nutans*). Nodding thistles were also removed by hand after emergence.

3.2 Measurements

3.2.1 Seedling emergence

The unfolding of the two cotyledons was considered as emergence (Morrison & McVetty, 1991). The number of emerged seedlings per m² was determined, from 1 m² marked area per plot from 7 days after sowing at two day intervals. Counting ceased when plant numbers remained constant within the marked area.

3.2.2 Dry matter (DM)

Growth of plants may be expressed in a number of ways (Brown, 1984), with the increase in height the most obvious manifestation of growth, although of little significance. Increase in dry weight is the most important aspect of growth in forage and pasture crops and was the key measurement in the present study.

3.2.2.1 Seedling DM accumulation and partitioning

Measurements were taken from each plot by digging up a single 300 mm length along one drill row. This was done one and two weeks after emergence for 'Pasja' and two and three weeks after emergence for kale. The number of plants harvested was counted. Samples were gently cleaned with cold water and separated into root and shoot components. This was based on colour changes, with green parts considered as shoots and white parts as roots. Fresh weight was determined for both root and shoot components. The shoots were then separated into leaves and stems (crown for 'Pasja'). Shoot and root components were then dried in a forced air oven at 70°C to constant weight to determine DM.

3.2.2.2 DM production

Measurements were taken from each plot by harvesting a single 0.5 m² quadrat (six central rows) at ground level for 'Pasja' and 10 mm above the ground for kale to reduce soil contamination. Initial DM harvests were made 17 days after emergence (DAE) for 'Pasja' and 24 DAE for kale. Subsequent harvests were at regular intervals, weekly for 'Pasja' and fortnightly for kale. Final harvest took place 73 DAE for 'Pasja' and 122 DAE for kale. 'Pasja' samples were gently cleaned in tap water to remove soil and then dried. The number of plants in the quadrat was determined and fresh weight measured. A representative 10 plant sub sample was retained for

measurements of leaf area, fresh and dry weight of the leaf and stem components. DM samples were dried in a forced air oven at 70°C to constant weight.

Total dry matter content, leaf and stem yield was determined using the following formula:

$$\frac{DW_{sub} \times FW_{total} \times 2^*}{FW_{sub}} \text{ ----- Equation 3.1}$$

Where DW_{sub} – sub-sample dry weight

FW_{sub} – sub-sample fresh weight

FW_{total} – total fresh weight of harvested sample

*multiplied by two to convert measurements into per m² basis.

A functional growth analysis was made using a Maximum Likelihood Programme (MLP) from Rothamsted Experimental Station, UK (Rose *et al.* 1987). Generalised logistic (Equation 3.2) or gompertz (Equation 3.3) curves were used to describe DM accumulation of the crops (Gallagher & Robson, 1978).

$$Y = C / (1.0 + T \exp (-b(x-m)))^{1/T} \text{ ----- Equation 3.2}$$

$$Y = C / (1.0 + \exp (-b(x-m))) \text{ ----- Equation 3.3}$$

Where Y=the yield

C is the final (maximum) above ground dry matter

and T , b and m are constants.

The weighted mean absolute growth rate (WMAGR-mean growth rate over the period when the crop accumulated most of its DM), duration of exponential growth (DUR-duration of crop growth over which most of the growth occur) and maximum crop growth rate (C_{max}) were derived for the crops using the values of C , T , b and m according to Equations 3.4-3.9. The forms of the equations used vary depending on whether a generalised logistic or gompertz curve was fitted:

Generalised logistic curves:

$$WMAGR = (b \cdot C) / 2(T+2) \text{ -----Equation 3.4}$$

$$DUR = 2(T+2)/b \text{ -----Equation 3.5}$$

$$C_{max} = (b \cdot C) / (T+1)^{(T+1/T)} \text{ -----Equation 3.6}$$

Gompertz curves:

$$WMAGR = (b \cdot C) / 4 \text{ -----Equation 3.7}$$

$$DUR = 4/b \text{ -----Equation 3.8}$$

$$C_{max} = (b \cdot C) / e \text{ -----Equation 3.9}$$

Where base e is the natural logarithm (value = 2.7183)

3.2.3 Canopy development and radiation interception

Canopy development was assessed as leaf appearance rate and leaf area index (LAI).

3.2.3.1 Leaf appearance rate (LAR)

Leaf appearance was defined as being once the leaf was fully expanded and the petiole was visible. The number of days from crop emergence to the appearance of each leaf was determined for both species at all methods of application and rates of P combinations.



Plate 3.2: 'Pasja' plants marked for leaf appearance count (Note: bamboo flags to mark the plants and red paint to mark every 5th leaf on each of the 10 chosen plants).

A total of 10 uniform plants per plot were selected and marked. Every fifth leaf was marked with red paint (Plate 3.2), as a reference point to determine rate of leaf appearance and senescence. Counting was done in three and four day cycles (every Tuesday and Saturday). Leaf appearance rate was determined from first day of counting, rather than seeding, to avoid the effect of soil conditions on seed germination masking the true effects of treatments on leaf development.

3.2.3.2 Leaf Area

The retained 10 plant sub sample was separated into stems and leaves. Leaf area was determined by an Area meter- model LI-3100 in cm². The total leaf area per quadrat was determined by substituting DW_{sub} in Equation 3.1 with leaf area (LA_{sub}) of the sub-sample. Leaf area was converted into leaf area index by the following formula:

$$\frac{LA_{sub} (cm^2) \times FW_{total}}{FW_{sub}} \times \frac{1}{10\ 000cm^2} \times 2^* \text{ ----- Equation 3.10}$$

A functional growth analysis was made using a Maximum Likelihood Programme (MLP) from Rothamsted Experimental Station, UK (Section 3.2.2.2)

3.2.3.3 Radiation interception

Fractional radiation interception (I/I_0) was measured with a ceptometer at 6-14 day intervals, depending on the weather. Four above canopy, followed by five below canopy measurements and another four above canopy measurements were taken per plot, around noon on clear days. The two above canopy references were designed to take account of any changes in radiation reaching the crop during the measurement period. Measurement positions were selected at random (Brown *et al.* 2005). Measurements were stopped when 95% of the incoming radiation was being intercepted.

Daily radiation from Broadfield meteorological station (located in the same block as the experiment) was used to determine total photosynthetically active radiation (PAR). Intercepted PAR was calculated at 0.5 times the total intercepted radiation.

The proportion of radiation intercepted by the canopy was calculated as (Yunusa *et al.* 1993):

$$i = 1.0 - (I/I_0) \text{ ----- Equation 3.11}$$

Where i is the total solar radiation intercepted,

I is the irradiance under the crop canopy &

I_0 is the irradiance above the crop canopy.

Accumulated solar radiation (RI_{cum}) was calculated as the sum of daily radiation interception (RI) for the duration of the crop for 'Pasja' and 73 days (half of the growing season; at full canopy) for kale. Differences in the amount of daily RI are a function of LAI and extinction coefficient (k). Solar radiation penetration (into crop canopy) can be related to LAI as (Brown, 1984):

$$\log_e (I/I_0) = -k (LAI) \text{ ----- Equation 3.12}$$

Where k is the extinction coefficient.

The extinction coefficient (k) of the canopy was therefore calculated from Equation 3.13:

$$-k = -\log(I/I_0)/LAI \text{ -----Equation 3.13}$$

The value of k is determined from the regression of natural logarithm (\log_e) of radiation transmissivity ($1.0 - i$) against green area index (GAI) for each crop. All regressions are forced through the origin.

3.2.4 Data analysis

Intercepted PAR, leaf appearance rate, leaf area and all dry matter yield values were analysed by analysis of variance (ANOVA). Data for the individual crops were analysed by two-way ANOVA (in Randomised Blocks) for individual harvests, while analysis over time was done by ANOVA (Repeated measurements) to compare treatment factors, species, method and rate of phosphorus application. Repeated measures were used, as it was assumed there would be no correlation between successive harvests. Significant interactions and main effects were separated by least significant difference (LSD) tests at the 5% level. Where values show $P < 0.1$ a trend is indicated in the text.

Harvested area for the seedling DM was small (0.045 m^2) and this resulted in a high coefficient of variation (CV) for both 'Pasja' (48.2% for the root & 46.3% for the shoot) and kale (41.4% for the shoot & 41.2% for the root). High CVs mask the expression of treatment effect (Clewes & Scarisbrick, 2001) as they indicate inadequate replications. A decision was made to log transform all the data to conform to the basic assumptions of ANOVA, hence reducing the CVs (Appendix 4.3).

All analyses were performed using Genstat version 10 statistical package.

3.2.5 Meteorological conditions

The total rainfall and Penman potential evaporation (mm) were 296 mm and 599 mm respectively, giving a total deficit of 303 mm. A total of 185 mm of water was added as irrigation (75 mm in January and 80 mm in March) throughout the growing period. The summary of meteorological data taken from Broadfield weather station is shown in Figure 3.1. January, March and April were drier than the long term average, and February received more than double the long term average rainfall (Figure 3.1a).

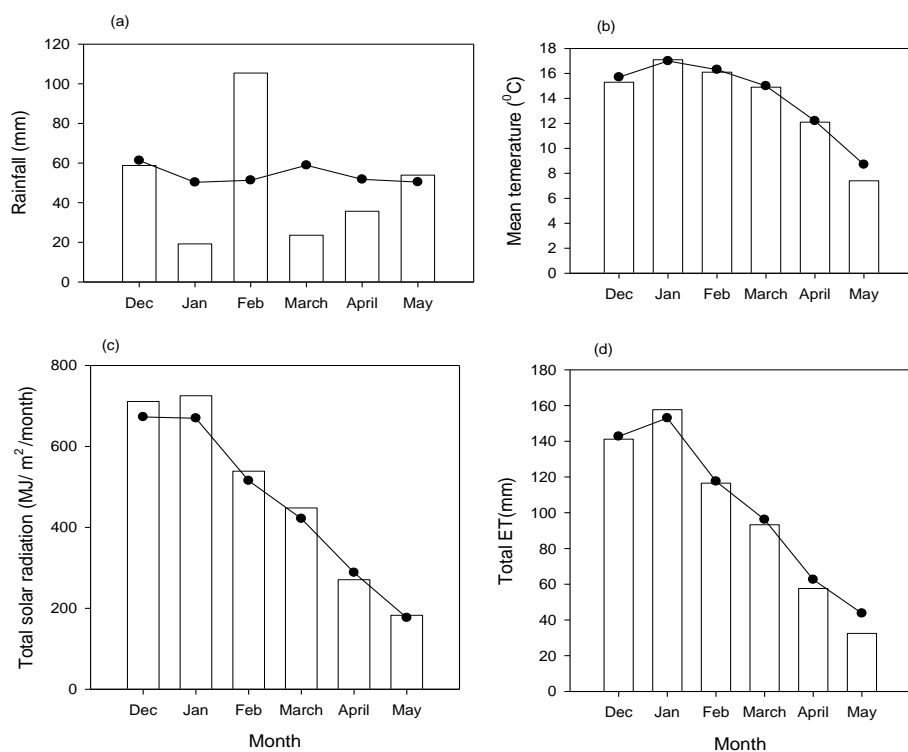


Figure 3.1: Meteorological data from 1 December 2007 to 31 May 2008; long term average (●) and experimental period (monthly) totals (□).

Over the crop growth period there were 20 ground frosts. The highest daily temperature recorded was 32.7°C on the 12th of January and the lowest daily temperature was -3.4 °C recorded on the 6th of May. The highest daily rainfall (62.4 mm) was recorded on 15 February.

Chapter 4: Yield, leaf and stem partitioning in Pasja and Kale

4.1 Introduction

This chapter focuses on the agronomic response of ‘Pasja’ and kale to the different methods of application and rates of fertiliser P (Section 3.1). The value of ‘Pasja’ and kale as forage crops is predominantly related to the amount of leaf produced and therefore the proportion of leaf to stem components was also determined (Sections 4.3.3 & 4.4.2.3). Dry matter for ‘Pasja’ reported in this thesis is for one cut, whereas there are 3-4 cuts (grazing) in practice.

Appendix 3.1 shows a wide variation in the Olsen P levels among the plots. However an analysis with the Olsen P as a covariate did not show a significant effect. Based on this result, analyses use the rate of P applied as the independent variable.

There was no significant interaction between method of application and rate of P fertiliser unless stated, but interaction tables are presented for all variables for clarity.

4.1.1 Plant establishment

Measurements of emergence of both species showed an adequate population in all treatments, regardless of P application method. Both ‘Pasja’ and kale seedlings started emerging five days or 87°Cd ($T_b=0^{\circ}\text{C}$) after sowing and reached 50% emergence 19 days or 300°Cd after sowing. The average number of plants per m^2 for ‘Pasja’ was 60 and 43 for kale. These were similar to the target recommended plant population of 45 plants per m^2 for turnips (Moot *et al.* 2007) and 40-100 plants per m^2 for kale (Wilson *et al.* 2004).

4.2 Final ‘Pasja’ dry matter (DM) yield

At the final harvest, yield was not affected ($P=0.800$) by P application method but increased ($P<0.001$) with P rate from 3730 kg DM/ha for the control to ~4900 kg DM/ha at 60 kg P/ha (Table 4.1). A breakdown of total DM showed that leaf to stem ratio was 10-11 regardless of method of P application. There was an indication of an interaction between method of application and rate of P ($P=0.086$) with the ratio increasing with P level for the banded treatments but decreasing with the broadcast. Specifically, the stem DM tended to increase ($P=0.072$) in broadcast versus banded treatments. The actual stem and leaf yields are presented in Appendix 4.1

Table 4.1: Final dry matter yield (kg/ha) and leaf to stem ratio on the 20th of March for ‘Pasja’ sown with different methods of application and rates of phosphorus, at Lincoln in 2008.

Phosphorus	Yield (kg /ha)			
	Leaf: Stem ratio		Total	
Method (M)	Ba ¹	Br	Ba	Br
	11.0	10.1	4370	4420
Significance	P=0.174		P=0.800	
Rate (R) (kg P/ ha)				
0	10.6 _a ²	10.6 _a	3730 _b	3730 _b
20	10.6 _a	10.4 _a	4390 _b	4440 _{ab}
40	11.3 _a	10.0 _a	4320 _a	4610 _a
60	11.3 _a	9.78 _a	5080 _a	4870 _a
LSD _(p<0.05)	2.1		766	
Significance ³	P=0.834		***	
Interaction M* R	P=0.086		P=0.124	
CV (%)	13.5		9.4	

¹ Ba = Banding & Br = Broadcast ²

² Means with the same letters as subscripts within columns are not significantly different at $\alpha=0.05$.

³ Levels of significance are *** (P<0.001), ** (P<0.01), *(P<0.05)

4.3 Seasonal DM accumulation

The pattern of seasonal DM accumulation for ‘Pasja’ is shown in Figure 4.1. This was examined by fitting logistic curves (Section 3.2.2.2) set to pass through the origin based on the assumption that when the number of days after emergence (DAE) was zero, then DM produced must also be zero.

There was no response to the method of phosphorus application, but the pattern of DM accumulation differed (P<0.01) with rate of P, between the control and those that received P fertiliser. Dry matter accumulation in the lag phase is included based on the seedling data (Sections 3.2.2.1 & 3.2.4) added to the quadrat harvests which were used subsequently.

4.3.1 'Pasja' Seedling DM accumulation

Analyses of the individual seedlings showed neither the root nor shoot DM was affected by the method of application but both doubled ($P<0.01$) as the rate of P application increased from 0 to 60 kg P/ha (Table 4.2). For example at 10 DAE the total DM for the control was 75 g/m² which increased to 150 g/m² at 60 kg P/ha. On both sampling dates the shoot and root weights increased ($P<0.05$) in similar proportions between the control and 60 kg P/ha treatments. The shoot to root ratio ranged from 1.20 to 1.40 at 3 DAE and was lower ($P<0.05$) at about 1.07 at 10 DAE. The shoot to root ratio tended to decrease ($P=0.069$) with time, for example from 1.40 to 1.08 for the control and 1.20 to 1.05 for the 60 kg P/ha treatments. The total DM of the seedlings more than quadrupled ($P<0.001$) between the two sampling dates.

Table 4.2: Shoot to root ratio and total dry matter (DM) accumulation for ‘Pasja’, 3 & 10 days after emergence (DAE), sown with different methods of application and rates of phosphorus, at Lincoln in 2008.

Phosphorus	Shoot & Root DM (g/m ²)			
	3 DAE		10 DAE	
Yield Component	Shoot ¹ : Root	Total	Shoot ¹ : Root ¹	Total
Method (M)				
Banding	1.22	20.6	1.30	120
Broadcast	1.22	23.4	1.20	119
Significance	P=1.00	P=0.915	P=0.927	P=0.947
Rate (R) (kg P/ha)				
0	1.40 _a ¹	18.0 _b	1.08 _a	75.0 _b
20	1.20 _a	18.0 _b	1.08 _a	116 _a
40	1.23 _a	22.0 _b	1.07 _a	137 _a
60	1.20 _a	36.0 _a	1.05 _a	150 _a
LSD	0.37	6.6	0.14	40.0
Significance ²	P=0.244	**	P=0.834	**
Interactions				
M*R	P=0.283	P=0.174	P=0.217	P=0.105
Rate * Time (total DM)				**
Rate * Time (S:R ratio)				P=0.069
M*R*Time (total DM)				P=0.114
CV (%)	19.1	20.5	7.8	11.7

¹Means with the same letters as subscripts within columns are not significantly different at $\alpha=0.05$.

²Levels of significance are *** (P<0.001), ** (P<0.01), *(P<0.05)

4.3.2 'Pasja' crop DM accumulation

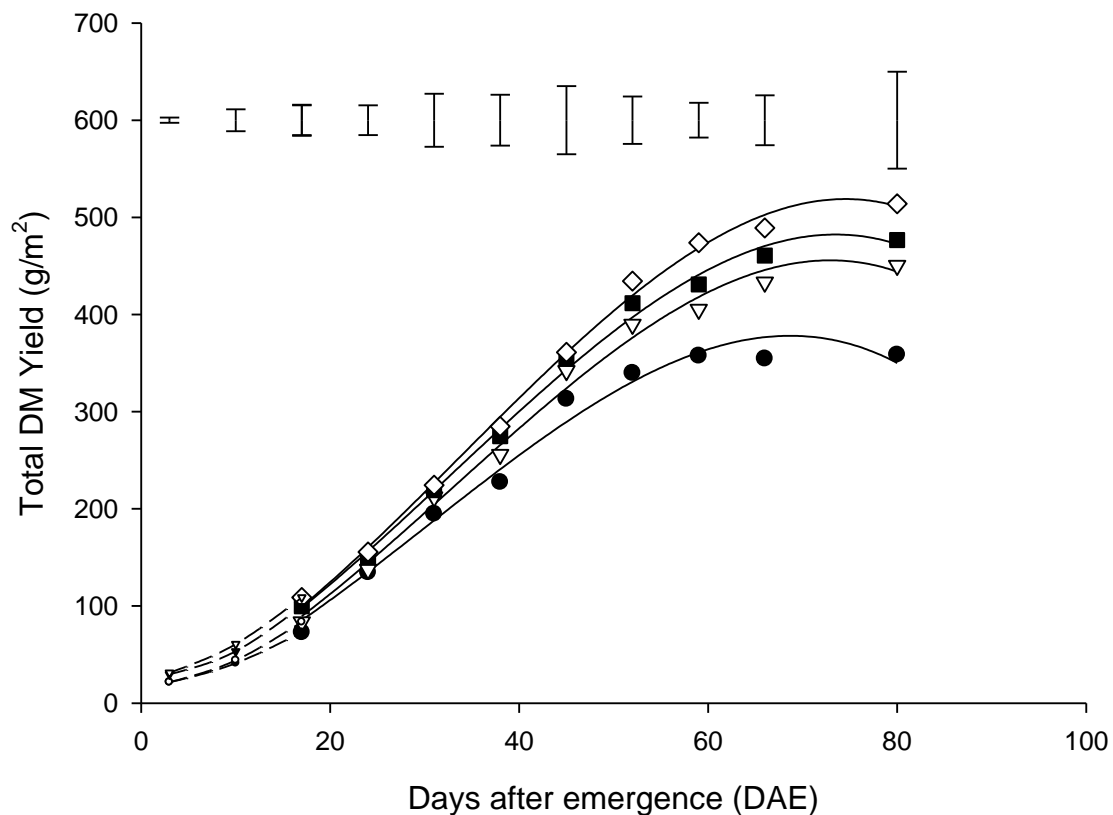


Figure 4.1: Pasja dry matter (DM) accumulation over 73 days after emergence at 0 kg P/ha (●); 20 kg P/ha (▽); 40 kg P/ha (■) or 60 kg P/ha (◇). Bars represent the least significant difference ($LSD_{p<0.05}$). (See Table 4.3 for variables derived from the fitted logistic curves). Solid lines represent quadrat (0.5 m²) sampling and dashed lines represent seedling sampling (Sections 3.2.2.1 & 3.2.4). 'Pasja' crop was sown on 17/12/2007 and had attained 50% seedling emergence by 5/01/2008.

Figure 4.1 (dashed lines) shows the shoot DM accumulation of 'Pasja' seedlings over 10 days after emergence based on seedling data was consistent with that from quadrat harvests. Yields were not significantly different among fertiliser rates until 44 DAE after which the impact of different P rates was more apparent. Differences ($P<0.05$) between the control and other treatments were detected for the last four sampling dates but there was no difference in crop DM accumulation among the three higher rates.

Table 4.3: Weighted mean absolute growth rate (WMAGR), maximum crop growth rate (C_{\max}), time to reach 50% of total dry matter (M) and duration of exponential growth phase (DUR) for 'Pasja' sown with different methods of application and rates of phosphorus, at Lincoln in 2008.

Phosphorus	M (days)	DUR (days)	WMAGR (g/m ² per day)	C_{\max} (g/m ² per day)
Method				
Banding	35	44	11.5	17.9
Broadcast	35	48	10.2	15.0
LSD _(p<0.05)	6	10	1.26	1.86
Significance	P=1.00	P=0.438	P=0.05	P=0.05
Rate (kg P/ha)				
0	32 _a ¹	43 _a	8.97 _b	13.20 _b
20	36 _a	48 _a	9.99 _b	14.69 _b
40	34 _a	44 _a	11.8 _a	17.40 _a
60	39 _a	49 _a	12.4 _a	18.40 _a
LSD _(p<0.05)	8	14	1.79	2.63
Significance ²	P=289	P=0.762	**	**
Method * Rate Interaction	P=0.976	P=0.589	P=0.282	P=0.273
CV(%)	18.4	24.3	13.3	16

¹Means with the same letters as subscripts within columns are not significantly different at $\alpha=0.05$.

² Levels of significance are *** (P<0.001), ** (P<0.01), *(P<0.05)

Table 4.3 shows that the time to attain 50% of the total DM (M) and duration of the exponential phase (DUR) did not respond to the method of application or rate of P. However, the weighted mean absolute growth rate (WMAGR) and maximum crop growth rate (C_{\max}) both responded (P<0.05) to the method of application and rate of P but there was no interaction. The WMAGR increased (P<0.05) by 12% when P was banded compared with broadcast and was 32% more (P<0.05) at 40 kg P/ha compared

with the control. Maximum growth rate (C_{\max}) also increased ($P<0.053$) 13% for banding over broadcast and 33% from the control to the 40 kg P/ha crops. The response of both WMAGR and C_{\max} to method of application is not reflected in the final yield (Table 4.1).

4.3.3 'Pasja' leaf and stem partitioning

Leaf DM increased ($P<0.001$) rapidly with time (Figure 4.2), up to 52 DAE then plateaued while the stem yield remained less than 50 g/m² throughout the season. Leaf DM did not respond to the rate of P application early in the season and the control was lower ($P<0.001$) than those receiving P fertiliser at all sampling dates, after 52 days. The impact of these differences on the actual leaf to stem ratio by the end of the season is shown in Table 4.1.

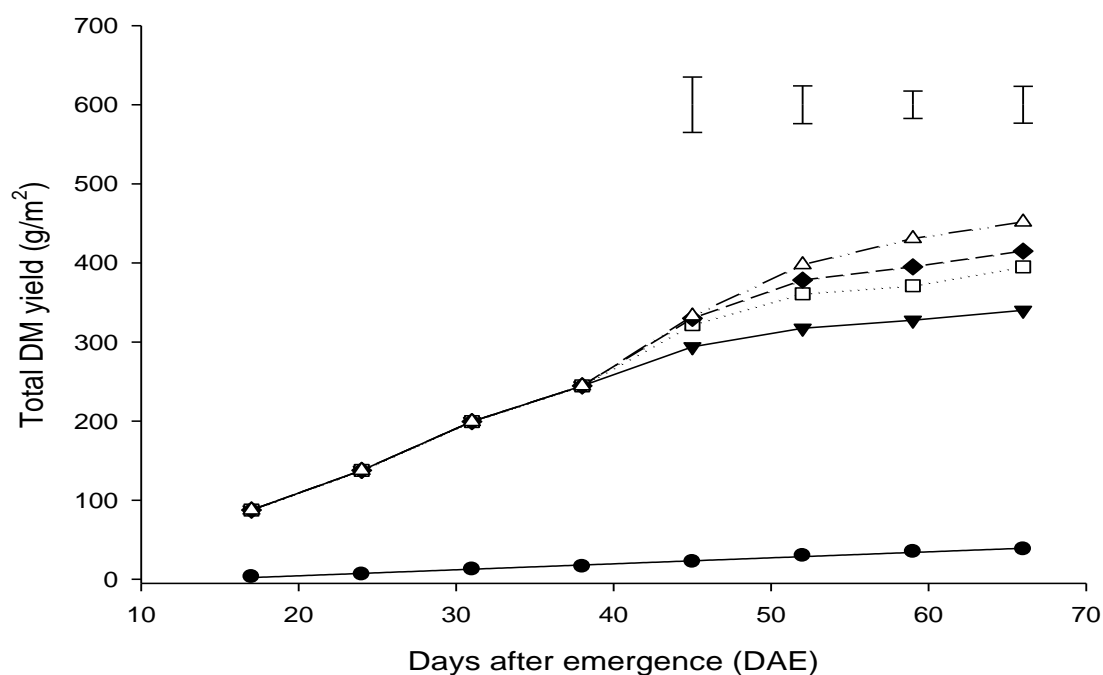


Figure 4.2 'Pasja' leaf and stem (●) dry matter (DM) accumulation over the season. Leaf DM at different rates of P (0 kg P/ha (▼); 20 kg P/ha (□); 40 kg P/ha (◆) or 60 kg P/ha (△)

Both the final leaf and stem DM responded ($P<0.01$) to the rate of P application irrespective of method of application (Appendix 4.1). However there was no response

to method of application. Pasja DM is essentially made up of the leaf which makes up more than 90% (Figure 4.2 & Appendix 4.2) of total DM.

4.4 Thermal time and DM

Dry matter accumulation for 'Pasja' (Figure 4.1) shows that the control treatments were lower ($P<0.05$) than fertiliser treatments and there were no differences among the fertiliser treatments. The analyses of thermal time (T_t) effect on DM accumulation were therefore based on the control and mean fertiliser P treatments. Thermal time was calculated on a 0°C base (See Section 5.7.2).

4.4.1 'Pasja' DM accumulation

Figure 4.3 shows that there was a strong relationship ($R^2=0.96$ & 0.90) between total DM and T_t for the fertiliser and control treatments respectively. The slope of the regression lines represent DM produced/ hectare per $^{\circ}\text{Cd}$. The control treatments accumulated 340 kg DM/ha and the P treatments accumulated 420 kg DM/ha for every 100 $^{\circ}\text{Cd}$.

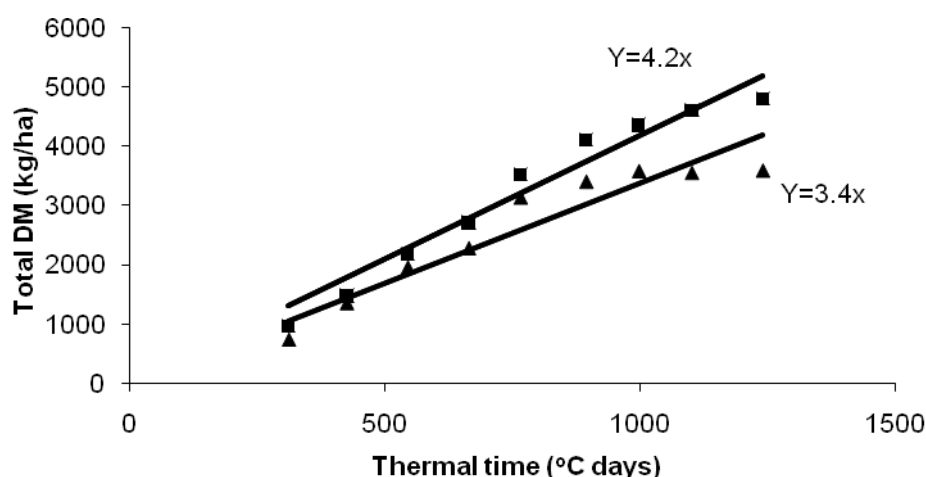


Figure 4.3: 'Pasja' DM accumulation as influenced by thermal time ($T_b=0^{\circ}\text{C}$), at 0 kg P/ha (▲) and mean P fertiliser (■) at Lincoln in 2008.

Figure 4.3 also shows that most of the DM was accumulated within 1000 $^{\circ}\text{Cd}$ although the final harvest (whole season) was after 1240 $^{\circ}\text{Cd}$.

4.5 Kale DM accumulation

4.5.1 Final DM yield

At the final harvest, DM yield was not affected ($P=0.229$) by the method of P application although there was an indication of an interaction ($P=0.067$). Specifically all P rates increased yield to ~11400 kg DM/ha from banded treatments but at 20 kg P/ha the yield from broadcast plots was only 9980 kg DM/ha (Table 4.4). The leaf to stem ratio was stable at about 0.63 regardless of application method or P fertiliser level. The final leaf DM ($P=0.086$) ranged from 3610 kg DM/ha for the control to ~4400 kg DM/ha for the 60 kg P/ha treatments (Appendix 4.1). The stem DM ranged from 5100 kg DM/ha for the control to ~7200 kg DM/ha for the 60 kg P/ha.

Table 4.4: Total DM and leaf: stem ratio on 6th May (final harvest) for kale sown with different methods of application and rates of phosphorus, at Lincoln in 2008.

Phosphorus	Yield (kg DM/ha)			
	Leaf: Stem ratio		Total	
Method (M)	Ba ¹	Br	Ba	Br
	0.63	0.64	10830	10260
Significance	P=0.244		P=0.229	
Rate (R) (kg P/ ha)				
0	0.71 _a ²	0.71 _a	8710 _b	8710 _b
20	0.64 _a	0.63 _a	11160 _a	9980 _b
40	0.66 _a	0.61 _a	11380 _a	11390 _a
60	0.67 _a	0.65 _a	11660 _a	11420 _a
LSD _(p<0.05)	0.17		1260	
Significance ³	P=0.441		***	
Interaction M* R	P=0.766		P=0.067	
CV (%)	14.3		8.9	

¹ Ba = Banding & Br = Broadcast

² Means with the same letters as subscripts within columns are not significantly different at $\alpha=0.05$.

³ Levels of significance are *** ($P<0.001$), ** ($P<0.01$), * ($P<0.05$)

4.5.2 Seasonal DM accumulation

The pattern of seasonal DM accumulation for kale is shown in Figures 4.3. This was examined by fitting logistic curves (Section 3.2.2.2) set to pass through the origin based on the assumption that when the number of days after emergence (DAE) was zero, then DM produced must also be zero.

4.5.2.1 Kale seedlings DM accumulation

Analyses of the individual seedlings showed that both the root and shoot DM were affected ($P < 0.05$) by the rate of P application (Appendix 4.3) but did not respond to the method of application. Shoot DM responded ($P < 0.05$) to the rate of application at both 10 and 17 days after emergence (DAE) and also tended to increase ($P = 0.088$) with rate of P over time.

Table 4.5 shows that total DM responded ($P < 0.05$) linearly to the rate of P at 10 DAE with an increase from 7.7 to 22 g/m². At 17 DAE, there was still a response, but this plateaued off at 40 kg P/ha.

Table 4.5: Shoot and root dry matter accumulation for kale, 10 & 17 days after emergence (DAE), when sown by different methods of application and rates of phosphorus, at Lincoln in 2008.

Yield Component	Shoot & Root DM (g/m ²)			
	10 DAE		17 DAE	
	Shoot: Root	Total	Shoot: Root	Total
Method (M)				
Banding	2.60	13.2	3.25	49.0
Broadcast	2.80	14.5	3.37	54.0
Rate (R) (kg P /ha)				
0	3.50 _a ¹	7.70 _d	2.60 _a	29.0 _c
20	2.60 _b	12.0 _c	2.30 _b	38.0 _b
40	2.50 _b	17.0 _b	2.00 _b	71.0 _a
60	2.30 _b	22.0 _a	2.20 _b	69.0 _a
LSD	0.70	4.00	0.30	7.6
Significance ²	**	**	**	**
Interactions				
M*R	P=0.343	P=0.221	P=0.307	P=0.561
Rate * Time (total DM)				P=0.075
Rate * Time (S:R)				P=0.142
M*R*Time (total DM)				P=0.211
CV	20.9	11.6	16.2	12.5

¹Means with the same letters as subscripts within columns are not significantly different at $\alpha=0.05$.

² Levels of significance are *** (P<0.001), ** (P<0.01), *(P<0.05)

Table 4.5 also shows that total seedling DM more than doubled (P<0.05) as the rate of P application increased from 0 to 40 kg P/ha at 17 DAE and more than trebled (P=0.075) between the two sampling dates. For example at 10 DAE, the total DM increased from 7.7 g/m² for the control to 29 g/m² 17 DAE. The shoot to root ratio declined (P<0.05) with increasing rate of P application. For example, the shoot to root

ratio was 3.50 for the control decreasing to 2.30 for the 60 kg P/ha at 10 DAE and decreased from 2.60 for the control to ~2.20 for P fertilised plots at 17 DAE respectively.

4.5.2.2 Kale crop DM accumulation

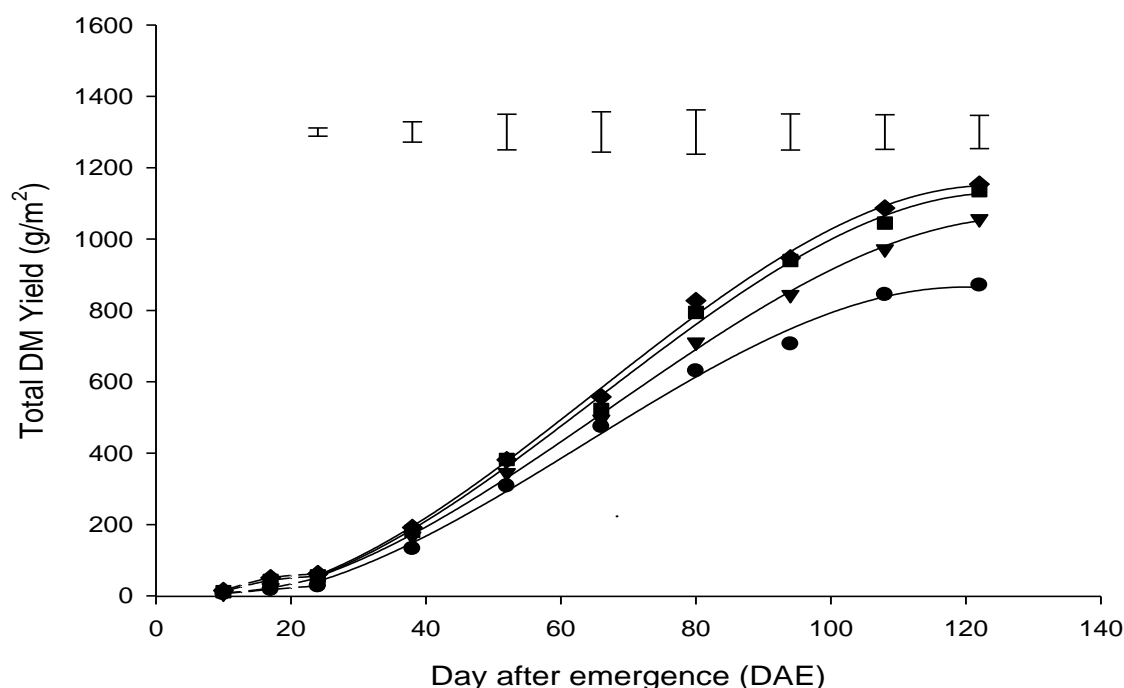


Figure 4.4: Kale dry matter (DM) accumulation over 122 days after emergence at 0 kg P/ha (●); 20 kg P/ha (▼); 40 kg P/ha (■) or 60 kg P/ha (◆). Bars represent the least significant difference ($LSD_{p<0.05}$). (See Table 4.7 for variables derived from the fitted logistic curves). Solid lines represent quadrat (0.5 m^2) sampling and dashed lines represent seedling sampling (Section 3.2.2.1 & 3.2.4). Kale crop was sown on 17/12/2007 and had attained 50% seedling emergence by 5/01/2008.

Figure 4.4 (dashed lines) shows the shoot DM accumulation of kale seedlings over 17 days after emergence based on seedling data was consistent with that from quadrat harvests. Figure 4.4 also shows that DM accumulation increased ($P<0.05$) by 167 g/m^2 during the first 38 days and then more than doubled in the next 14 days to 349 g/m^2 . This exponential increase continued up to 94 DAE. Dry matter yields were not different among the fertiliser rates until 66 DAE. A response to different P rates was more apparent as the season progressed, with differences ($P<0.05$) among the

control and other treatments detected on the last four sampling dates (Figure 4.4). The control was also lower ($P<0.05$) than any of the higher rates of P in final total DM (Table 4.4) and took less ($P<0.05$) time to accumulate 50% of the total DM (Table 4.6). The linear growth phase, which accounted for 55% of the duration from emergence to final harvest, was the period when the major proportion of DM accumulation (84–97%) took place (Table 4.6; Figure 4.3)

Table 4.6: Weighted mean absolute growth rate (WMAGR), maximum crop growth rate (C_{\max}), time to reach 50% of TDM (M) and duration of exponential growth phase (DUR) for kale sown with different methods of application and rates of phosphorus, at Lincoln in 2008.

Phosphorus	M (days)	DUR (days)	WMAGR (g/m ² per day)	C_{\max} (g/m ² per day)
Method				
banding	62	65	15.0	22.0
broadcast	66	69	14.0	20.6
LSD _(p<0.05)	5	10	2.06	3.03
Significance	P=0.142	P=0.439	P=0.372	P=0.370
Rate (kg P/ha)				
0	58 _b	58 _a	12.7 _c ¹	18.7 _c
20	66 _a	71 _a	13.3 _{bc}	19.6 _{ab}
40	68 _a	71 _a	15.6 _b	23.1 _{ab}
60	66 _a	68 _a	16.2 _a	23.9 _a
LSD _(p<0.05)	8	20	2.89	4.28
Significance ²	**	P=0.194	**	**
Method * Rate Interaction	P=0.784	P=0.860	P=0.921	P=0.941
CV (%)	8	17	16	16

¹Means with the same letters as subscripts within columns are not significantly different at $\alpha=0.05$.

²Levels of significance are *** ($P<0.001$), ** ($P<0.01$), * ($P<0.05$)

Table 4.6 shows that the duration of the exponential growth period when most of the growth occurred (DUR), did not respond to either the method of application or rate of

P. None of the measured variable responded to the method of P application. However, the WMAGR, M and C_{\max} responded ($P<0.05$) to the rate of P application. The WMAGR and C_{\max} were ~28% more ($P<0.05$) at 60 kg P/ha compared with the control. The control treatments took the least number of days to reach 50% of total DM.

4.5.2.3 Kale leaf and stem partitioning

There was a higher ($P<0.01$) proportion of leaf component early in the season (Table 4.7) compared with the stem and a higher stem DM proportion at the end of the season (Table 4.4).

Table 4.7: Total DM and leaf to stem ratio on 29th January (first harvest) for kale sown with different methods of application and rates of phosphorus, at Lincoln in 2008.

Phosphorus	Yield (kg/ha)			
	Leaf: stem ratio		Total	
Method (M)	Ba ¹	Br	Ba	Br
	2.64	2.77	545	439
Significance	P=0.132		P=0.451	
Rate (R) (kg P/ha)				
0	2.86 _a ²	2.86 _a	300 _b	300 _a
20	2.66 _a	2.82 _a	570 _{ab}	440 _a
40	2.68 _a	2.63 _a	560 _{ab}	520 _a
60	2.47 _a	2.76 _a	830 _a	420 _a
LSD _(p<0.05)	0.41		280	
Significance ³	P=0.105		**	
M * R Interaction	P=0.238		**	
CV (%)	31		32	

¹ Ba = Banding & Br = Broadcast

² Means with the same letters as subscripts within columns are not significantly different at $\alpha=0.05$.

³ Levels of significance are *** ($P<0.001$), ** ($P<0.01$), * ($P<0.05$)

The leaf to stem ratio did not respond to either the method of application or rate of P and was on average 2.7 at the first harvest on the 29th of January (Table 4.7) and 0.64 at the final harvest (Tables 4.4). There was a method of application and rate of P interaction for the leaf and total DM early in the season (Appendix 4.2). This was due to the seedling DM increasing ($P<0.05$) with rate of P when banded and not responding to the rate of P, when broadcast.

The method of P application and rate of P tended to interact ($P=0.09$) for the stem DM at the first harvest (Appendix 4.2). This was because of the irregular increases of DM as the rates of P increased, highlighted by a 63% increase from 40 kg to 60 kg P/ha when P was banded compared to a 21% decrease in DM when P was broadcast at the same rates. Stem DM tended to be a higher proportion ($P=0.091$) when P was banded than broadcast but leaf DM did not respond to the method of application. Both the stem and leaf DM responded ($P<0.01$) to the rate of P application when P was banded and did not differ when P was broadcast early in the season.

At the initial harvest the leaf component accounted for 73% of total DM under the control but by the final harvest leaf component was only 41%.

4.6 Thermal time and DM

Dry matter accumulation for kale (Figure 4.4) also showed that the control treatments were lower ($P<0.05$) than fertiliser treatments. Therefore, as for 'Pasja', the analyses of Tt effect on DM accumulation will be based on the control and pooled mean fertiliser P treatment.

4.6.1 Kale DM accumulation

There was a strong linear relationship ($R^2=0.99$) between DM accumulation and thermal time (Tt) for the control and fertilised treatments (Figure 4.5). Dry matter accumulation for kale was 640 kg DM/ha for the control and 800 kg DM /ha for every 100°Cd for the mean of all P fertiliser treatment at $T_b=0^\circ\text{C}$ (See Section 5.7.2).

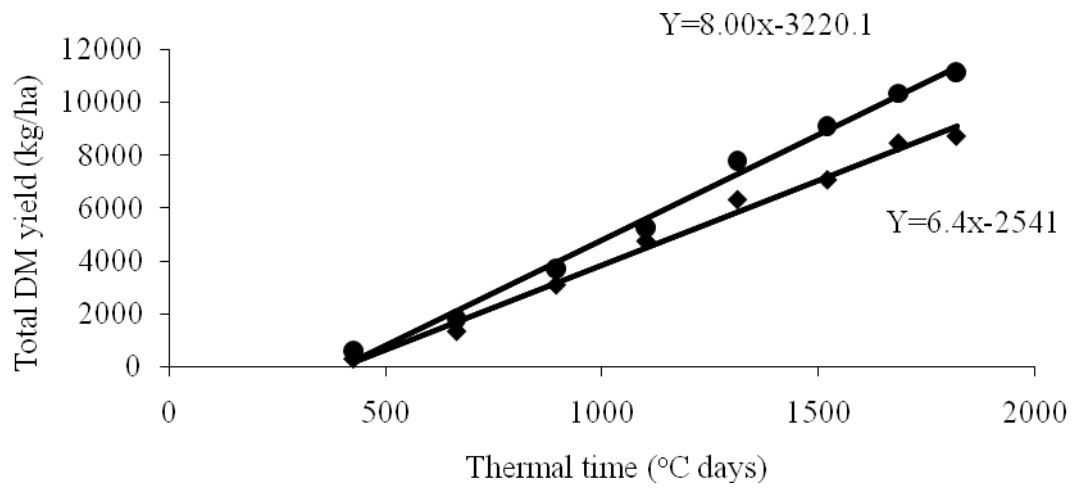


Figure 4.5: Kale DM accumulation as influenced by thermal time ($T_b=0^{\circ}\text{C}$) at 0 kg P/ha (◆) and pooled mean P fertiliser (●), at Lincoln in 2008.

4.7 Discussion of DM results

The main difference in the final DM yield between ‘Pasja’ and kale was a result of time to the final harvest (Figure 4.1 & 4.4), with ‘Pasja’ taking 73 days and kale, 122 days to maturity. This means kale intercepted more radiation and produced more DM per unit area. This will be discussed in detail in Chapter 5.

4.7.1 Method of P application

The method of P application did not affect the seasonal or final DM accumulation for either ‘Pasja’ (Figure 4.1, Tables 4.1) or kale (Figure 4.4, Tables 4.4). However, there was an indication of method of application and rate of P interaction ($P=0.086$) on ‘Pasja’ stem development (Appendix 4.1). These results are in contrast to most reports in literature (Section 2.2.4), which suggest that banding of P fertilisers increases crop DM yield. This could be a result of the difference in initial Olsen P levels for the experimental sites. For example, results by Wilson *et al.* (2006) for ‘Pasja’ were from a site with an initial mean soil P level of 6 mg/L compared with an average of 13.3 mg/L in this experiment. The results could also have been affected by soil P retention (Section 2.2.2; Chapter 6). The lack of a significant result means the method of P application will not be discussed further in this section.

4.7.2 Effects of the rate of P application on ‘Pasja’ and kale DM accumulation

The experiment demonstrated the dependence of DM yield on rate of P application. For both ‘Pasja’ and kale the control treatments were lower ($P<0.05$) than those receiving P fertiliser (Tables 4.1 & 4.4). The shoot to root ratio for ‘Pasja’ seedlings did not respond to fertiliser P (Table 4.2) but decreased ($P<0.05$) for kale seedlings, as the rate of P increased (Tables 4.5). The differences in kale shoot to root ratio suggests that P availability encouraged root development early in the season. This supports findings by Davies (1970) and reports by Claridge (1972) that P is important in brassica establishment.

4.7.2.1 ‘Pasja’ DM accumulation

The DM yield of the control crops of ‘Pasja’ were lower ($P<0.05$) than those receiving P fertiliser but there were no differences among the fertiliser rates (Figure 4.1) when P was broadcast. Higher ($P<0.05$) DM yield for P fertiliser treatments supports conclusions by Grant *et al.* (2000) who stated that P was important during

early crop growth. Any deficit can restrict seedlings at early crop growth, which can carry through to reduce final crop yields. The final leaf to stem ratio was stable at 10-11 regardless of method of application or rate P application (Table 4.1). Early P response may also assist in weed control by competition.

The differences in total seasonal DM yield of P fertilised crops (Figure 4.1) were attributed to higher ($P<0.05$) weighted mean absolute growth rates for the fertiliser treatments during the exponential growth phase (Table 4.3). This is because there was no difference in the duration of the growth phase. This response to P fertiliser may be a result of more P availability to the crop as the rate of application was increased. The WMAGR and C_{\max} responded ($P<0.05$) to the method of P application (Table 4.3), but this did not translate into differences in their final yield. 'Pasja' DM yield accumulation was similar to reports by Jung *et al.* (1984) that turnips responded to P fertiliser up to 60 DAE.

The higher growth rates were evident early in the season as both seedling shoots and roots responded to the rate of P application (Appendix 3.3). Phosphorus application increased the size of seedlings shortly after emergence (Table 4.2). Over time the plant went from shoot growth priority to root growth. This probably improved the ability of the plant to take up water and nutrients and as a result establish full canopies earlier in the season (Chapter 5).

The final DM yield (Table 4.1) was less than that reported by Wilson *et al.* (2006) of 609-1300 g/m² at Lincoln. The difference could be a result of pest damage ~6 weeks after emergence (Section 3.1.2). At the final harvest maximum yield was obtained at 40 kg P/ha for both methods of application. This was unexpected, as Grant *et al.* (2000) commented that P was easily accessible to roots when banded beneath the seed than distributed through out the soil when broadcast, as banding reduces the reaction zone. The high rates of P needed for maximum DM yield could be an indication of a feeble root system of 'Pasja', unable to access most of the P fertiliser.

The optimum P level (40 kg P/ha) is similar to 50 kg P/ha reported by Wilson *et al.* (2006) and Jung *et al.* (1984), although the actual rate depends on initial Olsen P levels and method of application. Surprisingly, this was not affected by the initial Olsen P level (Section 4.1) which suggests the application of fertiliser P at establishment was more important than the soil P level in the 9-17 range (Appendix 3.1) in this experiment. The high leaf to stem ratio (Table 4.1, Figure 4.2) is an indication that 'Pasja' DM was essentially made up of the leaf. The stem is

represented by a 'crown' usually at or below ground level, from where leaves are produced. This crown enables leaf regeneration after defoliation and remained less than 50 g/m² throughout the experiment. This was similar to the ~80 g/m² reported by Wilson *et al.* (2006). There is no other published literature on 'Pasja' leaf to stem ratio with P as the treatment.

Thermal time is a useful concept for summarising temperature accumulation which affects both growth and development or leaf appearance (Chapter 5). Leaf development (LAI) in turn influences light interception which is the main driver of growth (Collie & McKenzie, 1998). The DM yield of P fertilised 'Pasja' crops in relation to Tt (Figure 4.3) of 420 kg DM /ha /100°Cd (T_b=0°C) was less than the 1000 kg DM /ha /100°Cd (T_b=4°C) reported by Scott & Pollock (2004) for brassica crops. The differences could be due to different T_b used in these studies. With a mean temperature of 10°C, the 1000 °Cd reported by Scott & Pollock (2004) would take 100 days to accumulate and will be equivalent to 600 °Cd with a base temperature of 0°C. The DM for the control of 342 kg DM /ha /100°Cd was lower (P<0.05) than P fertiliser treatments and may be an indication of reduced growth due to P deficiency. There is no published literature on the effects of P on the relationship between DM accumulation and Tt for brassica crops.

4.7.2.2 Kale DM accumulation

Final kale DM yield was lower (P<0.05) for the control treatments than those that received P fertiliser (Figure 4.4) except for the 20 kg P/ha broadcast (Table 4.4). This suggests that at low P application rates, banding was more effective than broadcasting. Similar results for the control and 20 kg P/ha broadcast could be a result of the P spread evenly in the soil (increased reaction zone) being less accessible to the roots, especially at the seedling stage (Appendix 4.3) than banded fertiliser. The difference in DM yield was shown by the control treatments reaching 50% of total DM earlier (P<0.05) than those receiving P fertiliser and accumulating DM at the lowest (P<0.05) WMAGR and C_{max} (Table 4.6).

Final DM yield (Table 4.4) was comparable to the 1400-1900 g/m² for 'Gruner' kale reported by Wilson *et al.* (2006). Maximum total DM was achieved at 20 kg P/ha when P was banded and 40 kg P/ha when broadcast. This was less than the optimum recommendations by Wilson *et al.* (2006) and Jung *et al.* (1984) for maximum yield production. It is unlikely that this could be attributed to differences in

the initial Olsen P levels of ~13.3 mg P/kg soil in this experiment compared with 11.5 mg P/kg soil reported by Wilson *et al.* (2006). The final leaf DM did not respond to rate of P application (Appendix 4.1) while the maximum stem DM yield was at 40 kg P/ha (broadcast) and 60 kg P/ha (banding).

The difference between the application method could be a result of P being more easily accessible to roots when banded beneath the seed than distributed throughout the soil when broadcast (Barber, 1977). Effectively the band placement of P restricts the volume of soil in the reaction zone thus less soil P fixation occurs than when broadcast (Tisdale *et al.* 1985).

The shoot to root ratio decreased ($P < 0.05$) with increasing P levels (Table 4.5). Phosphorus application increased the size of seedlings shortly after emergence and over time they switched from shoot growth priority to root growth. This agrees with findings for barley (Brenchley, 1929) and pepper (Bar-Tal *et al.* 1990), where the shoot to root ratio decreased with increasing P rates. These results were from solution culture experiments hence should be treated with caution as they may not be replicated in the field. As the uptake of P is proportional to the root density (Barber, 1977) the enlarged root surface area increases the ability of the kale crop to access and absorb more P from the soil.

The leaf to stem ratio did not respond to method of application and rate of P throughout the season (Tables 4.4 & 4.7). This may be an indication of stable allometry, where as the plant grows in size, both the leaf and stem components increase at the same rate. There is no literature published on leaf to stem ratio in relation to rate of P application for kale crops.

The DM accumulation for P fertilised kale (Figure 4.5) of 800 kg DM /ha /100°Cd was similar to 1000 kg DM /ha /100°Cd reported by Scott & Pollock (2004) but less than the 1300 kg DM /ha /100°Cd reported by Adams (2004) for 'Gruner' kale. As for 'Pasja', the differences could be due to different T_b used to calculate T_t . The DM for the control crop was 640 kg DM /ha /100°Cd, which reflects the effects of P deficiency on total DM accumulation.

Conclusions

Based on the results in this Chapter, the following conclusions can be made:

- ‘Pasja’ total DM yield increased ($P < 0.05$) with the rate of P application and kale total DM increased up to 40 kg P/ha but neither crop responded to the method of P application. The final DM yield for ‘Pasja’ increased by 32% from the control (3730 kg DM/ha) to the 60 kg P/ha treatment (4900 kg /ha), while kale final DM yield increased by 29% to 11000 kg /ha when P was applied regardless of application method.
- The leaf to stem ratio for kale declined ($P < 0.05$) with time after emergence from 2.7 at the first harvest to 0.64 at the final harvest while ‘Pasja’ DM was essentially 90% leaf.
- During the exponential growth phase, ‘Pasja’ accumulated dry matter (DM) at 120 kg DM/ha per day at 40 kg P/ha compared with 90 kg DM/ha per day for the control. Kale accumulated 162 kg DM/ha per day at 60 kg P/ha compared to 127 kg DM/ha per day for the control. The duration of the exponential growth phase did not affect dry matter accumulation for both species.

This chapter identified P as critical for ‘Pasja’ and kale growth and development. To understand the mechanisms resulting in the crop yield differences Chapter 5 describes and analyses the crop physiological processes in relation to leaf development, radiation interception and radiation use efficiency.

Chapter 5: Leaf appearance, leaf area index (LAI), solar radiation interception (RI) and radiation use efficiency (RUE) in ‘Pasja’ and kale crops grown with different rates of phosphorus.

5.1 Introduction

Both ‘Pasja’ and kale crop’s seasonal and final DM yields responded ($P < 0.05$) to the rate of P fertiliser application (Chapter 4) but not the method of application. The growth of both species was characterised by a sigmoidal relationship. Canopy photosynthesis, dry matter production and final yields can all be affected by leaf (canopy) development (Warrington & Kanemasu, 1983). Thus, the differences in seasonal DM accumulation and final DM yield in this experiment may be attributed to the interception of more solar radiation or a difference in the radiation use efficiency (RUE). This chapter will investigate the mechanisms that resulted in the crop yield differences in Chapter 4. This is only possible through accurate quantification of the amount of solar radiation intercepted by each crop under different treatments.

Canopy development is determined by the number of leaves produced, leaf appearance rate, rate and duration of expansion of individual leaves (Warrington & Kanemasu, 1983). The number of leaves, leaf appearance rate and leaf area development (which was converted into an index) were measured in this project and will be analysed. The regression of number of leaves against days after emergence (DAE) and thermal time (T_t) was used to describe the leaf appearance rate, determine base temperature (T_b) and phyllochron. The number of leaves was regressed against T_t at a range of base temperatures (T_b range 0 to 10°C) to identify T_b with the best fit to the data (highest R^2).

Radiation interception (Figure 5.2 & 5.8) and accumulated radiation (RI_{cum}) (Tables 5.2 & 5.4) were calculated as described in Section 3.2.3.3. Daily RI_{cum} was interpolated as a linear increase in leaf area from emergence and between successive radiation interception measurements.

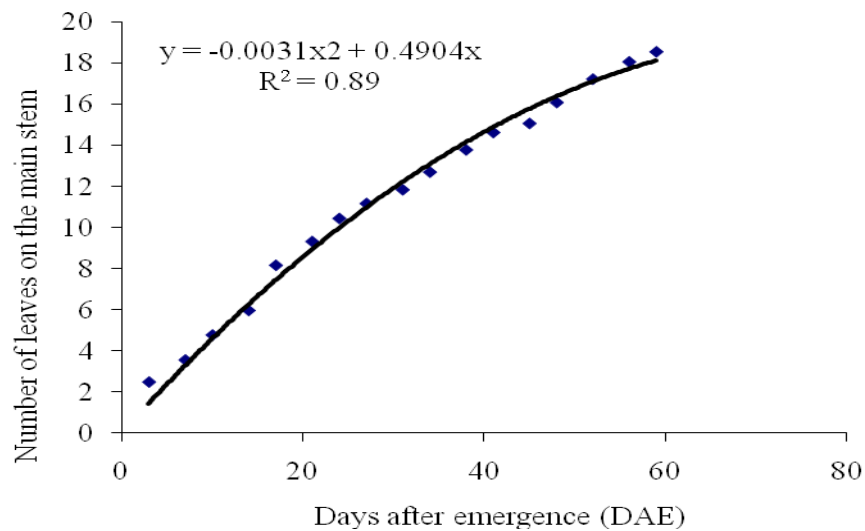
5.2 Leaf appearance rate

Leaf appearance rate did not respond to either the method ($P=0.898$) or rate of phosphorus ($P=0.677$) application, so only one line is fitted to the mean of all data. Fitted lines were forced through the origin based on the assumption that when DAE or T_t was zero, then the number of leaves produced was zero (Figures 5.1 & 5.6).

5.2.1 Analysis of 'Pasja' leaf appearance

The relationships between the number of leaves on the main stem and DAE or thermal time (T_t) was best explained by a polynomial (Figure 5.1a) and linear equation (Figure 5.1b) respectively. The slope of the regression lines was the leaf appearance rate. Figure 5.1a shows a leaf appearance rate of 0.4904 leaves per day (i.e. a phyllochron about 2.04 days/ leaf), with a systematic decrease in the rate shown over time.

(a)



(b)

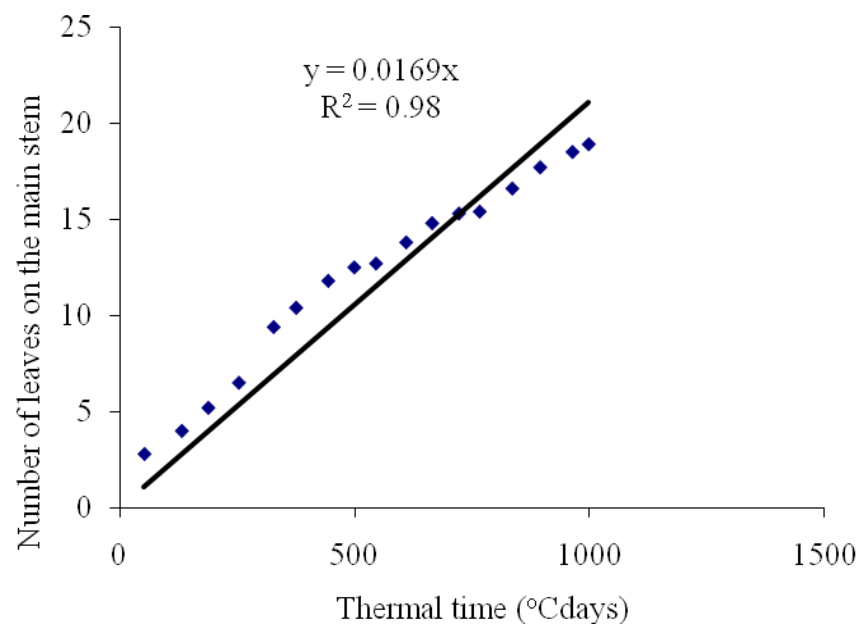


Figure 5.1: The number (n) of leaves on the main stem for 'Pasja' plotted against (a) time after emergence (DAE) and (b) thermal time (T_t) at Lincoln in 2008; at $T_b=0^\circ\text{C}$. Lines are fitted to the mean of all data from crops grown with different methods of application and rates of phosphorus.

Figure 5.1b also shows some systematic variation with 'Pasja' leaves produced at an average rate of 0.0169 leaves per $^\circ\text{C}$ day (i.e. phyllochron about 60 $^\circ\text{C}$ days).

5.3 Leaf area index (LAI) and radiation interception (RI)

Leaf area index was determined, as described in Section 3.2.3.2. The LAI for ‘Pasja’ was affected ($P<0.05$) by the rate of phosphorus application but did not respond to the method of application.

5.3.1 ‘Pasja’ leaf area index (LAI)

As expected LAI increased ($P<0.001$) over the growing season and varied ($P<0.001$) with the application of P. The increase in LAI was most rapid during the first 38 DAE and became more gradual thereafter for all the treatments (Figure 5.2).

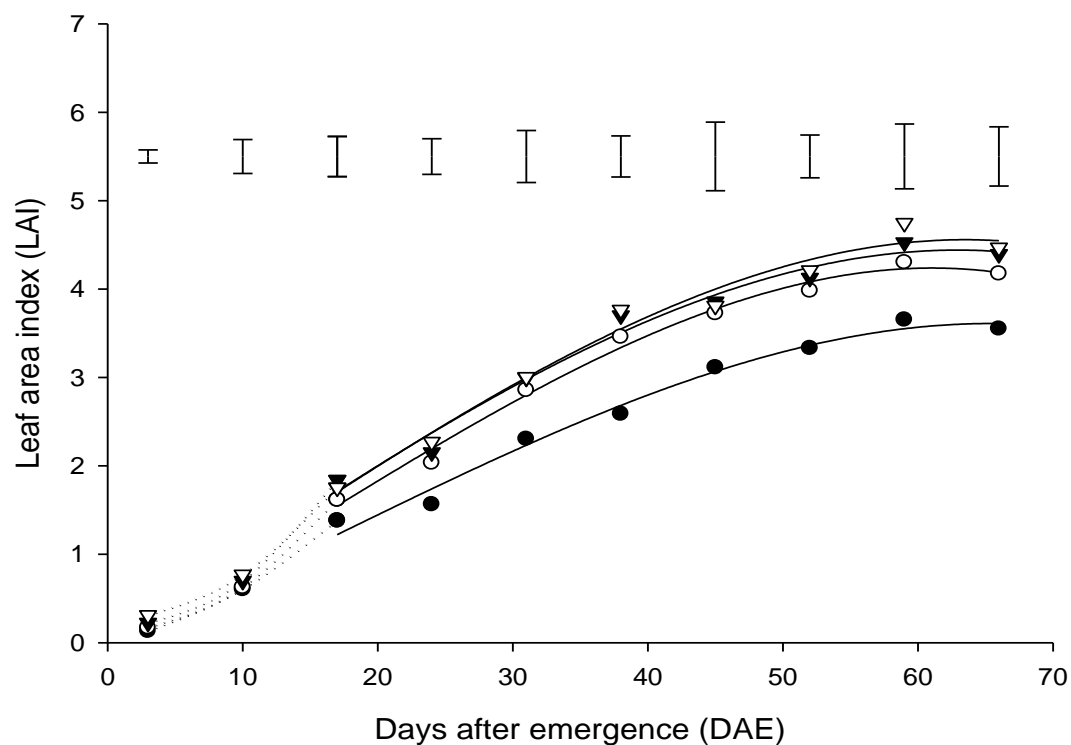


Figure 5.2: ‘Pasja’ leaf area index accumulation over 66 days, at 0 kg P/ha (●); 20 kg P/ha (○); 40 kg P/ha (▼) or 60 kg P/ha (▽). Bars are levels of significance ($LSD_{(p<0.05)}$) (See Table 5.1 for variables derived from the fitted logistic curves and Table 5.2 for the critical LAI (LAI_{crit}), percentage interception of radiation and accumulation of radiation). Solid lines represent quadrat (0.5 m^2) sampling and dotted lines represent seedling sampling (Section 3.2.2.1). ‘Pasja’ crop was sown on 17/12/2007 and had attained 50% seedling emergence by 5/01/2008.

Figure 5.2 (dotted lines) shows that LAI development for ‘Pasja’ seedlings over 10 days after emergence based on the seedling data was reasonably consistent with that from quadrat harvests. Leaf area index and hence canopy closure were affected ($P<0.001$) by the rate of P application but did not respond ($P=0.77$) to the method of P application. The maximum LAI for the control treatments was 3.6 at 59 DAE (Table 5.1, Figure 5.2). Leaf area index for the control was consistently lower ($P<0.001$) than the P fertiliser treatments throughout the season. There was no difference in the pattern of LAI accumulation among the crops sown with higher rates of P.

Table 5.1: Weighted mean absolute leaf area expansion rate (LAER), maximum leaf area index (max LAI), maximum leaf area expansion rate (C_{\max}), time to reach 50% of max LAI (M) and duration of exponential leaf area expansion phase (DUR) for ‘Pasja’ sown with different methods of application and rates of phosphorus, at Lincoln in 2008.

Phosphorus	max LAI (cm^2/m^2) ^A	M (days)	DUR (days)	LAER (cm^2/m^2 per day)	C_{\max} (cm^2/m^2 per day)
Method (M)					
Banding	4.15	28	41	0.12	0.18
Broadcast	4.53	26	47	0.12	0.17
Significance	$P=0.77$	$P=0.53$	$P=0.49$	$P=1.00$	$P=0.63$
Rate (R) (kg P/ha)					
0	3.56 _b ¹	25 _a	46 _a	0.08 _b	0.11 _b
20	4.61 _a	28 _a	38 _a	0.13 _a	0.20 _a
40	4.83 _a	26 _a	48 _a	0.13 _a	0.18 _a
60	4.96 _a	29 _a	44 _a	0.15 _a	0.21 _a
LSD($p<0.05$)	0.7	5.41	25	0.05	0.07
Significance ²	**	$P=0.65$	$P=0.87$	**	**
M*R Interaction	$P=0.94$	$P=0.84$	$P=0.68$	$P=0.90$	$P=0.89$
CV(%)	13.3	16.2	46.0	35.2	34.6

¹Means with the same letters as subscripts within columns are not significantly different at $\alpha=0.05$.

² Levels of significance are *** ($P<0.001$), ** ($P<0.01$), * ($P<0.05$)

^AUnits are cm^2 leaf area / m^2 soil area.

Table 5.1 shows that the weighted mean absolute leaf area expansion rate (LAER), maximum leaf area index (max LAI) and maximum leaf area expansion (C_{\max}) over the exponential leaf area expansion period were all increased ($P<0.05$) by the rate of P but unaffected by the method of P application. The LAER increased ($P<0.05$) by 71% and C_{\max} increased ($P<0.05$) by 81% when P was applied (mean of all P treatments compared with the control). The max LAI for the control crops was 35% less ($P<0.05$) than the mean of all P treatments. The DUR of canopy expansion and time to attain 50% of maximum LAI (M) did not respond to either the method or rate of P application.

5.3.2 ‘Pasja’ radiation interception

The relationship between radiation interception and leaf area index was asymptotic with no treatment effect. This enabled a single function to be used to estimate total accumulated radiation for each treatment (Figure 5.3). At LAI values zero to three, small increases in LAI resulted in large increases in radiation interception. Canopy closure was calculated at the point where 95% of the incident radiation was intercepted. This point is defined as the critical LAI (LAI_{crit}) which was ~3.8 for ‘Pasja’. Leaf area indices above 3.8 gave negligible increases in radiation interception.

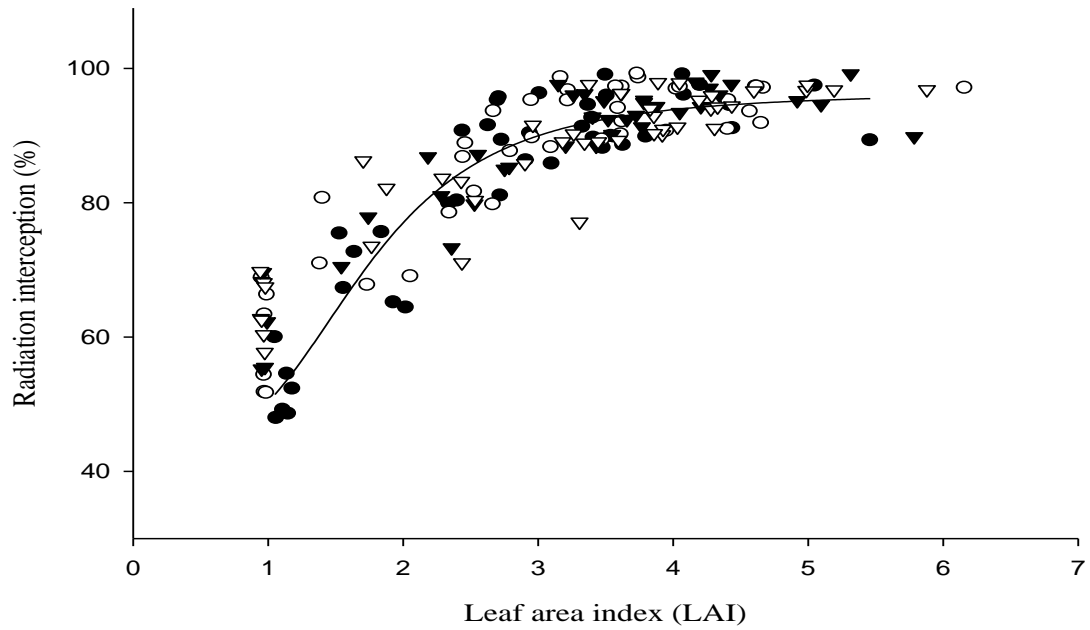


Figure 5.3: The percentage (%) interception of incident photosynthetically active radiation (PAR) by 'Pasja' canopies of differing leaf area index. The different symbols show the different P rates, 0 kg P/ha (●); 20 kg P/ha (○); 40 kg P/ha (▼) or 60 kg P/ha (▽). ($Y = \frac{95.4}{1 + e^{(-x+0.96)/0.73}}$), $R^2=88$.

The general equation for the asymptotic equation is:

$$Y = \frac{p}{1 + e^{(-LAI+i)/b}} \quad \text{----- Equation 5.1}$$

Where p is the asymptotic value of RI

i is the position of the inflection point (LAI)

and b is a parameter defining the curvature of the function

5.3.3 ‘Pasja’ extinction coefficient (k)

The extinction coefficient (k) was determined from the relationship between radiation penetration plotted on a logarithmic scale against LAI. The slope of the line indicates an extinction coefficient (k) of 0.77. All regressions were forced through the origin based on the assumption that when LAI is zero, all light is transmitted to the ground.

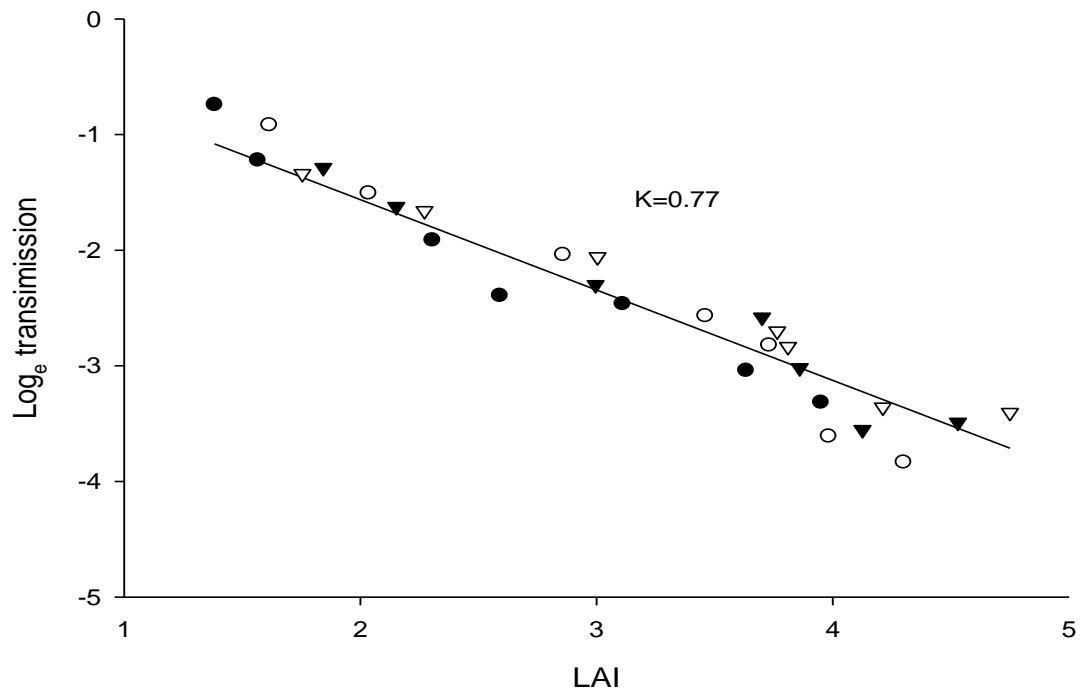


Figure 5.4: Natural logarithm of radiation transmission against LAI for ‘Pasja’ at different rates of P, 0 kg P/ha (●); 20 kg P/ha (○); 40 kg P/ha (▼) or 60 kg P/ha (▽), when grown at Lincoln in 2008. ($Y = -0.77x$)

Figure 5.4 shows that when LAI increases the amount of light transmitted through the canopy to the ground decreased.

5.3.4 ‘Pasja’ leaf area index, percentage radiation interception and accumulated intercepted radiation (RI_{cum})

The total RI_{cum} was 8% greater ($P < 0.05$) when P was applied (mean of all P rates) compared with the control at the end of the season (Table 5.2) when the crop had attained LAI_{crit} .

Table 5.2: Leaf area index (LAI), percentage interception of radiation (%RI) and accumulated intercepted radiation (RI_{cum}) for ‘Pasja’, 38 & 59 days after emergence when sown with different methods of application and rates of phosphorus, at Lincoln in 2008.

Phosphorus	Days after emergence (DAE)					
	38			59		
	LAI ^A	% RI	RI _{cum} ^B	LAI	% RI	RI _{cum}
Method (M) of application						
Banding	3.29	93.1	256.7	4.22	96.3	405.9
Broadcast	3.47	94.0	253.6	4.39	96.8	404.6
Significance ²	P=0.26	P=0.76	P=0.97	P=0.85	P=0.82	P=0.83
Rate (R) of P (kg P/ha)						
0	2.59 _b ³	90.7 _c	236.2 _b	3.85 _b	95.3 _a	383.4 _b
20	3.46 _a	93.0 _b	254.6 _a	4.90 _a	97.5 _a	406.1 _a
40	3.80 _a	94.9 _{ab}	263.0 _a	4.93 _a	96.9 _a	413.4 _a
60	3.87 _a	95.5 _a	266.7 _a	4.95 _a	96.5 _a	418.2 _a
LSD _(p<0.05)	0.66	2.00	21.5	1.04	3.2	22.6
Significance	**	**	**	**	P=0.26	**
M*R Interaction	P=0.38	P=0.66	P=0.36	P=0.23	P=0.93	P=0.65
CV(%)	11.1	1.5	4.8	13.7	1.9	3.2

^ALAI_{crit}=3.5 (Figure 5.3) & ^BMJ/m²

²Levels of significance are *** (P<0.001), ** (P<0.01), *(P<0.05)

³Means with the same letters as subscripts within columns are not significantly different at $\alpha=0.05$.

Table 5.2 shows that LAI, %RI and RI_{cum} did not respond to the method of P application at 38 or 59 DAE but were affected (P<0.05) by the rate of P. The LAI and RI_{cum} at 38 DAE show that there were no differences among the P fertiliser treatments (Figure 5.2). However, the % RI (Table 5.2) indicates that only the 60 kg P/ha treatment had reached the 95% threshold at that time.

5.4 ‘Pasja’ radiation use efficiency (RUE)

The efficiency of canopy photosynthesis in using solar radiation to convert carbon-dioxide to DM can be expressed either as intercepted or total radiation on above or total biomass.

The relationship between ‘Pasja’ total DM and RI_{cum} was insensitive to both the method and rate of P application (Figure 5.5), so only one line is fitted to the mean of all data. The regression line was forced to pass through the origin based on the assumption that when RI_{cum} was zero, no DM was produced.

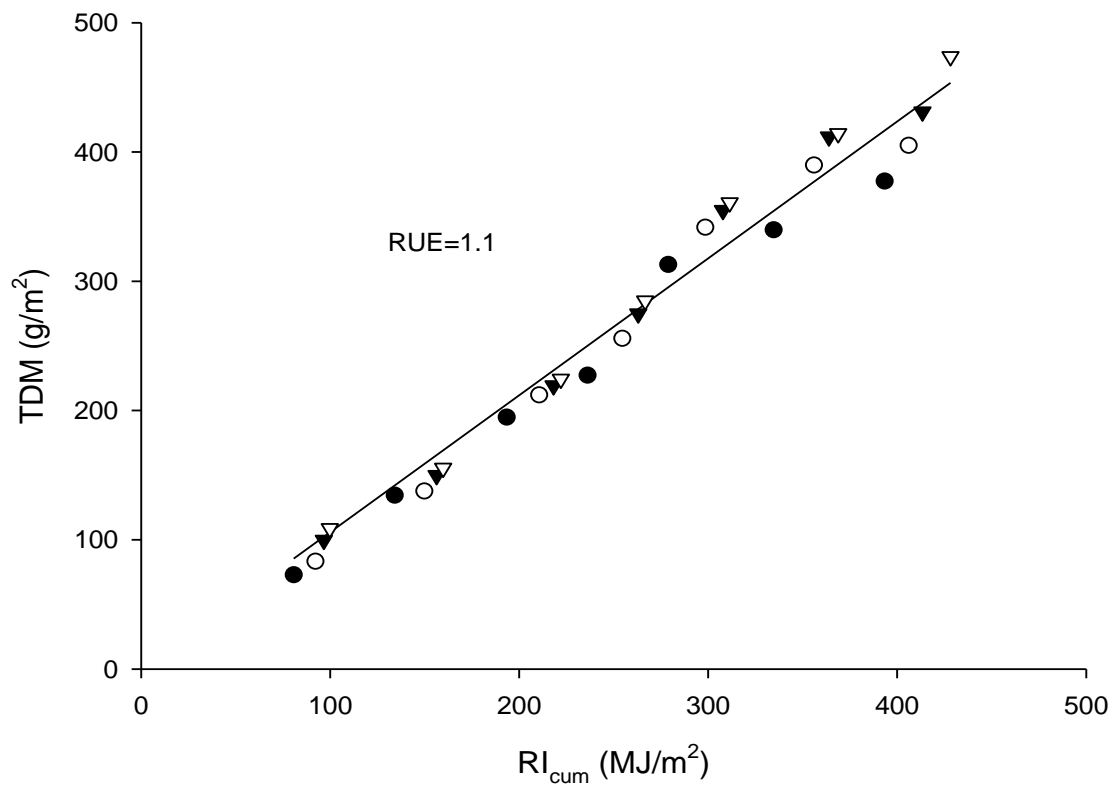


Figure 5.5: ‘Pasja’ total dry matter (TDM) against RI_{cum} for different P rates, 0 kg P/ha (●); 20 kg P/ha (○); 40 kg P/ha (▼) and 60 kg P/ha (▽), when grown at Lincoln in 2008. ($Y=1.1x$).

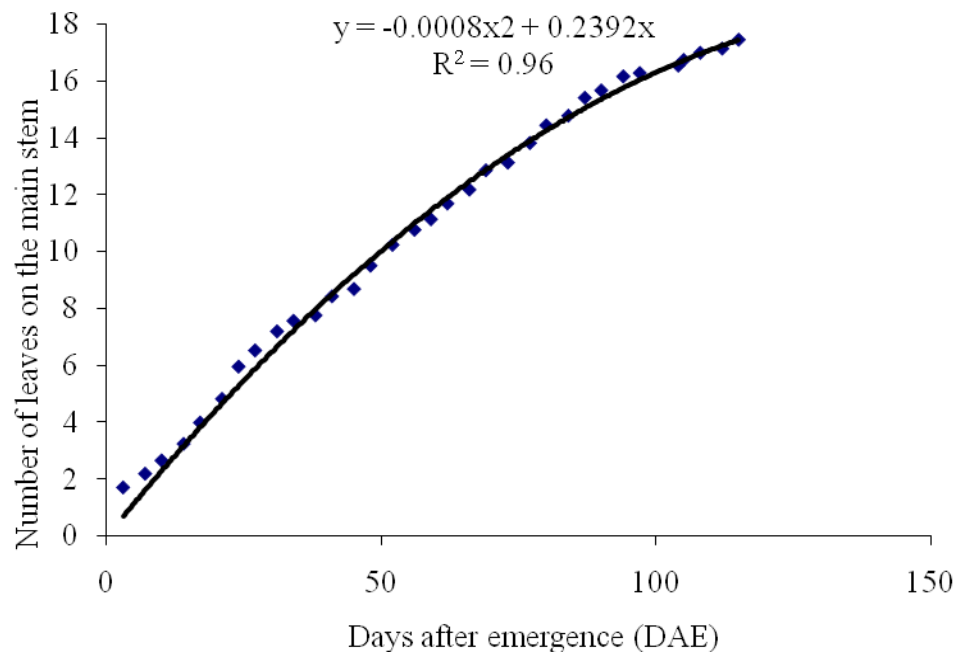
The slope of the regression line is the radiation use efficiency (RUE) (Figure 5.5), which was 1.1 g DM/ MJ PAR for ‘Pasja’.

5.5 Analysis of kale leaf appearance

The relationship between the number of leaves on the main stem and DAE or thermal time (Tt) was explained by polynomial (Figure 5.6a) and linear equation (Figure 5.6b) respectively.

Figure 5.6a shows a leaf appearance rate of 0.24 leaves per day (i.e. a phyllochron about 4.2 days/ leaf) with a systematic decrease in the rate shown over time. Figure 5.6b also show some systematic variation with kale leaves produced at an average rate of 0.0092 leaves per °C day (i.e. phyllochron about 109 °C days) but with a distinct levelling off after 14 leaves.

(a)



(b)

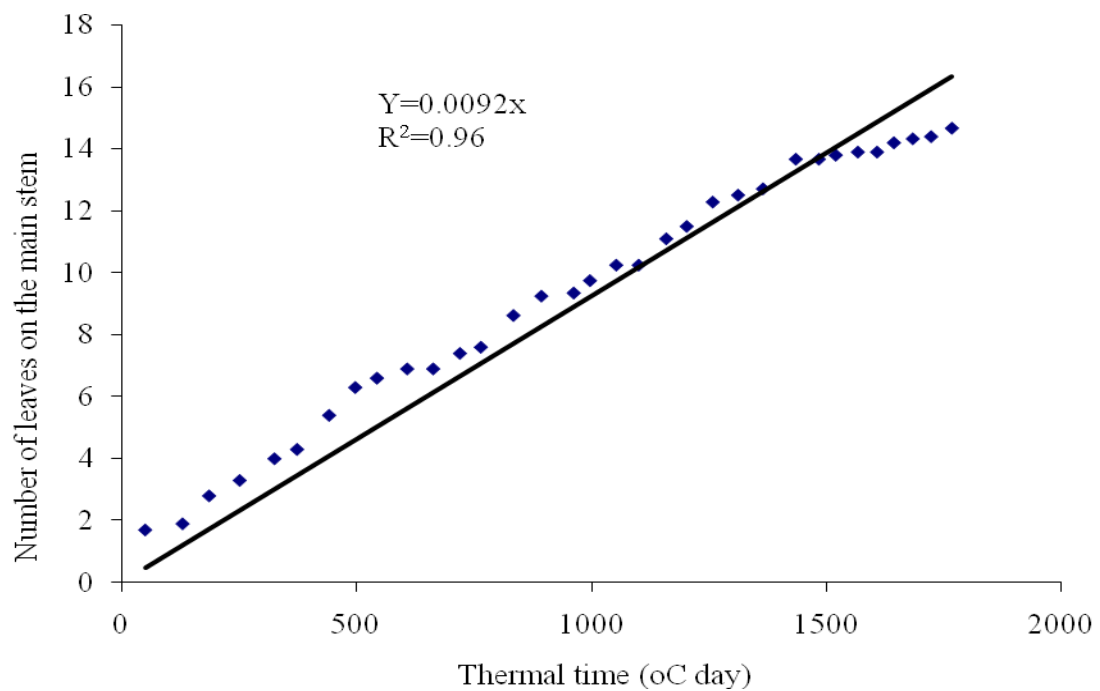


Figure 5.6: The number of leaves on the main stem for kale plotted against (a) days after emergence (DAE) and (b) thermal time (Tt) at Lincoln in 2008; at $T_b = 0^\circ\text{C}$. Lines are fitted to the mean of all data, from crops sown with different methods of application and rates of phosphorus.

5.5.2 Kale leaf area index (LAI) and Radiation interception (RI)

Leaf area index for kale was also affected ($P < 0.05$) by the rate of phosphorus application but did not respond to the method of application.

5.5.2.1 Kale leaf area index

As expected, LAI increased ($P < 0.001$) over the growing season and varied ($P < 0.05$) with the rate of P application. The increase in LAI was most rapid during the first 66 DAE and became more gradual thereafter for all the treatments (Figure 5.7).

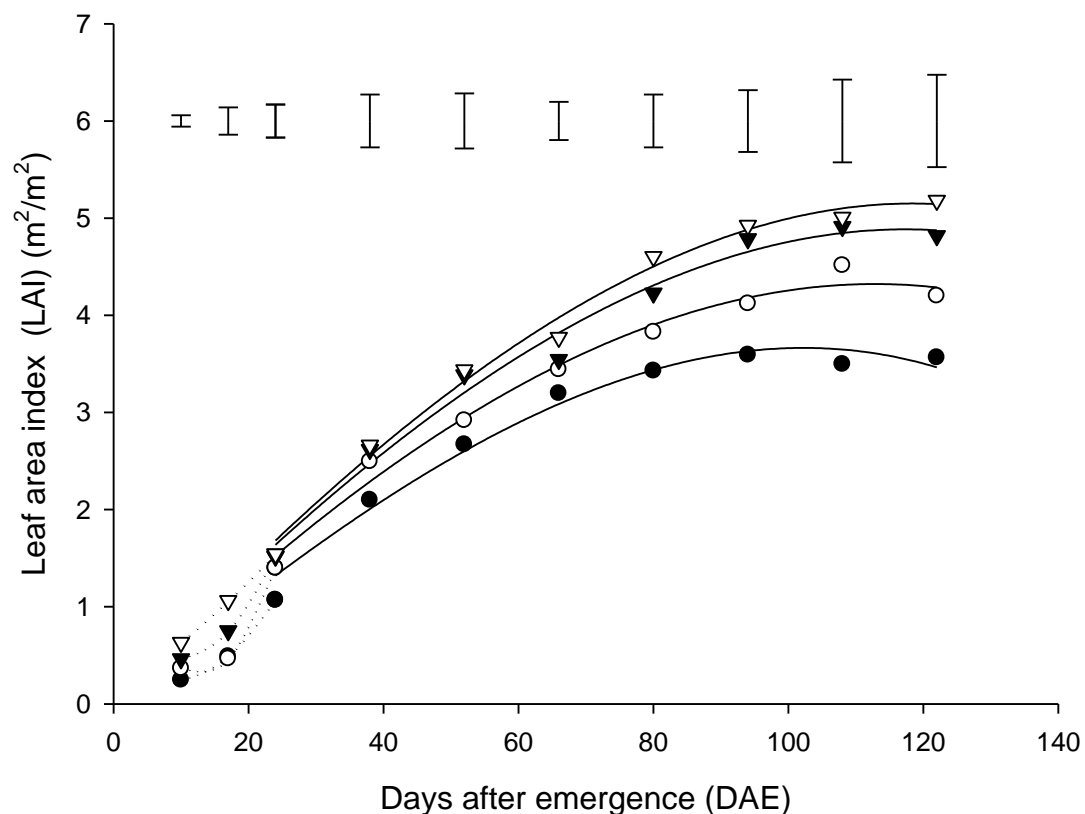


Figure 5.7: Kale leaf area index accumulation over 122 days at 0 kg P/ha (●); 20 kg P/ha (○); 40 kg P/ha (▼) or 60 kg P/ha (▽). Bars are levels of significance ($LSD_{(p < 0.05)}$) (See Table 5.3 for variables derived from the fitted logistic curves and Table 5.4 for the critical LAI (LAI_{crit}), percentage interception of radiation and accumulation of radiation). Solid lines represent quadrat (0.5 m^2) sampling and dotted lines represent seedling sampling (Section 3.2.2.1). Kale crop was sown on 17/12/2007 and had attained 50% seedling emergence by 5/01/2008.

Figure 5.7 (dotted lines) shows that LAI development for kale seedlings over 17 days after emergence based on the seedling data was reasonably consistent with that from quadrat harvests. Leaf area index and hence canopy closure were affected ($P<0.05$) by the rate of P application but did not respond ($P=0.58$) to the method of application. The maximum LAI for the control treatments was 3.8 at 94 DAE (Table 5.3). This was lower ($P<0.05$) than for treatments receiving P fertiliser. There was no difference in LAI between the crops that received 40 or 60 kg P/ha.

Table 5.3: Weighted mean absolute leaf area expansion rate (LAER), maximum leaf area index (max LAI), maximum leaf area expansion rate (C_{\max}), time to reach 50% of max LAI (M) and duration of exponential leaf area expansion phase (DUR) for kale sown with different methods of application and rates of phosphorus, at Lincoln in 2008.

Phosphorus	max LAI (cm^2/m^2) ^A	M (days)	DUR (days)	LAER (cm^2/m^2 per day)	C_{\max} (cm^2/m^2 per day)
Method					
Banding	4.5	40	51	0.10	0.15
Broadcast	4.3	41	50	0.11	0.15
Significance	$P=0.58$	$P=0.81$	$P=0.91$	$P=0.85$	$P=0.86$
Rate (kg P/ha)					
0	3.8 _c ¹	40 _a	46 _a	0.08 _a	0.12 _a
20	4.2 _{bc}	39 _a	44 _a	0.13 _a	0.20 _a
40	4.6 _{ab}	40 _a	49 _a	0.10 _a	0.15 _a
60	5.1 _a	43 _a	62 _a	0.09 _a	0.14 _a
LSD _($p<0.05$)	0.7	10	22	0.06	0.1
Significance ²	**	$P=0.79$	$P=0.63$	$P=0.37$	$P=0.36$
M*R Interaction	$P=0.98$	$P=0.91$	$P=0.86$	$P=0.96$	$P=0.95$
CV (%)	12.8	18.2	31.9	43.3	42.3

^AUnits are cm^2 leaf area / m^2 soil area.

¹Means with the same letters as subscripts within columns are not significantly different at $\alpha=0.05$.

²Levels of significance are *** ($P<0.001$), ** ($P<0.01$), * ($P<0.05$)

Table 5.3 shows that the maximum LAI responded ($P < 0.05$) to the rate of P application but did not respond ($P=0.575$) to method of P application. Maximum LAI was 26% higher ($P < 0.05$) at 60 kg P/ha compared with the control. The DUR of canopy expansion, LAER, C_{\max} and time to reach 50% of maximum LAI did not respond to either the method or rate of P application. There was no treatment interaction. The duration of the exponential growth was on average 41 days, which is about a third of the growing season.

5.5.2.2 Kale radiation interception

The relationship between radiation interception and leaf area index was asymptotic with no treatment effect. This enabled a single function to be used to estimate total accumulated radiation for each treatment (Figure 5.8).

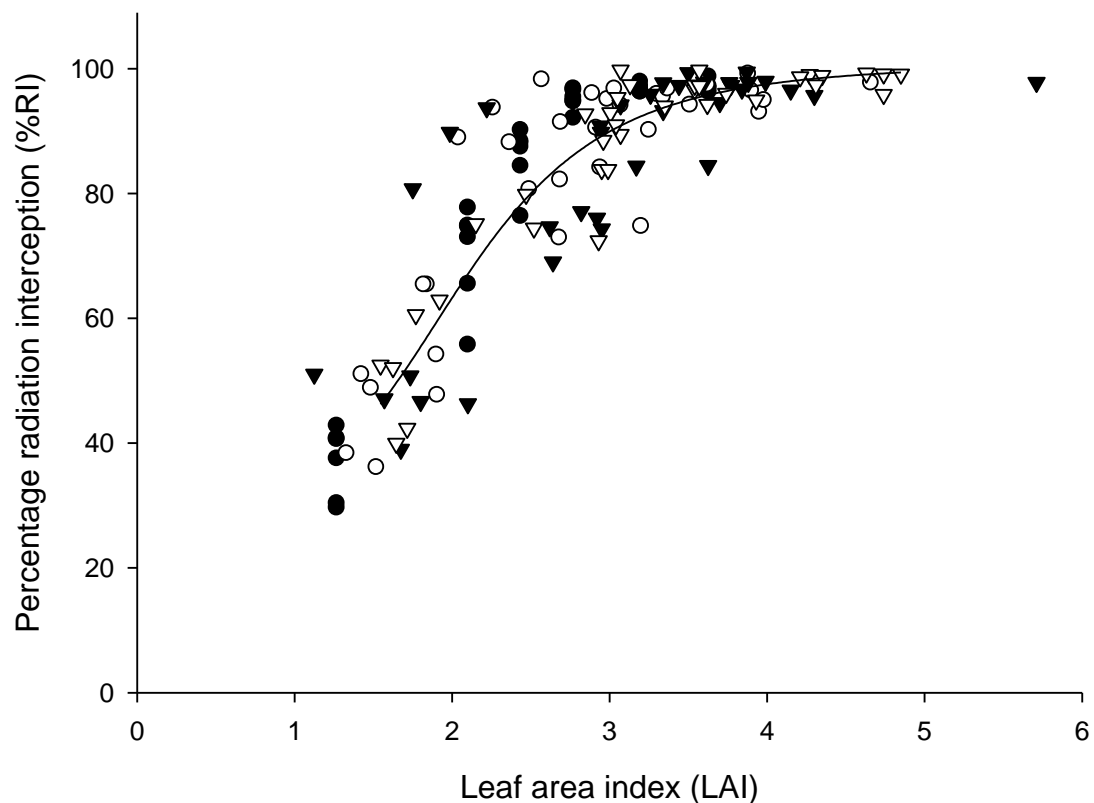


Figure 5.8: The interception of incident PAR by kale canopies of differing leaf area index. The different symbols show the different P rates (0 kg P/ha (●); 20 kg P/ha (○); 40 kg P/ha (▼) or 60 kg P/ha (▽), ($Y = \frac{96.1}{1 + e^{(-x + 1.54)/0.46}}$); $R^2=81$).

At LAI values zero to three, small increases in LAI resulted in large increases in radiation interception. Canopy closure at 95% of the incident radiation is defined as the critical LAI (LAI_{crit}) and was ~ 3.5 for kale. Leaf area indices above 3.5 gave only marginal increase in radiation interception.

5.5.2.3 Kale extinction coefficient (k)

The extinction coefficient (k) was determined from the relationship between radiation penetration plotted on a logarithmic scale against LAI. The slope of the line indicates an extinction coefficient (k) of 0.9.

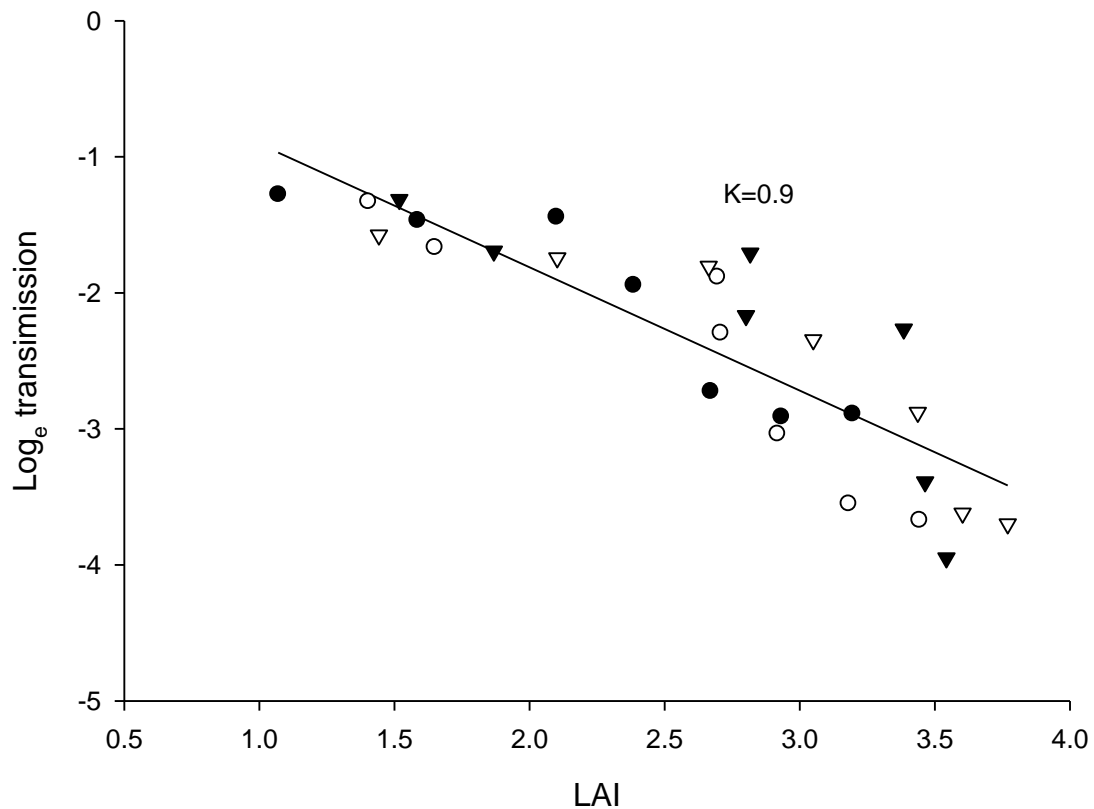


Figure 5.9: Natural logarithm of radiation transmission against LAI for kale at different rates of P (0 kg P/ha (●); 20 kg P/ha (○); 40 kg P/ha (▼) or 60 kg P/ha (▽), when grown at Lincoln in 2008. ($Y=-0.9x$).

Figure 5.9 shows that when LAI increases the amount of light transmitted through the canopy to the ground decreases.

5.5.2.4 Kale leaf area index, percentage radiation interception and accumulated intercepted radiation

The critical LAI (LAI_{crit}) for kale was ~3.5 (Figure 5.8). Thus, the control treatments attained LAI_{crit} at 73 DAE (Table 5.4). The total RI_{cum} was 11% greater when P (mean of all P rates) was applied compared with the control treatments.

Table 5.4: Leaf area index (LAI), radiation interception (%RI) and accumulated intercepted radiation (RI_{cum}) for kale at 52 and 73 days after sowing when sown with different methods of application and rates of phosphorus, at Lincoln in 2008.

Phosphorus	Days after emergence (DAE)					
	52			73		
	LAI ^A	% RI	RI _{cum}	LAI	% RI	RI _{cum}
Method (M) of application						
Banding	3.16	95.7	271.6	3.86	96.8	381.3
Broadcast	3.04	95.2	271.8	3.65	96.7	381.3
Significance ²	P=0.53	P=0.74	P=0.97	P=0.11	P=0.94	P=1.00
Rate (R) of P (kg P/ha)						
0	2.87 _b ³	93.0 _b	246.0 _b	3.51 _b	95.0 _a	353.0 _b
20	3.12 _a	94.0 _b	277.0 _a	4.14 _a	97.0 _a	386.0 _a
40	3.59 _a	97.0 _a	275.0 _a	4.21 _a	98.0 _a	386.0 _a
60	3.64 _a	98.0 _a	290.0 _a	4.38 _a	98.0 _a	400.0 _a
LSD _(p<0.05)	0.58	1.71	28.8	0.37	3.22	28.9
Significance	**	**	**	**	P=0.11	**
M*R Interaction	P=0.54	P=0.97	P=0.37	P=0.27	P=0.64	P=0.43
CV(%)	15	1.0	6.1	7.8	1.9	4.3

^ALAI_{crit}=~3.3 & ^BMJ/m²

²Levels of significance are *** (P<0.001), ** (P<0.01), *(P<0.05)

³Means with the same letters as subscripts within columns are not significantly different at $\alpha=0.05$.

Table 5.4 shows that LAI, %RI and RI_{cum} did not respond to the method of P application at 52 or 73 DAE but were affected (P<0.05) by the rate of P.

The LAI and RI_{cum} at 52 DAE show that there was no difference among the P fertiliser treatments. However, the % RI indicates that only the 40 & 60 kg P/ha treatments had reached the 95% threshold. Although both LAI and RI_{cum} show that the control treatments were lower ($P<0.05$) than P fertiliser treatments, the %RI showed no difference ($P=0.11$) as the crop had attained LAI_{crit} .

5.6 Kale RUE

The relationship between RI_{cum} and total above ground crop DM is examined for kale for the first 73 DAE (half of the season). RUE was insensitive to both the method and rate of P application (Figure 5.10), so only one line is fitted to the mean of all data. RUE was 1.33 g DM/ MJ PAR.

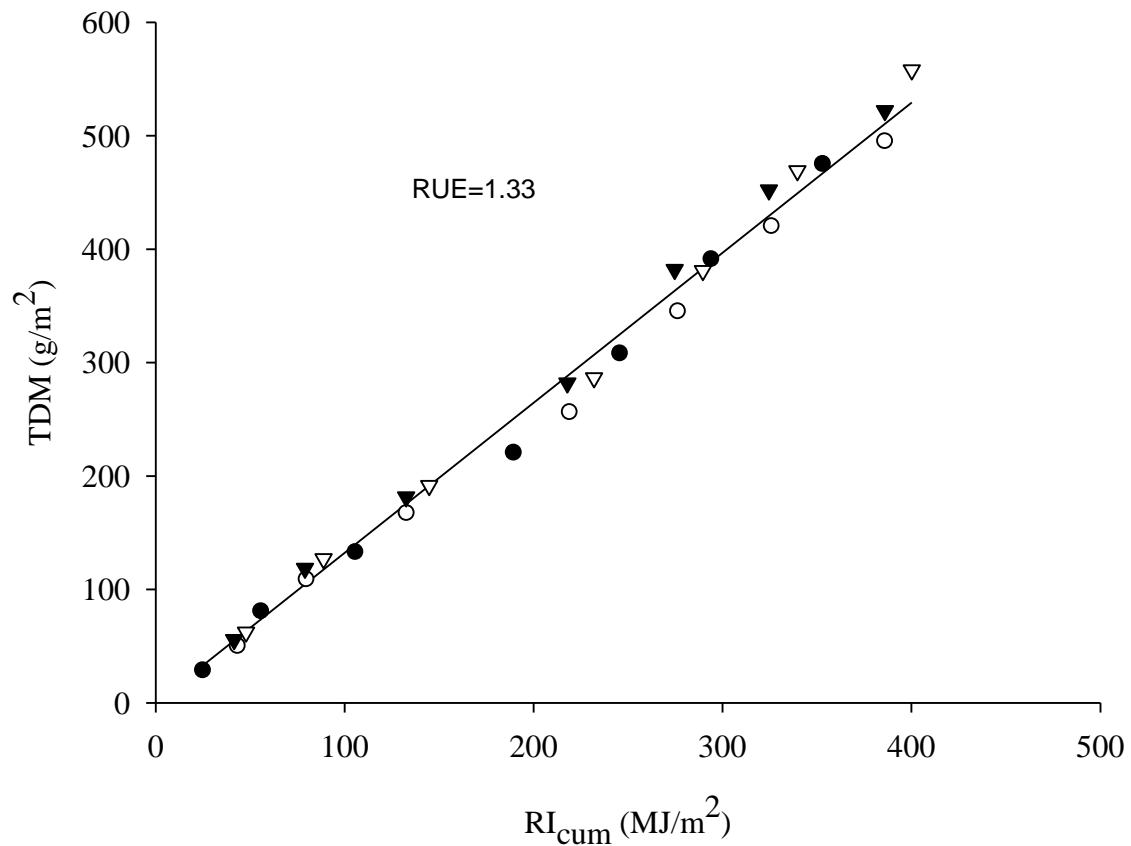


Figure 5.10: Kale radiation use efficiency under different P rates ((0 kg P/ha (●); 20 kg P/ha (○); 40 kg P/ha (▼) and 60 kg P/ha (▽), for crops grown at Lincoln in 2008. ($Y=1.33x$).

5.7 Discussion of leaf development and radiation interception results

5.7.1 Method of P application

The method of P application did not affect leaf development or radiation interception for either 'Pasja' (Table 5.2) or kale (Table 5.4) and there was no interaction of method of application and rate of P. Method of application will therefore not be discussed further in this section.

5.7.2 Base temperature

Base temperature (T_b) was determined from leaf number regressed against thermal time (T_t) (Section 5.1). The R^2 for both 'Pasja' and kale increased with T_b . The differences between T_b of 0 and 10 for 'Pasja' (97.1 versus 97.6) and for kale (99.1 vs. 99.8) were minor and of little practical significance (Appendix 5.1). The ANOVA for the R^2 showed no difference ($P=0.402$) among the leaf appearance rate per plot when regressed at each T_b . Thus a T_b of 0°C was chosen and used for all the T_t discussions in this report. This T_b is the same as reported by Wilson *et al.* (2004) for 'Pasja' and kale and Nanda *et al.* (1995) for a range of brassica crops but different from 4°C reported by Adams (2004).

5.7.3 Effects of the rate of P application on 'Pasja' leaf development, solar radiation interception and radiation use efficiency

5.7.3.1 Leaf appearance rate

The final number of leaves and phyllochron were unaffected by the rate of P application. This is in contrast to reports on other crops, for example maize (Plenet *et al.* 2000; Fletcher, 2005) where the phyllochron for the control treatments was lower than for P fertilised crops. The differences in phyllochron response to P application could be a result of initial Olsen P values, as both maize experiments were started at soil P levels less than 7.5 mg P/kg soil compared to an average of 13.3 mg P/kg soil in the present experiment. The differences could also be attributed to soil P retention (Section 2.2.2.1) or as a crop factor. There is no published literature on effects of P application rate on 'Pasja' leaf appearance rate. Based on this result the analyses and discussion of leaf appearance rate is based on days after emergence and thermal time as independent variables.

The counting of new leaves was discontinued at the final DM harvest, but new leaves were still being produced, albeit at a slower rate (Figure 5.1) compared with the start of the season. The continued production of leaves, when both LAI_{crit} (Figure 5.3) and maximum DM yield production (Figure 4.1) had been attained, supports reports by Wilson *et al.* (2004) that there is no limit to the number of leaves that brassica crops can produce in the first year.

The leaf appearance rate for 'Pasja' responded linearly to temperature above 0°C (Figure 5.1b). This is consistent with reports for other crops, for example summer rape (Morrison & McVetty, 1991), wheat (Gallagher, 1979) and corn (Warrington & Kanemasu, 1983) where the number of leaves on the main stem was a linear function of accumulated Tt. This means the phyllochron is constant over the growth period of the crops and supports suggestions by Barker *et al.* (1980) and Kirby *et al.* (1982) that phyllochron is fixed for the growing season by the conditions during seedling emergence. The 'Pasja' phyllochron (Figure 5.1b) of 60 °Cd was similar to 62 °Cd reported by Wilson *et al.* (2004) and 59.9 °Cd reported by Nanda *et al.* (1995) for turnips.

5.7.3.2 Leaf area index (LAI) and radiation interception (RI)

The experiment demonstrated the dependence of LAI and RI on the rate of P application. Leaf area index for the control crops of 'Pasja' was lower ($P < 0.001$) than those receiving P fertiliser but there was no difference among the higher rates (Figure 5.2). This agrees with findings by Plenet *et al.* (2000) for maize, where LAI for the control treatments were consistently lower ($P < 0.05$) than P fertiliser treatments over a three year period. Since P treatments had no effect on the final number of leaves and leaf appearance rate, the effect of P on LAI can be attributed to reduced leaf area expansion rates, smaller final leaf area per leaf (Table 5.1) and potentially accelerated senescence of leaves. Leaf senescence was not measured in this experiment because there was little evidence of senescence of 'Pasja' leaves.

The differences in LAI (Figure 5.2 & Table 5.1) could be attributed to a higher ($P < 0.05$) leaf area expansion rate (LAER) for the fertiliser P treatments during the exponential leaf area expansion phase (Table 5.1), rather than any difference in the duration of the exponential phase. The differences due to the rate of P application were apparent in the maximum LAI. This can be a result of more availability of P as the rate of application increased. Differences in LAI were more evident late in the

season (Figure 5.2) and suggests a shift from root growth priority to shoot growth late in the season, compared with the reduced ($P<0.05$) shoot to root ratio (Section 4.3.1) early in the season. Leaf area index did not respond to the rate of P early in the season. These effects of P deficiency on LAER and maximum LAI are consistent with observation made on other dicotyledonous C_3 crop species: common bean (*Phaseolus vulgaris* L.)(Lynch *et al.* 1991), wheat (Rodríguez *et al.* 1998a) and sunflower (*Helianthus annuus* L.)(Rodríguez *et al.* 1998c).

The percentage interception of radiation (%RI) was affected ($P<0.05$) by the rate of P application (Table 5.2) but did not respond to the method of application. The %RI for the control was lower ($P<0.05$) than those receiving P fertiliser early in the season (up to 38 DAE) but there were no differences ($P=0.26$) at the end of the season. These results indicate that the deficit in radiation interception for the control may be ascribed mainly to the early delay in the leaf area expansion process. This results in a lower LAI on each day and hence a reduced surface area to intercept radiation early in the season. This is particularly important early in the season before LAI_{crit} is attained and radiation receipts are highest. Later, when all treatments had attained the LAI_{crit} there will be no differences in the amount of radiation intercepted. This agrees with findings by Plenet *et al.* (2000) for maize.

Neither the method of application nor the rate of P affected the relationship between %RI and LAI (Figure 5.3). The LAI_{crit} of 3.8 is within the range reported by Hay & Porter (2006) of 3-5. Brown (1984) stated that it is important that leaf area expands rapidly and LAI_{crit} is attained early in a season so that photosynthesis and growth rates reach a maximum early in the life of a plant. In this experiment the 60 kg P/ha crop attained LAI_{crit} ~21 days earlier than the control (Table 5.2) which translate into an extra 149 MJ PAR/m². This was probably the main physiological process that contributed to the difference in final DM yield (Table 4.1). The DM yield at 59 DAE, estimated from RI_{cum} (Table 5.2) and RUE (Figure 5.5) of 350 kg DM/ha was 51% of the actual difference from the harvested crop (Table 4.1). This difference could be due to underestimation of RI_{cum} or RUE. Effectively the differences in leaf area expansion and hence time to LAI_{crit} affected ($P<0.05$) DM production because of their impact on the interception of solar radiation (Table 5.2).

The canopy extinction coefficient (k) (Figure 5.4) for 'Pasja' was similar to the 0.75 proposed by Zyskowski *et al.* (2004) for brassica crop simulation. The k value of 0.77 reported in this experiment indicates moderately horizontally inclined

leaves. 'Pasja' leaves are classified as plagiophile (Hay & Porter, 2006) and are similar to values for rape, sugar beet and soybean.

The RUE (Figure 5.5) was not affected by the rate of P application. This was in agreement with findings by Colombo *et al.* (1995) on sunflower. RUE of 1.1 g DM /MJ PAR was comparable to other C₃ species for example 1.19 for wheat (Wilson & Jamieson, 1985) and 1.16 for barley (Jamieson *et al.* 1995). The linear relationship between total DM and accumulated radiation interception (RI_{cum}) is consistent with reports by Gallagher & Biscoe (1978). The implication is that there was adequate P for photosynthesis and other growth processes for all crops regardless of initial soil P values in this experiment.

5.7.4 Effects of the rate of P application on kale leaf development, solar radiation interception and use efficiency

5.7.4.1 Leaf appearance rate

The final number of leaves and phyllochron for kale were also unaffected by the rate P application. There is no published literature on the effects of P application rate on kale leaf appearance rate, but coupled with the 'Pasja' results they appear to be insensitive to P provided initial soil P values are above 9 mg P/kg soil (Table 3.1, Appendix 1).

The counting of new leaves was discontinued at the final DM harvest, but new leaves were also still being produced at the top of the kale canopy but at a slower rate (Figure 5.6) than earlier in the season. This continued production of leaves also supports reports by Wilson *et al.* (2004) that there is no limit to the number of leaves that brassica crops can produce in their first vegetative year.

The leaf appearance rate for kale was also linear against temperature above 0°C (Figure 5.6b). The phyllochron (Figure 5.6b) of 109 °Cd was similar to the 110°Cd reported by Wilson *et al.* (2004) (Section 2.3.3). The phyllochron for kale decreased after leaf 14 (Figure 5.6) at 80 DAE (end of March). This could be attributed to the change in mean temperature, as it decreased by 2°C from mid to the end of March and by 5°C at the end of April, when measurements were stopped.

5.7.4.2 Leaf area index (LAI) and radiation interception (RI)

Kale results mirrored those of 'Pasja' showing the dependence of LAI and RI on the rate of P application. Leaf area index for the control crops of kale were also lower ($P < 0.001$) than those receiving P fertiliser and there was no difference between the 40 and 60 kg P/ha treatments (Figure 5.7). Again the lack of effect on the final number of leaves and leaf appearance rate indicates the effect of P on LAI can be attributed to reduced leaf area expansion rates, smaller final leaf area per leaf (Table 5.3) and potentially accelerated senescence of leaves. Senescence of kale leaves was particularly noticeable after the crop had attained LAI_{crit} but this was not monitored and therefore could not be attributed to P treatments. It is expected that the capture of most radiation by the upper leaves increased the competition for the lower leaves and hence senescence commenced (Stephen, 1976; Adams, 2004).

The differences in LAI (Figure 5.7 & Table 5.4) could be attributed to higher ($P < 0.05$) leaf area expansion rate (LAER) for the fertiliser P treatments than the control during the exponential leaf area expansion phase (Table 5.3). However, there was no difference in the duration of the exponential leaf area expansion phase, so the control had a lower ($P < 0.05$) maximum LAI. Differences in LAI were also more evident late in the season (Figure 5.7) which may be a result of a shift from root growth priority to shoot growth late in the season, compared to the reduced ($P < 0.05$) shoot to root ratio (Section 4.4.2.1) early in the season. The differences in LAI between P treatments (Table 5.4) translated into differences ($P < 0.05$) in the percentage interception of radiation (%RI). Specifically the %RI for the control was lower ($P < 0.05$) than those receiving P fertiliser. Thus the deficit in radiation interception for the control can also be ascribed mainly to the early delay in leaf area expansion processes which resulted in low LAI and hence reduced surface area for radiation interception early in the season.

Neither the method of application nor the rate of P affected the relationship between %RI and LAI (Figure 5.8). The LAI_{crit} of ~3.5 was within the range reported by Watson (1958) of 3-5 for kale, but less than the 4-6 reported by Monteith (1981). In this experiment P fertiliser treatments attained LAI_{crit} ~21 days earlier than the control (Table 5.4) which translate into an extra 110.4 MJ PAR/m². The DM yield at 73 DAE, estimated from RI_{cum} (Table 5.4) and RUE (Figure 5.10) of 627 kg DM/ha was similar to the actual difference from the harvested crop (Table 4.4; 830 kg DM/ha). The differences in leaf area development and hence time to LAI_{crit} affected

($P < 0.05$) DM production because of their impact on the interception of solar radiation (Table 5.4).

The canopy extinction coefficient (k) (Figure 5.9) of 0.9 was similar to 0.87 reported by Monteith (1969) for kale but larger than the 0.75 proposed by Zyskowski *et al.* (2004) for brassica crop simulation. The kale canopy extinction coefficient value (Figure 5.9) of 0.9 indicates more horizontally orientated leaves. The k value is similar to the 0.9-1 reported by Monteith (1977) for horizontal or planophile leaves similar to sunflower (Bange *et al.* 1997).

The RUE of 1.33 g DM /MJ PAR (Figure 5.10) was insensitive to the rate of P application and comparable to a constant of 1.2 proposed by Wilson *et al.* (2004) and Zyskowski *et al.* (2004) for forage brassica. The RUE was also comparable to other dicotyledonous C_3 species for example sunflower (Colomb, *et al.* 1995; Bange *et al.* 1997). The consistent RUE value across the range of P treatments (Figure 5.10) suggests the increase in DM associated with increasing P fertiliser were a result of changes in RI_{cum} (Table 5.4), rather than the efficiency of use of intercepted radiation. These results are consistent with those of Planet *et al.* (2000) who showed maize RUE was unaffected by fertiliser P.

Conclusion

Based on the results in this Chapter, the following conclusions can be made:

- Leaf appearance rate for both 'Pasja' and kale did not respond to either method of application or rate of P.
- The phyllochron for 'Pasja' (60 °Cd) was shorter than that for kale (109 °Cd), so it developed its canopy and reached LAI_{crit} earlier than kale.
- Leaf area index for the control crops for both species was consistently lower ($P < 0.05$) than for P fertiliser treatments. The maximum LAI for 'Pasja' control crop was 3.6 compared with 3.8 m² leaf area /m² soil area for kale control crops. There was no difference among the P fertiliser treatments for 'Pasja', while for kale LAI varied with the rate of P application up to 40 kg P/ha.
- Total RI_{cum} was 8% and 11% greater when P was applied (mean of all P rates) compared with the control crops, for 'Pasja' and kale respectively.
- The k value for 'Pasja' was 0.77 and 0.9 for kale and did not respond to either the method of application or rate of P.
- Radiation use efficiency for 'Pasja' was 1.1 g DM /MJ PAR and 1.33 for kale and both values were unaffected by either the method of application or rate of P, suggesting the differences in yield associated with P fertiliser (Chapter 4) were a result of changes in RI_{cum}.

Chapter 6: General Discussion and Conclusions

The overall aim of this experiment was to quantify dry matter (DM) production as affected by fertiliser P and examine the influence of leaf development and interception of radiation and its efficiency of use. This information would be used to provide method of application and fertiliser P recommendations for 'Pasja' and kale establishment, growth and development.

None of the variables measured were affected by the method of P application, although banding tended to be better for kale. In contrast there was a strong response of DM, LAI and interception of radiation to the rate of P. The analyses in Chapter 4 & 5 showed that the differences ($P < 0.05$) were predominantly due to a reduced RI_{cum} under P deficiencies, with no changes in RUE.

6.1 Agronomic implications

Dry matter yields in this experiment for the P fertilised (assumed to be the optimum conditions) crops are within the ranges reported in published literature (Wilson *et al.* 2006; Stephen 1976).

6.1.1 Method of application

The failure to detect a response to the method of application for both 'Pasja' and kale, can be attributed to low soil P retention capacity (Appendix 2.1) and the initial Olsen P levels (Appendix 3.1) averaging 13.3 mg P/ kg soil.

The moderately deep Templeton silt loam (Pallic) soils in this experiment are moderately well drained. Pallic soils have low P retention of ~20% (Saunders, 1965) compared with around 35-43% for the yellow brown pumice and loam soils (Section 2.2.2.1.1) and >85% for the allophanic soils (Appendix 2.1). This means most of the P applied to Pallic soil will be available for plant uptake when P is either banded or broadcast, thus the method of application in this experiment seems to have made little difference to P availability. This is in contrast to yellow brown soils (high in amorphous clay allophone) where most of the P will be adsorbed onto or occluded into soil minerals (McLaren & Cameron, 1996) and hence reduced amounts of P are available plants.

New Zealand soils differ in P retention capacities, as affected by soil chemical properties and mineralogy (Section 2.2.2.1.1). For example, the semiarid (yellow

grey) soils of central Otago and Waitaki valley have low P retention compared with the yellow brown pumice and loam soils of the Central Plateau and Taranaki respectively which are characterised by high P retention capacities (Appendix 2.1). Thus, the banding of fertiliser P under soils of high P retention tends to be more effective than broadcasting.

Also the average initial Olsen P levels (Appendix 3.1) of 13.3 mg P /kg of soil in this experiment were probably not low enough to show differences in the method of P application. Mean Olsen P values for individual plots showed the control plots of ~13.75 mg P /kg compared with 12.75 mg P /kg soil for the 60 kg P /ha plots, a small difference that was most unlikely to affect the result.

6.1.2 Rate of application

Final total DM yield for 'Pasja' increased by 31% (to 4900 kg DM/ha) when 60 kg P /ha was applied and kale DM increased by 29% (to 11000 kg DM/ha) when 40 kg P /ha was applied compared with the control crops. The leaf to stem ratio for both species did not respond to either the method of application or rate of P. Partitioning of final DM yield into leaf to stem ratio showed that 'Pasja' DM is essentially made up the leaf component (at 90%; Figure 4.2) and about 63% of the final kale DM is the stem. This is consistent with reports by Wilson *et al.* (2006) for 'Pasja' and Adams (2004) and Stephen (1976) for kale.

The maximum DM yield (Table 4.4) for 'Pasja' was obtained at 40 kg P /ha, when P was broadcast and 60 kg P /ha under banding. This was not expected as Grant *et al.* (2000) reported that banding exposed available P to a smaller colloidal surface area and hence reduced soil-P reaction zone. This was assumed to leave adequate amounts of available P in soil solution resulting in greater uptake and utilisation of P especially for plants with feeble root systems like 'Pasja'. Wilson *et al.* (2006) found that 'Pasja' utilised P seven times more when banded than broadcast. The result in this experiment could be due to the initial Olsen P levels (Section 6.1).

The maximum DM yield of kale was obtained at lower rates (20 kg P /ha) when P was banded than broadcast (40 kg P /ha). This could be due to a more vigorous root system and longer growth period for kale than 'Pasja' which resulted in more time for the kale roots to scavenge for P.

The agronomic implication of these results is that to get maximum 'Pasja' and kale DM yield, management of P fertiliser is critical. The optimum P rate will depend

on the initial Olsen P levels, method of application and soil type (Sections 2.2.1 & 6.1). Based on these results it seems likely that on the same soil a 'Pasja' crop would benefit from a higher rate of P than kale.

6.1.3 Effect of the rate of P on leaf development, interception of radiation and radiation use efficiency

The final number of leaves and phyllochron for both species were unaffected by either the method of application or rate of P. This may be because the P deficiency was not severe enough to affect phyllochron. There are reports in literature where P deficiency increased phyllochron, for example in maize (Plenet, 2000; Fletcher, 2005). These experiments were carried out on soils of severe P deficiencies with initial Olsen P values of less than 7.5 mg P /kg soil. The leaf appearance rate for 'Pasja' and kale was analysed with thermal time (Tt) as the independent variable (Figure 5.1 & 5.6) and the phyllochron were consistent with findings by Wilson *et al.* (2006)(Sections 5.7.3 & 5.7.4).

Phosphorus deficiency affected both leaf area index (LAI) and consequently accumulated intercepted radiation (RI_{cum}). The maximum LAI was 39% less in the control than fertiliser P crops for 'Pasja' (Table 5.1) and 26% less for kale (Table 5.3). RI_{cum} was 8% less for the control than fertiliser P crops for 'Pasja' (Table 5.2) and 11% for kale (Table 5.4). The reduction of LAI for the control crops led to lower interception of radiation and hence a low RI_{cum} . This is consistent with previous results (Plenet, 2000; Fletcher, 2005).

The consistent RUE values across the range of P treatments (Figure 5.5 & 5.10) suggests the increase in DM yield in Chapter 4 associated with P fertiliser were solely the result of changes in RI_{cum} (Table 5.2 & 5.4).

6.2 Practical implications to New Zealand farmers

Figure 4.1 show that farmers could start grazing 'Pasja' crops about 66 DAE if sown in similar conditions to this crop. Grazing earlier would result in loss of potential DM yield. For example, grazing P fertilised crops 56 DAE, at the mean growth rate of 115 kg DM/ha/day (Table 4.3) would lead to a loss of 1265 kg DM/ha at the first grazing.

Table 6.1: Long term regional and the current season thermal time means from 17/12/1971 to 31/05/2000, at $T_b=0^{\circ}\text{C}$. (Based on mean temperature from NIWA and Broadfields meteorological station)

Area	Tt to the final harvest ($^{\circ}\text{Cd}$)		Potential yield production at final harvest in 2008 (kg DM/ha)			
	11/03*	6/05	Control crops		P fertiliser crops	
			'Pasja'	kale	'Pasja'	kale
Lincoln	1240¹	1820	4220	11650	5210	14560
	Long term averages		Potential production to end of May ^A (kg DM/ha)			
	11/03^A	6/05	'Pasja'	kale	'Pasja'	kale
Kaitaia	1380	2348	4690	15000	5800	18800
Rotorua	1240	2037	4220	13000	5210	16320
Masterton	1226	2011	4200	12900	5150	16100
Blenheim	1252	2060	4260	13200	5260	16480
Timaru	1115	1815	3800	11620	4700	14520
Dunedin	1047	1732	3560	11090	4410	13860
Invercargill	965	1574	3300	10080	4050	12600

* Both crops were sown on 17th December 2007 and final harvest for 'Pasja' was on 11/03 and kale on 6/05/2008

¹Accumulated Tt for the experimental period at Lincoln was 104% and 93% of the long term average on 11/03 and 6/05 respectively

^AThe long term average was calculated from 1971 to 2000.

Table 6.1 shows accumulated Tt for Lincoln, for the experimental period and long term accumulated Tt for other regions in New Zealand. The potential yield is calculated from 'Pasja' and kale DM yield accumulation per unit of Tt (Figures 4.3 & 4.5) and the calculated long term mean Tt for the different regions.

Thermal time (Tt) accumulated from sowing to first grazing (66 DAE) at Lincoln was 1240 $^{\circ}\text{Cd}$ (Table 6.1; Figure 4.3). This was similar to the long term mean Tt of 1226 $^{\circ}\text{Cd}$ for Masterton and it is assumed the two areas would have a growth period of similar chronological time. Based on the long term Tt and DM yield /ha/ $^{\circ}\text{Cd}$ (Figure 4.3) the growing season for 'Pasja' can be predicted for the different agro-ecological regions in New Zealand. For example the control crop for 'Pasja' produces

3.4 kg DM/ha per °Cd (Figure 4.3) and the long term mean Tt for Dunedin during the experimental period was 1047 °Cd, giving a total of 3560 kg DM/ha. As expected, longer growing periods are in cooler compared with the warmer regions. For example, it is estimated 'Pasja' would take 85 days to become grazeable in Invercargill and 78 days in Dunedin compared with only 60 days in Kaitaia.

Similarly, Figure 4.4 shows that grazing could start about 122 DAE or after 1800 °Cd for kale (Table 6.1). As for 'Pasja', grazing earlier reduces potential yield. Grazing the control kale crop about 108 DAE, at a mean growth rate of 127 kg DM/ha/day (Table 4.6) leads to a loss of 1780 kg DM/ha. Delaying grazing for kale would also lead to loss of the leaf DM (Section 5.7.4.2).

The growing season for kale is also dependent on temperature being longer in cooler than warmer climates. For example, it is estimated kale would need 140 days to mature in Invercargill compared with only 95 days in Kaitaia.

The use of Tt model to summarise growth and development is important because results are not time or site specific. The disadvantage is the model does not account for extremes in environmental conditions. For example, brassica crops may not grow well in Kaitaia due to warm and humid conditions that are favourable to fungal diseases, however a model based simply on Tt would predict high yield for the same area (Table 6.1)

The Tt prediction model is probably of less practical importance for kale than 'Pasja' as kale crops are normally used for a once only winter grazing starting around early June almost regardless of yield and time of sowing. 'Pasja' on the other hand gives more flexibility for initial grazing time but the regrowth may be also grazed several times subsequently.

Recommendations for future research:

1. To determine the effect of method of application and rate of P on bulb brassica crops, specifically bulb turnips and swedes. There is lack of information on the effect of method of application and rate of P on bulb turnips and swedes. The results can also be used to confirm 'Pasja' results in this experiment as they have similar root systems, although they require a much longer season.

2. To determine the effect of method and rate of P application on growth and development of 'Pasja' and kale crops grown on volcanic and greywacke soil and/or soils of very low Olsen P levels. The effect of soil pH and liming, particularly in relation to exchangeable aluminium levels should also be included in studies relating to P fertiliser practice. This is important as there are different soil types in New Zealand, with different P retention capacities (Appendix 2.1). Determining the methods and rate of P application for different types of soils can help in the development of P fertiliser models for brassica crops.

Conclusions

Based on the results in Chapter 4 & 5, the following conclusions can be made:

- The maximum DM yield for 'Pasja' was attained at 40 kg P/ha for both methods of P application and maximum DM yield for kale was attained at 20 kg P/ha when P was banded and 40 kg P/ha when P was broadcast. Therefore farmers growing 'Pasja' and kale under similar conditions to this experiment should apply 40 kg P/ha for 'Pasja' and band 20 kg P/ha for kale.
- 'Pasja' and kale crops grown without P fertiliser produced less DM yield which was conservatively partitioned into leaf and stem components. Leaf DM made up ~37% of total kale DM yield and $\geq 90\%$ of total 'Pasja' DM yield at the final harvest regardless of method of application or rate of P.
- Crops grown without P fertiliser had low maximum ($P < 0.05$) leaf area indices; 3.6 for 'Pasja' and 3.8 for kale compared with 4.9 and 5.1 for the 60 kg P/ha crops respectively. Phosphorus fertiliser did not affect the coefficient of extinction (k) or radiation use efficiency (RUE) for both 'Pasja' and kale crops.
- 'Pasja' and kale crops grown without P fertiliser intercepted $\sim 149 \text{ MJ/m}^2$ and $\sim 110 \text{ MJ/m}^2$ less solar radiation respectively, compared with fertilised crops. This was due to reduced leaf area expansion when P was deficient.
- The differences in DM yield associated with P fertiliser were therefore attributed to the changes in accumulated intercepted radiation (RI_{cum}).

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Appendix 2.1: Phosphorus retention by topsoils of New Zealand soil orders (Adapted from McLaren & Cameron, 1996).

Soil order	P retention category		
	Low (0-30%)	Medium (31-85%)	High (86-100%)
Semiarid Soils	_____		
*Pallic Soils	_____		
Brown Soils		_____	
Ultic Soils	_____		
Podzols	_____		
Pumice Soils		_____	
Allophanic Soils			_____
Granular Soils			_____
Oxidic Soils		_____	
Melanic Soils		_____	
Gley Soils ⁺			
Organic Soils	_____		
Recent Soils	_____		
Raw Soils	_____		
Anthropic Soils ⁺			

* Soils in the present experiment

⁺ No specific category

Appendix 3.1: Soil test results

Plot	pH	Olsen P (mg/kg)	Potassium (me/100g)	Calcium (me/100g)	Magnesium (me/100g)	Available N (15 cm depth) (kg/ha)
1	6.3	13	0.32	8.5	0.38	71
2	5.9	17	0.25	6.5	0.39	69
3	6	13	0.38	6.7	0.38	75
4	5.8	16	0.3	6.4	0.43	74
5	5.8	15	0.27	6.5	0.45	71
6	5.8	15	0.24	6.4	0.46	77
7	5.9	15	0.26	7.2	0.45	99
8	6.1	15	0.26	7.3	0.44	68
9	6.1	15	0.23	7.0	0.43	78
10	6.4	14	0.26	9.7	0.50	69
11	6.5	12	0.24	9.4	0.36	83
12	6.4	13	0.32	8.8	0.45	85
13	6.3	12	0.23	8.4	0.48	80
14	6.2	10	0.21	8.7	0.47	68
15	6.2	12	0.32	7.7	0.50	73
16	6.5	13	0.34	9.8	0.49	74
17	6.2	12	0.31	8.5	0.55	67
18	6.2	13	0.29	7.3	0.59	72
19	5.9	11	0.24	5.8	0.57	72
20	6	13	0.31	6.6	0.63	75
21	6.1	12	0.31	6.7	0.72	75
22	6.1	14	0.32	7.3	0.66	68
23	6	11	0.3	6.5	0.57	70
24	6	12	0.33	6.7	0.55	85
25	6	14	0.37	6.6	0.53	65
26	6.1	14	0.33	6.9	0.53	65
27	6.4	11	0.4	9.2	0.57	71
28	6.3	14	0.32	8.1	0.50	76

29	6.2	14	0.26	7.3	0.45	63
30	6.3	13	0.41	8.1	0.49	84
31	6.1	14	0.32	6.9	0.42	71
32	6.2	13	0.3	6.6	0.46	75
33	6.4	11	0.51	9.6	0.88	87
34	6.2	15	0.4	8.2	0.73	66
35	5.9	11	0.32	6.9	0.68	70
36	6.2	13	0.37	7.9	0.91	75
37	6.2	13	0.39	8.2	0.83	70
38	6.4	9	0.31	8.2	0.74	68
39	6.5	11	0.43	9.2	0.80	89
40	6.4	14	0.57	10.1	0.87	99
41	6.2	14	0.49	7.9	0.79	63
42	6.3	14	0.59	8.7	0.78	83
43	6.2	13	0.52	8.5	0.73	86
44	6.4	14	0.49	10.3	0.74	87
45	6.3	15	0.46	9.0	0.76	73
46	6.3	16	0.44	8.8	0.69	78
47	6.2	15	0.64	8.7	0.79	107
48	6.3	14	0.53	8.0	0.70	84
Mean	6.18	13.27	0.347	7.88	0.578	76.1

Appendix 4.1: Final leaf and stem DM yield (kg/ha) for ‘Pasja’ and kale sown with different methods of application and rates of phosphorus, at Lincoln in 2008.

Phosphorus	Final DM yield (kg /ha)							
	‘Pasja’				Kale			
	Leaf		Stem		Leaf		Stem	
Method (M)	Ba ¹	Br	Ba	Br	Ba	Br	Ba	Br
	4000	4017	369	401	4200	3950	6630	6310
Significance	ns		P=0.072		ns		ns	
Rate (R) (kg P/ ha)								
0	3405 _b	3405 _b	322 _b ²	322 _b	3610 _a	3610 _a	5100 _b	5100 _b
20	4012 _b	4092 _{ab}	379 _b	350 _b	4100 _a	3870 _a	7060 _a	6100 _b
40	3973 _b	4174 _a	351 _b	434 _a	4500 _a	4180 _a	6880 _a	7140 _a
60	4624 _a	4413 _a	460 _a	461 _a	4270 _a	4470 _a	7400 _a	6950 _a
LSD _(p<0.05)	706		72		940		1380	
Significance ³	**		***		P=0.086		**	
Interaction M* R	P=0.84		P=0.086		P=0.601		P=0.061	
CV (%)	10		10.6		13.2		11.2	

¹ Ba = Banding & Br = Broadcast

² Means with the same letters as subscripts within columns are not significantly different at $\alpha=0.05$.

³ Levels of significance are *** (P<0.001), ** (P<0.01), *(P<0.05)

Appendix 4.2: Initial leaf and stem DM yield (kg/ha) for ‘Pasja’ and kale sown with different methods of application and rates of phosphorus, at Lincoln in 2008.

First harvest Yield (kg/ha)												
Phosphorus	‘Pasja’						Kale					
	Leaf		Stem		Total		Leaf		Stem		Total	
Method (M)	Ba ¹	Br	Ba	Br	Ba	Br	Ba	Br	Ba	Br	Ba	Br
	851	903	32	39	886	941	385	323	160	116	541	441
Significance	P=0.62		P=0.16		P=0.59		P=0.19		P=0.09		P=0.15	
Rate (R) (kg P/ha)												
0	698 _b ²	698 _b	32 _a	32 _a	730 _b	730 _b	219 _b ²	219 _a	77 _b	77 _a	296 _b	296 _a
20	767 _b	830 _b	37 _a	35 _a	804 _b	865 _b	410 _{ab}	319 _a	154 _b	118 _a	564 _a	437 _a
40	818 _{ab}	1110 _a	30 _a	42 _a	848 _b	1152 _b	405 _{ab}	377 _a	154 _b	142 _a	559 _a	519 _a
60	1062 _a	1040 _a	34 _a	38 _a	1096 _a	1078 _a	574 _a	306 _a	251 _a	112 _a	825 _a	418 _a
LSD _(p<0.05)	274.71		16.68		284.3		194		94		279.5	
Significance ³	**		P=0.96		**		**		**		**	
M * R Interaction	P=0.57		P=0.65		P=0.12		**		P=0.09		*	
CV (%)	25.3		31.3		25.3		31		39		32.5	

¹ Ba = Banding & Br = Broadcast

² Means with the same as subscripts letters within columns are not significantly different at $\alpha=0.05$.

³ Levels of significance are *** (P<0.001), ** (P<0.01), *(P<0.05)

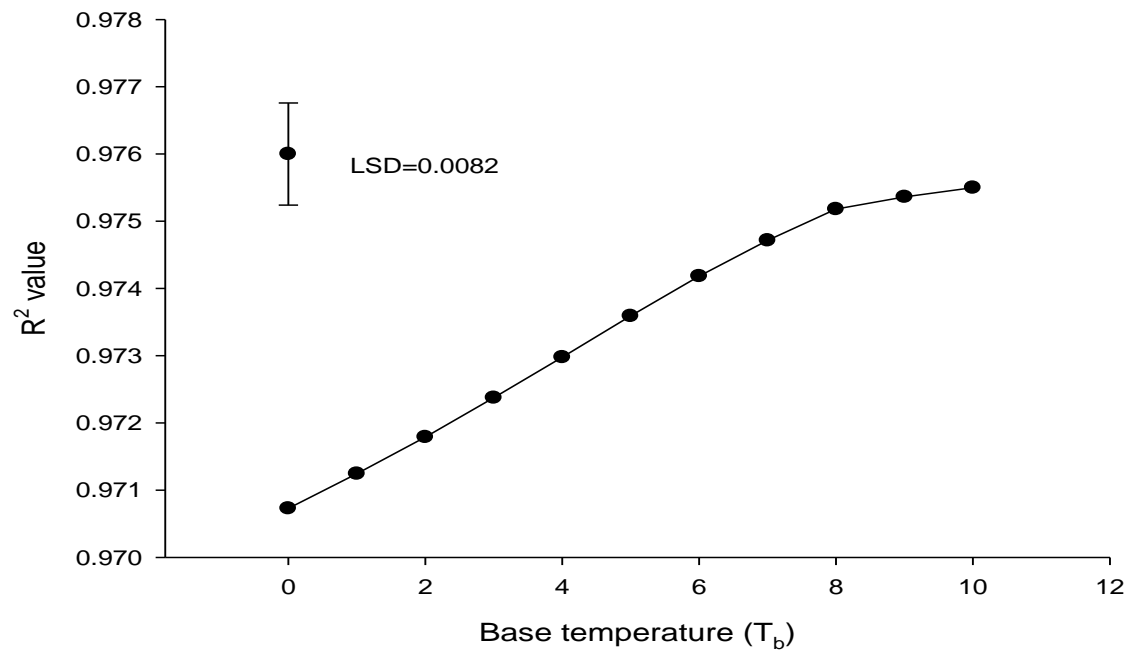
Appendix 4.3 Shoot to root dry matter (DM) accumulation for ‘Pasja’, 3 & 10 days after emergence (DAE) and kale at 10 and 17 DAE, sown with different methods of application and rates of phosphorus, at Lincoln in 2008.

Root & Shoot DM (g/m ²)								
Phosphorus	‘Pasja’				Kale			
	3 DAE		10 DAE		10 DAE		17 DAE	
Yield Component	Shoot	Root	Shoot	Root	Shoot	Root	Shoot	Root
Method (M)								
Banding	11.3	9.32	67.1	53.1	3.64	9.56	37.2	11.4
Broadcast	13.8	9.56	64.7	53.9	3.83	10.7	41.3	12.3
Significance	P=0.49	P=0.53	P=0.15	P=0.13	P=0.71	P=0.81	P=0.62	P=0.64
Rate(kg/ha)								
0	10.6 _b ¹	7.60 _b	38.9 _b	36.0 _b	5.94 _d ²	1.71 _b	21.0 _b	8.28 _b
20	9.39 _b	8.61 _b	60.1 _a	55.6 _a	8.45 _c	3.25 _a	26.3 _b	11.4 _a
40	12.3 _b	10.0 _b	70.7 _a	66.0 _a	11.9 _b	4.80 _a	47.1 _a	23.5 _a
60	19.4 _a	16.4 _a	76.5 _a	72.9 _a	15.6 _a	6.61 _a	47.5 _a	21.5 _a
LSD	4	5.36	22.1	22.5	2.61	4.10	7.03	10.5
Significance ²	**	**	**	**	**	**	**	**
Interactions								
Rate * Time (root)		***					P=0.098	
Rate * Time (shoot)		***					P=0.088	
CV	24.6	20.5	9.4	11.7	27.9	11.9	21	8.8

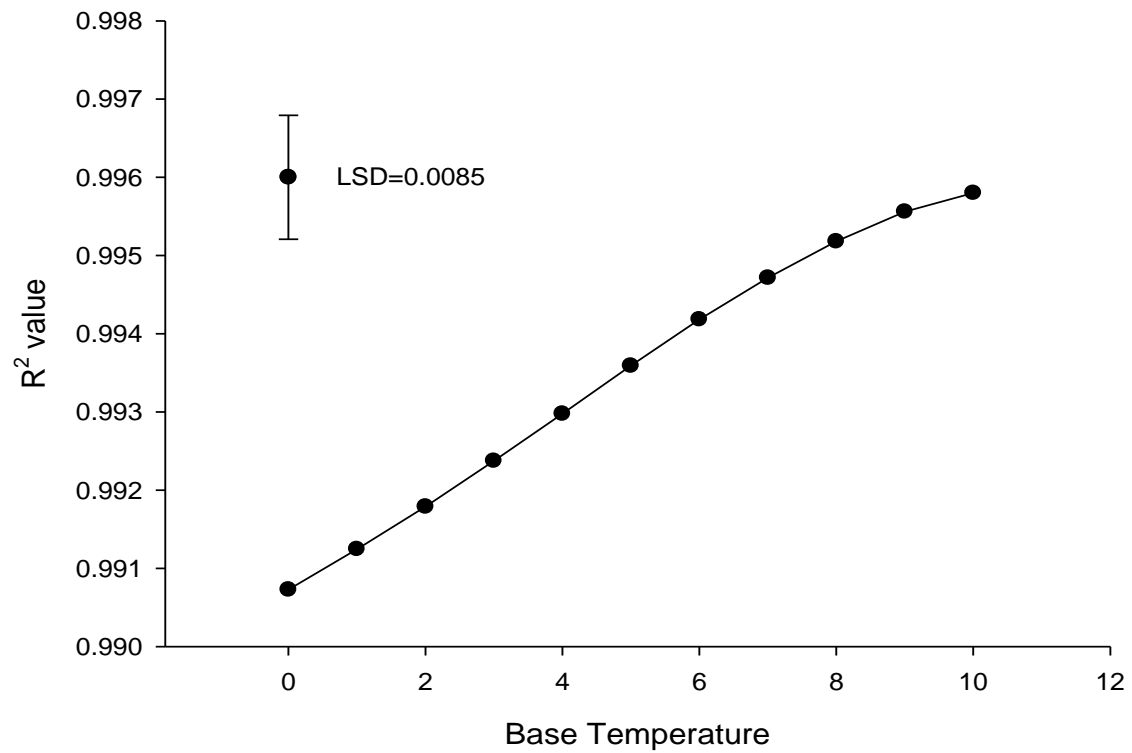
¹Means with the same as subscripts letters within columns are not significantly different at $\alpha=0.05$.

²Levels of significance are *** (P<0.001), ** (P<0.01), *(P<0.05)

(a)



(b)



Appendix 5.2: The regression of R^2 values against base temperature for (a) 'Pasja' and (b) kale crops, for determination of the most appropriate base temperature.