Project title:	Developing Nutrient Management Recommendations for Rhubarb
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Project leader:	Jill England, ADAS Boxworth
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Date project commenced: 1 April 2019

Date project completed 31st March 2023

DISCLAIMER

AUTHENTICATION

We declare that this work was done under our supervision according to the procedures described herein and that the report represents a true and accurate record of the results obtained.

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GROWER SUMMARY

Headline

- Nitrogen response experiments at three commercial farm sites between 2020 and 2022 showed no significant increase in marketable yield of rhubarb from increasing N application rates at any of the sites.
- The project provides no evidence that the current recommended N application rates (given in the Fresh Produce Crop Protocol and RB209 5th Edition) should be increased.
- However, growers should be cautious about significantly reducing their N application rates based on the results of this project, without further work to quantify the cumulative effect of reduced N application rates over a number of years.

Background

Rhubarb production in the UK currently occupies 543 ha of land, producing 15,000 tonnes from forced and field-grown rhubarb with a farm gate value of £20m (Defra, 2022).

Fertiliser recommendations for rhubarb are provided in the Fresh Produce Crop Protocol for Rhubarb, and these are based on the recommendations in the 5th edition of RB209 (1988) for crops in the year of establishment. Whilst the Fresh Produce Crop Protocol gives a single set of recommendations, the 5th edition of RB209 gives separate recommendations for establishment and established crops. These recommendations are understood to be based on research carried out at Stockbridge Technology Centre in the 1970's and 1980's, but the evidence to support these recommendations does not appear to be readily available. Due to the lack of available supporting data and changes to modern production systems growers did not wish these recommendations to be re-instated in RB209 when it was updated in 2016 (9th Edition) without further research into the crop's nutrient requirements.

With regard to changes to production, the fertiliser guidance in the Fresh Produce Crop Protocol is believed to be for crops harvested only once in a season (traditionally from March to May). To achieve an extended season supply to meet retailer's demands, growers now harvest up to 3 crops from the same crowns within a single season. As rhubarb is a perennial crop these multiple harvests can occur year on year from the same crowns, placing increased demand on the plants. The Fresh Produce Crop Protocol does include a footnote that extra N can be applied based on previous crop vigour and growth, but little further information is available to the grower, and there is no guidance on the timing of N applications for crops pulled more than once in a season. In addition, newer perpetual varieties have been developed which do not have a period of dormancy, and these may not have the inherent vigour of the older varieties. Therefore research was required on the nutrient requirements of these perpetual varieties before recommendations for these can be included.

In the absence of recommendations in the 8th edition of RB209, growers and consultants use a combination of expert opinion and the recommendations for established crops from the 5th edition of RB209 and the Fresh Produce Crop Protocol. Typical annual applications of N for established outdoor crops range from 70 to 300 kg N/ha depending on whether the crop is being pulled once or several times in a season, as well as factors such as soil type. Higher applications are usually split. Despite using this advice and recommendations, growers and consultants are concerned that the crop may not be reaching its maximum potential due to the lack of available data to support these practices.

Rhubarb is a perennial crop which requires considerable investment during establishment, and suboptimal nutrient management may adversely affect yields and economic returns over the lifetime of the crop.

The overarching aim of this project was to produce clear fertiliser recommendations for growers of rhubarb for inclusion in RB209 to help growers to optimise nutrient management and minimise the environmental impact of their business activities.

Summary

Field trials were carried out to test the effect of nitrogen application rate and timing in field grown rhubarb at three different sites over three years (2020 to 2022). Field sites were located in an established commercial crop of Timperley Early on the following farms:

- Barfoots Farms Ltd. Sefter Farm, Pagham Road, Bognor Regis, W. Sussex (2020)
- T H Hammond & Sons, New Farm, Redhill, Nottingham (2020 & 2021)
- E Oldroyd and Sons, Hopefield Farm, The Shutts, Leadwell Ln, Rothwell, Leeds (2021 & 2022)

All sites were Soil Nitrogen Supply (SNS) Index 0, and therefore most likely to show a response to N fertiliser. Nitrogen treatments tested the effect of N application rate (up to 360 kg N/ha), and timing (**T1** – early applied pre-emergence/early after bud break; **T2** – after 1st harvest & before 2nd crop regrows; **T3** – after 2nd harvest and before 3rd crop regrows; **T4** – autumn application after final harvest).

Year 1 2020 – Barfoots and Hammonds

The onset of the Covid-19 outbreak in March 2020 had a significant impact on delivery of planned trials work in this first year. The first (pre-emergence) N fertiliser application was

applied at the end of January 2020, followed by a single harvest at each site in April 2020. No further N applications were made, or harvest taken from these sites in 2020.

Although Covid-19 impacted on treatment application in 2020, the treatments applied do allow us to test the effect of different early N application rate. Both sites were SNS Index 0 and therefore likely to be responsive to N application. Despite this, there was no significant increase in marketable yield with N rates of up to 375 kg N/ha applied following bud break at either site. This may be because early season growth in established plantations is driven by N reserves in the crown rather than from soil N. These results do not support early N applications to established rhubarb plantations.

Year 2 2021 –Hammonds and Oldroyds

Following the outputs of the 2020 trials, which showed no yield response to early N applications, the N treatment timings were adjusted in 2021 to focus on later season and autumn N applications. There were 16 treatments at each site testing the impact of N rate (0-360 kg N/ha) and application timing. Each site was harvested three times in 2021.

Overall, there was no significant effect of N application rate on marketable yields at either site in 2021, although there was a significant increase in N offtake with increasing N rate.

All treatments at the Oldroyds site were also harvested once in May of the following season to test the effect of the autumn 2021 N treatments. When analysed together, there was no effect of any of the N treatments on total yield or marketable yield. However, there was an indication of increasing marketable yield where N was applied in September 2021 after the third harvest.

Year 3 2022 - Oldroyds

The drought and extreme heat in summer 2022 had a significant effect on crop growth and performance at the site. Only one harvest was taken from the site rather than the planned three. The results from this harvest allow us to test the effect of 60 kg N/ha early N application compared to zero N. There was no effect of early N on total or marketable yields at the first harvest. This is similar to findings from the first year, where there was no significant increase in marketable yield with early N rates of up to 375 kg N/ha applied following bud break at either site. This may be because early season grown in established plantations is driven by N reserves in the crown rather than from soil N.

However, unlike in 2019, application of N did significantly increase stem N content and stem N offtake. This indicates that the crop took up some of the applied N, but did not translate this into increased yield. Because there was only one harvest at the site, it is not possible to determine whether the additional N uptake would have had any effect on marketable yield at later harvests.

Field trials - conclusions

The lack of a significant yield response to N at all sites is surprising, especially as all had low levels of nitrogen in the soil (SNS Index 0). When this project was commissioned, some growers were questioning whether there should be an increase to the current recommended N rates given in the Fresh Produce Crop Protocol and RB209 5th Edition. The results from this project provide no evidence that the current recommended N application rates should be increased, and conversely actually indicate that recommended N rate should be reduced.

However, growers should be cautious about significantly reducing their N application rates based on the results of this project without further work to quantify the cumulative effect of reduced N application rates over several years. The lack of yield response to N indicates that the crown's reserves from the established crop were likely to have been sufficient to supply most if not all the crop N requirement. The high crop N offtake measured from the zero N control treatments also supports the conclusions that a significant proportion of N for crop growth is taken from reserves in the crown. Total crop (leaves and stem) N offtake from the zero N control treatments from the three harvests at Hammonds and Oldroyds in 2021 was around 100 kg N/ha; accounting for SNS of around 50 kg N/ha at Oldroyds and 30 kg N/ha at Hammonds, still indicates at least 50-70 kg N/ha from crown reserves.

Given that current fertiliser practices may meet (or exceed) N requirements of the crop, it is likely that the crops used for this trial had ample supplies of N in the previous season to ensure strong reserves for the following spring. However, under conditions where poor reserves are set aside – either due to weak crop growth or suboptimal N application over a number of years – there is a potential risk that the crowns could be depleted sooner (and therefore require greater or earlier N applications) to ensure that sufficient yields are produced.

The results from the project does provide some evidence on optimum N application timings. Results from the first and third year of the project when a single early N application was made to the crop and no yield response was measured indicate that there is little need for early N applications. Conversely the yields results from the May 2002 harvest at Oldroyds following the September 2021 N fertiliser treatments indicates that there may be yield benefit to the next season crop from autumn N applications following the final harvest.

Financial Benefits

This project has provided information on the N fertiliser requirements (rate and timing) for rhubarb. Current recommended N rates given in the Fresh Produce Crop Protocol and RB209 5th Edition are for a maximum of 250 kg N/ha at SNS Index 0. Based on the results of this project, it is suggested that this can conservatively be reduced to 200 kg N/ha, saving 50 kg N/ha, equivalent to *c.*£90/ha based on an ammonium nitrate price (34.5%N) price of £600/t.

Action Points

- Review current N application rates and timings for rhubarb based on the results and recommendations from this project.

SCIENCE SECTION

Introduction

Rhubarb production in the UK

Rhubarb production in the UK currently occupies 543 ha of land, producing 15,000 tonnes from forced and field-grown rhubarb with a farm gate value of £20m (Defra, 2022a). Rhubarb can be a highly valuable crop, particularly Yorkshire forced rhubarb which has been given 'Product of Designated Origin' status. It is grown across a broad geographic range outside of the "rhubarb triangle" between Leeds, Wakefield and Bradford and this has given rise to a range of different practices including the timing of propagation planting (set splitting), harvest period and nutrient management practice across a range of soil types from sand to loamy clay.

Rhubarb as a product is the harvested petioles of *Rheum rhubarbarum* produced from a perennial crown in early spring, giving a crop with unique requirements and challenges. Rhubarb is grown as one of two primary product types – green pull rhubarb, harvested from mature plants in the field, and forced rhubarb grown from lifted crowns raised in darkness in forcing sheds. The latter form has the greatest market value (as a result of an intense red colour, thinner sticks with a tender texture) but requires additional production costs associated with the labour of lifting crowns and of maintaining conditions in forcing sheds. Forcing also exhausts crowns, so that only a single harvest can be achieved compared to multiple year's harvest from field-grown crops.

Field grown rhubarb is a perennial crop, with petioles harvested from crowns in the early spring with the crop remaining in the ground for up to five years. Typical yields of field-grown rhubarb can be between 20 – 40 t/ha, although this can be greatly impacted by water availability, crop condition and management choices.

Nutrient management

Recommendations for N, P, K, and Mg were given in the 5th Edition of RB209 (published in 1988; Table 1), most likely based on work done in the 1970/80s although the evidence for these recommendations is not available and they are unlikely to fulfil the nutrient requirement of crops grown to modern practice. Fertiliser recommendations for rhubarb were removed from the 6th Edition of RB209, however many growers still refer back to the RB209 5th Edition recommendations, which are now significantly out of date and may not reflect current practice such as the use of multiple selective pulls or include references to practices that are no longer suitable (e.g. manure use).

Table 1. Fertiliser recommendations for Rhubarb from RB 209 5th Edition (1988)

Index	0	1	2	3	4	>4
Establishment						
Nitrogen (N)	175	125	75	0	0	0
Phosphate (P_2O_5)	175	150	125	100	50	0
Potash (K_2O)	250	225	200	150	125	0
Field crops subsequent annual dressings						
Nitrogen (N)[a]	250	250	250	0	0	0
Phosphate (P_2O_5)	100	100	75	75	0	0
Potassium (K_2O)	300	250	175	150	100	0
Magnesium (Mg) (all years)						
Light soil	90	60	0	0	0	0
Other soils	60	30	0	0	0	0

a. The top dressing of 250 kg/ha N can be applied as a single dressing

Forcing After the establishment year annual dressings of 300 – 400 kg/ha N should be applied as 2 or more equal top dressings before the crop has grown enough to be damaged. P, K, Mg not required

Growers now harvest up to three crops from a single crown per season, although current fertiliser usage may not be suitable for this practice. For instance, 2014 assurance protocols give some guidance for single pull rhubarb while noting that extra fertiliser can be applied for repeated pulls, but little information is available to growers to optimise further fertiliser applications in either quantity or timing (Assured Food Standards, 2014). Therefore, a new assessment of the nutrient requirements of crops grown following these techniques is required to support the development of up to date recommendations for nutrient management in modern practice using the novel SNS index and matching application rates to crop needs.

The 5th edition of RB209 recommends up to 175 kg N/ha at Nitrogen Index 0 in the establishment year, and up to 250 kg N/ha for established crops (Table 1). Total N% as reported in MAFF plant analysis data (1976) and dry matter at c. 7.2% as given by Allison (1966), indicating that rhubarb may have high nitrogen uptake requirements. Assuming yields of 15 – 20 tonnes/ha, typical applications of N needed to replace crop offtake at these values is 60 - 85 kg N/ha. However, growers taking a 2nd pull from crops are finding higher applications of approximately 100 kg N/ha on top of that applied to the 1st crop is achieving better subsequent growth and canopy development. Conversely, over application of N (especially as a single large dose) can lead to undesirable crop responses such as flowering and overly extended petioles which develop stronger green pigmentation, losing red colouring which is sought by customers. Therefore, nutrient management techniques will be approached as a method of optimising marketable yield in rhubarb as opposed to maximised gross yield.

The effects of supplementary nutrient application may also impact crop growth later in the season, and subsequent harvests in the following season. Culpepper and Caldwell (1932) demonstrated that the N content of leaves and petioles decreased by 50% as the crop matures, matched with an increase in N content of the crown/roots of the crop. Late-season N remobilisation may impact carry-over of N between crops, and scant information is available relating to the potential nitrogen value of leaves and un-marketed produce that remain in the field after harvest. Quantification of this N reserve would allow further optimisation of fertiliser application to reduce the risk of over application, and this is an option that could be explored in the later stages of the project. The timing of nutrient applications may also impact crop growth and yields in the subsequent season, and additional later harvests can weaken the crop in the following year. Therefore, break of dormancy and crop vigour in the following year after nutrient application trials will be assessed to see whether supplementary provision leads to an improvement in the following year, or a lessened detrimental effect from late harvests.

Rhubarb is a perennial crop which requires considerable investment during establishment, and suboptimal nutrient management may adversely affect yields and economic returns over the lifetime of the crop. Given the paucity of evidence on which to base nutrient management guidelines, this work is required to ensure that growers are given sufficient guidance to maximise the potential productivity of their crop, while avoiding practices which would adversely affect crop growth or a possible environmental hazard.

Project aims and objectives

There is a strong need for growers to have clear guidance as to optimal nutrition management in rhubarb so as to maximise yield productivity whilst minimising the economic and environmental cost of application.

The overarching aim of this project was to produce clear fertiliser recommendations for growers of rhubarb for inclusion in RB209 to help growers to optimise nutrient management and minimise the environmental impact of their business activities. Specific objectives were:

1. To update information on nutrition and feeding for rhubarb
2. To determine whether additional feeding of green rhubarb increases yield, quality and season length when pulled multiple times during a season
3. Knowledge exchange to include provision of speakers for AHDB or third parties events throughout the project duration
4. To update relevant sections of the Nutrient Management Guide (RB209)

Literature review and grower survey

Introduction

An initial literature review was carried out to summarise current evidence relating to rhubarb nutrition. A review of published scientific literature was carried out using Google Scholar. No date limit was placed on this search, and papers addressing related crop systems (e.g. the production of *Rheum tanguticum* for Chinese medicinal use) were also included. This also included other aspects of the review, such as the use of wool waste (or “shoddy”) as a nitrogen source. So-called “grey literature” was examined for additional evidence. This covered non-peer reviewed publications and commercial literature such as the early additions of RB 209/205, and publications from grower groups. Publications from outside of the UK (e.g. USA) that see significant rhubarb production were also included.

In addition, a grower survey was carried out to understand current commercial practice. Interviews with current UK rhubarb growers were carried out to define current typical practice. A prepared questionnaire (see Appendix 1) was used as a foundation for interviews with growers that were carried out by expert ADAS consultants either face-to-face or by telephone to allow interpretation of the evidence collated. Eight growers were interviewed, representing in the north and south of England, and Scotland. Grower choice was based on a range of cultivation practice (e.g. forced and field-grown) and to maximise the diversity of growing approach and target market in the evidence obtained. The growers interviewed grew a total of 213 ha of rhubarb (c.40% of UK total), with 39 ha of this used for forced rhubarb production.

The information gathered through these channels was standardised wherever possible, and summary results of this is presented below.

General Crop Management – grower survey

A limited range of cultivars were grown by the growers interviewed for this review: Timperley Early, Stockbridge Arrow and Stockbridge Harbinger were most common, although Raspberry Red, Livingstone, Hammonds Early and Victoria were also reported. Typical yields reported were 22-33 t/ha. Of interest to growers was whether there were any significant differences in nutrient requirements between cultivars – do naturally more vigorous cultivars such as Timperley Early require more or less feed to maximise yield potential?

Crops were grown for multiple pulls, with most pulls targeting 100% of the crop although this may be reduced to around 80% if harvests select sticks only within specification (this may be particularly the case in the first pull to not weaken the crop, or to allow smaller sticks in the first pull to grow before later harvests). In one instance, a single complete pull is carried out to avoid weakening the crop, while a second grower pulled selectively across the season in response to customer requirements. Multiple-pull growers reported one to three pulls in a season, largely dependent on crop vigour or cultivar: for instance, Stockbridge Arrow may be harvested once with two or three pulls targeted in Timperley Early and Victoria.

Nutrition Management Approach

No standard approach to fertiliser application timings was evident in the literature review, or between growers, although a general consensus of multiple applications across the season is evident. Recommendations suggest that applications should be split into two applications (early spring and after first growth); three or more applications at season start, initial growth and after each harvest (Schrader, 2000); or every 1-3 weeks over the season (Burt, 2016). Of the growers surveyed, multiple applications were typical, with feed applied after every harvest. Perception among growers was that feeding between harvests drove subsequent yields, but application rates were varied based on seasonal conditions, crop vigour, crop history and planned harvesting regime. Therefore, in addition to identifying optimum feed rates, the timing of those applications across the season may also need to be addressed.

Nitrogen

Nitrogen (N) is likely to have the most significant impact on crop yield. The perennial nature of rhubarb, with potentially multiple harvests across the season, makes N management more complex than traditional crop systems. In addition, N applications are likely to be required outside of normal application periods so an evidence base must be provided to justify high dosages, particularly if applied in the NVZs (nitrate vulnerable zones) closed spreading period for N fertiliser. The current NVZ rules in England state that you must not spread manufactured N fertiliser on or between 1st September and 15th January, unless you have written advice from a FACTS qualified advisor to state that the N application is recommended and justified (Defra 2022b).

Lastly, the timing of N application may have a significant effect on yield response, and therefore growers will require guidance on when to apply, as well as how much, N to maximise yield potential in the crop. The impact of splitting N is likely to vary depending on the ability of the crop to uptake and use it, although this may have greater impact on sandy soils by extending the period over which N is available before significant leaching can occur.

General belief is that rhubarb responds well to N, showing significant uptake over the course of the season, although there is no evidence relating to N offtake by the crop. Different rates of N application are routinely reported between establishment and field crop. RB 209 5th Edition recommends up to 175 kg/ha N during establishment and up to 250 kg/ha N in subsequent years for a field crop, and this falls within the typical ranges of recommended N rates found in this review (Table 2). There is significant variation in recommendations in total

N application for both mature and establishing crops, but this is likely to be a reflection of both soil/climate variation and differences in typical practice on which these recommendations are based. As a general consensus, N applications of 150kg/ha and above for established crops is typical.

Table 2. Summary of recommended nitrogen application rates for newly planted and established rhubarb crops. Application recommendations have been converted into total available nitrogen applications for newly propagated and established crops – these include the contribution from manure applications based on estimates of available N in cow farm yard manure given in RB 209 (2017 edition). Application recommendations are given at mass of N unless specified, with manure recommendations given in italics.

Source	Application Recommendations	Applied N 1st Year – kg/ha	Applied N Mature – kg/ha
RB 209 6th Edition 1994 UK	0-175kg/ha during establishment, up to 250kg/ha in later years in a mature crop.	175 (Index 0) 125 (Index 1) 75 (Index 2) 0 (Index >3)	250 (Index 0-2) 0 (Index >3)
RB 113 (1949) – UK	2 cwt (hundredweight) of ammonium sulphate after planting. In the second year 2 cwt of ammonium sulphate should be applied in the spring, followed by a further 2 cwt after the first pull. In later years 3 cwt of ammonium sulphate should be applied. *40 t/a of manure should be applied before planting, followed by 20-30t/a per year for mature crops.*	112	165-194 in 2nd year, 139-168 in 3rd and later years.
Barney & Hummer, 2012 - USA	78-90kg during planting year, 157-179 kg/ha in later years. *Manure at 56-78 t/ha before planting.*	112-137	157-179
Burt, 2016 – Western Australia	80 kg of urea or 110 kg ammonium nitrate per ha, applying every 1-3 weeks. Apply up to 50 m^3/ha composted manure before planting, and annually thereafter.	148 (assuming 4 applications at 37 kg/ha, excluding compost)	
Schrader, 2000 – California, USA	70-80 lb/acre in planting year, then 140-160 lb/acre in later years. Applications should be split into 3 or more sidedress applications before spring, after growth starts and after harvest. *15 t/a of composted manure before planting, followed by 15-30 t/a each year in the autumn or spring.*	87-98	166-197
Helsel, Marshall, Zandstra, 1981 – Michigan, USA	200 lb/acre before planting, followed by 50 lb/acre every month during establishment, then 50lb/acre in later years. *15 t/a of manure should be applied before planting.*	224 + 56 monthly	56
Warncke *et al.*, 1998 – Michigan, USA	100 lb/acre split equally between early spring and a second application after new growth.	224	
OSU, 2004 – Oregon, USA	70-80 lb/acre in planting year, then 140-160 lb/acre in later years.	78-89	157-179

Scant information was available in the published literature regarding N applications to rhubarb. Xiong *et al*. (2018) trailed N application on the allied *Rheum tanguticum* at levels of 0, 75, 150, 225 kg/ha, with greatest growth responses at 150 and 225 kg/ha although no significant differences were seen between these levels. Applications of 150 kg/ha of N would be in line with the recommendations given above.

The grower survey found annual N application rates of 100-229 kg N/ha, with applications typically split with 50-100 kg N/ha applied following each harvest. Total N application was reported to vary with year, crop vigour and intended market. Information on N applications given by individual growers included:

- 200 kg N/ha as ammonium nitrate in early spring
- 50-100 kg N/ha per cut, giving around 150 – 250 kg/ha per year.
- 79 kg N/ha (estimated annual release from 3 t/ha of shoddy application) combined with 75 kg/N top dressing after each pull (giving an estimated 229 kg N/ha assuming two harvests).
- 63 kg N/ha (as ammonium sulphate) before 69 kg/ha after each pull (giving a total of 201 kg/ha assuming two pulls).
- 130 kg N/ha applied as a combination of ammonium nitrate and Tropicote in a 2:1 ratio.
- 100 - 125 kg N/ha applied as a 20:10:15 compound fertiliser applied.
- 126 kg N/ha applied as ammonium nitrate once a year.

Nitrogen applications followed common themes between different UK growers. Initial applications (along with liming if required) were applied in early spring before bud break, followed by subsequent applications after each pull. The evidence accumulated in the grower interviews reflect previous anecdotal evidence that applications of c. 100 kg N/ha after the first pull can significantly increase subsequent harvests. While post-pull applications were widely reported, these varied with current crop condition (vigour), past yield history, intended market and harvesting schedule. One grower reported varying applications between 50 – 100 kg/ha of N indicating that current crop condition is a significant determining factor in application strategy.

However, growers also noted concern that excessive application of N may lead to promotion of flowering, stick elongation and greater green pigmentation of the sticks. Based on these observations it is considered that there is a potential to control both yield quantity and stick condition using crop nutrition. Therefore, timings of N application in the context of crop growth responses and soil type/climate may need to be considered in addition to rates of application.

Phosphate and potash

Only limited information is available regarding application rates of phosphate and potash. RB209 5th Edition recommends up to 175 kg/P_2O_5 ha at P Index 0 during establishment and up to 100 kg P_2O_5/ha for established crops, and up to 250 kg/K_2O ha at K Index 0 during establishment and up to 300 kg K_2O/ha for established crops (Table 1). Rhubarb is known to have a high potash requirement (Forest, 1958) and anecdotal evidence suggests that additional potash can enhance red pigmentation of the petioles.

Typical phosphate and potash application ranges cited by other authors in Table 3 are generally in the region of 100-200 kg P_2O_5/ha and 200-300 kg K_2O/ha. Although it should be noted that several of these references include applications of phosphate/potash in manure as well as fertiliser.

There was very little information in the literature on crop response to phosphate or potash. The review identified one relevant study by Shen *et al.* (2017) which showed that application rates of 90 kg/ha of P_2O_5 and 75 kg/ha K_2O increased fresh weight (FW) yields but had no impact on phytochemical content in *Rheum tanguticum*.

Table 3. Summary of phosphate and potash application rates for newly planted and established rhubarb crops. Additional manure recommendations are given in italics based on calculations for cow FYM P_2O_5/K_2O content given RB 209 (2017 Ed.).

Source	Phosphate			Potassium		
	P_2O_5 App. (kg/ha)			K_2O App. (kg/ha)		
	Index	Establishing	Mature	Index	Establishing	Mature
RB 209 5th Edition 1988 UK	0	175	100	0	250	300
	1	150	100	1	225	250
	2	125	75	2	200	175
	3	100	75	3	150	150
	4	50	0	4	125	100
	> 4	0	0	> 4	0	0
RB 113 (1949) – UK	188 kg/ha at planting from 99t/ha manure, followed by 94 – 141 kg/ha from 50-75 t/ha manure in later years.			840 kg/ha at planting from 99t/ha manure, followed by 420 – 840 kg/ha from 50-75 t/ha manure in later years.		
Barney & Hummer, 2012 - USA	78 – 90 kg/ha P_2O_5 during planting year, followed by 56-78 kg/ha in subsequent years. *Additional 106 – 148 kg/ha from manure applications of 56 – 78t/ha at planting.*			157 – 179 kg/ha K_2O in planting years, repeat in subsequent years. Additional 683 – 911 kg/ha from manure applications of 56 – 78t/ha at planting.		
Burt, 2016 – Western Australia	105 kg/ha of P (240 kg/ha P_2O_5)			75kg/ha K_2O as muriate of potash every 1-3 weeks		

Schrader, 2000 – California, USA	70 – 80 kg/ha P_2O_5 during planting year, repeat in subsequent years. Additional 28.5 kg/ha from manure applications of 15t/ha at planting. Further annual applications of 15 – 30 t/ha will provide 28.5 – 57 kg/ha.	140 – 160 kg/ha K_2O in planting years, repeat in subsequent years. Additional 127.5 kg/ha from manure applications of 15t/ha at planting. Further annual applications of 15 – 30 t/ha will provide 127.5 – 255 kg/ha.
Helsel, Marshall, Zandstra, 1981 – Michigan, USA	112 kg/ha P_2O_5 prior to planting. Additional 28.5 kg/ha from manure applications of 15t/ha at planting.	224 kg/ha before planting, followed by 112 kg/ha every 3 – 5 years in the spring. *Additional 127.5 kg/ha from manure applications of 15t/ha at planting.*
Warncke *et al.*, 1998 – Michigan, USA	Soil Test (P kg/ha) / P_2O_5 App. (kg/ha): 0 / 254 50 / 191 100 / 128 150 / 65 200 / 0	Soil Test (K kg/ha) / K_2O App. (kg/ha): 0 / 353 75 / 285 150 / 217 225 / 149 300 / 80 375 / 12
OSU, 2004 – Oregon, USA	70 – 80 P_2O_5 in planting year and in subsequent years	140 – 160 K_2O in planting years and in subsequent years.

The growers interviewed for this review, provided the following information on phosphate and potash use:

- 220 kg/ha K_2O applied as muriate of potash applied only once to new crops.
- 50 – 62 kg/ha P_2O_5 and 75 – 93.75 kg/ha K_2O applied as a 20:10:15 product applied in the spring.
- 300 kg/ha of K_2O applied at muriate of potash.
- 12.5 kg/ha P_2O_5 and 27.5 kg/ha K_2O estimated from 10 t/ha shoddy application on an annual basis.

Nutrient Sources

The majority of growers interviewed used straight fertiliser mixes (ammonium nitrate/sulphate and muriate of potash). A limited number of other products were also used (e.g. Limex, Topicote) and propriety mixes.

A diverse range of products can be used for nutrition management – applications of typical fertiliser products (e.g. ammonium nitrate, muriate of potash and ammonium sulphate), with smaller use of proprietary feeds (Tropicote, Calcifert). Recommendations given to growers in

America suggest manure applications before planting at rates of 56 – 78 t/ha (Barney & Hummer, 2012) to 15 t/ha (Helsel, 1981). However, despite the benefits of manure use, no growers interviewed for this review used manures in their rhubarb crops (although one instance of digestate was reported). There is interest in the potential for manure as part of a fertiliser program, although there is also concern that manure application on a limited scale may be of limited practicality. Application of shoddy wool waste was reported by several growers, at a rate of 3-10 t/ha. The absence of an analysis of the seasonal NPK availability from shoddy application precludes quantification of contribution of shoddy application to the crop nutrient requirement, although its relevancy to a significant portion of the industry is likely to make this a worthwhile area for subsequent analysis.

In addition to applied nutrients, two crop-originated sources of nutrients are likely to be available during growth. Firstly, nutrients accumulated in the crown during the previous growing season are likely to feed forward into the early growth of the next crop. Culpepper and Caldwell (1932) demonstrated that the N content of leaves and petioles decreased by 50% as the crop matures, matched with an increase in N content of the crown/roots of the crop. Depending on the proportion of stored nutrients, growers may wish to modify their late-season and early-season feed regime to ensure that optimum levels are maintained in the crop. It was of interest to the growers interviewed whether it would be possible to use nutrient analysis of the crown at specific points in the season (after harvest or before bud break) to provide a mechanism for predicting subsequent nutrient requirements or yield potential. Therefore, it would be of benefit if target values for N content of crowns for field and forced production could be used to guide nutrient applications.

Secondly, nutrients taken up by the crop but not removed during harvest may represent an additional source to subsequent crops. Besides crown reserves, another biological source of nutrients may be found in removed leaf material that is typically discarded on the soil surface during harvest which is liable to return a significant proportion of nutrients back into the soil as it decays. Anecdotal evidence from Brassica crops suggests that rates of decay in cabbage/cauliflower is sufficient for foliar nutrients from the crop to be returned to the soil within 2-3 months after cutting, so there is some potential for a nutrient store to be present that may offer nutrient supplies to the crop.

Micronutrients

The effect of availability of other nutrients on crop performance is less widely reported. Burt (2016) recommended magnesium sulphate application at 50 kg/ha every three months, with 20 kg/ha manganese sulphate and 18 kg/ha each of borax, ferrous sulphate, copper sulphate and zinc sulphate and 2 kg/ha sodium molybdate every 18 months. Schrader (2000) recommended 0.6 kg/ha of boron applied as a foliar spray when sticks are 6 – 8” tall, with OSU (2004) recommending 1 – 2 kg/ha of boron applied to established crops. Of the growers interviewed, sulphate was applied either through shoddy (30 kg SO_3/ha from 3 t/ha shoddy) or ammonium sulphate application (72 kg SO_3/ha). There was interest in whether magnesium, manganese or boron nutrition impacted stalk quality as evidence here is lacking.

Other Aspects Impacting Nutrition Status

Besides the influence of quantity and timing on NPK applications, and the possible influence of micronutrient requirements, a number of additional areas of interest were identified during grower consultation. Specific environmental influences, which could be addressed in eventual recommendations, were identified – e.g. the influence of soil type (e.g. issues of leaching and acidification in sandy soils) and the availability of water (reduced efficacy of nutrient applications in dry periods where irrigation is unavailable). There was also a perception that there is a paucity of information relating to correct nutrition management, the impact of different products (e.g. liquid vs. granular fertiliser) and innovative products (e.g. biostimulants).

Forcing

Very little information is available on crops grown for forcing. Recommendations derived from RB 209 (5^{th} Ed.) suggest that annual dressings of 300 – 400 kg/ha N should be applied as two or more equal dressing before the canopy has grown sufficiently to be damaged by application. Of the growers interviewed for this review, second year forced crops are only fertilised if in a weak condition, and if extra application is required this is limited to 75 kg N/ha as ammonium nitrate. While this is primarily judged on an *ad hoc* basis, evidence-based support (e.g. target nutrient levels in the crown) may be of benefit for growers here. Another grower observed that crops destined for forcing might be topped off and given an additional N application in the late season to keep the crop greener for longer – this was done in the belief that this will stimulate larger crowns, giving greater potential yields when forcing. In crops grown for forcing, peak crop activity across the season should be targeted to promote crown development. As a result, it is considered unlikely that forced crops will require reduced nutrient input compared with pulled crops, but nutrition management should be targeted to maintain crop condition as long as possible to promote light capture and dry matter accumulation in the root. Therefore, these crops may benefit from later applications of N than would typically be required for pulled crops.

Varying Nutrient Applications

Present in both the recommendations and responses from grower practice are two key influences of variation in applied nutrients: crop condition and age of crop. In the first instance, growers routinely report a broad range of nutrient applications based on crop condition, scheduling and history. This aspect is too vague to be properly addressed in recommendations, as this will reflect each individual growers' conditions, requirements and beliefs, but judgments regarding quantity and timings of applications can still be supported by a well-developed evidence base. Second to short-term variation, recommendations and grower practice support differing levels of application to crops that are establishing compared with mature crops. This will reflect the different biological potential (and need) of the crop to absorb and use soil nutrients, and differing demands placed on a maiden crop that is not being pulled relative to one that is subject to harvesting.

Field trials

Field trials were carried out to test the effect of nitrogen application rate and timing in field grown rhubarb at three different sites over three years (2020 to 2022). Field sites were located in a commercial crop on the following farms:

- Barfoots Farms Ltd.Sefter Farm, Pagham Road, Bognor Regis, W. Sussex (2020)
- T H Hammond & Sons, New Farm, Redhill, Nottingham (2020 & 2021)
- E Oldroyd and Sons, Hopefield Farm, The Shutts, Leadwell Ln, Rothwell, Leeds (2021 & 2022)

Figure 1. Location of trial sites

The initial experimental approach was informed by the outputs of the literature review and agreed with growers. The treatments and measurement programme were modified in later years. Therefore, the experimental approach is described separately for each year of the study.

The project focussed on N requirements of commercially grown rhubarb in an established crop. The requirements of rhubarb during the establishment year are likely to be different to that of an established crop, and while this is likely to be of significant interest, the primary focus of this project was in an established crop of two years or older.

Table 4. Summary of trial sites

Site	Year	Variety	Soil type
Barfoots	2020	Timperley Early	Sandy loam SNS Index 0
Hammonds	2020	Timperley Early	Sandy clay loam SNS Index 0
Hammonds	2021	Timperly Early	Sandy loam SNS Index 0
Oldroyd	2021	Timperly Early	Sandy clay loam SNS Index 0
Oldroyd	2022	Timperly Early	Sandy clay loam SNS Index 0

Year 1 field trials (2020)

Field sites

Field trials were carried out at within a commercial farm planted rhubarb crop of Timperley Early at two sites in 2020:

- Barfoots Farms Ltd.Sefter Farm, Pagham Road, Bognor Regis, W. Sussex (site 1)
- T H Hammond & Sons, New Farm, Redhill, Nottingham (site 2)

Both sites included main season N rate and timing treatments. Hammonds site included additional autumn N treatments.

Sites were selected that were likely to show a response to N (i.e. low SNS Index site). The area used had not received any applications N fertiliser or organic manures since autumn 2019.

Experimental treatments and design

Main season nitrogen treatments

At the start of the season there were nine fertiliser N treatments planned comprising combinations of rates and timings of N application, plus a zero N control treatment (10 treatments in total). Each treatment was replicated three times and arranged in a randomised block design. **However, because of Covid-19 restriction only the first N treatment (T1) was applied.** Details of planned treatments are given below and in Table 5.

The planned treatments tested three N rates:

- 175, 275 and 375 kg N/ha

In addition, the planned treatments would have tested three N application timings:

- All of the N applied in a single application just after bud-break (T1)
- 60% of the N applied just after bud-break (T1) and 20% before re-growth of each subsequent crop (T2 and T3)
- 30% of the N applied just after bud-break (T1) and 35% before re-growth of each subsequent crop (T2 and T3)

Table 5. Year 1 (2020) **planned** nitrogen fertiliser treatments (main season applications)

Treatment number	Rate category	Timing category	Application timing (kg N/ha)			Total applied (kg N/ha) Note only T1 application applied
			T1 (just after bud-break – 2 leaves per bud)	T2 (before 2nd crop regrows) Not applied	T3 (before 3rd crop regrows) Not applied	
1	**0**	**0**	0	0	0	0
2	**1**	**A**	175	0	0	175
3	**1**	**B**	105	35	35	175
4	**1**	**C**	53	61	61	175
5	**2**	**A**	275	0	0	275
6	**2**	**B**	165	55	55	275
7	**2**	**C**	83	96	96	275
8	**3**	**A**	375	0	0	375
9	**3**	**B**	225	75	75	375
10	**3**	**C**	113	131	131	375

Table 6 shows the actual N rates applied in the single T1 application at the end of January 2020. There were ten N rates, including a zero N control, from 53 to 375 kg N/ha.

Table 6. Year 1 (2020) **actual** nitrogen fertiliser treatments (main season applications)

Treatment number (treatment numbers ordered by N rate)	Total applied (kg N/ha) *Applied in single application at T1 (just after bud-break – 2 leaves per bud)*
1	0
4	53
7	83
3	105
10	113
6	165
2	175
9	225
5	275
8	375

Pulled and unpulled trial with autumn nitrogen treatments

Supplementary to the 2020 trials, a limited trial was carried out at the Hammonds site to explore the impact of late season N application – a single application of 0, 75 and 150 kg N/ha were made to three replicate plots of a pulled and unpulled crop on 02/09/20 to test the impact of late season application.

Individual plot size was 7 m x 4 beds (3.3 m). Measurements and harvests were all taken from 5m of the central 2 beds. Nitrogen treatments were topdressed by hand as Calcium Nitrate (27% N). With the exception of N fertiliser, the farm sites managed all other inputs to the trial as for the rest of the commercial crop.

Barfoots Farm site: the farm applied lime at 6 t/ha and K at 150 kg K_2O/ha across the whole trial area to ensure these nutrients aren't limiting. There was sufficient P_2O_5 and Mg from the soil analysis and no additional applications were made.

Hammonds Farm site: the farm applied potash at 250 kg K_2O/ha across the trial area.

Measurements

Soil analysis

Topsoil samples (0-15 cm) were taken from each site at the start of the experiment and analysed for pH, extractable P (Olsen's method), extractable K and Mg, and soil texture (percentage sand, silt and clay). Soil profile samples were taken for soil mineral N determination in January 2020 prior to bud break; samples were taken in 30 cm depths to 0-60 cm at the Barfoots site (where sampling depth was limited by shallow soil) and 0-90 cm at the Hammonds site.

Harvest assessments

Due to Covid-19 restrictions only one harvest was carried out at the sites (instead of the planned three harvests). There was a single harvest in April 2020 at both sites.

Yield

Eight plants per plot were harvested. Harvesting was done using commercial practice from a single harvest with the leaves removed from the petioles. All the sticks were harvested per crown keeping each crown separate. The harvested leaves were bulked together to record the fresh weight per plot.

For each plot the following assessments were made:

- Number of crowns per plot
- Number of petioles - Total

- Total Fresh Weight of Harvestable petioles
- Total Fresh Weight of Marketable/Unmarketable petioles

Marketable yield was measured as the number of petioles within marketable specification and then weighed to give weight of all marketable petioles. Sticks were considered marketable if the cut length exceeded 25cm, with a minimum diameter of 1cm, were free of significant bending/twisting and pest/disease damage. Petioles that did not meet the criteria were considered unmarketable.

A sub-sample of the stem and leaf crop material was dried for 48 hours at 80ºC to determine dry matter content, and then sent to NRM laboratory for nutrient analysis.

Crop quality

In addition to yield assessments, crop quality was assessed on five sticks from each plot. Assessments included:

Dimensions: Total length of the stick, additionally petiole width and depth was measured 5 cm from the snapped end.

Colour: Petiole colour is a key criterion for the marketability of rhubarb. Red pigmentation in the petiole fades as chlorophyll concentration increases, particularly near the top of the stick in green pull rhubarb. Measurement of colour based on visual assessment (e.g. categorical assessments) can be subjective. To avoid this, sticks were subject to assessment by colorimeter to determine stick colour against the L*, a* and b* axes (white-black, green-red and blue-yellow respectively). These parameters were used to calculate the color index value using the equation 2000 x a*/L* x (a*2 + b*2)0.5. This approach was described previously by López Camelo & Gomez (2004) to numerically quantify the green-to-red shift in tomato ripening, and given that a similar transition is seen in rhubarb, this approach was considered justified. A more positive colour index indicates a stronger red, while a smaller (or negative value) indicates increasing depth of green. L* a* b* values were taken using a Konica Minolta CR-400 Chroma Meter. Measurements were taken at three equidistant points along each petiole, with the first 5 cm from the snapped end to represent the top, middle and bottom measurement from the inside face of the petiole.

Results

Soil analysis

Soil analyses were obtained for both sites are detailed in the Table 7 below. The Barfoots site was a sandy clay loam soil, and Hammonds site was a sandy loam site. Both sites were SNS Index 0.

Table 7. Topsoil and SMN analysis - year 1 sites

Site	pH	Index			SMN* kg N/ha (Index)	Soil type
		P	K	Mg		
Barfoots	6.0	4	3	3	38.6 (0)	Sandy clay loam
Hammonds	7.18	4	1	2	15.7 (0)	Sandy loam

*0-60 cm at Barfoots and 0-90 cm at Hammonds

Crop Condition at First Harvest – March 2020

The average number of crowns was 6000 crowns/ha at the Barfoots site and 8600 crowns/ha at the Hammonds site (Figure 2). Crown variability at this stage would be due to past crop history independent of nutrition management, but the crop was assessed at this stage to quantify the extent of variation in whole plant number across the trial. Similarly, there was significant variation in bud numbers between crowns recorded in each treatment. Average bud number at Barfoots varied from 2.2 – 5.5 buds/crown, compared with 1.5 – 4.6 buds/crown at Hammonds (Figure 3). Bud number is likely to be predominantly determined by the crop condition at the end of the previous season rather than new formation at the season start.

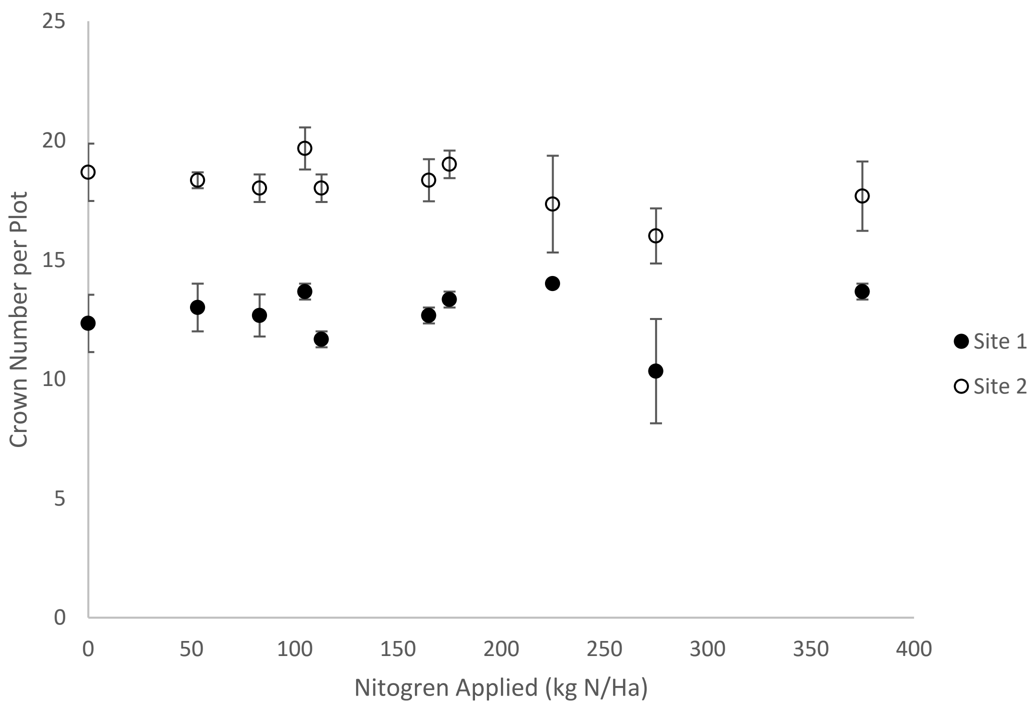

Figure 2. Number of Crowns per plot. Average number of crowns per 7 m x 3 bed plot area for each site against nitrogen treatment (site 1 = Barfoots; site 2 = Hammonds)

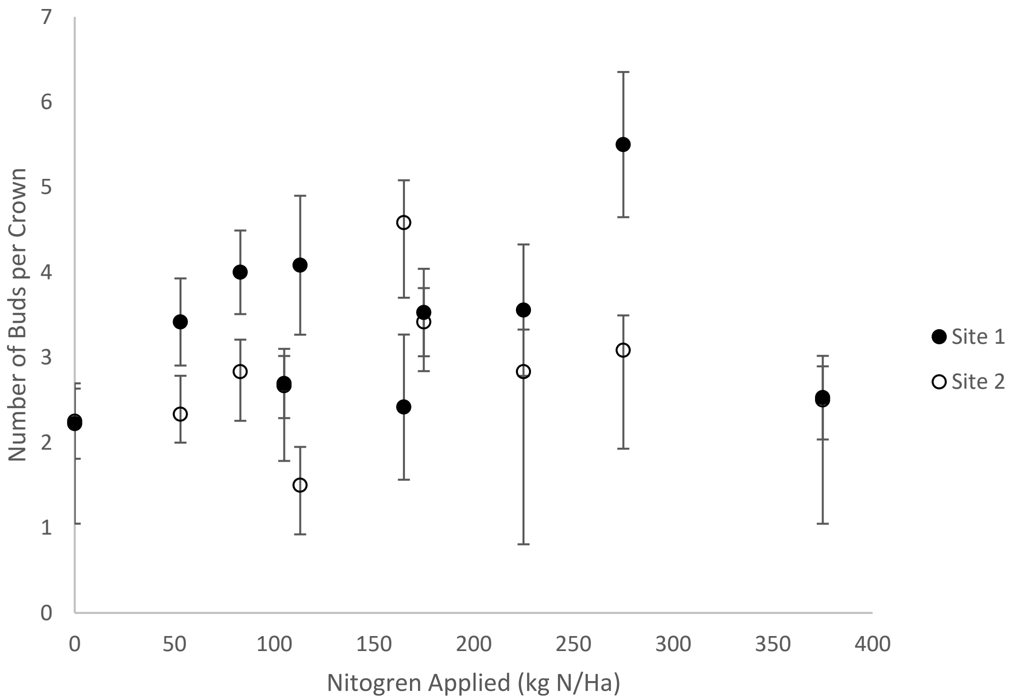

Figure 3. Number of buds per crown. Average number of buds per crown recorded in each treatment plot before treatments applied (site 1 = Barfoots; site 2 = Hammonds)

Crop Productivity

Crop productivity showed similar variation between sites (Figure 4, Figure 5). Gross stick number per crown was higher at Barfoots, but gave a smaller gross weight than Hammonds, indicating that the sticks at Barfoots were shorter/thinner than that seen at Hammonds. Stick number varied broadly between plots at Barfoots with an increase in stick number seen between 175 – 275 kg N/Ha compared with relatively consistent stick numbers at lower treatments, although stick number declined at 375 kg N/Ha. Marketable stick number was relatively consistent between treatments at Barfoots, with only a marginal insignificant increase at 275 kg N/Ha. At Hammonds both gross and marketable stick number was consistent between different N treatments. Stick numbers could be higher due to older crowns, although these are liable to produce thinner sticks. However, these data do not suggest any direct relationship between stick number and N application.

Gross and marketable yield by weight at Barfoots showed strong variation with declines in both gross and marketable yield between 83 and 225 kg N/Ha, followed by increases at 275 kg N/Ha and a decline at 375 kg N/Ha. At Barfoots ANOVA of gross yield and marketable yield showed no significant difference with P=0.67 and P=0.83 respectively. Gross and marketable yield by weight was greater at Hammonds, but showed a more consistent profile across treatments, although a general increase in yield was seen with increased N application treatments. However, the differences in yield in gross and marketable yield were insignificant, returning *P* values of 0.17 and 0.38 respectively. Similarly, these data do not imply a relationship between yield outputs and N applications.

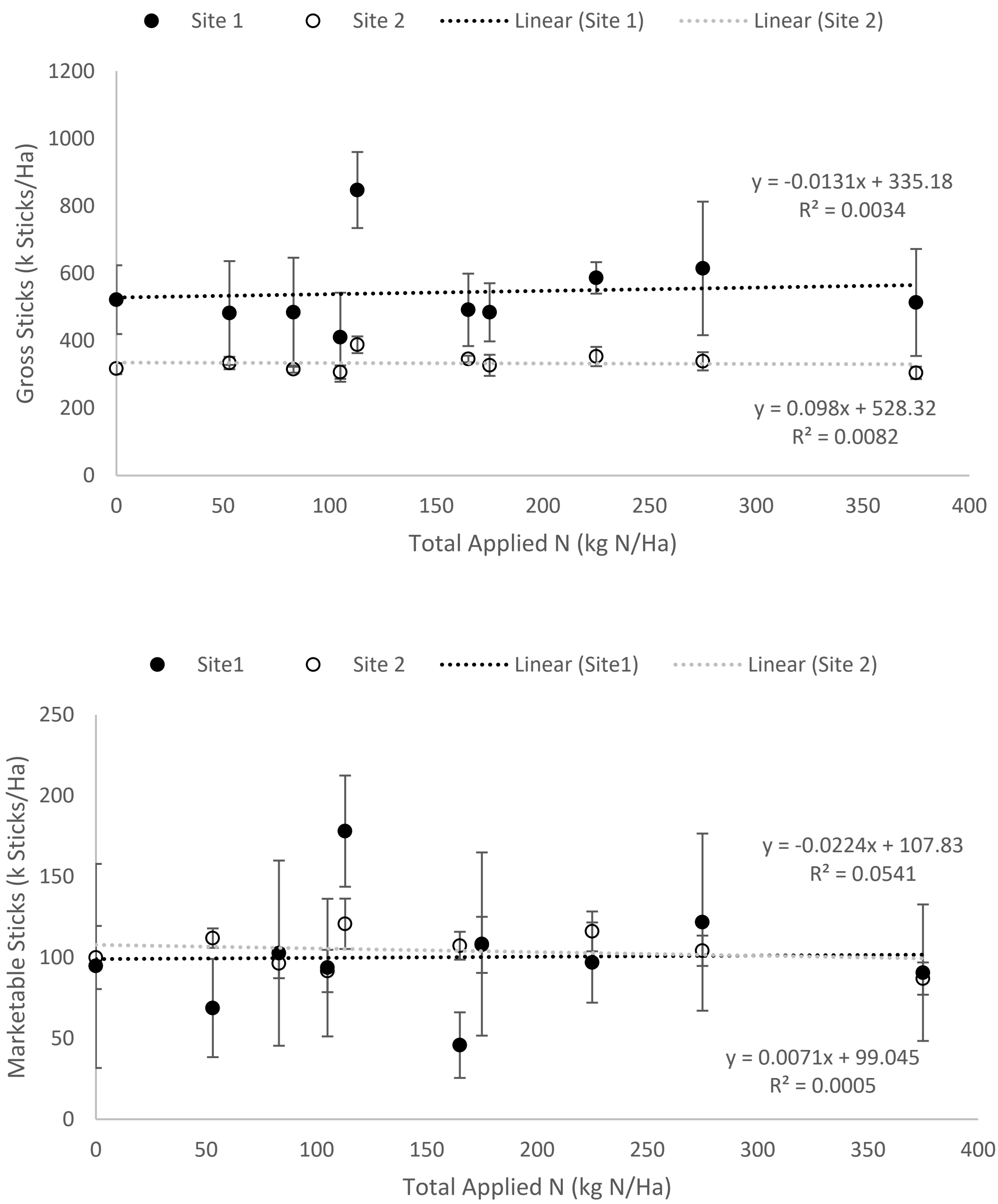

Figure 4. Gross and marketable yield per Ha (standardised to a crown density of 12500 crowns/Ha) presented as number of thousand sticks harvested, averaged across plots at site 1 (Barfoots) and site 2 (Hammonds)

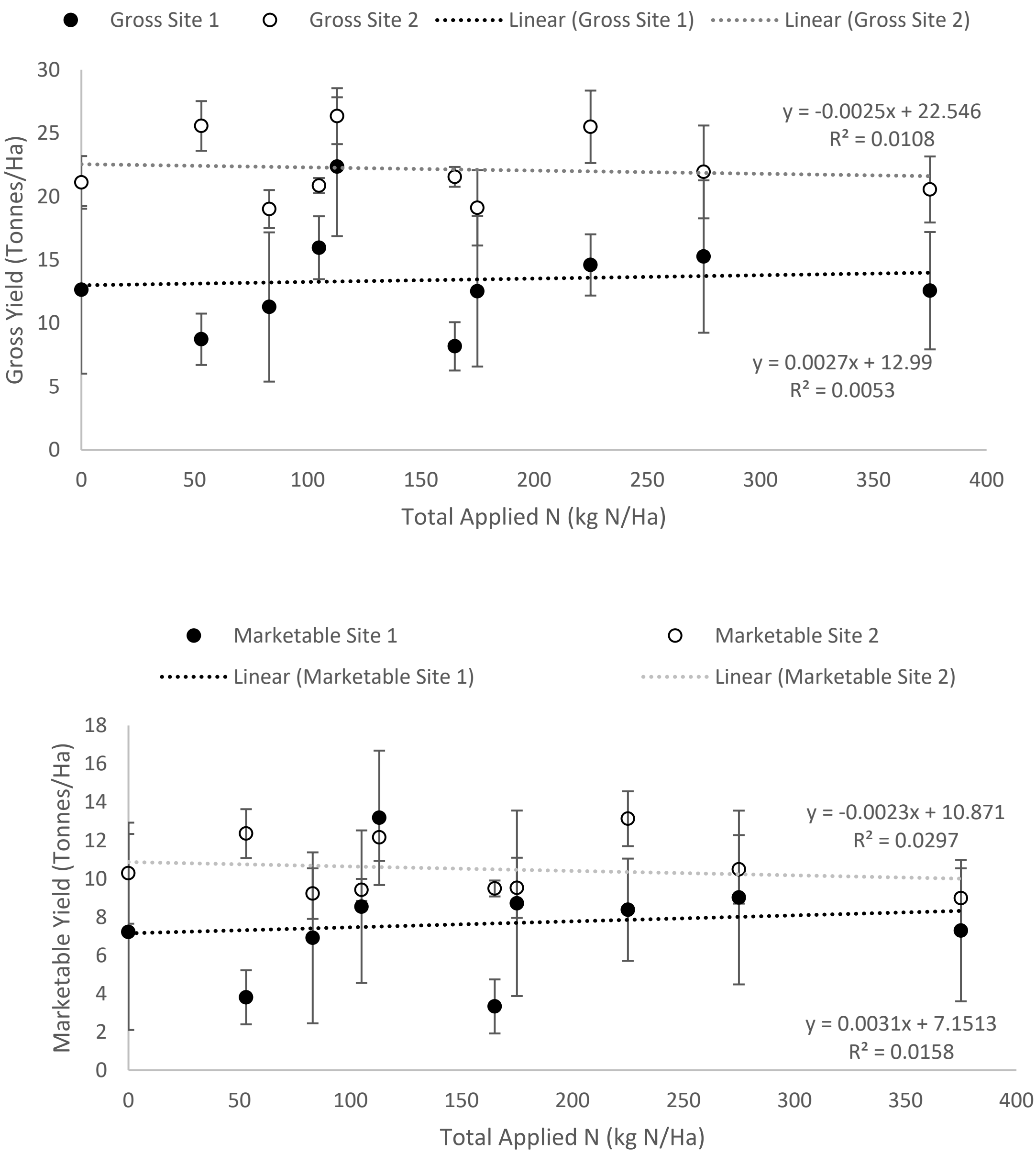

Figure 5. Gross and marketable yield per Ha (standardised as 12500 crowns/Ha) presented as weight for site 1 (Barfoots) and site 2 (Hammonds)

Examination of stick dimensions largely corresponds with the observations above. Average stick dimensions were greater at the Barfoots site, showing increased length and width to those sampled from the Hammonds site (Figure 6). There were significant differences between N application and stick length (*P*<0.001) but not width (*P*=0.12) although this is most likely to be due to innate variation as there is no clear correlation between N application and stick length. At Hammonds there were no significant differences for either length or width (*P* = 0.35 and 0.67 respectively). Therefore, while large variability can be seen between the treatments at both sites, there is no overriding relationship between N applications and stick quality as measured within these parameters.

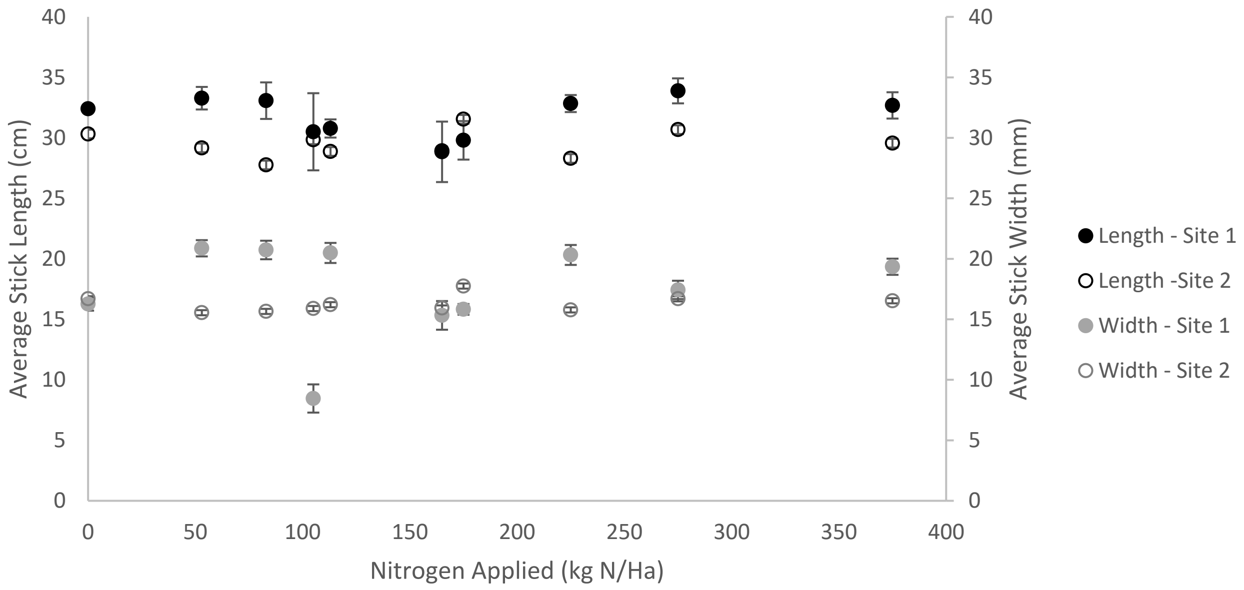

Figure 6. Average stick length and width as recorded from subsamples taken at site 1 (Barfoots) and site 2 (Hammonds)

Nitrogen Uptake

Nitrogen content of above ground biomass was relatively comparable between the two sites, although sticks harvested at Hammonds had greater proportions of N than that seen at Barfoots (Figure 7). When compared against gross crop yields, it is possible to determine the crop N uptake as represented by above ground yields (leaf and stick) of the crop (Figure 8). Total N uptake at Barfoots exceeded that seen at Hammonds, largely due to the increased yield seen at this site. While there is broad variability in N uptake at Barfoots, the N uptake at Hammonds was proportionately more uniform. However, neither site showed a correlation between applied N and N uptake (*P*=0.47 for Barfoots; *P*=0.37 for Hammonds), implying that the observed N uptake is independent of N application at this stage in the season.

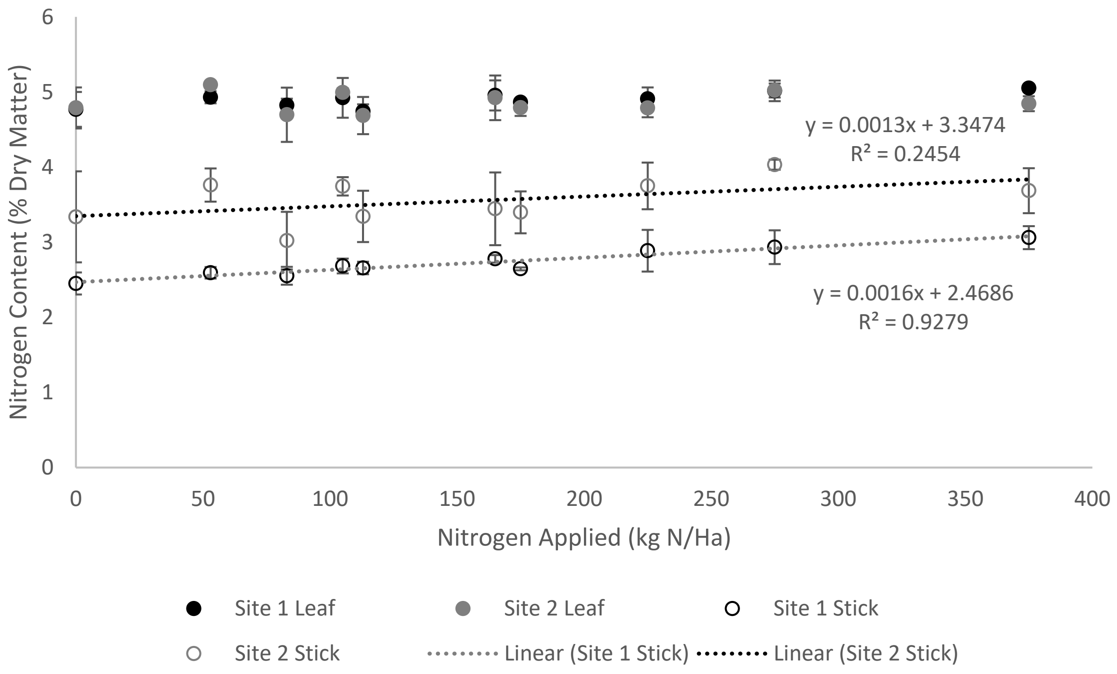

Figure 7. Percentage nitrogen of plant dry matter of stick and leaf fractions at harvest (site 1 = Barfoots; site 2 = Hammonds)

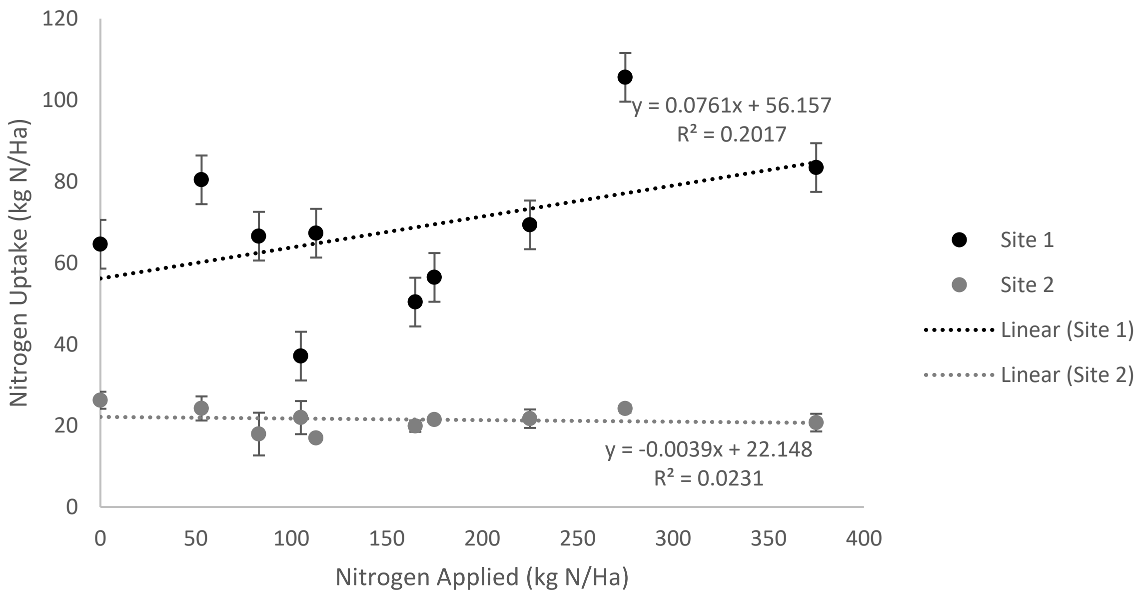

Figure 8. Nitrogen uptake per Ha based on combined leaf and stick samples at site 1 (Barfoots) and site 2 (Hammonds)

Pulled and unpulled trial with autumn nitrogen treatments

The late pulled trial area showed a significant reduction in yield in terms of both gross and marketable fresh weight, although this did not translate through to a reduction in gross or marketable number (Figure 9). A similar number of sticks indicates that bud inception was not altered, although a reduction in weight indicates that less reserves were available from the crown in the following spring as a result of the late pull. This also supports the concept that early spring growth is heavily reliant on the reserves of the crowns, and that weakness in conditions in the late autumn (including a harvest) would translate through to reduced yield performance in the following spring.

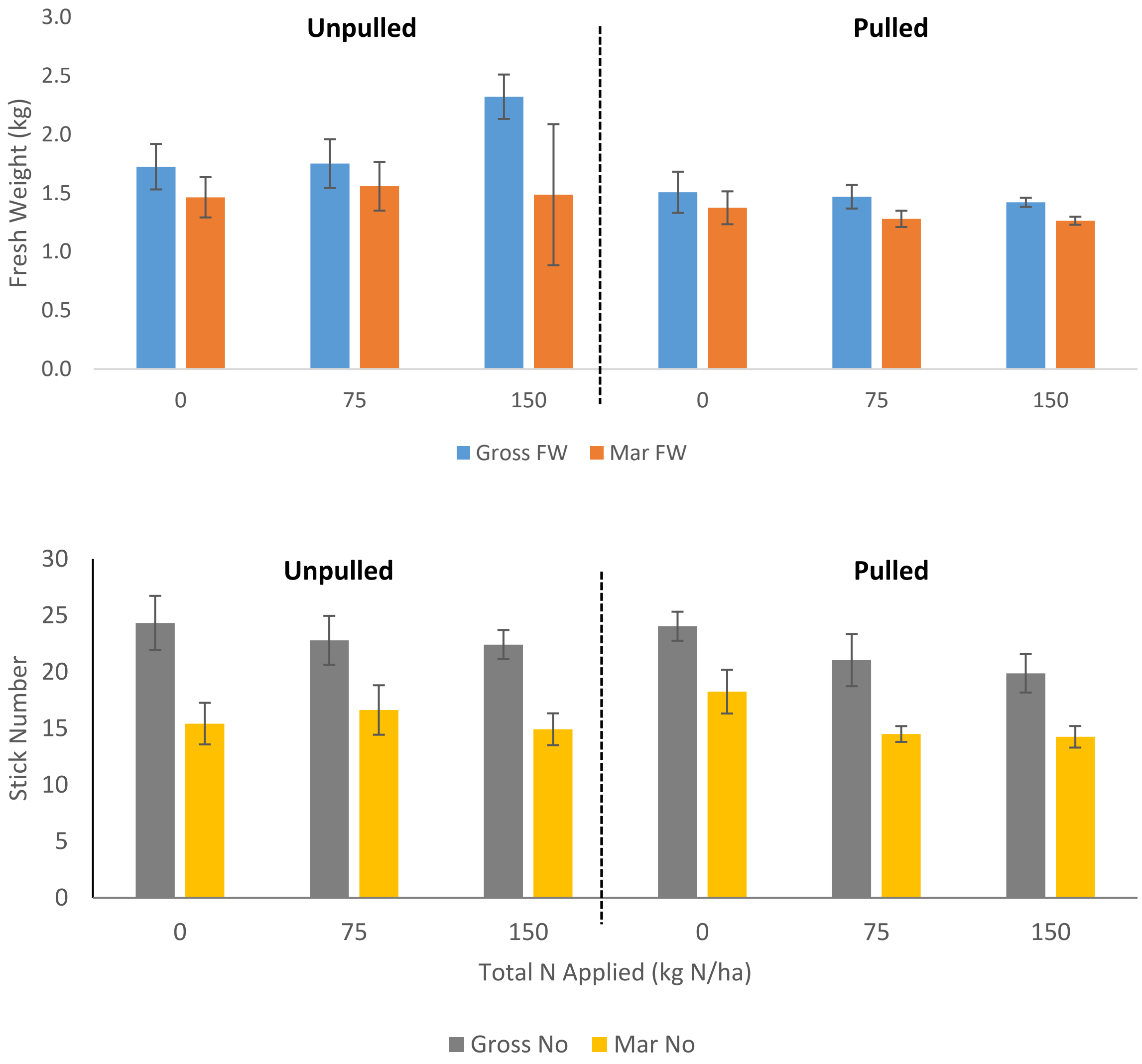

Figure 9. Yield performance from the pulled vs. unpulled trial at Hammonds

Discussion – Year 1 results

The onset of the covid-19 outbreak in March 2020 had a significant impact on delivery of planned trials work in this first year. The first (pre-emergence) N fertiliser application was carried out at the end of January 2020, followed by a single harvest at each site in April 2020. The limits on non-essential work and travel meant that further applications and assessments could not be carried out, and reduced the range of assessments that could be made on the achieve harvest. The single harvest means that reported yields are likely to be significantly below the gross and marketable yield achievable on the site (due to normal practice having a second or third pull).

However, the treatments applied do allow us to test the effect of early N application. Both sites were SNS Index 0 and therefore likely to be responsive to N application. Despite this, there was no significant increase in marketable yield with N rates of up to 375 kg N/ha applied following bud break at either site. This may be because early season grown in established plantations is driven by N reserves in the crown rather than from soil N. These results do not support early N applications to established rhubarb plantations.

Year 2 field trials (2021)

Field sites

Field trials were carried out at within a commercial farm planted rhubarb crop of Timperley Early at two sites in 2021:

- T H Hammond & Sons, New Farm, Redhill, Nottingham
- E Oldroyd and Sons, Rothwell.

Sites were selected that were likely to show a response to N (i.e., low SNS Index site). The area used had not received any applications N fertiliser or organic manures since autumn 2020.

Experimental treatments and design

Following the outputs of the 2020 trials, which showed no yield response to early N applications, the N treatment timings were adjusted in 2021 to focus on later season and autumn N applications. There were 16 treatments at each site split across three separate trial 'areas', each representing a different application timing category (Figure 10 and Table *8*). Total N application rates of 0, 120, 180, 240, 300 and 360 kg N/ha/year were tested either with the majority of application following the first harvest followed by a small application (60 kg N/ha) following the second harvest (Category A – Trial area 1) or with a small pre-emergence application followed by a majority post first harvest (Category B – Trial area 2). A third trial tested equal applications following the first, second and third harvests (Category C – Trial area 3). Post-harvest applications were made before the regrowth of the subsequent crop.

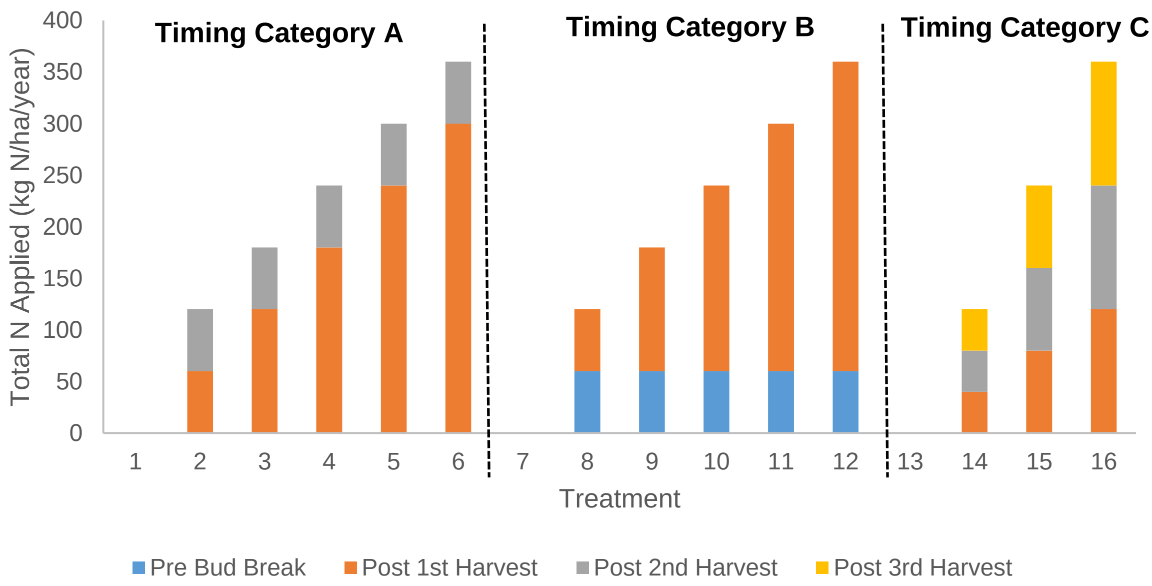

Figure 10. Trial approach for the 2021 season.

Table 8. Year 2 (2021) nitrogen fertiliser treatments

	Treatment Number	Application timing (kg N/ha)				Total applied (kg N/ha)
		T1 (Pre-emergence)	T2 (Post 1st Harvest)	T3 (Post 2nd Harvest)	T4 (Autumn - September)	
Timing A	1	0	0	0	0	0
	2	0	60	60	0	120
	3	0	120	60	0	180
	4	0	180	60	0	240
	5	0	240	60	0	300
	6	0	300	60	0	360
Timing B	7	0	0	0	0	0
	8	60	60	0	0	120
	9	60	120	0	0	180
	10	60	180	0	0	240
	11	60	240	0	0	300
	12	60	300	0	0	360
Timing C	13	0	0	0	0	0
	14	0	40	40	40	120
	15	0	80	80	80	240
	16	0	120	120	120	360

Fertiliser treatments were applied:

- Hammonds site: 5/3/21 (pre-emergence), 21/4/21 (post first harvest), 5/5/21 (post second harvest), and 06/09/21 (autumn application)
- Oldroyds site: 8/3/21 (pre-emergence), 3/6/21 (post first harvest), 9/8/21 (post second harvest), and 20/09/21 (autumn application)

Individual plot size was 7 m x 4 beds (3.3 m). Measurements and harvests were all taken from 5m of the central 2 beds. Nitrogen treatments were topdressed by hand as Calcium Nitrate (27% N). With the exception of N fertiliser, the farm sites managed all other inputs to the trial as for the rest of the commercial crop.

To ensure that potassium (K) was not limiting, the host grower at each site applied 175 kg K_2O/ha. Soil sampling indicated that sufficient soil pH, P_2O_5 and magnesium was present at the start of the trial.

Measurements

Soil analysis, yield and crop quality assessments are as described for 2020 trials.

The treatments in timing categories A and B (treatments 1-12) were harvested three times at both sites. However, in the interest of time constraints and budget only two harvests were taken from the treatments in timing category C (treatments 13-16) at Hammonds, and one harvest at Oldroyds.

Harvests at site 1 (Hammonds) were taken on the 13th April, 8th June and 6th August 2021. Harvests at site 2 (Oldroyds) were taken on the 6th May, 13th July and 27th September 2021, with a final harvest the following season on 04/05/22

Results

Soil analysis

Soil analyses were obtained for both sites are detailed in the Table 9 below. The Oldroyds site was a sandy clay loam soil, and Hammonds site was a sandy loam site. Both sites were SNS Index 0.

Table 9. Topsoil and SMN analysis - year 2 sites

Site	**pH**	**Index**			**SMN***	**Soil type**
		P	**K**	**Mg**	**kg N/ha 0-90 cm (Index)**	
Oldroyds	7.5	5	3	3	49 (0)	Sandy clay loam
Hammonds	7.5	4	2+	2	30 (0)	Sandy loam

Crop performance – summary

Crop performance was good at both sites, and applications were made as planned. The results are discussed below for timing category A and B for each site, followed by the additional trials – timing category C.

Yield Responses: Hammonds site

The crop at site one showed a good level of consistency between plots, with strong growth in the crowns and an even first harvest in terms of stick and yield (Figure 11, Figure 14). On average there were 14.8 active crowns per plot and target crown density in the field was 14,200 crowns/ha. Harvest figures are summarised in Table 10.

Hammonds Timing category A – Majority N application after 1st harvest, small N application after 2nd harvest

There was no significant difference in gross stick number between treatments, varying between 42.1 sticks/crown (0 kg N/ha) and 65.2 sticks/crown (180 kg N/ha). Likewise, there was no significant difference in marketable stick number which varied between 24.5 sticks/crown (0 kg N/ha) and 38.4 sticks/crown (240 kg N/ha). The only difference approaching significance difference within Trial 1 at Hammonds was for total gross stick number (P = 0.06). When viewed across treatments a minor trend is evident in both marketable and gross stick number, which showed a peak around 180 – 240 kg N/ha (Figure 11 & Figure 12). This was largely due to reductions in sticks harvested at the later harvests, especially the third harvest on the 6th August.

For yield, gross fresh weight varied between 3.3 kg/crown (0 kg N/ha) and 6.5 kg/crown (360 kg N/ha) (Figure 14). Marketable weight was greatest at 240 kg N/ha (4.2 kg/crown) and least at 0 kg N/ha (2.4 kg/crown) (Figure 15).

There was a small, but not significant, relationship between treatment and harvest. Marketable stick number was relatively equal between harvests at the first pull, although reductions in stick number at low N rates (especially 0 kg N/ha) at the second, and most notably, the third pull were demonstrated. It is also notable that marketable stick number declined at 360 kg N/ha (Figure 13) although this was largely due to sticks being outside of specification for length rather than a specific reduction in number. Fresh weight (both gross and marketable) was more consistent between treatments (Figure 16), although a similar reduction in the second and third harvests was seen at 0 kg N/ha compared with the other treatments.

Overall, there was no significant interaction between N treatment and yield output, although minor trends demonstrate peak N response around 240 kg N/ha.

Hammonds Timing category B – Small N pre-emergence application, majority N application after 1st harvest

Stick numbers were similarly comparable between treatments in timing category B. The number of sticks varied between 54.2 sticks/crown (0 kg N/ha) to 68 sticks/crown (240 kg N/ha). Marketable stick number was lowest at the 120 kg N/ha treatment (31.7 sticks/crown) and greatest at 240 kg N/ha (37.9 sticks/crown). Gross fresh weight yield was highest at 120 and 300 kg N/ha (6.7kg/crown) whilst marketable yield was greatest at 180 kg N/ha (4.1 kg/crown).

Similar patterns in stick number (both gross and marketable) were seen for timing category B as for timing category A, with a minor increase in stick number at 180 and 240 kg N/ha compared with the higher or lower doses (Figure 11, Figure 12). Gross and Marketable fresh weight yields showed more variation between treatments, with greatest yields seen at 120 and 300 kg N/ha for both gross and marketable yield (Figure 14, Figure 15). Similarly, when examined on a per crown basis, these is less of a clear response to N application changes compared with timing category A (Figure 16) These data would suggest the lack of any significant trend, and that observed differences are reflective of natural variation between plots rather than as a direct response to N applications.

Table 10. Summary yield figures for Trial 1 and Trial 2 in total across the 2021 season – Hammonds.

	N Application (kg N/ha)	Gross Fresh Weight (kg/crown)	Marketable Fresh Weight (kg/crown)	Gross Number (sticks/crown)	Marketable Number (sticks/crown)
Timing category A	0	3.3 ± 0.6	2.4 ± 0.4	42.1 ± 5.6	24.5 ± 3.7
	120	4.7 ± 0.7	3.1 ± 0.4	58.4 ± 11.6	32.3 ± 4.4
	180	5.3 ± 0.7	3.4 ± 0.5	65.2 ± 8.7	35.5 ± 5
	240	5.9 ± 0.7	4.2 ± 0.6	61.3 ± 8.1	38.4 ± 5.1
	300	5.8 ± 0.7	3.7 ± 0.5	63.6 ± 7.7	35.8 ± 5
	360	6.5 ± 0.7	3.2 ± 0.5	62.1 ± 8.1	30.4 ± 4.4
Timing category B	0	4.2 ± 0.6	3.3 ± 0.5	54.2 ± 7.4	34.9 ± 5.3
	120	6.7 ± 0.7	3 ± 0.5	59.6 ± 8	31.7 ± 4.6
	180	5.5 ± 0.8	4.1 ± 0.6	63.5 ± 8.1	36.5 ± 5
	240	5.8 ± 0.8	3.5 ± 0.5	68 ± 8.5	37.9 ± 5.4
	300	6.7 ± 0.8	3.4 ± 0.5	67 ± 8.1	30.8 ± 4
	360	5.9 ± 0.8	3.7 ± 0.6	66.5 ± 8.6	34.7 ± 4.9

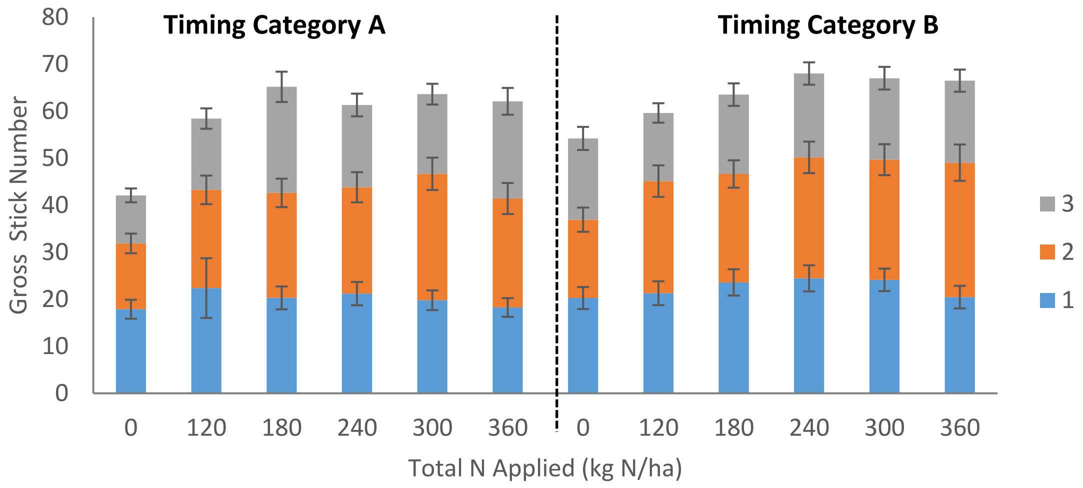

Figure 11. Gross stick number per crown by harvest (Hammonds)

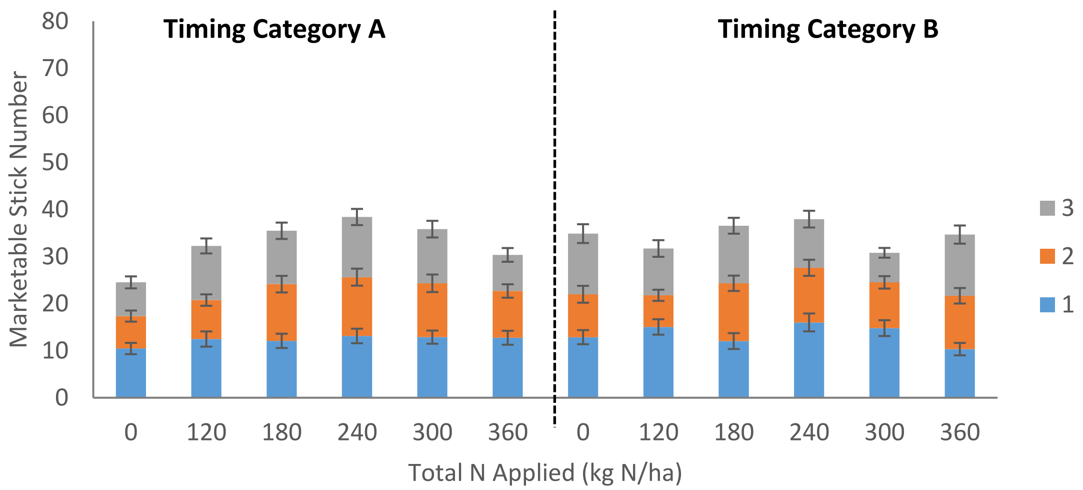

Figure 12. Marketable stick number per crown by harvest (Hammonds)

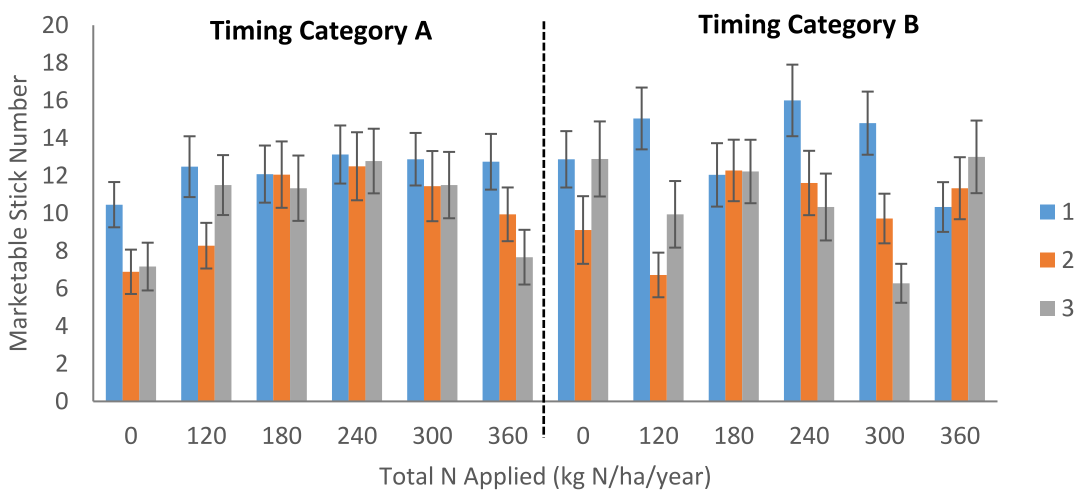

Figure 13. Marketable yield – sticks per crown by harvest (Hammonds).

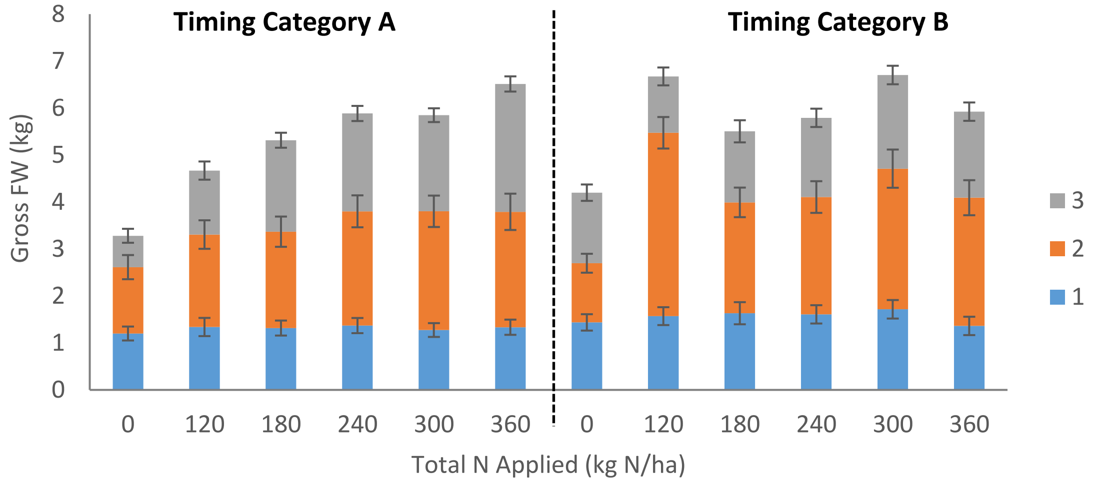

Figure 14. Gross yields per crown by harvest (Hammonds)

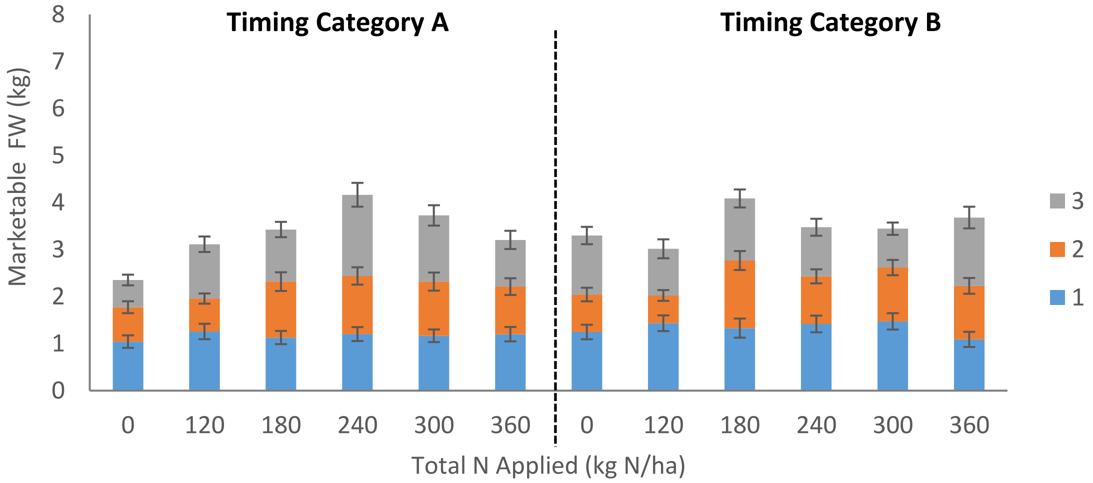

Figure 15. Marketable yields per crown by harvest (Hammonds)

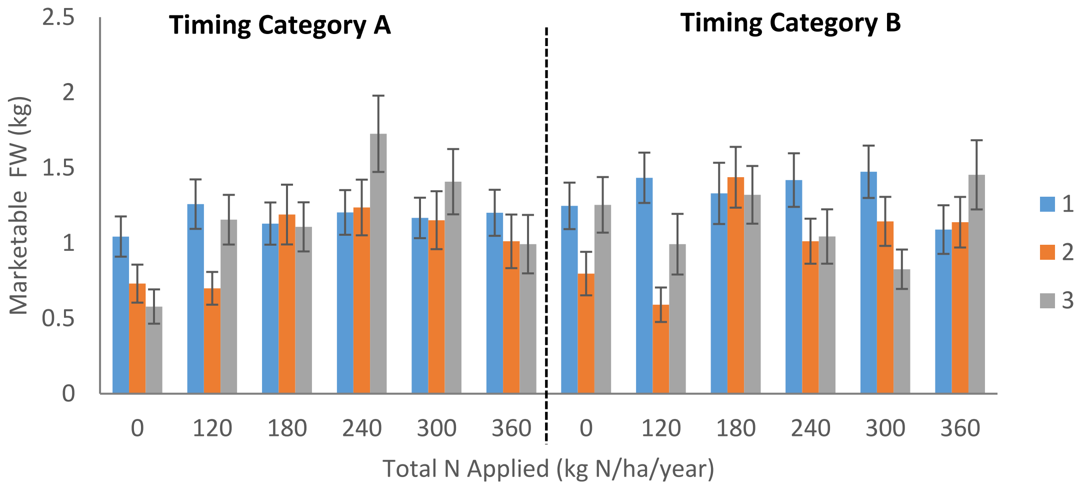

Figure 16. Marketable yields per crown by harvest (Hammonds)

Yield Responses: Oldroyds site

The average number of crowns per plot was 14.8, and the target field density was 13,600 crowns per ha. Crop condition was generally good, although the older crop showed slightly less uniformity compared with the crop trialled at Hammonds. Summary harvest results are presented in Table 11. The final harvest was taken later in the season (27th September) and the crop was starting to senesce, although later harvests are generally lower yielding compared with harvests in the earlier season.

Oldroyds Timing category A – Majority N application after 1st harvest, small N application after 2nd harvest

Overall yield responses were relatively consistent between treatments according to all yield outputs. There was a slight reduction in gross stick number at 120 kg N/ha (33.1 sticks/crown compared with 39.9 - 43.1.1 sticks/crown across other treatments - Figure 17), although marketable stick number was consistent across all treatments (Figure 18). Marketable stick number was also relatively consistent between harvests (Figure 19), although there was a minor but non-significant reduction in stick number (especially for the second harvest) at 0 kg N/ha compared with the other treatments.

Oldroyds Timing category B – Small N pre-emergence application, majority N application after 1st harvest

Yield responses for timing category B treatments showed a more pronounced response to N application, although no significant differences were evident between treatments. Gross stick number was greatest at 180 kg N/ha (49.8 sticks/crown) (Figure 17), and marketable stick number was increased with greater N application which was greatest at 240 and 300 kg N/ha (32.7 and 30 sticks/crown respectively) (Figure 18).

Gross fresh weight was greatest at 180 kg N/ha (3.2 kg/crown), and 300 kg N/ha (3.1 kg/crown) although there were no significant differences between treatments (Figure 20). Marketable fresh weight yields were much more consistent between treatments, although there were minor reductions at 0 and 360 kg N/ha compared with the other treatments (Figure 21). The reduction at 360 kg N/ha was largely due to an increase in oversized sticks rather than a reduction in total stick mass. When broken down by harvest, the second harvest was generally greater that the first or third harvest (Figure 22), although this is likely to be the long time gap between the first and second harvest (6th May – 13th July) compared with the third harvest (27th September).

Whilst the crop was relatively variable, and there were no significant differences between treatments, there are some minor trends that are evident when compared across treatments. When considering the relative proportions of the first and second harvests there appears to be a small increase in yield outputs around 180 – 240 kg N/ha at Timing Category B, particularly through harvested stick number. However, the lack of significance and high background variability makes it difficult to define any clear response to N application.

Table 11. Summary yield figures for Trial 1 and Trial 2 in total across the 2021 season – Oldroyds

	N Application (kg N/ha)	Gross Fresh Weight (kg/crown)	Marketable Fresh Weight (kg/crown)	Gross Number (sticks/crown)	Marketable Number (sticks/crown)
Timing category A	0	2.7 ± 0.5	1.9 ± 0.3	43.1 ± 5.8	26.9 ± 4
	120	2.5 ± 0.5	2 ± 0.3	33.1 ± 4.8	24.8 ± 3.6
	180	2.5 ± 0.4	1.8 ± 0.3	40.9 ± 5.5	26.6 ± 3.7
	240	2.7 ± 0.4	1.9 ± 0.3	39.9 ± 5.2	27.2 ± 3.7
	300	2.6 ± 0.5	1.9 ± 0.3	41 ± 5.6	26.8 ± 3.8
	360	2.8 ± 0.5	2 ± 0.3	41 ± 5.7	27.3 ± 3.7
Timing category B	0	2.6 ± 0.4	1.8 ± 0.3	39.9 ± 5.4	26.7 ± 3.8
	120	2.8 ± 0.4	2.2 ± 0.3	42.9 ± 5.9	29.4 ± 4
	180	3.2 ± 0.6	2.1 ± 0.3	49.8 ± 6.5	29.8 ± 4.4
	240	2.8 ± 0.5	2.1 ± 0.3	47.4 ± 6.2	32.7 ± 4.4
	300	3.1 ± 0.5	2.2 ± 0.3	47 ± 5.7	30 ± 3.9
	360	2.7 ± 0.5	1.9 ± 0.3	37.2 ± 4.8	24.5 ± 3.4

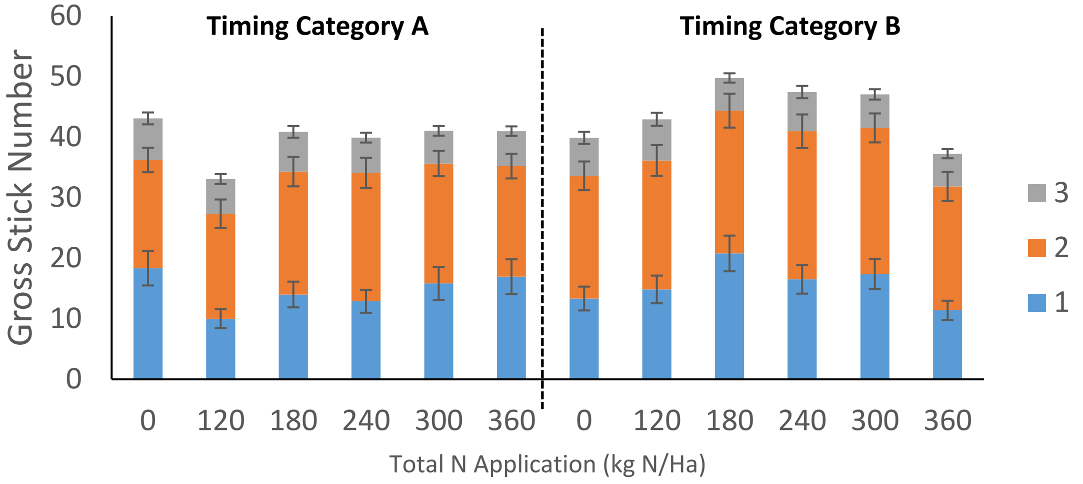

Figure 17. Gross stick number per crown by harvest (Oldroyds)

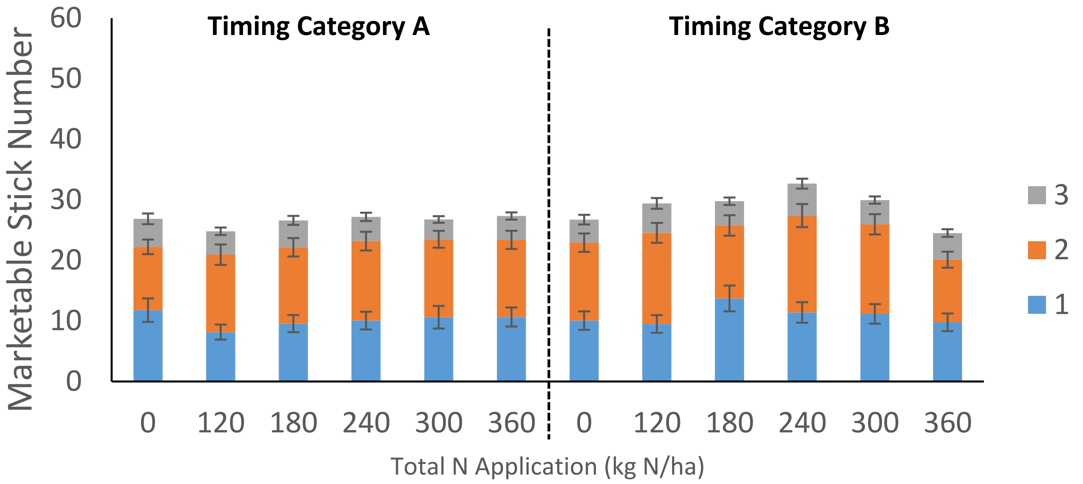

Figure 18. Marketable stick number per crown by harvest (Oldroyds)

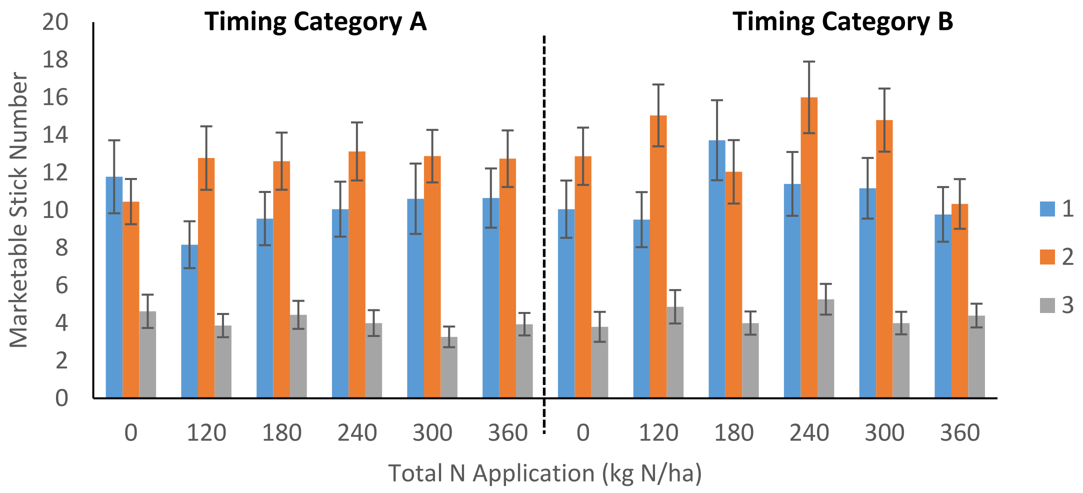

Figure 19. Marketable stick number per crown by harvest at Oldroyds.

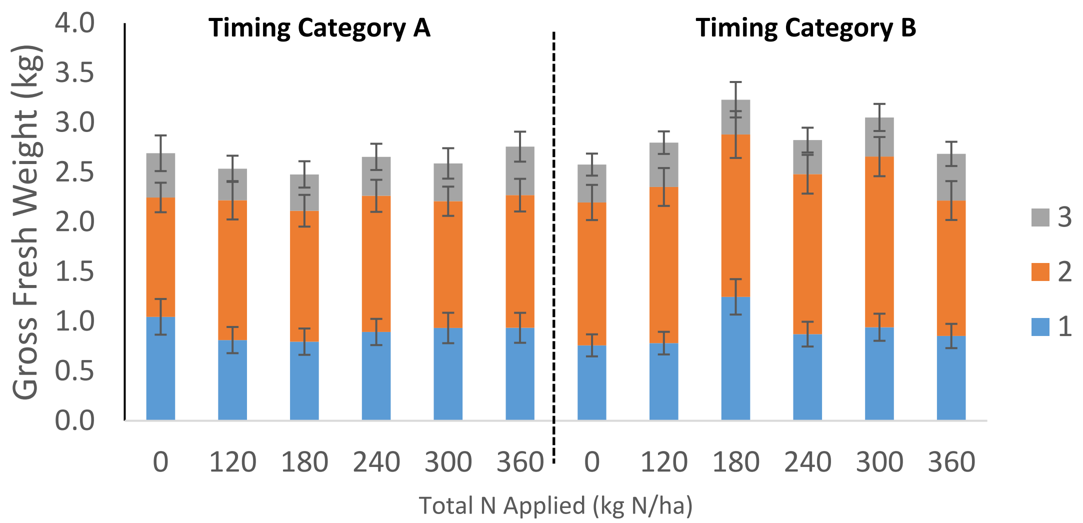

Figure 20. Gross Fresh Weight per crown by harvest (Oldroyds)

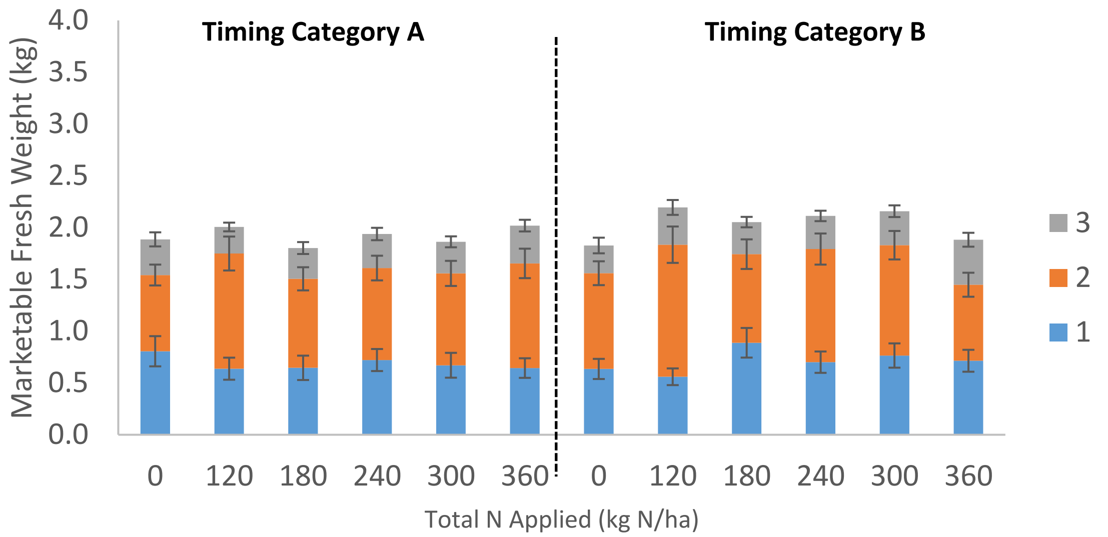

Figure 21. Marketable Fresh Weight per crown by harvest (Oldroyds)

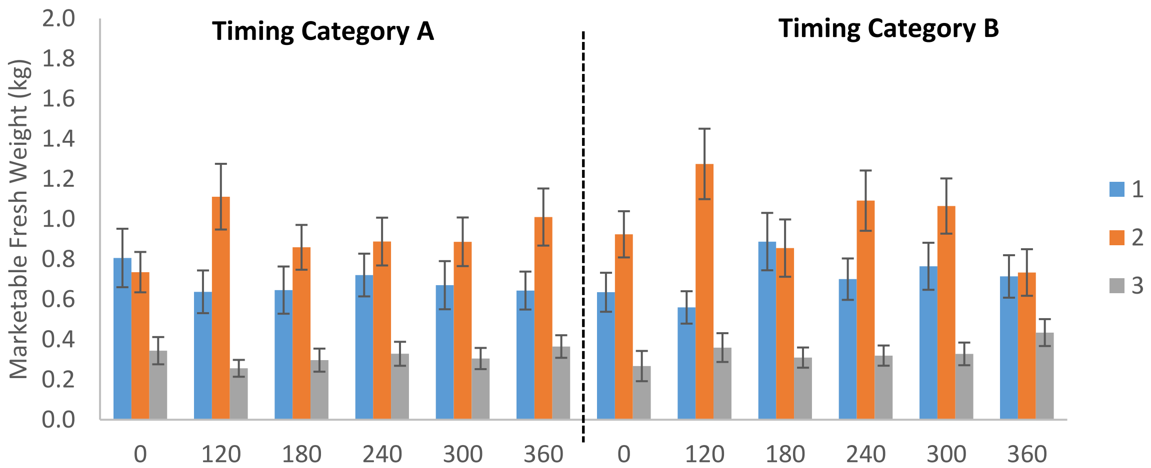

Figure 22. Marketable fresh weight per crown by harvest at Oldroyds.

Nitrogen Uptake

Dry biomass samples were taken for stick and leaf portions to provide estimates from above ground dry matter content. Samples submitted for laboratory analysis were used to determine N content of dry biomass. When compared against biomass figures total crop offtake was calculated for each N application and timing category according to target field density assuming 85% establishment. There were no significant differences found in tissue N content between treatments at each site, indicating that allocations of N to the stick and petiole did not show variation between treatments, although biomass N figures were assessed on a per plot basis to ensure accurate estimation of crop offtake.

Nitrogen uptake: Hammonds timing categories A and B

At Hammonds there was a significant increase in N offtake with increased N application at both timing categories (Figure 23). Overall, timing category B showed a greater offtake compared with timing category A, although due to significant variation between plots the only N application at which this difference was significant was at 300 kg N/ha. These data suggest a substantial amount of N is removed from the ground, even at 0 kg N/ha application, which showed offtake of c. 110 kg N/ha although this was significantly lower than the greatest N offtake of 295 kg N/ha which was seen at category B applications of 300 kg N/ha.

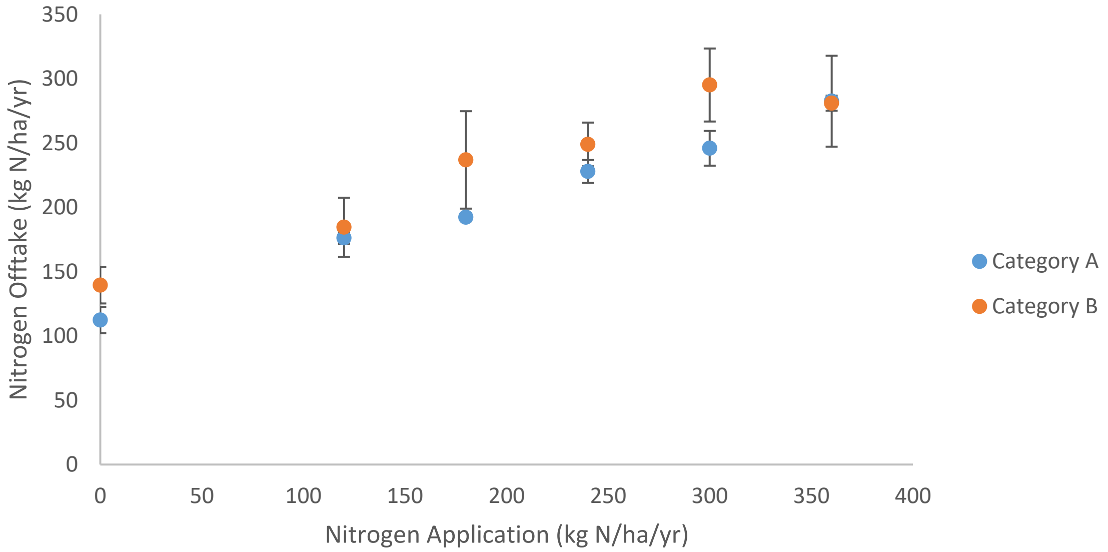

Figure 23. Total crop N offtake at Hammonds

Due to differences in the proportion of biomass removed at each harvest, the N offtake showed significant variation between the subsequent harvests (Figure 24). For the first harvest relatively equal N offtake was seen across treatments in both timing categories, mirroring the equal gross fresh weight between harvests. For the second and third harvests the rate of N offtake showed a clear positive response in both timing categories. The even offtake for the initial growth would suggest that the plants are largely drawing on internal reserves in the crown and are not impacted by soil N availability. For later growth, especially for the third harvest, the plants are more reliant on external N sources and so are showing a greater response to soil N applications. Given the third harvest was taken in early August, this would be at a time when the plants are fully established with both good root and canopy development, unlike the first April harvest whereby early plant development will be limited meaning that the plants are more reliant on crown reserves.

When broken down by stick or leaf partition, the N offtake was consistent between treatments for the first harvest but showed significant variation with the second and third harvests (Figure 24). The relative increase in offtake to the leaf showed greater variation between treatments compared with the stick, especially at higher N applications. This would suggest that the greater N uptake at higher applications is being channelled into the leaves without impacting N content of the stick – this would correlate with the greening up of the leaf as increased leaf protein content. The more consistent offtake in the first harvest (and greater N response at the third harvest) would also correlate with the theory that initial growth is supplied with N from the crown while later growth utilises new N taken up from the soil. If initial growth was impacted by the availability of soil N then more variation would be seen in stick/leaf N offtake for the first harvest – as this is only seen in the third harvest it would imply that it is only later growth that is impacted by soil N availability which the plant is utilising to supplement depleted N stores in the crown.

Overall, these results suggest that a minimum of 80 kg N/ha is taken off, even without supplementary N application, from the soil with a background SMN 29.7 kg N/ha, indicating that sufficient reserves are present in the crown which are exploited at the start of the season.

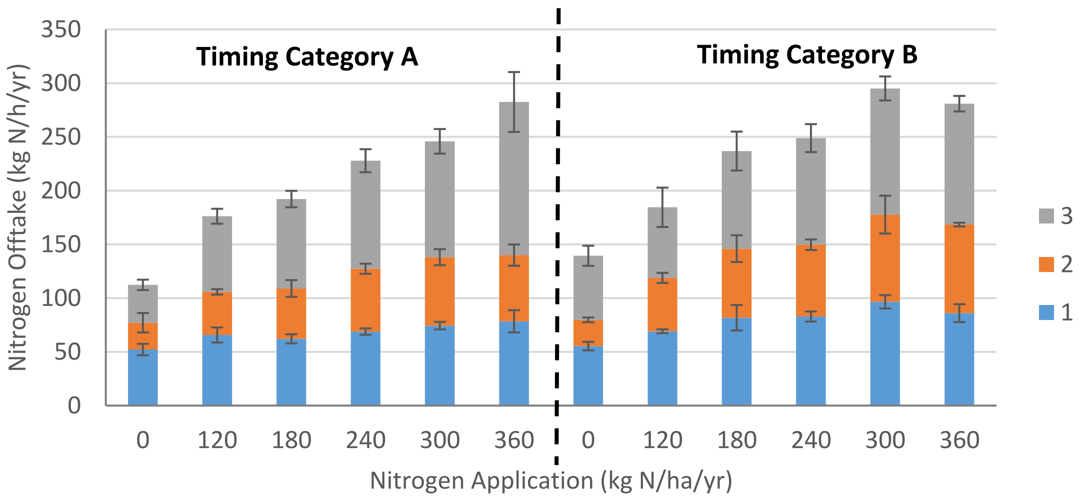

Figure 24. N offtake at Hammonds by harvest.

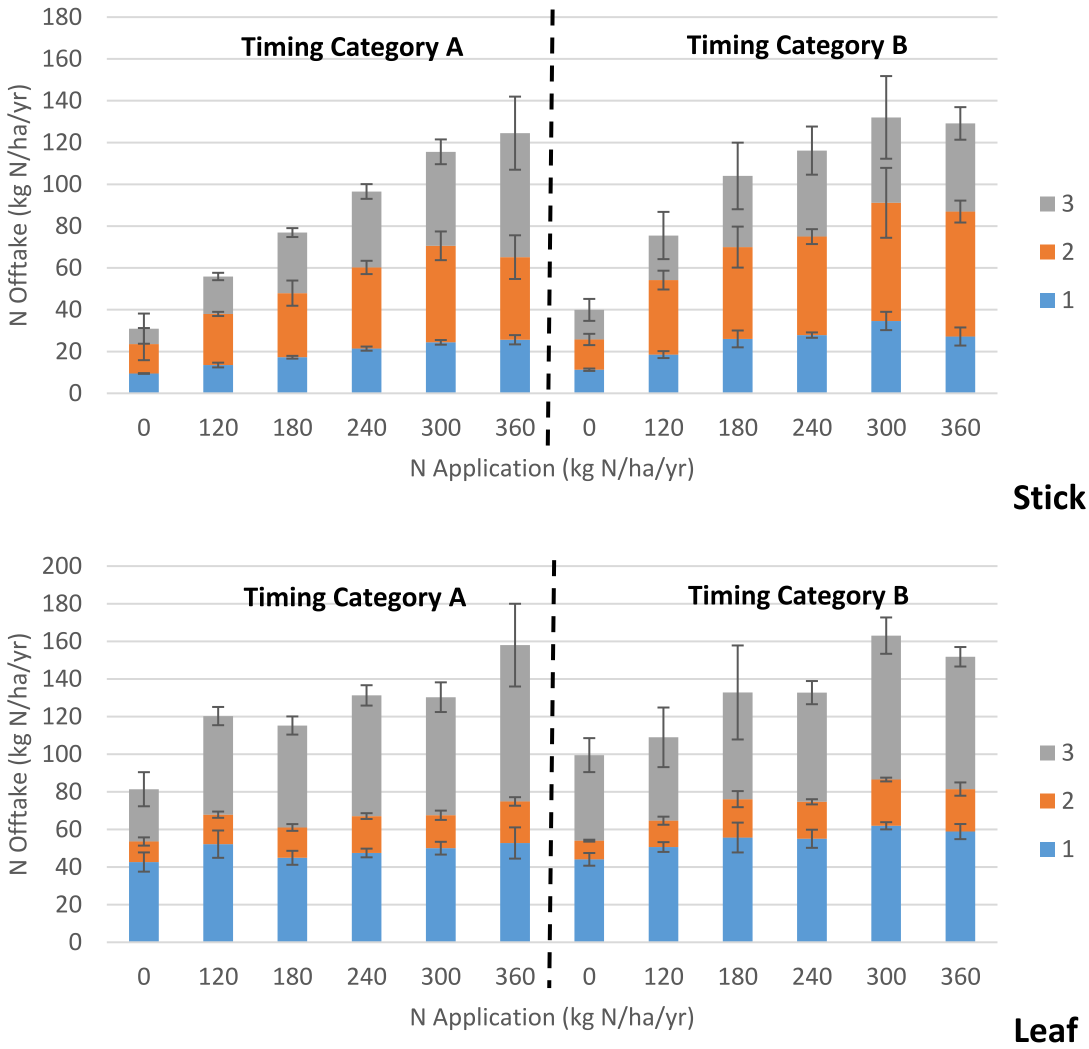

Figure 25. N offtake by leaf and stick partition by harvest at Hammonds.

Nitrogen uptake: Oldroyds timing categories A and B

Nitrogen offtake at Oldroyds showed a more varied response than Hammonds. Whilst there were no significant differences between timing categories, there was a minor (non-significant) trend which showed increasing N offtake from 0 to 180 kg N/ha (Figure 26). After this rate there was a small apparent decline, although high variation at the higher N rates makes this hard to determine. However, these data suggest that a positive N response is seen up to 180 kg N/ha. A similar trend was identifiable when split between harvests, particularly within timing category B (Figure 27). Both the first and second harvest show a similar response to N application, with an uplift in N offtake which peaks at 180 and 240 kg N/ha.

Both trials demonstrate a significant offtake even at 0 kg N/ha, replicating what was seen at Hammonds. This also suggests that early N is taken from reserves in the crown rather than utilising newly absorbed N, especially timing category B which includes small pre-emergence applications, and for the second harvest which would have seen large applications beforehand.

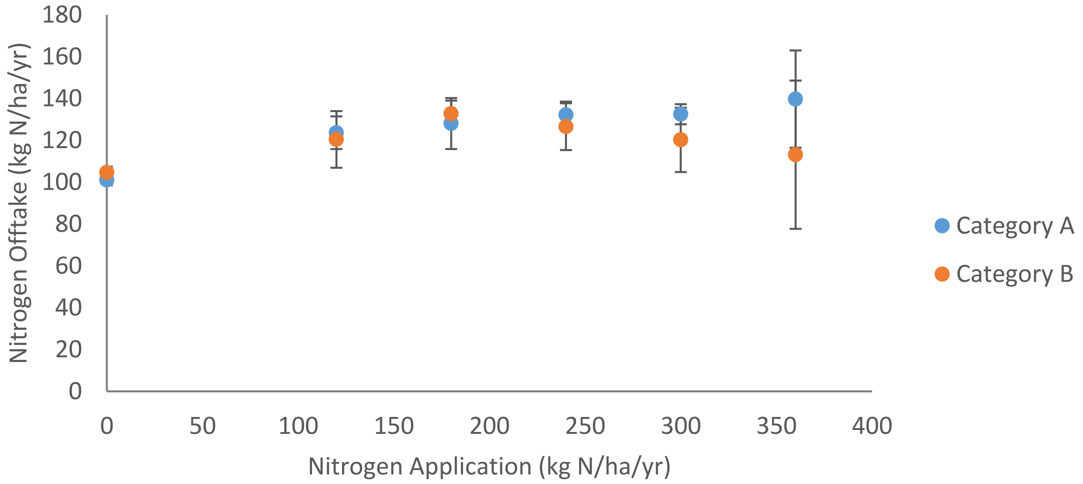

Figure 26. Total crop N offtake – Oldroyds

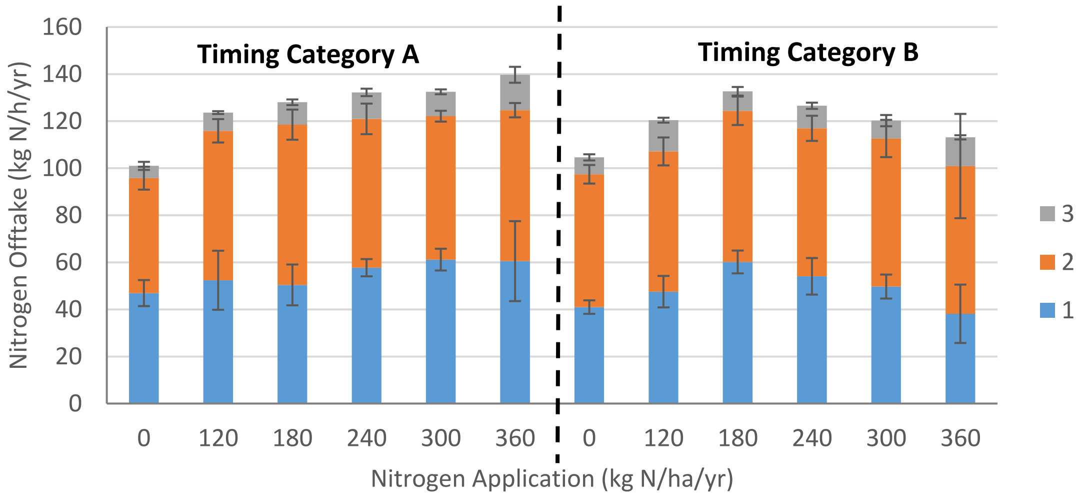

Figure 27. Total crop N offtake broken down by harvest – Oldroyds.

When broken down by above ground partition, there is significantly greater partitioning to the leaf section relative to the stick compared with Hammonds (Figure 28). This is most likely as a result of the later harvests at Oldroyds compared with Hammonds – each harvest was roughly a monthly later at each site, meaning that a greater proportion of leaf was developed at Oldroyds compared with Hammonds. As canopy expansion and development of light capture and photosynthesis machinery will have been prioritised, there would have been proportionately greater investment in the leaf relative to the stick.

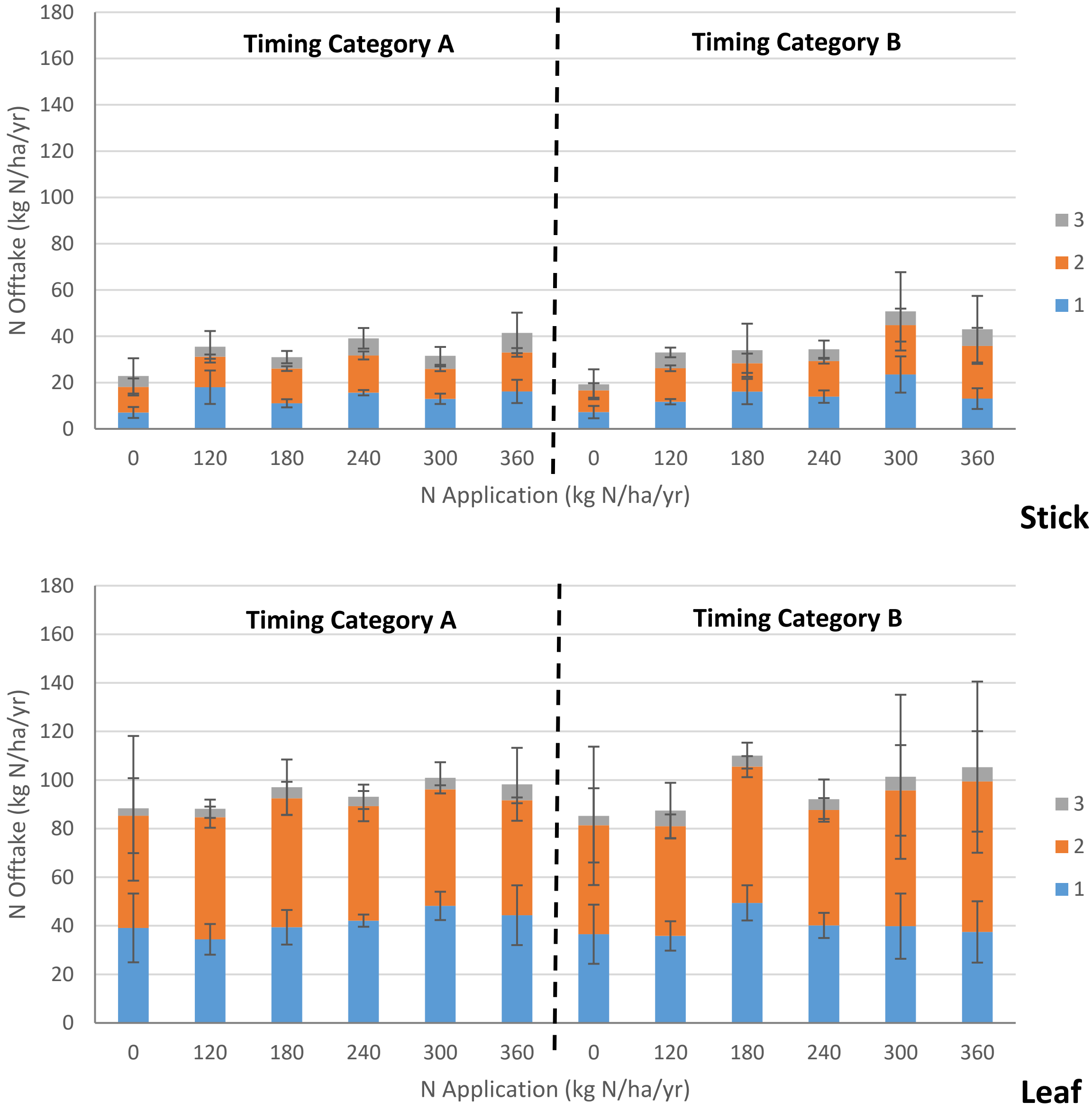

Figure 28. Crop N offtake broken down by over ground partition and harvest – Oldroyds

Yield response: Hammonds Timing Category C

Timing Category C was a limited trial testing 120, 240 and 360 kg N/ha split into three equal applications following the first, second and third harvests with no pre-emergence applications. This was only carried out at Hammonds, and results are available only from the later two harvests in June and August (which correspond to the main commercial harvest windows). Similar to the timing category A and B trials, background variation was high and there was no significant response to N response through either stick weight or number (Figure 29). Similarly, there was no significant difference in stick quality between treatments (discussed below and presented in Figure 30 for comparison). As only limited harvest data is available N offtake cannot be estimated in a way that is comparable with the main trial data, although the muted yield response would indicate that it is unlikely that this treatment approach has had any significant impact on N offtake.

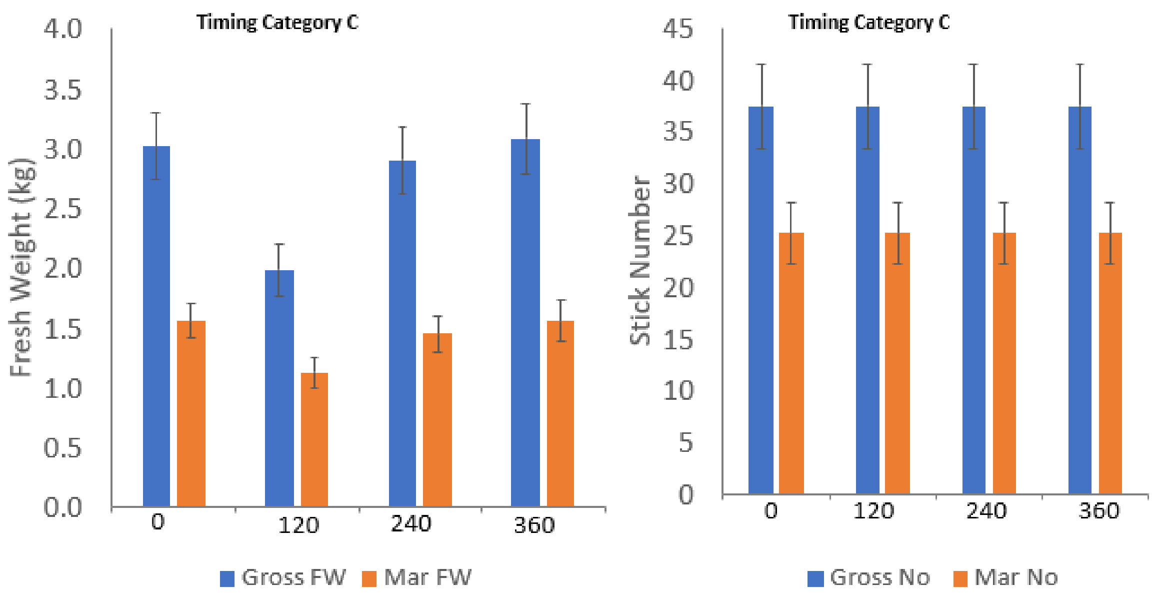

Figure 29. Yields from timing category C treatment (Hammonds) as expressed through gross/ marketable yield and gross/marketable stick number

Yield Quality Measures

Stick quality was assessed through stick colour assessment using a chromameter, with average colour values developed for each stick (Figure 30 and Figure 31). Average stick colour was highly variable between sites and treatments. There was no effect of N rate on colour. Stick colour, whilst a key quality requirement for customers, is difficult to express on average as it is an integrated value along stick length. Furthermore, longer more mature sticks are more liable to green up giving a reduced colour value despite retaining strong red pigmentation at the base.

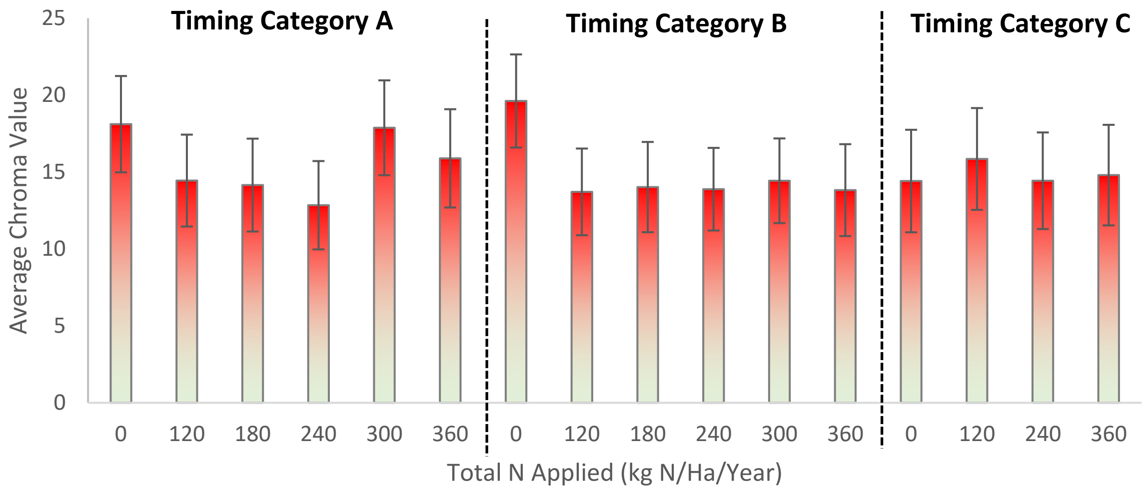

Figure 30. Average stick colour taken at Hammonds. A more positive chroma value indicates a stronger red colour of the stick.

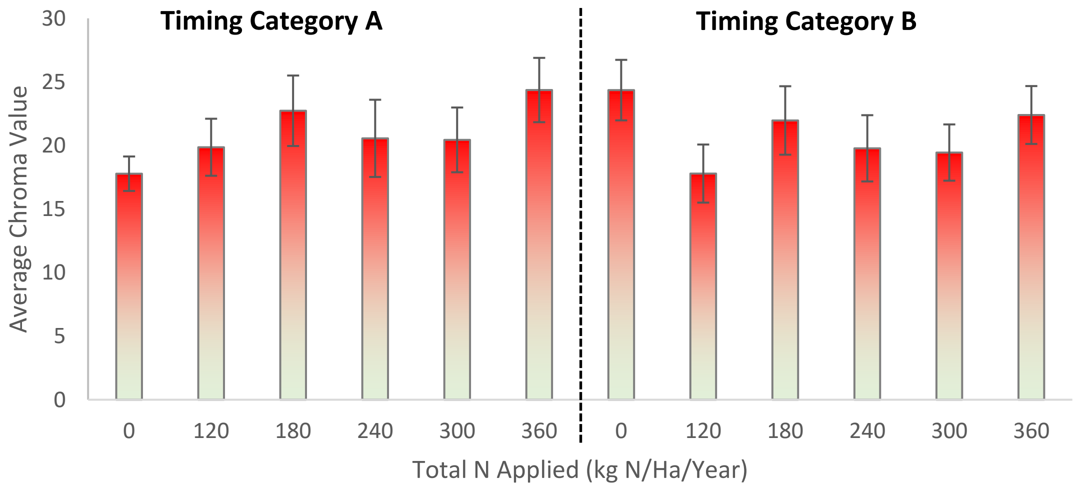

Figure 31. Average stick colour taken from the second harvest at Oldroyds. A more positive chroma value indicates a stronger red colour of the stick.

Hammonds – April 2022 harvest (following 2021 fertiliser treatments)

All of the 2021 fertiliser treatments at the Hammonds site were harvested for a final time in April 2022. The aim of this final second year harvest was to test the effect of the autumn 2021 N applications (timing category C) on yields of the first harvest of the next season crop.

There was no effect (*P*>0.0.5) of any of the N treatments on total number of stalks per plant (Figure 32) or number of marketable stalks per plant (Figure 33).

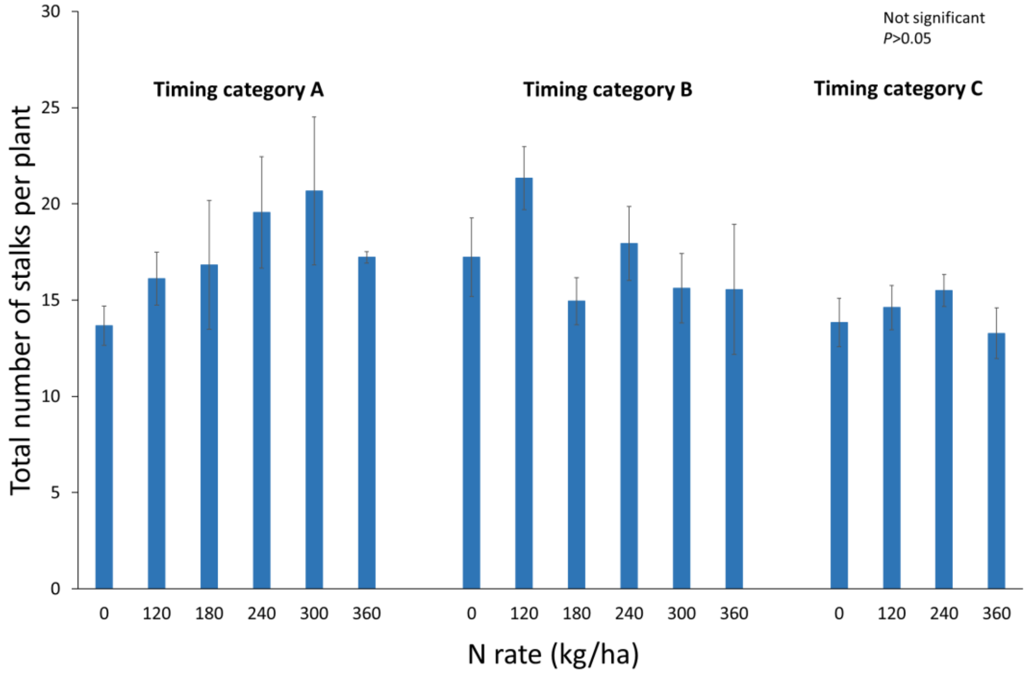

Figure 32. Total number of stalks per crown - April 2022 harvest at Hammonds

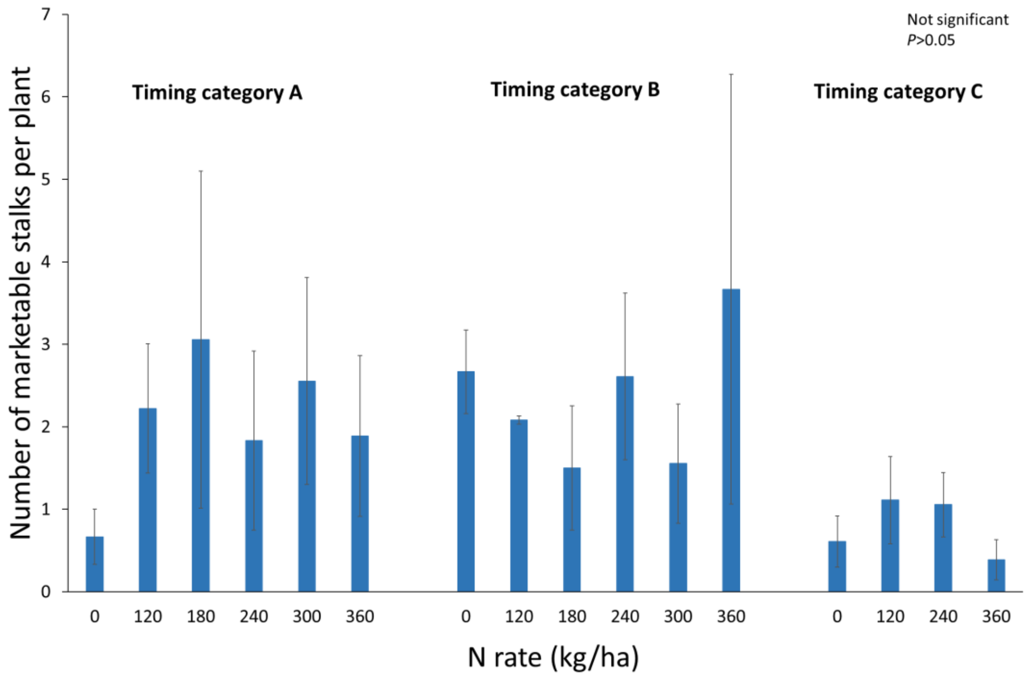

Figure 33. Number of marketable stalks per crown - April 2022 harvest at Hammonds

There was no effect (*P*>0.0.5) of any of the N treatments on total yield (Figure 34), marketable yield (Figure 35) or stalk colour (Figure 36).

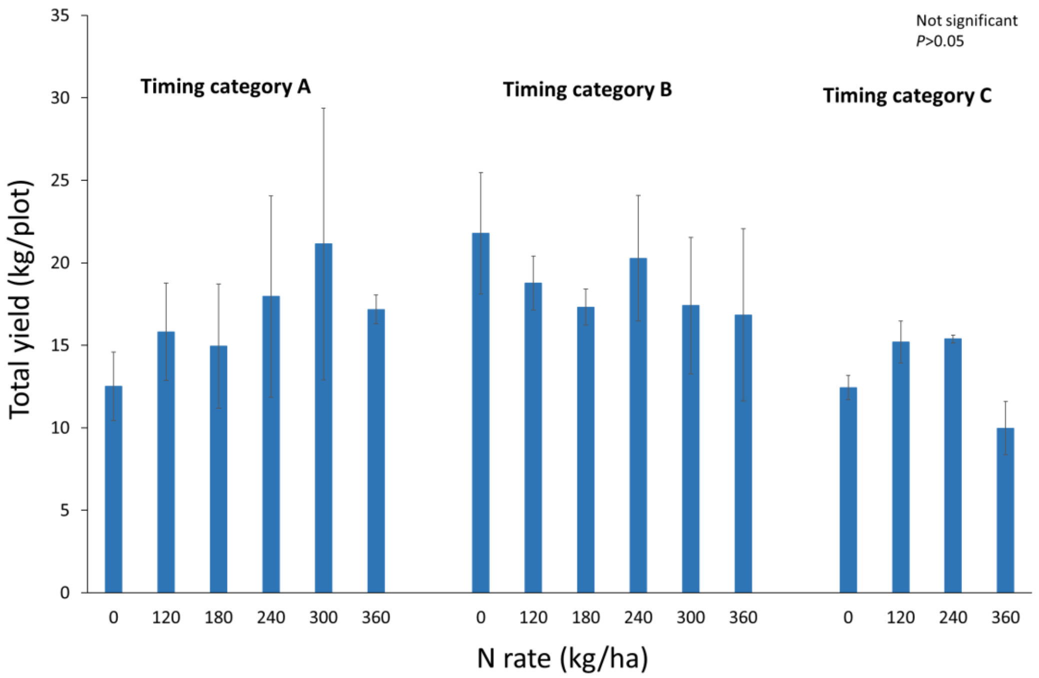

Figure 34. Total yield (kg per plot) - April 2022 harvest at Hammonds

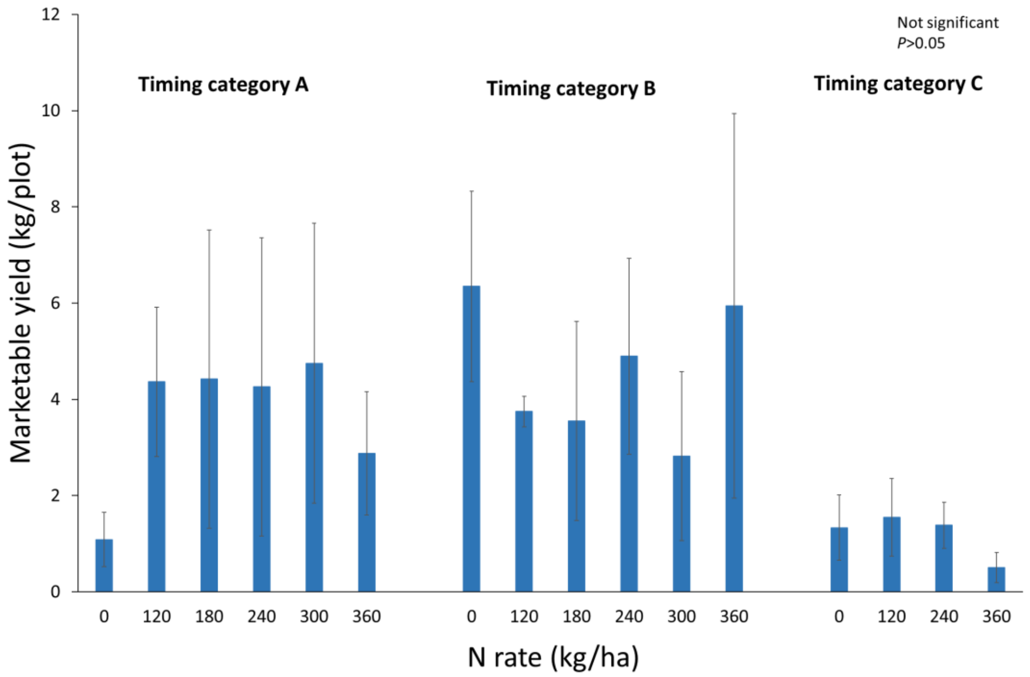

Figure 35. Marketable yield (kg per plot) - April 2022 harvest at Hammonds

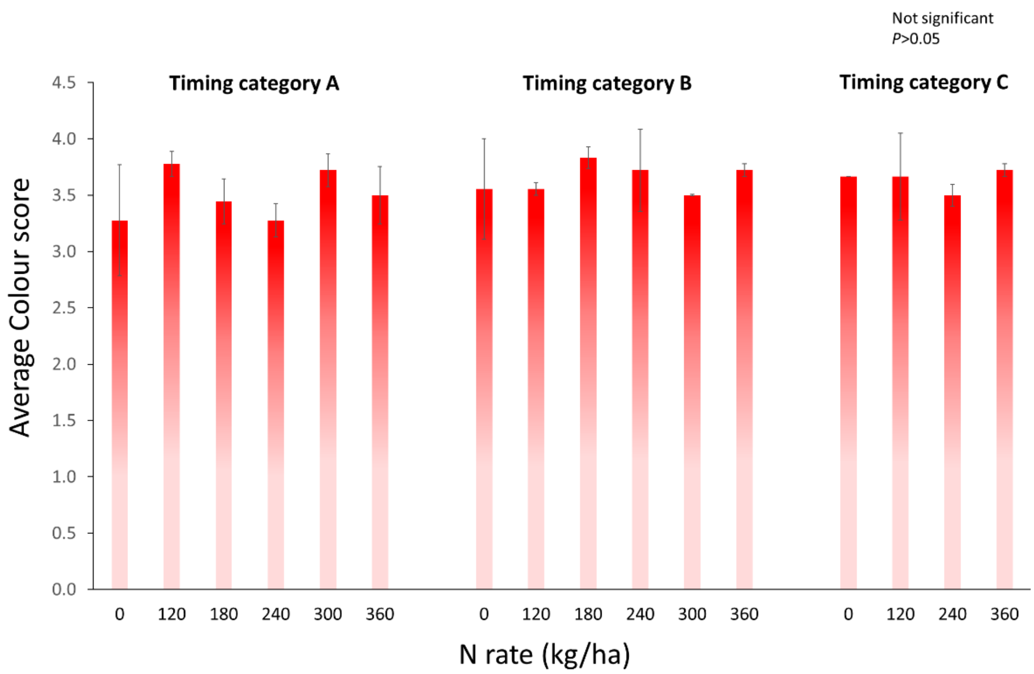

Figure 36. Average colour score (1=green; 5=red) - April 2022 harvest at Hammonds

Oldroyds – May 2022 harvest (following 2021 fertiliser treatments)

All of the 2021 fertiliser treatments at the Oldroyds site were harvested for a final time in May 2022. The aim of this final second year harvest was to test the effect of the autumn 2021 N applications (timing category C) on yields of the first harvest of the next season crop.

There was no effect (*P*>0.0.5) of any of the N treatments on total number of stalks per plant (Figure 37) or number of marketable stalks per plant (Figure 38).

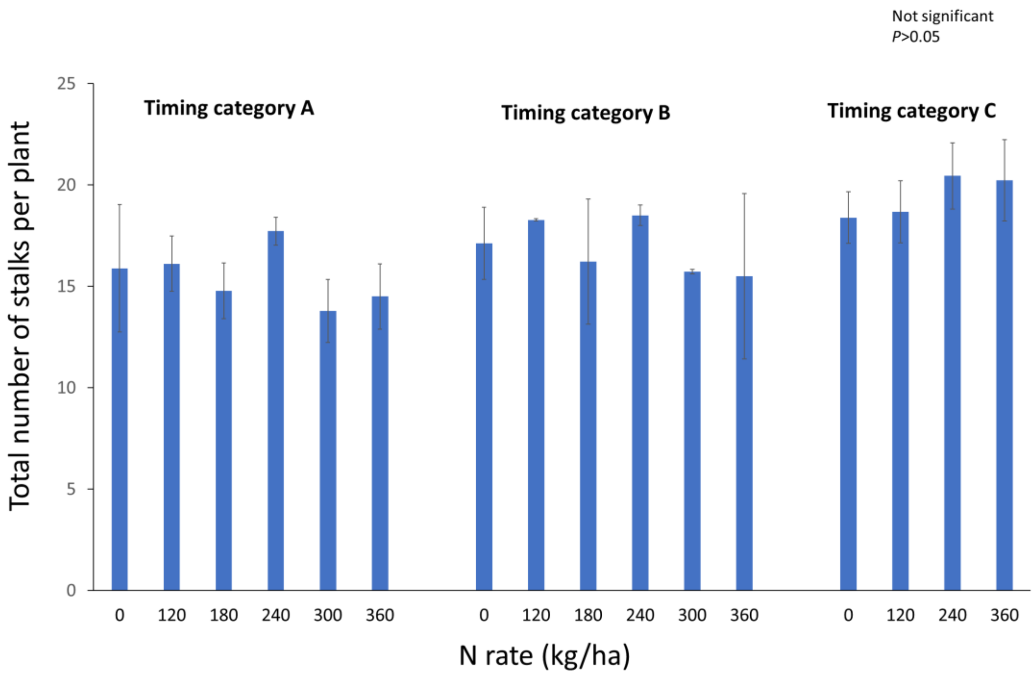

Figure 37. Total number of stalks per crown - May 2022 harvest at Oldroyds

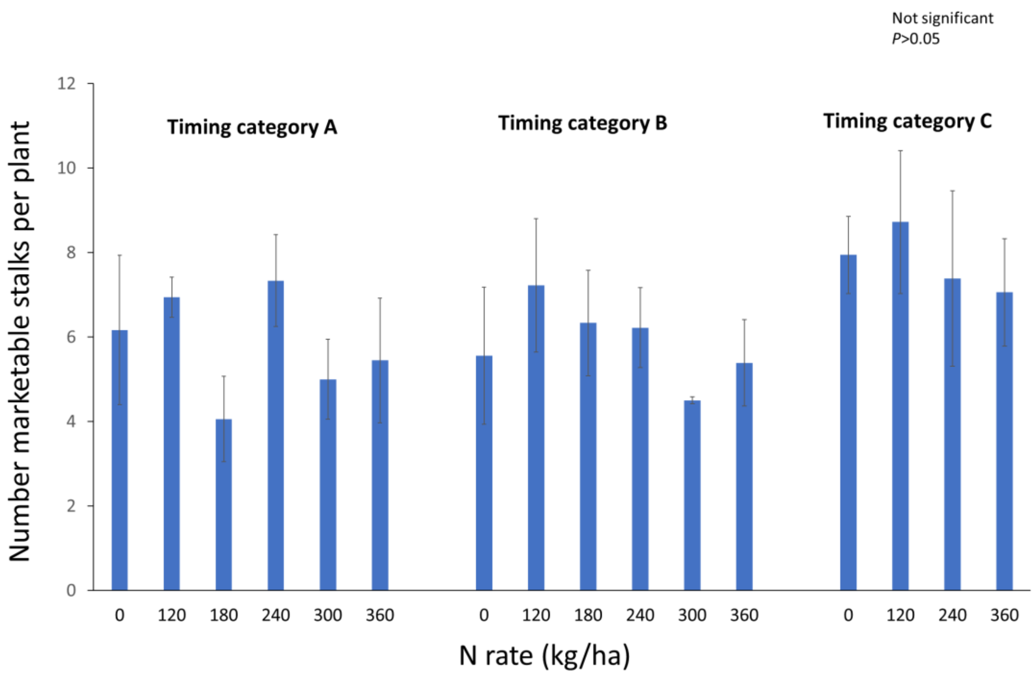

Figure 38. Number of marketable stalks per crown - May 2022 harvest at Oldroyds

When analysed together, there was no effect (*P*>0.0.5) of any of the N treatments on total yield (Figure 39) or marketable yield (Figure 40). However, there was an indication of increasing marketable yield with N rate for the autumn N treatments in timing category C. Timing category C treatments received 40, 80 and 120 kg N/ha post first harvest, post second harvest and in the autumn post third harvest, giving total N applications of 120, 240 and 360 kg N/ha. Application of N in September 2021 post third harvest increased marketable yields by about 60% at the May 2022 harvest. This increase is likely to be due to the autumn N as the marketable yield results from treatments in timing category A and B indicate that earlier N applications in 2021 (post first and post second harvest) had no effect on marketable yield at the following May 2022 harvest. However, it should be noted that there was quite a bit of variation in the May 2022 harvest data, particularly for the timing category A and B treatments, and when all the treatments were analysed together, there was no significant effect (*P*>0.05) of N treatment. There was no effect (*P*>0.05) of N treatment on stalk colour (Figure 41).

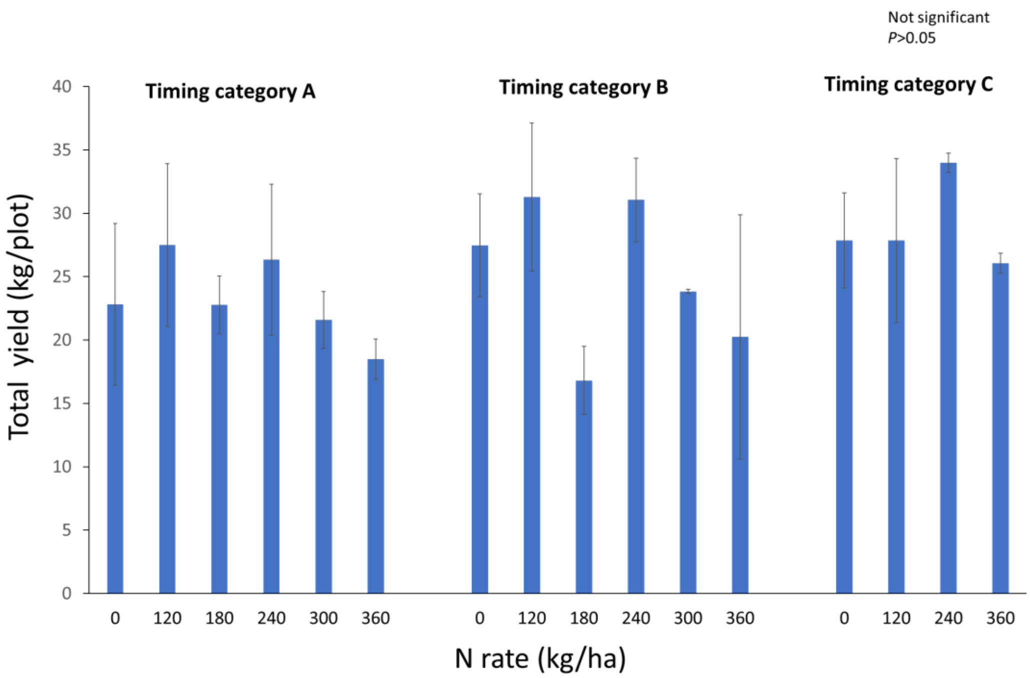

Figure 39. Total yield (kg per plot) - May 2022 harvest at Oldroyds

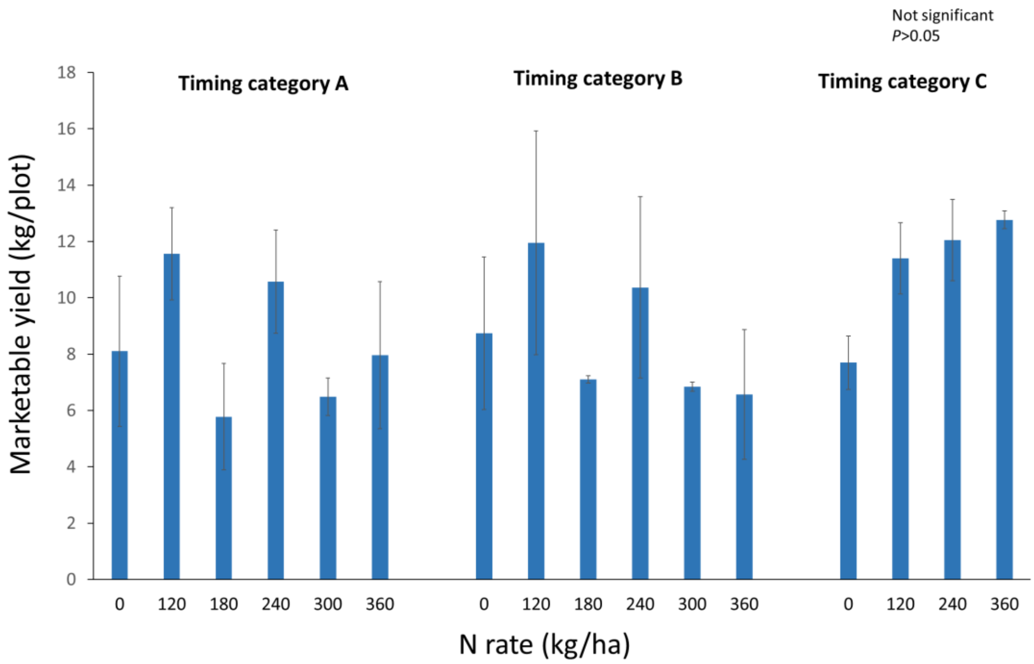

Figure 40. Marketable yield (kg per plot) - May 2022 harvest at Oldroyds

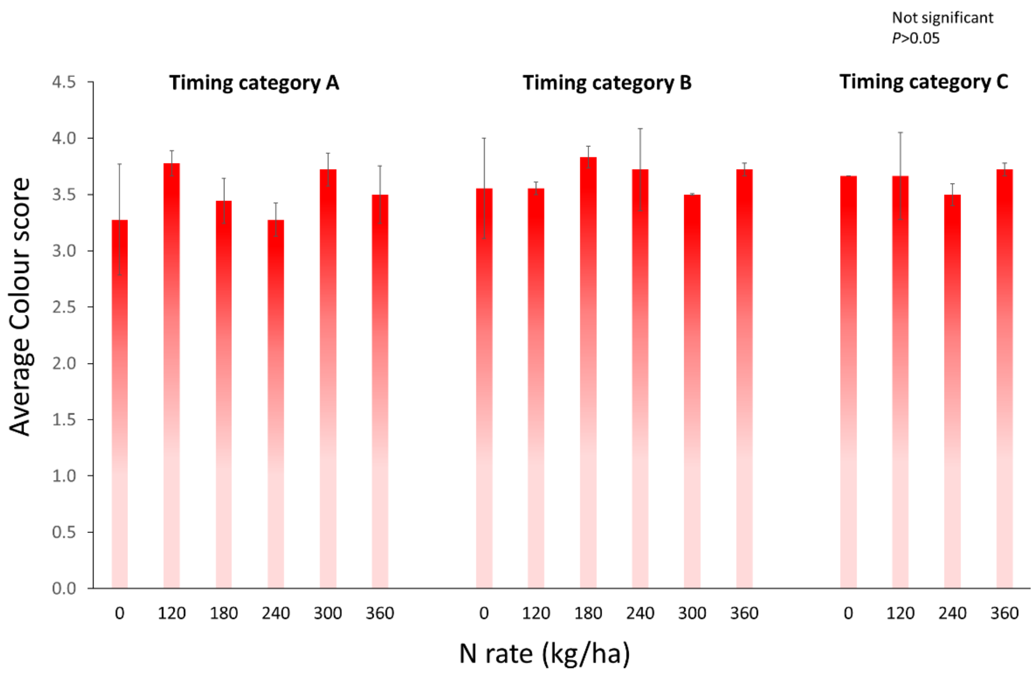

Figure 41. Average colour score (1=green; 5=red) - May 2022 harvest at Oldroyds

Discussion – Year 2 results

Crown Contributions to Early Growth

The 2021 trials represent the first complete set of trials for this project where both harvests and N applications were completed as planned. However, the general findings of the first year of this project coincide on the whole with the findings from 2022 which were based on a single harvest at the start of the season. Whilst N offtake was significantly different between sites (c. 24 – 26 kg N/ha vs. 37 – 105 kg N/ha) this range relatively corresponds with the first harvest offtake recorded in the 2021 season (c. 50 – 78 kg N/ha at Hammonds, 40 – 60 kg N/ha at Oldroyds). It was notable there was significant N offtake even from the crop in the zero N control treatment – for example, c. 120 kg N/ha was taken off soils with a background level of 48.6 kg N/ha at 0 kg N/ha application, indicating that substantial internal reserves of nitrogen are available to the crop (although this does include N offtake from later crops which may have utilised N cycling from leaves from the first harvest).

These data would suggest that early growth is heavily reliant on nitrogen reserves in the crown rather than the uptake of new nitrogen from the soil. While these data would suggest that pre-emergence N applications do not necessarily impact subsequent yield, there may still be some benefit from early spring applications – especially as there is anecdotal evidence from growers that harvests can be adversely affected where nitrogen applications are limited. Furthermore, without specific guidance as to when the transition from internal to external nitrogen reserves (e.g. when the crown is depleted), there is a risk that delaying N applications could lead to short-term N limitations on growth.

It is noteworthy that there is different response to nitrogen between the second and third harvests at the two sites. At Hammonds, a significant response in N offtake is seen with increasing N application, particularly at timing category B where total applied N (at the point of harvest) was greater due to the early small N application. However, at Oldroyds offtake during the second harvest was relatively consistent between treatments, except for a minor decrease at 0 kg N/ha. This would suggest that the crop was more responsive to N application and less able to rely on internal reserves at Hammonds compared with Oldroyds leading to the greater response. The third harvest at both sites shows a significant response to N application.

These data would suggest that the point at which a crown→soil transition in N reliance occurred between harvest 1 and 2 at Hammonds, and between harvest 2 and 3 at Oldroyds. It is noteworthy that the transition at each site is not necessarily linked with point in the season – the second harvest at Oldroyds was a month later than Hammonds, although at this stage the crop was still utilising internal nitrogen reserves. The timing of this transition is likely to be subject to the influence of current season growth rates, the development of the canopy and available N in the crown (as impacted by the previous season's growth) and therefore may be difficult to predict with any certainty. As such, the use of a pre-emergence application may be of benefit to ensure that adequate soil N is available when the transition occurs.

An additional aspect not examined in these figures is the proportion of N stored from the previous season. Given that current practices may meet (or exceed) N requirements of the crop (see the literature review in the SF 172 2019 report) it is likely that the crops used for this trial had ample supplies of N in the previous season to ensure strong reserves for the following spring. However, under conditions where poor reserves are set aside – either due to weak crop growth or suboptimal N application – there is a potential risk that the crowns could be depleted sooner (and therefore require greater or earlier N applications) to ensure that sufficient yields are produced.

Overall, these results suggest that crowns reserves are likely to be sufficient to supply early N requirements, most likely until the canopy and root system have developed to the point at which new uptake of N from the soil can be carried out at sufficient pace. Whilst applications of N before this point may be unrequired, the need to ensure sufficient soil reserves are in place is likely to continue to promote early N applications, particularly where growth in the previous season is likely to have limited N uptake and storage reducing the availability of reserves in the following spring.

Effect of Application Timing

In terms of yield outputs, the use of alternative timings (favouring either pre-emergence or postharvest applications) has not had a significant effect on yield at either site this season. At Hammonds, both application timings showed relatively comparable trends in response to N application although high variability between treatments make identification of even minor trends difficult. At Oldroyds, however, timing category B (postharvest applications only) showed a more positive response to N application that timing category A – particularly at the second harvest – although only in a minor way. This data could suggest that a greater response to N will be seen when applied earlier in the season, and this matches with observations at the site that areas that did not receive early N applications showed reduced yield. It is also noteworthy that Oldroyds also had significantly greater N offtake in the leaf partition, particularly at the third harvest in September. This means that overall N cycling from cut leaves may have been reduced as more was present in the canopy, increasing the reliance of the crowns on soil N. However, given that the crown is liable to provide an early buffer of stored N the timing of N applications may be less relevant than the total applied –

particularly in crops where growth in the previous season has been strong and the crowns have ample stores to promote early season growth.

N Requirements

Overall, results from this season have demonstrated that that there has not been a significant correlation between N response, yield output or N offtake. However, given that significant N offtake has occurred even at 0 kg N/ha treatments, it is likely that the crop requires significant amounts of N to achieve target yields. Given that the crown is likely to provide a burst of N for early development, it would be necessary to look at N applications over multiple seasons in order to fully appraise N requirements over the lifespan of the crop.

However, minor trends across both sites indicate that peak response may fall between 180 – 240 kg N/ha given that responses have levelled out at this stage. Furthermore, increases in gross stick number and weight which have not translated through to marketable outputs (most commonly as a result of oversized sticks) this would imply that applications beyond this level may approach “luxury” levels of N application whereby increased leaf matter is seen without a proportion increase in marketable yield, reducing nitrogen use efficiency. However, given that high N availability in the summer may feed forward into the early spring growth, some level of “luxury” availability may need to be achieved beyond replacing that taken up by the leaves and sticks – especially in conditions where cycling of N from cut leaf material is reduced (e.g. dry weather).

Conclusions

Results from the 2021 season have confirmed earlier findings that there is likely to be significant contributions from the crown for early growth rather than relying on external sources for new uptake. This means that pre-emergence applications may be less likely to have a positive effect than applications later in the spring after initial harvests. However, as it is likely to be difficult to identify the point at which crown reserves are depleted (which may vary in response to conditions in both the current and past season), and to mitigate the risk of weak crowns, some early applications may be beneficial.

Year 3 field trials (2022)

Field site

A single field trial was carried out at within a commercial farm planted rhubarb crop of Timperley Early at Oldroyds in 2022. The site selected was chosen as it was likely to show a response to N (i.e. low SNS Index site). The area used had not received any applications N fertiliser or organic manures since autumn 2021.

Experimental treatments and design

Following the outputs of the 2021 trials, which showed no yield response to N applications, the highest N application rate of 360 kg N/ha was removed from the timing category A and B trials; all other treatments were the same as in 2021. There were 14 treatments planned split across three separate trial 'areas', each representing a different application timing category (Table *8*). Each treatment was replicated three times and arranged in a randomised block design. **However, because of the summer 2022 extreme heat and drought only the first and second N treatments were applied and only one harvest was taken.** Details of **planned** treatments are given in Table 12.

Table 12. Year 3 (2022) **planned** nitrogen fertiliser treatments

	Treatment Number	Application timing (kg N/ha)				Total applied (kg N/ha) Note only T1 & T2 applied
		T1 (Pre-emergence)	T2 (Post 1st Harvest)	T3 (Post 2nd Harvest) Not applied	T4 (Autumn - September) Not applied	
Timing A	1	0	0	0	0	0
	2	0	60	60	0	120
	3	0	120	60	0	180
	4	0	180	60	0	240
	5	0	240	60	0	300
Timing B	6	0	0	0	0	0
	7	60	60	0	0	120
	8	60	120	0	0	180
	9	60	180	0	0	240
	10	60	240	0	0	300
Timing C	11	0	0	0	0	0
	12	0	40	40	40	120
	13	0	80	80	80	240
	14	0	120	120	120	360

The pre-emergence fertiliser treatment (T1) was applied on 17/03/22. The first harvest was taken on 18/05/22, and the second fertiliser treatment (T2) was applied on 06/06/22 before the summer heat/drought impacted the crop.

Because there was only one harvest at this site, the yield results reported here from this first harvest reflect the first N treatment only (T1); there was not a second harvest to test the effect of the second N treatment (T2).

The actual N treatments relevant to the first harvest results were 0 and 60 kg N/ha. There were 10 treatments (30 plots) which had no N fertiliser pre-emergence, and 4 treatments (12 plots) which had 60 kg N/ha applied pre-emergence.

Individual plot size was 7 m x 4 beds (3.3 m). Measurements and harvests were all taken from 5m of the central 2 beds. Nitrogen treatments were topdressed by hand as Calcium Nitrate (27% N). With the exception of N fertiliser, the farm sites managed all other inputs to the trial as for the rest of the commercial crop.

Measurements

Soil analysis, yield and crop yield assessments are as described for 2020 trials. Assessment of stalk colour was changed from use of a Chroma meter in 2019 and 2021, to a visual assessment of colour in 2022. Five stalks were taken from three crowns per plot (15 stalks per plot) and scored for colour on a scale of 1 (green) to 5 (red) (Table 13).

Table 13. Visual scoring of stalk colour used in 2022

Score category	1	2	3	4	5
	Unmarketable	Marketable			
Amount of red per stick	Green <20% red	20 -40% red	40-60% red	60-80% red	>80% red

Because of the summer 2022 extreme heat and drought only one harvest was taken.

Results

Soil analysis

Soil analyses are detailed in the Table 14 below. The site was a sandy clay loam soil and SNS Index 0.

Table 14. Topsoil and SMN analysis - year 2 sites

Site	pH	Index			SMN* kg N/ha 0-90 cm (Index)	Soil type
		P	K	Mg		
Oldroyds	7.5	3	2+	4	19 (0)	Clay loam

Crop Condition

The crop at this site was quite variable which was shown in baseline assessments of the number of crowns and number of buds per crown before any fertiliser treatments were applied. The number of crowns and number of gaps (i.e. dead crowns) in each plot was counted in March 2022. The average number of crowns per plot was 14 (range from 8-19), representing a mean of 73% of planted crowns (range 40-95%). The mean number of buds per crown was 4.7 (range 1.0-10.0).

The crop was badly affected by the extreme heat and drought in summer 2022. There was no irrigation at the site to minimise the effect of the drought. In addition, there was high weed pressure at the site. The decision was made between ADAS and the host farmer not to take any additional harvests from the site.

Figure 42. Oldroyds site in July 2022 showing crop affected by drought and weed competition

Crop yields and quality

There was no effect of the pre-emergence N application in March 2022 on the total number of stalks or number of marketable stalks per crown (Figure 43), total or marketable yield (Figure 44), or stalk colour (Figure 45). However, application of 60 kg N/ha pre-emergence did significantly increase the stem N content ($P<0.001$) and N offtake ($P=0.002$) in the stems (Figure 46).

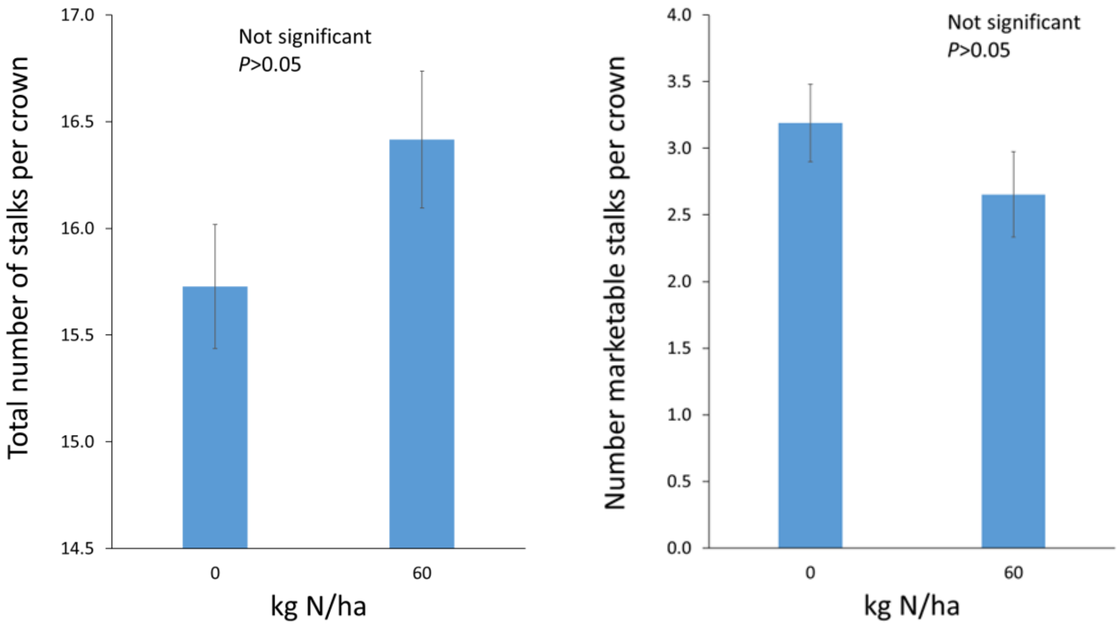

Figure 43. Total number of stalks per crown (left) and number of marketable stalks per crown (right)

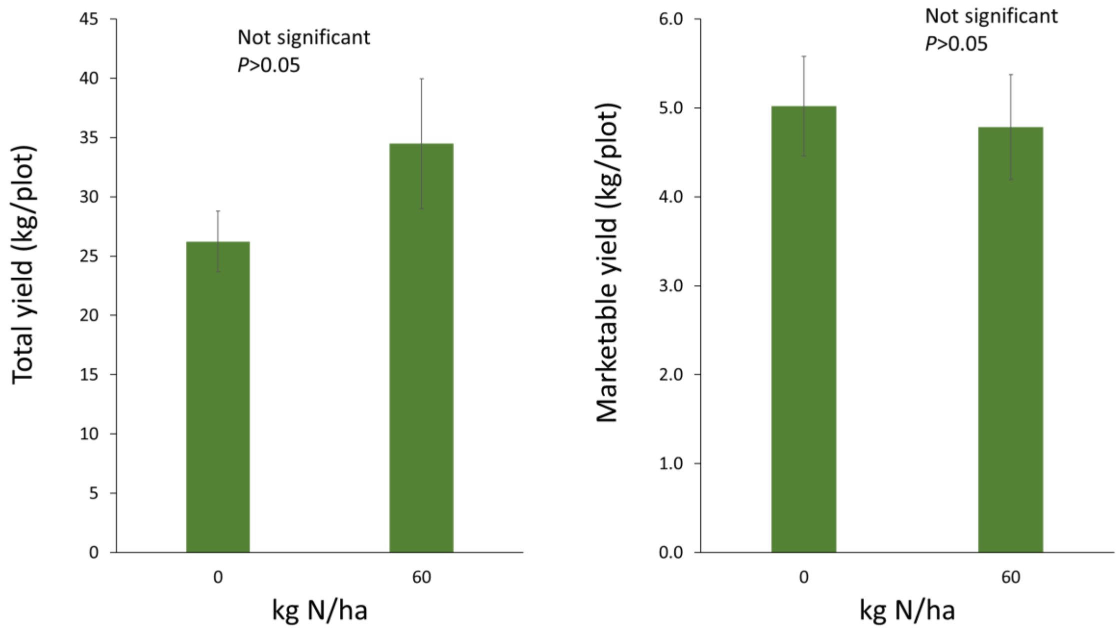

Figure 44. Total yield in kg per plot (left) and marketable yield in kg per plot (right)

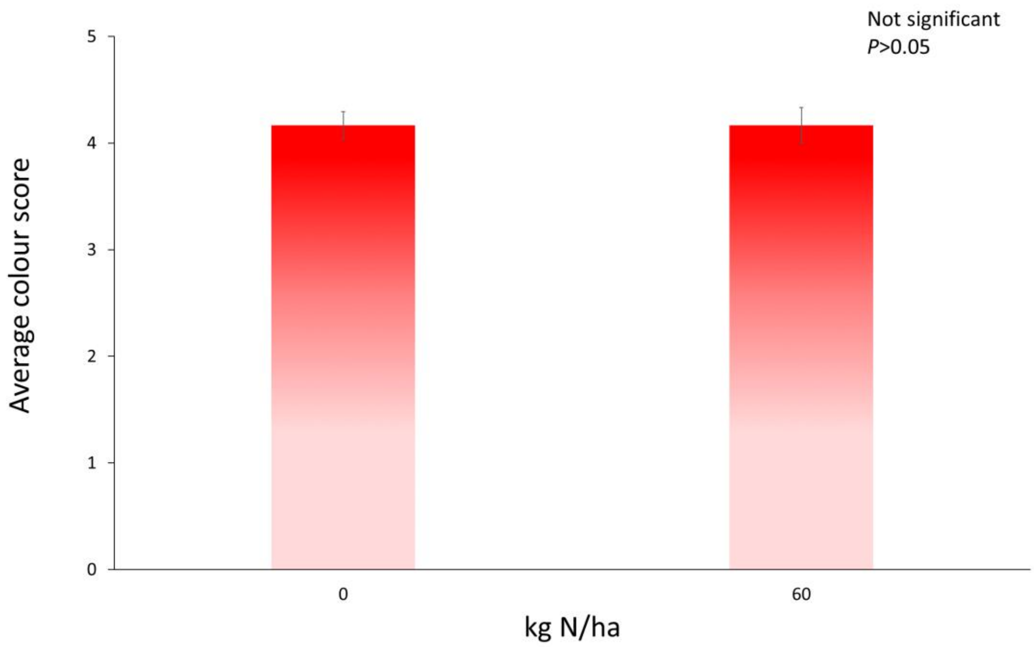

Figure 45. Average colour score

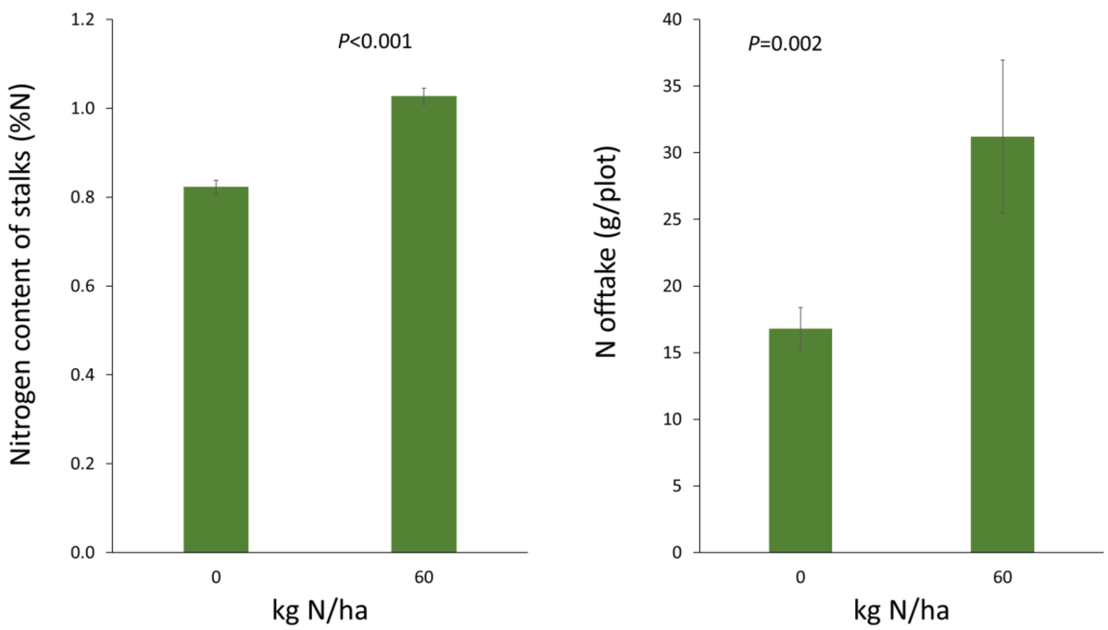

Figure 46. Stem N content (%) (left) and stem total N offtake (kg/ha) (right)

Discussion – Year 3 results

The drought and extreme heat in summer 2022 had a significant effect on crop growth and performance at the site. Only one harvest was taken from the site rather than the planned three. The results from this harvest allow us to test the effect of 60 kg N/ha early N application compared to zero N. There was no effect of early N on total or marketable yields at the first harvest. This is similar to findings from the first year, where there was no significant increase in marketable yield with early N rates of up to 375 kg N/ha applied following bud break at either site. This may be because early season grown in established plantations is driven by N reserves in the crown rather than from soil N.

However, unlike in 2019, application of N did significantly increase stem N content and stem N offtake. This indicates that the crop took up some of the applied N, but did not translate this into increased yield. Because there was only one harvest at the site, it is not possible to determine whether the additional N uptake would have had any effect on marketable yield at later harvests.

Conclusions and recommendations

Field trials - conclusions

The lack of a significant yield response to N at all sites is surprising, especially all had low levels of nitrogen in the soil (SNS Index 0). When this project was commissioned, some growers were questioning whether there should be an increase to the current recommended N rates given in the Fresh Produce Crop Protocol and RB209 5th Edition. The results from this project provide no evidence that the current recommended N application rates should be increased, and conversely actually indicate that recommended N rate should be reduced.

However, growers should be cautious about significantly reducing their N application rates based on the results of this project without further work to quantify the cumulative effect of reduced N application rates over several years. The lack of yield response to N indicates that the crown's reserves from the established crop were likely to have been sufficient to supply most if not all the crop N requirement. The high crop N offtake measured from the zero N control treatments also supports the conclusions that a significant proportion of N for crop growth is taken from reserves in the crown. Total crop (leaves and stem) N offtake from the zero N control treatments from the three harvests at Hammonds and Oldroyds in 2021 was around 100 kg N/ha; accounting for SNS of around 50 kg N/ha at Oldroyds and 30 kg N/ha at Hammonds, still indicates at least 50-70 kg N/ha from crown reserves.

Given that current fertiliser practices may meet (or exceed) N requirements of the crop, it is likely that the crops used for this trial had ample supplies of N in the previous season to ensure strong reserves for the following spring. However, under conditions where poor reserves are set aside – either due to weak crop growth or suboptimal N application over a number of years – there is a potential risk that the crowns could be depleted sooner (and therefore require greater or earlier N applications) to ensure that sufficient yields are produced.

The results from the project provide some evidence on optimum N application timings. Results from the first and third year of the project when a single early N application was made to the crop and no yield response was measured indicate that there is little need for early N applications. Conversely the yields results from the May 2002 harvest at Oldroyds following the September 2021 N fertiliser treatments indicates that there may be yield benefit to the next season crop from autumn N applications following the final harvest.

Recommendations for RB209

The main aim of this project was to provide fertiliser recommendations for growers of rhubarb for inclusion in RB209 to help growers to optimise nutrient management and minimise the environmental impact of their business activities.

Fertiliser recommendations have been produced for inclusion in RB209 based on a combination of results from this project, information from the literature review, current grower practice (informed by experience) and expert judgement.

It should be noted that it is rarely possible with minority crops like rhubarb to provide a sufficient number of N response experiments across a range of sites with different soil types and SNS indexes to provide a high level of confidence in the recommendations. However, knowledge gained from the current project in addition to grower experience and expert judgement does allow us to provide useful guidance to growers, which should be made available via the next revision to RB209.

Fertiliser recommendations have been updated for established crops. There is not sufficient information to update fertiliser recommendations for the establishment year.

Nitrogen application rate

If the results of this project were taken in isolation it is likely that maximum N application rates of around 125-150 kg N/ha would be recommended. This is based on the lack of yield response to N seen at all sites, knowledge of typical crop N offtake figures, and the recognition of the importance of maintaining sufficient crown N reserve to support N growth.

Current maximum N recommendations for established crops are 250 kg N/ha. Information from the literature review indicated N recommendations in other countries were typically around 150 kg N/ha, and information from the grower surveys found N application rates of around 100-230 kg N/ha. Based on this, we recommend a conservative reduction in the maximum N application rate from 250 to 200 kg N/ha. The N Index system was updated in

RB209 7th Edition from a 3 Index system (N Index 0 to 2) in RB209 6th Edition and earlier, to the current 7 index SNS system (SNS Index 0-6) in RB209 7th Edition. The updated SNS Index system also took into account over-winter rainfall and soil type. Nitrogen recommendations for rhubarb proposed here are based on a maximum rate of 200 kg N/ha at SNS Index 0, reducing with increase SNS Index at increments which are typical for other vegetable crops in RB209 and which account for the increasing SNS.

Nitrogen application timing

The following guidance wording is proposed:

Apply fertiliser N in two or three equal splits, typically after each harvest. Nitrogen fertiliser is not normally required prior to the first harvest as there is normally sufficient nitrogen reserves from the crown to support the first harvest. However, if early season growth is likely to be weak or limited for any reason, there may be benefit in applying up to 50 kg N/ha of the total N recommendation after bud break.

Under NVZ rules, no fertiliser nitrogen should be applied to rhubarb during the closed period, unless supported by written advice from a FACTS Qualified Advisor. If applying nitrogen in the closed period, then a FACTS Qualified Advisor must provide a written recommendation.

Note the wording relating to spreading N during the NVZ closed period is the same as given for leeks.

Phosphate and potash

This project did not investigate the impact of phosphate or potash applications. However, current phosphate and potash recommendations for rhubarb can be compared against crop offtake to ensure recommendations at the target P Index of 3 and target K Index of 2+ are sufficient to match crop offtake.

Assuming typical fresh weight yields of stems of 20 t/ha and a stem dry matter content of 8%, typical dry matter yields are 1.6 t/ha.

The average stem P content was 4,400 mg/kg; this equates to a crop offtake of 7 kg P/ha or 16 kg P_2O_5/ha. The current recommendation at the target Index of 3 is for 75 kg P2O5/ha which is more than sufficient to replace crop offtake.

The average stem K content was 42,500 mg/kg; this equates to a crop offtake of 68 kg K/ha or 82 kg K_2O/ha. The current recommendation at the target Index of 2 is for 175 kg K_2O/ha which is more than sufficient to replace crop offtake.

In this absence of any new data on crop P or K response, we recommend no changes to the current P and K recommendations for rhubarb.

Magnesium

Magnesium recommendations should be included at 150 kg MgO/ha at Index 0, 100 kg MgO/ha at Index 1 and zero at Index 2 or above. This is consistent with other vegetable crops in RB209.

Sulphur

The following guidance wording is proposed, which is consistent with other vegetable crops:

Where sulphur deficiency has been recognised or is expected, apply 25 kg SO_3/ha as a sulphate containing fertiliser at or soon after planting

RB209 recommendations for Rhubarb

Nitrogen, phosphate, potash and magnesium for Rhubarb

	SNS, P, K or Mg Index						
Index	**0**	**1**	**2**	**3**	**4**	**5**	**6**
Establishment year							
Nitrogen (N)	175	125	75	0	0	0	0
Phosphate (P_2O_5)	175	150	125	100	50	0	0
Potash (K_2O)	250	225	200	150	125	0	0
Subsequent years							
Nitrogen (N)[a]	200	170	140	100	50	0	0
Phosphate (P_2O_5)	100	100	75	75	0	0	0
Potassium (K_2O)	300	250	175	150	100	0	0
Magnesium (MgO) (all years)	150	100	0	0	0	0	0

Subsequent years – nitrogen

Apply fertiliser N in two or three equal splits, typically after each harvest. Nitrogen fertiliser is not normally required prior to the first harvest as there is normally sufficient nitrogen reserves from the crown to support the first harvest. However, if early season growth is likely to be weak or limited for any reason, there may be benefit in applying up to 50 kg N/ha of the total N recommendation after bud break.

Under NVZ rules, no fertiliser nitrogen should be applied to rhubarb during the closed period, unless supported by written advice from a FACTS Qualified Advisor. If applying nitrogen in the closed period, then a FACTS Qualified Advisor must provide a written recommendation.

Sulphur – all years

Where sulphur deficiency has been recognised or is expected, apply 25 kg SO3/ha as a sulphate containing fertiliser at or soon after planting

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Appendix 1: Rhubarb Nutrition Questionnaire

Business Name	
Address (Region)	
Area of Rhubarb Grown	
Varieties	
Forced or Field Grown (Field forced or shed forced?)	
Relative Area of Both	

Are you marketing a single pull or multiple pulls over the season?

If you have multiple pulls is it selective or complete clearance?

What are your typical yields?

What is your fertilization history? (Is this part of a rotation?)

What types of fertilizer do you use, and in what proportion?

(Products, chemical & biological e.g. shoddy)

What is your typical fertilizer program?

Does this vary at all? (e.g. with crop, history, harvesting, treatment)

Any fertilizer or nutrition-related problems?

Do you have any other ideas about rhubarb crop nutrition?

