Project title:	Developing Nutrient Management Recommendations for Rhubarb
Project number:	SF172
Project leader:	Angela Huckle, ADAS Boxworth
Report:	Annual report, 31 March 2020
Previous report:	None
Key staff:	Dr Ewan Gage (ADAS), Senior Horticulture Consultant Angela Huckle (ADAS), Senior Horticulture Consultant Chris Creed (ADAS), Senior Horticulture Consultant Dr Clive Rahn (Plant Nutrition Consulting) Dr Richard Weightman (Independent)
Location of project:	Barfoots Farms Ltd., Hammonds & Sons Ltd.
Industry Representative:	Neil Cairns, Barfoots Farms Ltd.Sefter Farm, Pagham Road, Bognor Regis, W. Sussex, PO21 3PX Philip Lilley, T H Hammond & Sons, New Farm, Redhill, Nottingham, NG5 8PB Lindsay Hulme-Oldroyd, E Oldroyd and Sons, Hopefield Farm, The Shutts, Leadwell Ln, Rothwell, Leeds, LS26 0ST

Date project commenced: 1 April 2019

Date project completed 31 March 2023

(or expected completion date):

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.

Angle Huckle

Senior Horticulture Consultant

ADAS

Signature Date 12/8/20

Dr Ewan Gage

Horticulture Consultant

ADAS

Signature Date 12/8/20

Chris Creed

Senior Horticulture Consultant

ADAS

Signature Date 12/8/20

Report authorised by:

Dr Barry Mulholland

Head of Horticulture

ADAS

Signature Date 12/8/20

1 Contents

Science Section

1.1 Introduction

Rhubarb production in the UK currently occupies 553 ha of land, producing 12,000 tonnes from forced and field-grown rhubarb with a farm gate value of £17m (Defra, 2018). 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 growing input requirements and challenges. There is scant evidence for growers as how best to approach nutrient management to maximise yields while optimising resource inputs for this niche crop. In order to address the knowledge gap, an evidence base must be developed for the optimum nutrient requirements of rhubarb to encapsulate the spread of existing commercial crop management. This information will be translated into revisions of the RB209 Nutrient Management Guide to provide advice for growers. Development of this evidence base will be achieved through targeted commercial trials of nutrient applications combined with a review of existing practice both in the UK and abroad.

1.2 Background

As a niche perennial field crop, rhubarb demonstrates a number of unique aspects when compared with traditional cropping systems. 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. 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.

Crop productivity in the past season (biomass and nutrients stored in the crown overwinter) will determine yield in the following spring, subject to interaction with the environment such as accumulated cold units and past life history of the crop. The perennial nature of the crop and changes in nutrient requirements from establishment, harvesting and re-growth periods creates a complex background of needs which is compounded by differences in cultivation practice between growers, target markets and methods of production (e.g. single/multiple pulls, cultivar habits and growing for forcing). There are also significant differences between geographical areas where rhubarb is grown in terms of nutrient management approach (e.g. use of wool waste in Yorkshire), climate/soil type and requirements. Despite this variability there is some consistency – only a limited number of established cultivars are used , and customer specifications are likely to be relatively uniform between different suppliers selling to the same customers. This creates a complex background for nutritional inputs that have precluded the development of nutrition guidelines, although the niche nature of the crop has significantly limited research into optimum responses from rhubarb precluding the provision of up-to-date guidance for growers.

1.3 Project Objectives

This project has the following core objectives:

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)

1.4 Project Workplan

This project objectives will be fulfilled through a series of work packages.

WP-R1: Literature Review
Period:
A comprehensive literature review will be prepared before the start of the first seasons trials summarising current evidence for rhubarb nutrition and to define the relationship between nutritional status and marketable yield. This will be expanded by including a review of current practice in the UK and abroad and will be used to inform trial activities in subsequent years. This will be used to inform the dimensions of the commercial trials in WP-R2.

WP-R2: Determination of the effect of additional fertiliser on green multi-pull rhubarb yield, quality and season length
Period:

Trial work will be carried out on commercial sites where practical, using industry standard cultivars grown using typical industry approaches for husbandry, pest/disease management and harvesting. This will allow the identification of suitable ranges of industry relevant cultivars for use in project activities. Where relevant, a range of cultural approaches will also be evaluated (e.g. irrigation type, substrate choice, product size and age) to ensure alignment with industry needs, and the range of approaches trialled will be agreed with industry representatives as described below. These trials will address the following objectives:

1. To measure yield responses of selected varieties of rhubarb in response to supplementary fertiliser treatments
2. To evaluate specified mineral utilisation in relation to soil indices and soil mineral content
3. To compare fertiliser treatments to nutrient uptake in the rhubarb canopy and crown sap, as related to yield and canopy development
4. To evaluate the effects of current season fertiliser application on the subsequent season crop develop and yield

Trials in 1 and 2 will primarily focus on nitrogen response, evaluating the response of an established crop to supplementary nitrogen applications of varying rates and timings over two successive seasons. Seasons 3 and 4 will be informed by the outputs of trials in seasons 1 and 2 to address other aspects so as potassium/phosphorous application, newly planted crops etc.

2 Literature Review

This review draws on three key sources of information:

1) An extensive 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.
2) 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.

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

3 Literature Review Outputs

3.1 General Crop Management

A limited range of cultivars were grown by the growers interviewed for this review: Timperley Early, Stockbridge Arrow and Stockbridge Harbinger cdominate, although Raspberry Red, Livingstone, Hammonds Early and Victoria were also reported. 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 the majority of 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.

3.2 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, 2005). 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, past 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.

3.2.1 Nitrogen

Nitrogen (N) has the most significant impact on crop responses to nutrition management. 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 closed period or in NVZs (nitrate vulnerable zones). Lastly, the timing of nitrogen application is likely to have significant interaction with response, both in terms of crop development, harvesting patterns and field/forced production and therefore growers will require guidance on how to apply, as well as how much, N to maximise yield potential in the crop.

Existing recommendations are for 175 kg N/ha at SNS (soil nitrogen supply) 2 during establishment, split between before and after initial crop growth, followed by applications of 70 – 300 kg N/ha in established crops (RB 209, 5th Ed.). Assuming yields of 15 – 20 tonnes/ha and total N content of 7.2% (Allison, 1966), crop offtake is 60 – 85 kg N/ha, considerably lower than recommended applications (although this does not take into account any N accumulation in the crown). 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.

The 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. Original RB 209 recommendations recommend 75 kg/ha N during establishment and 250 kg/ha N in a field crop, and this falls within the typical ranges of recommended N rates found in this review (

Table 1). 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, although this is greater than the typical recommendations of RB 209.

Table 1. 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 – 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, 2005 – 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 nitrogen would be in line with the recommendations given above.

Of the growers interviewed for this review N application was at or above this level. Typical answers were as follows:

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

N 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.

The range of treatments chosen was agreed after the above evidence was presented to the grower steering group. Although, the literature suggests a mean of 150 kgN/ha, it was agreed that the range of tested rates needed to go well above this to ensure we capture any higher responses. The rates can be revised down in subsequent trials in Year 2 based on evidence from Year 1 trials

3.2.2 Potassium (K) and Phosphorus (P)

Only limited information is available regarding application rates of K and P. Existing recommendations are of application rates of K up to 250 kg/ha at K Index 1. However, in a similar vein to N requirements, significant accumulation of K in the petiole is seen during maturation (Forest, 1958) and high K requirement, particularly as anecdotal evidence suggests that additional K provision can enhance red pigmentation of the petioles. Application rates of 90 kg/ha of P_2O_5 and 75 kg/ha K_2O gave increased fresh weight (FW) yields but had no impact on phytochemical content in *Rheum tanguticum* (Shen *et al*., 2017).

Recommendations for K/P application are given in **Table 2** below, followed by interview responses of growers. Recommendations for P applications during establishment are greater than those for mature crops, with typical ranges of P_2O_5 applications for mature crops in the region of 100 – 200 kg/ha for mid-level soils. This largely corresponds with current grower practice, with growers reporting applications of 220 and 330 kg K_2O/ha, although two growers reported applications of significantly less than this.

For potassium applications, broader ranges of K_2O are given as recommendations although higher levels of application are due to a some recommendations of high level of manure (e.g. 50-75 t/ha manure giving 420 – 840 kg K_2O, RB 113, 1949). However, a general trend in the recommendations gives application levels of 200 – 300 kg K_2O/ha/years, which is largely in line with current grower practice although some growers report application rates as low as 27.5 kg/ha K_2O from shoddy release. For both K and P it will be necessary to ensure sufficient concentrations in the root zone, and to replace offtake over and between seasons.

Table 2. Summary of potassium and phosphate 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 – 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, 2005 – Western Australia	600 kg/ha of double phosphate as P_2O_5			75kg/ha muriate of potash every 1-3 weeks as P_2O_5		

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.

Responses to grower interviews:

- 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 propriety products were 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, 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 either their late-season and early-season feed regimen 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 beneficial 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.

3.2.3 Micronutrients

The effect of availability of other nutrients on crop performance is less widely reported. Burt (2005) 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), ammonium sulphate application (72 kg SO_3/ha). There was interest in whether magnesium, magnesium 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).

3.2.4 Forcing

Limited information is available on crops grown for forcing. Recommendations derived from RB 209 (5th 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.

3.2.5 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. The recommendations given in Table 1 routinely support lower doses of N in establishing crops than in mature crops, reflecting the reduced demand for N posed by establishing crowns. Conversely, higher rates of phosphate and potassium are recommended for establishing crops than those freshly planted.

3.3 Informing Experimental Approach for the 2020 Season

The outputs of the literature review were used to refine an initial experimental approach for the 2020 season as a preliminary step of evidence generation to update RB209. The primary focus of the 2020 season will be an accurate determination of the nitrogen requirements of commercially grown rhubarb in an established crop. The requirements of a freshly-planted crop 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 will be in an established crop of two years or older (although contrasting sites of young/old crops will be used to explore the impact of age of crop on nutrient requirements). N is liable to have the greatest impact on yield (both in terms of over- and under-application), and evidence needs to be generated relating to the optimisation of both the quantity and timing of N applications. Single applications may reduce labour requirements but may lead to increased leaching or oversupply at a single point at the season (depending on soil type, rainfall, rooting depth etc.), potentially reducing the impact of the crop to generate yield in a multiple system. Conversely, the timing of multiple applications may have an impact on the magnitude of a response – will early applications (when the crop is breaking dormancy and soil moisture likely to be at a peak) give the greatest impact, or will later applications of an emergent crop (with increased potential to absorb and use soil nutrients) give a greater response? Timings of nitrogen application may also feed forward into crop quality and scheduling potential, or complement different requirements between cultivars.

Based on the evidence outlined above, three key elements can be identified that will be prioritised for examination in the trials work in this project:

1) N Requirements – As outlined in **Section 3.2.1** there is significant breadth in the recommended rates of N for establishing and mature rhubarb crops. As this is likely to have the most significant impact on marketable yield, both in forced and field-grown rhubarb, this will be prioritised.
2) Timing of applications – Similarly, routine support is found for splitting applications between different periods of the season in both recommendations and current grower

practice. However, the timing of such applications, and the partitioning of feed between different points in the season (e.g. pre-emergence or between harvests) is poorly documented.

3) Fine-tuning Nutrient Applications – Considerable grower interest was seen in the potential to better manage nutrient and yield outputs, such as coupling easy-to-measure indicators of crop condition with application, or using crop nutrition as a control mechanism for yield quality and scheduling.

Points 1) and 2) will be addressed in a single trial run over two seasons in which N application rates, and partitioning between three application points, will be trialled. **Table 3** given below summarises the proposed rates and timings of a variable N application trial, which are presented in comparison against recommended rates and current grower practice in **Section 3.2.1**. This approach will be followed in the first season and will be reviewed based on the responses of the first season. The total N application rates cover the range of rates discussed above, so the trial will encapsulate the breadth of variation seen in current commercial practice, allowing closer examination of the impact of different N application rates on crop responses. It is proposed that these are applied at three timing categories (100% before emergence, a large pre-emergence application followed by two smaller applications or a smaller pre-emergence application followed by larger post-harvest applications). Although it would be preferable to include additional treatment rates to refine the N response curve, the suggested range will allow sufficient data to be generated whilst streamlining experimental activities in the first season. The suggested range also extends beyond the range typically seen in production – this will allow testing of the higher end of the N response curve, exploring whether higher-than current N rates would be beneficial. In this fashion the scenarios discussed will be tested in the field to allow ideal responses to be identified. This proposed trial design will be applied to a range of contrasting cultivar/growing condition settings to identify whether these features have any impact on optimum N response.

Table 3. Trial design nitrogen application trials to be followed in field trials in the first season. Rate category 1 represents current practice, with category 2 providing an addition 100kg N/ha, and category 3 an additional 200 kg N/ha. Timing categories represent full application as a pre-emergence application (category 1), 60% pre-emergence application followed by two 20% further applications (before the second and third harvests, category 2) or equal applications of 30%, 35% and 35% (category 3).

Treatment Number	Timing Category	Rate Category	Application Point (kg N/Ha) Pre-Emergence	Pre-2nd Crop	Pre-3rd Crop	Total Applied (kg N/ha)
1	1	1	175	0	0	175
2	2	1	105	35	35	175
3	3	1	53	61	61	175
4	1	2	275	0	0	275
5	2	2	165	55	55	275
6	3	2	83	96	96	275
7	1	3	375	0	0	375
8	2	3	225	75	75	375
9	3	3	113	131	131	375

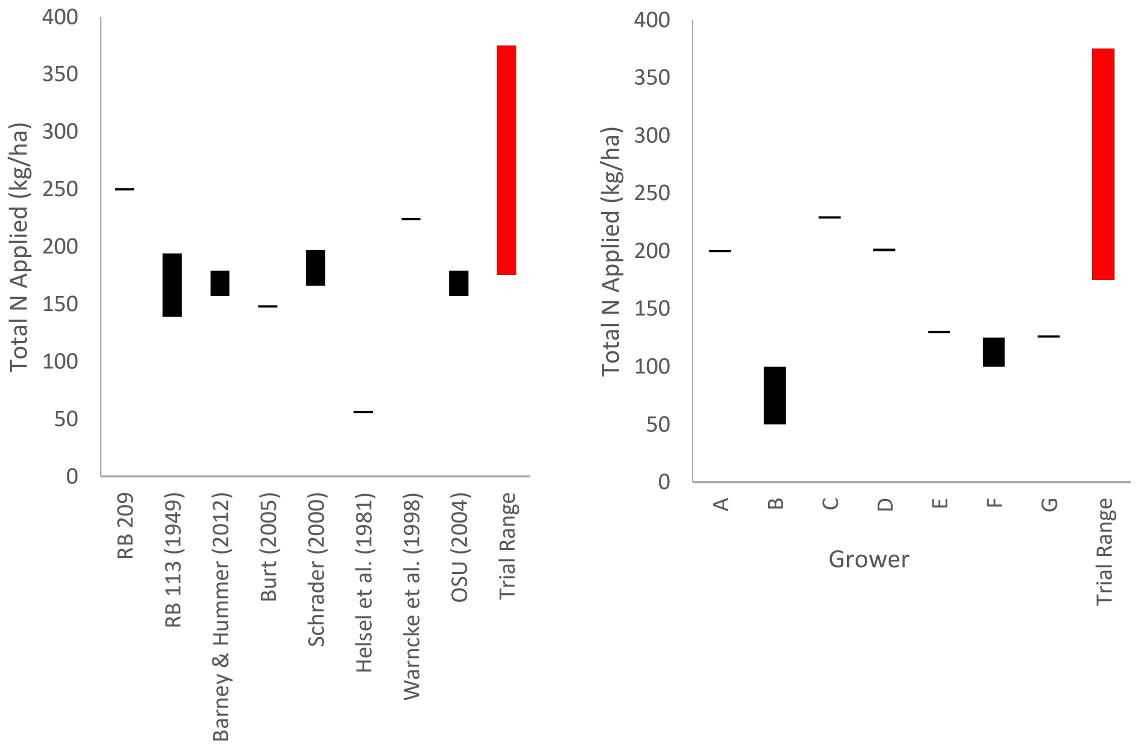


Figure 1. Proposed total nitrogen applications for nutrient management trials when compared with recommended applications (1A) and current grower practice (1B) as outlined above in Section 3.2.1 above. References have been quoted for published recommendations while alphabetic codes have been given to individual growers to preserve anonymity**.**

The suggested rates of N application for the first season will be sufficient to reflect current practice while accommodating the construction of a N response curve (e.g. application at levels beyond which a response is likely to be seen) while also testing whether current practice by growers is sufficient for the crop demands of a multiple pull system. These trials will be implemented in an established crop at two grower sites (Hammonds Ltd., Yorkshire, and

Barfoots Ltd., Southampton) to allow site variability to be taken into account. While this focuses on multiple pull systems, achieving maximum growth potential of a rhubarb crop will feed forward into subsequent yields in a forced crop once lifted.

Point 3) will be partially addressed through the nutrition trials as outlined above. Crop quality and yield responses will be monitored against a background of variable timing regimes. As a preliminary method of assessing links between crop nutrient demand and yield performance, crown samples will be collected at points across the season (e.g. end of season, pre-emergence, mid- and late-season) and subject to nutrient analysis to test whether any correlation between gross content and changes in crown status can be used to predict yield or nutrient requirements.

In addition to the outlined trials for N application, soil and plant material sampling will be used across the trials to quantify crop offtake for potassium, phosphate and magnesium. In the first and second seasons of trials work, we will focus specifically on N to allow impacts across subsequent seasons to be assessed. In the third year impacts of these additional nutrients will be explored, based on the analysis of crop offtake in the first two seasons. This will provide an opportunity to provide a robust, evidenced-based approach to the nutrition management of commercial rhubarb production. However, trials will be conducted with sufficient replication (e.g. over two seasons) so as to provide valid results for updating RB209. This approach was confirmed through discussion with the project's steering group where the results of the literature review was presented.

3.4 Experimental Approach Beyond the 2020 Season

The targeted trials outlined above will allow for the determination of the base crop responses to N application, while evaluating the impact of timing as well as gross N application. This will be combined with analysis of crown nutritional status and follow on trials into the 2021 season to determine how integrated nutritional status of the crop impacts future production. Subsequent seasons will allow further examination of other nutrient responses (e.g. phosphate) and how nutrient requirements of specific crop situations (e.g. newly established plantations) differ from that of an established crop. In addition, whilst crown nutrient content was to be assessed in the 2020 season, the lifting of crowns for weighing and dry matter analysis may also be included, particularly after optimum nutrient conditions have been identified.

4 Methods and Materials – 2020 Season

4.1 Site Selection and Trial Development

The trial was located in a crop of Timperly Early for both trial sites – the grower hosts ensured that both sites did not receive any N fertiliser, digestate or organic manure from autumn 2019. Soil analysis were obtained for both sites are detailed in the table below, and lime, phosphate and potash were applied as appropriate to ensure nutrients were not limiting. SNS indices at both sites were Index 0 (**Table 4**) at the start of the 2020 season before first fertiliser applications. The plots were marked out in January 2020 and measured 7 m x 3.8 m and consisted of four beds, with an experimental trial area of 42 m by 20 beds and a total trial area of 72 m by 28 beds. Four rows on either side of the trial area and 15 m either end will act as a guard to eliminate the edge effect. Callisto and Stomp were applied by the grower on the 7th of February to limit early season weed development. Site 1 applied lime at 6 t/ha and K at 150 Kg K_20/ha as recommended by The Fertiliser Manual across the whole site to ensure that these nutrients are not limited, and Site 2 applied K at 250 Kg K_20/ha across the trial area. Each plot represents a different treatment and arranged in a randomised block design (**Figure 3**, Error! Reference source not found.).

Table 4. Soil analysis and existing recommendations for rhubarb fertilisation. * This was applied in January ** taken at a depth of 0-60cm as the 60-90cm layer was too hard

			Index			Soil type
Site	pH	P	K	Mg	SMN (0-90cm) kg N/ha	
1	6.0	4	3	3	38.6**	Sandy clay loam
Amount recommended (old RB209)*	6 t/ha	0	150 kg K_2O/ha	0	-	
2	7.18	4	1	2	15.7	Sandy loam
Amount recommended (old RB209)*	0	0	250 kg K_2O/ha	0	-	

TREATMENT	1	10	6	2		
BLOCK	3	3	3	3		
PLOT	306	307	308	309		
TREATMENT	4	7	3	9	8	5
BLOCK	3	3	3	3	3	3
PLOT	301	301	303	304	305	310
TREATMENT	10	2	8	6	1	
BLOCK	2	2	2	2	2	
PLOT	206	207	208	209	210	
TREATMENT	3	4	9	5	7	
BLOCK	2	2	2	2	2	
PLOT	201	202	203	204	205	
TREATMENT	9	7	4	1	3	
BLOCK	1	1	1	1	1	
PLOT	106	107	108	109	110	
TREATMENT	5	10	8	2	6	
BLOCK	1	1	1	1	1	
PLOT	101	102	103	104	105	

Figure 2. Trial outline plan. NB. Plot 310 was relocated to be adjacent to plot 305 due to an insufficient number of crowns present in the original location adjacent to plot 309 at site 1 as indicated.

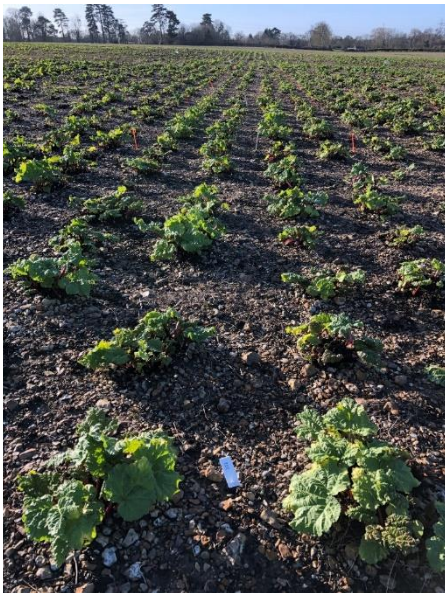


Figure 3. Photograph of trial area at site 2.

4.2 Treatments

The N treatments were top-dressed by hand as Calcium Nitrate (27%) and applied on the 30th January 2020. There were 10 treatments replicated three times, one of these treatments being a zero N control. Planned treatments are given in **Table 5** although only the first treatment application was made.

Table 5 Trial design nitrogen application trials to be followed in field trials. Rate category 1 represents current practice, with category 2 providing an addition 100kg N/ha, and category 3 an additional 200 kg N/ha. Timing categories represent full application as a pre-emergence application (category 1), 60% pre-emergence application followed by two 20% further applications (before the second and third harvests, category 2) or equal applications of 30%, 35% and 35% (category 3).

Treatment Number	Timing Category	Rate Category	Application Point (kg N/Ha)			Total Applied (kg N/ha)
			Pre-Emergence	Pre-2nd Crop	Pre-3rd Crop	
1	0	0	0	0	0	0
2	1	1	175	0	0	175
3	2	1	105	35	35	175
4	3	1	53	61	61	175
5	1	2	275	0	0	275
6	2	2	165	55	55	275
7	3	2	83	96	96	275
8	1	3	375	0	0	375
9	2	3	225	75	75	375
10	3	3	113	131	131	375

4.3 Assessments

All assessments were taken from the central 5 m of the trial beds.

4.3.1 Soil Assessment

Soil mineral nitrogen (SMN) samples were taken from each experimental plot on the 8th January prior to bud break at 30 cm, 60 cm and 90 cm horizons with eight cores taken per block for site 2. Due to the shallower nature of the soil profile at site 1, SMN was only sampled to 60 cm depth.

4.3.2 Start of season assessment crown assessment

At the start of the season four crowns per plot were marked with a numbered ringot and label, with a section of crown measuring 10 cm long x 5 cm x 5 cm taken from the centre of each of these. These were used to determine fresh and dry weight of the whole sample, drying the sample at 80^{0}C for 48 hours; a subsample was taken equal to 25% of the total mass to measure foliar mineral content.

4.3.3 Harvest and yield

Yield data for the rhubarb were harvested from the same eight crowns that were used for the Fieldspec data in the central bed and harvested in the same order that they were scanned.

Harvesting was done using commercial practice from a single harvest (see notes below relating to covid-19)., 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 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. Petioles that did not meet the criteria were considered unmarketable.

4.4 Postharvest Assessments

Following each harvest, material was subject to a range of assessments to quantify quality. For measurements that are routinely appraised as part of commercial supply (e.g. length, dimensions) assessments were based on commercial specifications.

Five sticks were selected at random from each plot and subject to the following measurements:

4.4.1 Dimensions

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

4.4.2 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 *et al*. (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.

4.4.3 Biomass

Petiole biomass were recorded from the remaining crowns taking a 25% subsample, together with the leaves that were removed from the petioles at harvest time. Fresh and dry weight were recorded from these samples, drying were done for 48 hours at 80 ^{0}C. Dried samples were sent for foliar mineral analysis.

4.4.4 Nitrogen Offtake Analysis

Stick and leaf samples were sent for dry matter nutrient analysis to allow for examination of nitrogen offtake, alongside evaluation of key nutrient differences.

4.4.5 Statistical Analysis

Trial results were tested for significance by analysis of variance (ANOVA) using Genstat (VSN International, 2019).

5 Limits of the 2020 Experimental Trials

The onset of the covid-19 outbreak in March 2020 had a significant impact on delivery of planned trials work. The first (pre-emergence) application was carried out, 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 below 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, as the project was implemented in a sufficiently robust way it is possible for some key elements to be identified from the results achieved in the 2020 season, as outlined below. This has also impacted our ability to use external inputs (e.g. external laboratory analysis of nutrient content) and so a complete analysis has not been possible at this time. While this project was initially planned over a three season period, at the time of writing it is believed that three further seasons will be available for trials work so that a full range of assessments and treatments as outlined above can be made.

5.1 Results

Crop Condition at First Harvest – March 2020

There was significant variation in starting crop condition both within and between sites. The average number of crowns per plot. On average 6000 crowns/Ha were recorded at site 1, compared with 8600 crowns/Ha at site 2 (**Figure 4**). 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 site 1 varied from 2.2 – 5.5 buds/crown, compared with 1.5 – 4.6 buds/crown at site 2 (**Figure 5**). 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.

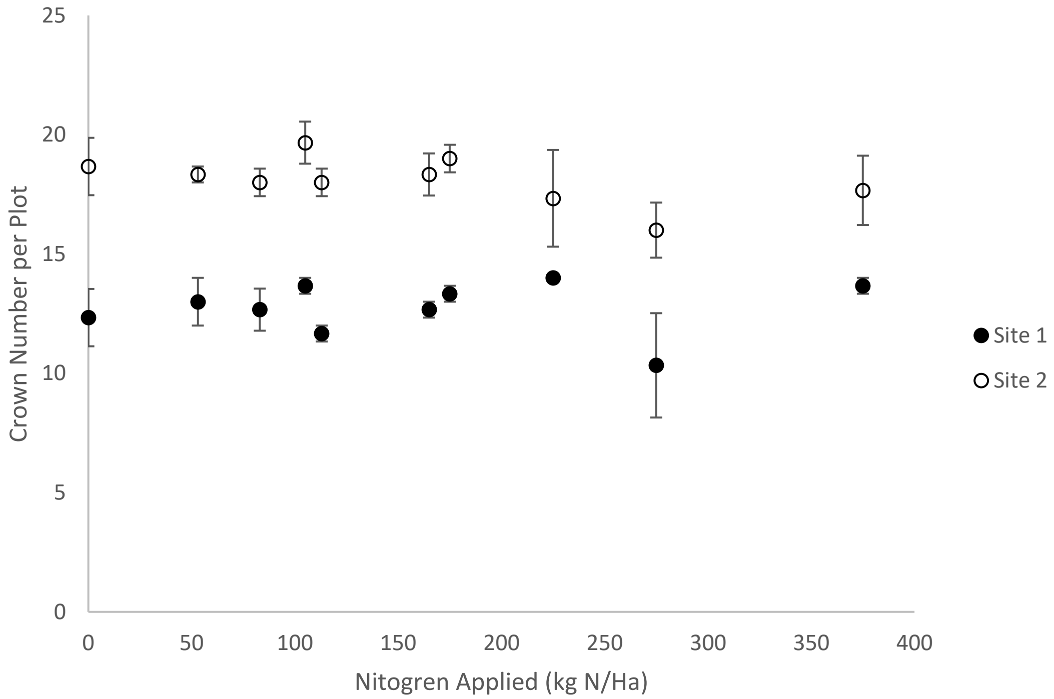


Figure 4. Number of Crowns per plot. Average number of crowns per 7 m x 3 bed plot area for each site against nitrogen treatment.

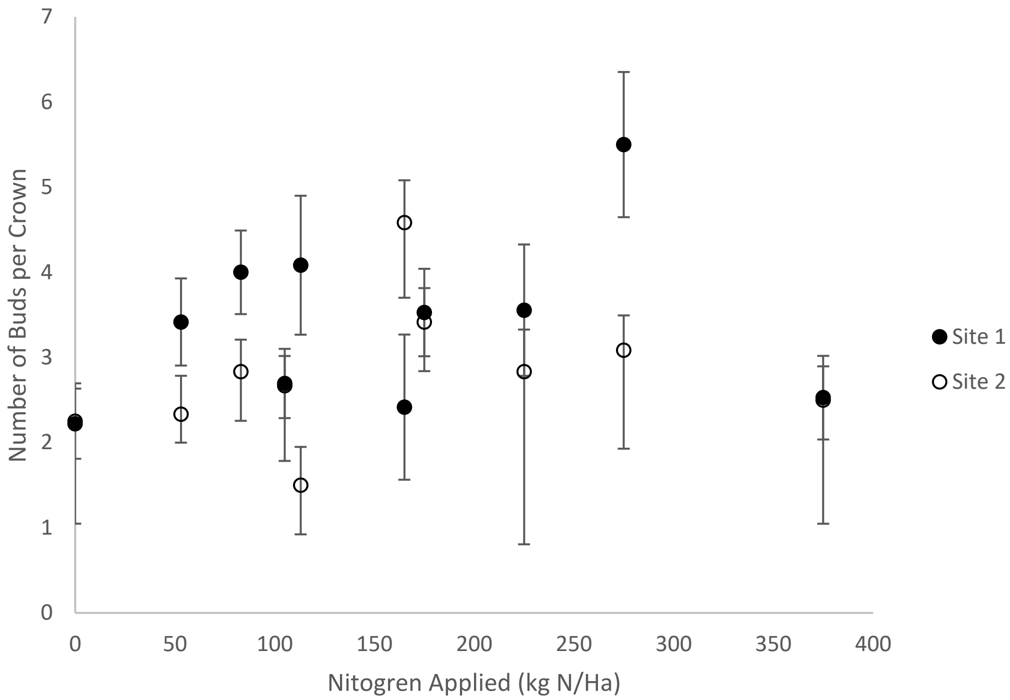


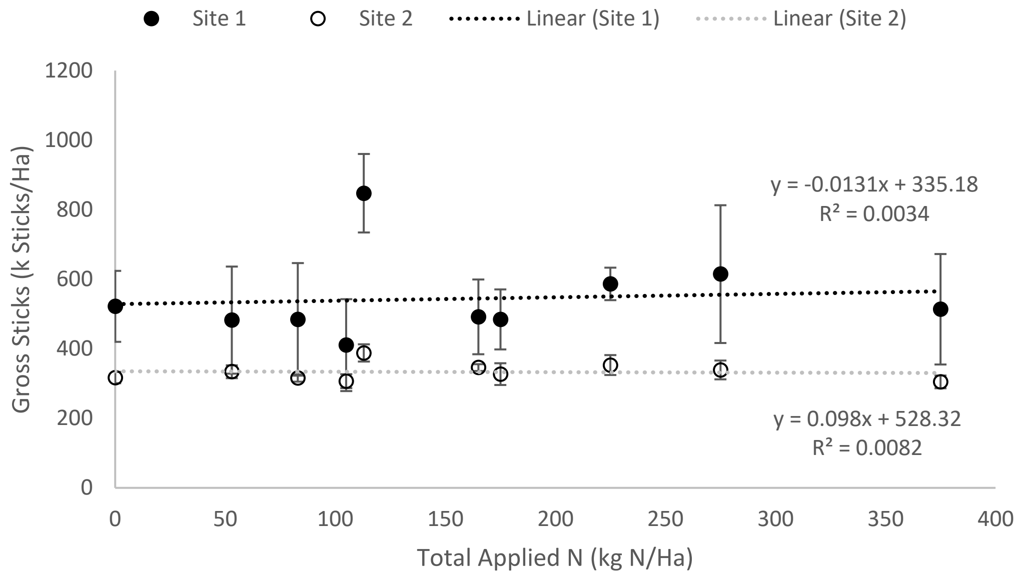
Figure 5. Number of buds per crown. Average number of buds per crown recorded in each treatment plot before treatments applied. Lines of best fit not given here as bud number is unrelated to N application.

Crop Productivity

Crop productivity showed similar variation between sites (**Figure 6, Figure 7**). Gross stick number was higher at site 1, but gave a smaller gross weight than site 2, indicating that the sticks at site 1 were shorter/thinner than that seen at site 2. Stick number varied broadly between plots at site 1 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 site 1, with only a marginal insignificant increase at 275 kg N/Ha. At site 2 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 site 1 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 Site 1 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 site 2, 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.



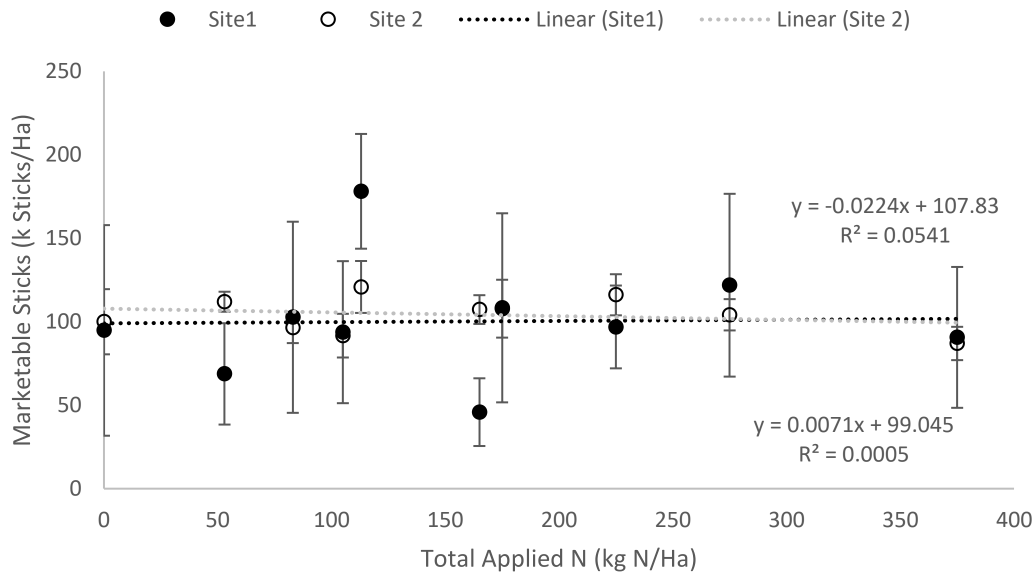


Figure 6. Gross and marketable yield per Ha (standardised to a crown density of 12500 crowns/Ha) presented as number of thousand sticks harvested, averaged across plots at site 1 and site 2.

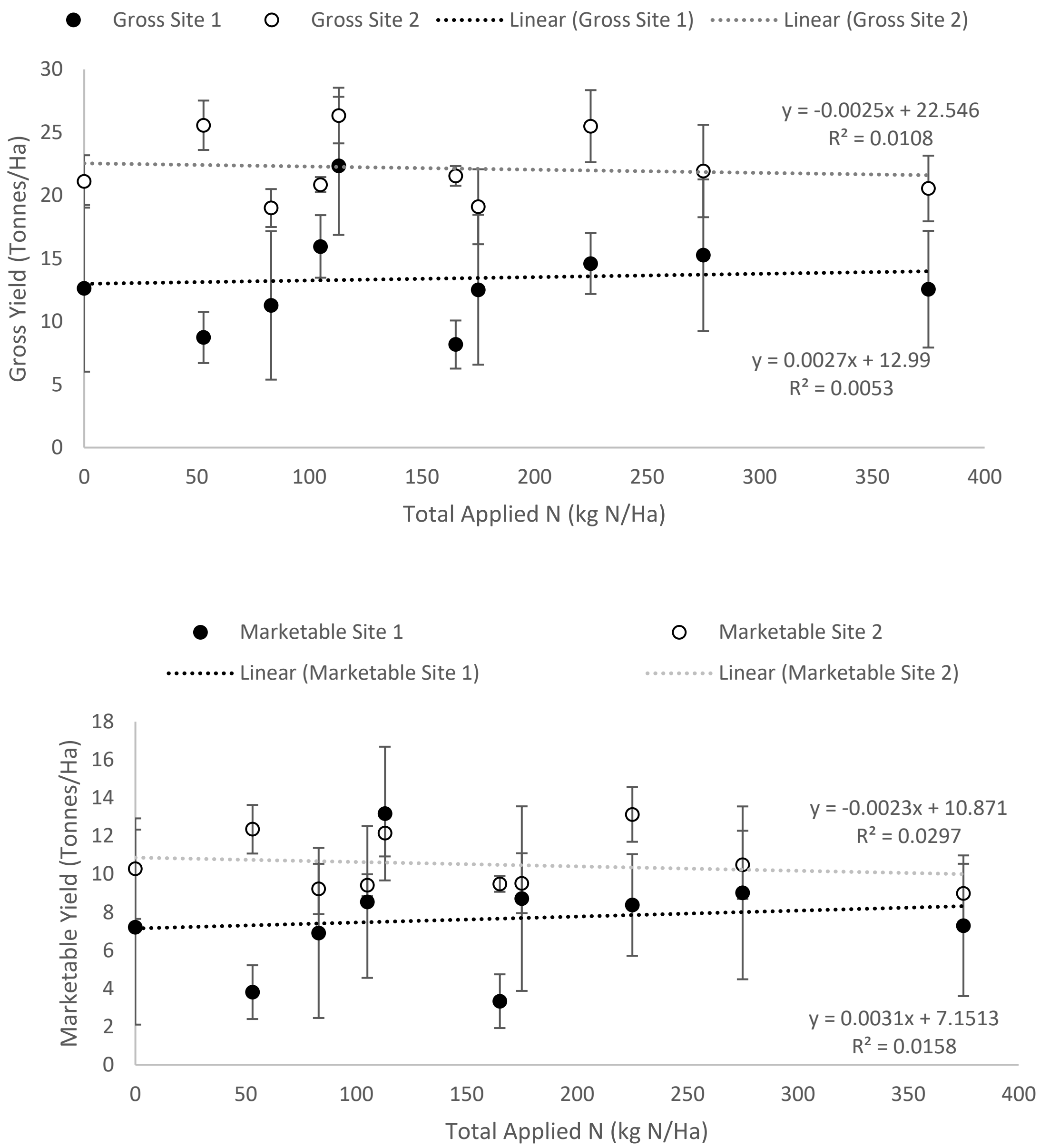


Figure 7. Gross and marketable yield per Ha (standardised as 12500 crowns/Ha) presented as weight for site 1 and site 2.

Examination of stick dimensions largely corresponds with the observations above. Average stick dimensions were greater at site one, showing increased length and width to those sampled from site 2 (**Figure 8**). 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 site 2 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.

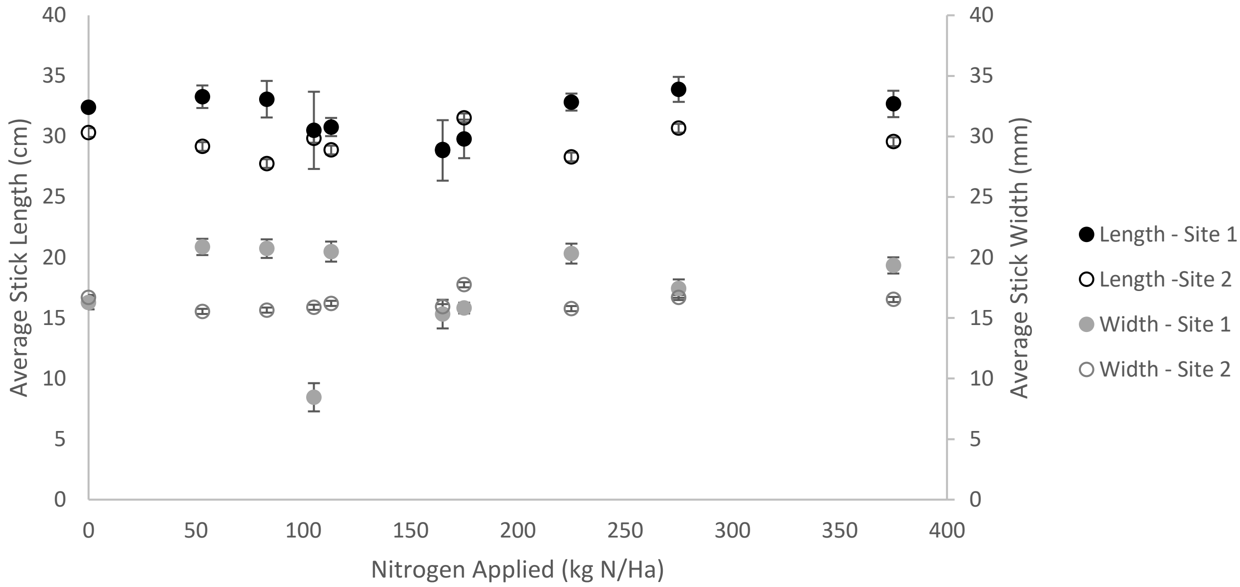


Figure 8. Average stick length and width as recorded from subsamples taken at site 1 and site 2.

Nitrogen Uptake

N content of above ground biomass was relatively comparable between site 1 and site 2, although sticks harvested at site 2 had greater proportions of N than that seen at site one (**Figure 9**). 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 10**). Total N uptake at site 1 exceeded that seen at site 2, largely due to the increased yield seen at this site. While there is broad variability in N uptake at site 1, the N uptake at site 2 was proportionately more uniform. However, neither site showed a correlation between applied N and N uptake (p=0.47 site 1, p=0.37 site 2), implying that the observed N uptake is independent of N application at this stage in the season.

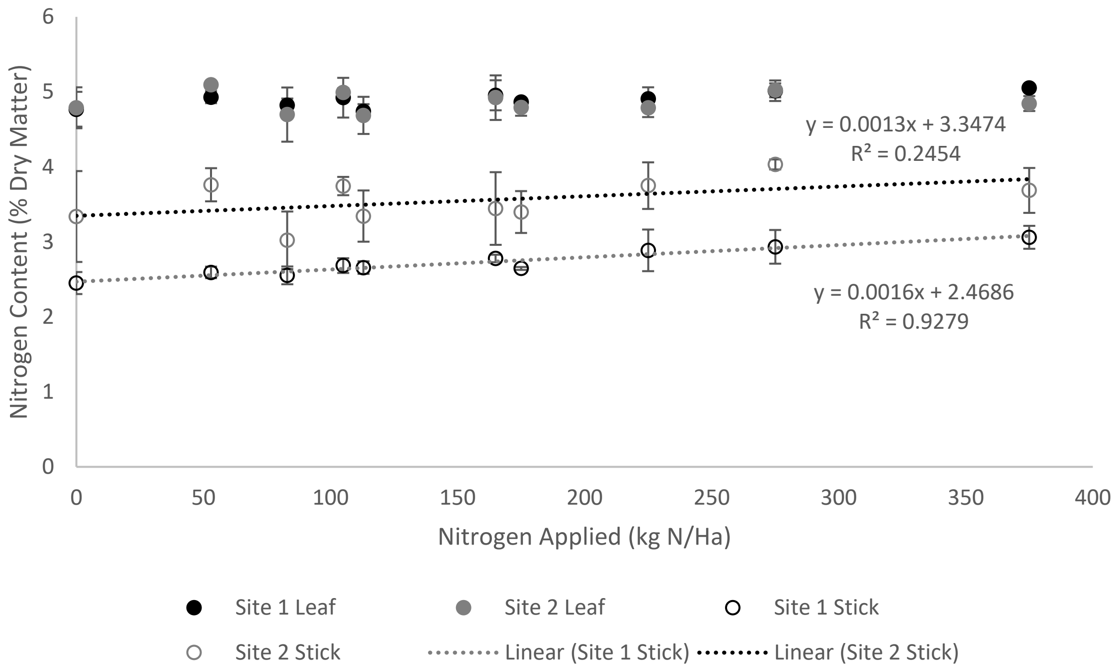


Figure 9. Percentage nitrogen of plant dry matter of stick and leaf fractions at harvest.

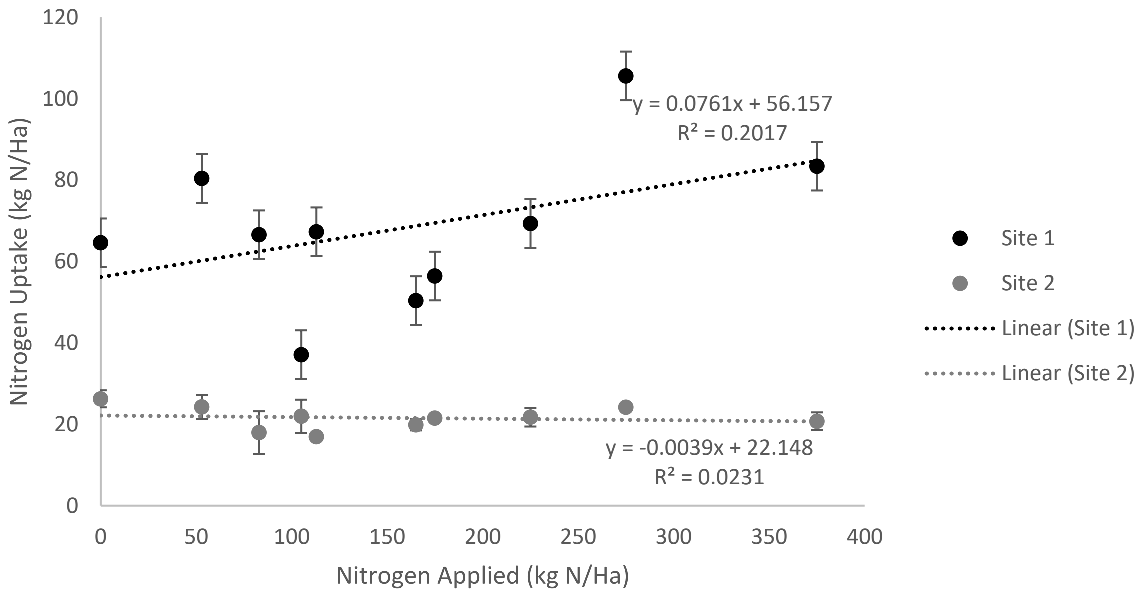


Figure 10. Nitrogen uptake per Ha based on combined leaf and stick samples at site 1 and site 2.

5.2 Discussion

While it is unfortunate that the onset of the covid-19 situation has significantly impacted on the planned activities of the project in the 2020 season, it has still been possible to produce a broad set of evidence to inform project activities for the later seasons of this project.

The literature review and survey of the UK industry demonstrated that a broad range of N management approaches were seen with rhubarb. Of the grey literature reviewed, many aspects were unsuitable for current practice (e.g. inclusion of manures as a nitrogen source).

A common theme in the literature review was a split application of N at bud break, with subsequent applications after each pull. While the data collected in the 2020 season is limited to a single pull, it is considered sufficient to test the impact of a pre-emergence application of N on subsequent yields. Based on these data different N application rates had no impact on gross or marketable yield, or on yield quality.

The extent of variation within the results obtained (independent of N applications) demonstrates there was strong variability in the crop examined, particularly in terms of crown number and initial potential (e.g. bud number) at site 1 as demonstrated in **Figure 4** and **Figure 5**. Early season yield potential is highly likely to be linked with crown condition, which in turn is linked with the integrated condition from the previous season. If the crop was grown under optimum conditions, with high light and water inputs, and with little competition from weeds, it is likely that a strong crown will enter dormancy with a high bud number compared with one grown under sub-optimal conditions. Local conditions (e.g. crown density within a given area, and the subsequent competition for light, water and nutrients), may likely have a greater influence on the yield of the crop in the early part of the subsequent season, than any variation in N applied at an early stage in crop growth. However, as the management of the crop through the year could influence the crown health and size, the nutrition of the crop throughout the season is still important and may still influence yields later in the year, and also in the subsequent year. Therefore, the post-harvest management of the crop may be a greater influence on the next season.

Based on the limited data it is difficult to fully explore the impact of early-season fertilisation on rhubarb production. While these data indicate that early season N application has limited to no impact on the N offtake in the early season, it is not possible to determine where from, and in what portion, N present in the petioles/leaves is sourced i.e. from the crown or from the soil. For example, studies on the rhizomatous perennial *Bistorta bistortoides* (in the same family as rhubarb and with similar phenology) showed 60% of annual above-ground N came from mobilised N from the underground rhizome. The implication is that rhizome-sourced nutrients were used when there was high demand during early season crop growth at a time when assimilation of new nutrients was insufficient (Jaeger & Monson, 1992). This supports the suggestion that significant nutrient provision from the crown may be seen in rhubarb.

Continuing with the *B. bistortoides* model, plants grown in a fertilised and non-fertilised soil showed comparable levels of biomass N in above-ground fractions despite significant differences in rhizome N, which was significantly greater with fertilisation (Lipson *et al*., 1996). These data indicate that rhubarb crowns with a high N content (assimilated in the previous season) will not give greater above-ground N content in the following year, but will instead see plants relying more on crown-sourced N than new uptake in the following spring. In the context of rhubarb this may indicate that the ability of the crown to assimilate N in the past season is more significant than early season uptake. However, the energetic cost of assimilating new N (compared with internal remobilisation of N in the crown) may mean that low-nutrient crowns will have to commit greater portions of stored energy to obtaining new N from the soil compared with internal remobilisation, and this may translate to proportionately lower yields.

While it is difficult to fully explore the implications of early season N application to rhubarb, a variety of scenarios are possible. Firstly, the lack of a significant impact of early season N on yield or N offtake indicates that crowns are predominately relying on internal stores. However, the availability of external N may mean that the extent of reduction on internal crown reserves is lessened, making more available for use later in the season. This is also set against a background where the crowns may have been at a high level of N storage from the previous year. Where crops had limited N uptake and storage in the past season (e.g. under-application, high competition from weeds or excessive harvesting) crowns may be more reliant on early season N (and therefore show more response to pre-emergence applications) than is demonstrated here. This demonstrates the need to replicate these treatments over successive seasons to further test the carry-over of nutrients between successive seasons and how N application strategies interact with this. As discussed above, there is potential for crown analysis to be used for yield estimation or to manage nutrient applications. For instance, if crowns were shown to be below a specific N content, pre-emergence N applications may be beneficial compared with crowns that have a high level of N accumulated from the previous season, and would show no response.

5.3 Conclusions

Our work to date has demonstrated that there is considerable scope to review nutrient management practices for rhubarb. The range of practice, including fertiliser rates and timings, plus soil and climatic variation for areas of the UK in which the crop is grown, alongside changing methods of cultivation, are not reflected fully in the range of recommendations available. While trials in the 2020 season have been significantly curtailed, we have been able to demonstrate that early season pre-emergence nitrogen applications have no identifiable impact on subsequent yield, most likely as a result of the crown relying on internal stores rather than newly assimilated material. However, this may have an impact on later season growth, although we have insufficient data to test this aspect at this stage. We would recommend that the trial approach in future seasons be updated to reflect this effect, and this will be discussed at subsequent meetings of the project advisory group. There is a need to develop a robust framework for activities in later seasons of this project to further our aim of updating nutrient management techniques for commercial rhubarb production in the UK.

5.4 Acknowledgements

Thanks are due to Neil Cairns, Lindsay Oldroyd, Phillip Lilley and Robert Tomlinson, and for Richard Weightman and Clive Rahn for their support of this project.

5.5 References

Barney, D., Hummer, K. (2012) Rhubarb: Botany, Horticulture, and Genetic Resources *Horticulture Reviews* **40**(1): 147 – 182.

Burt, J (2008) *Farm Note: Growing rhubarb in Western Australia* Western Australian Agricultural Authority www.agric.wa.gov.au/rhubarb/growing-rhubarb-western-australia accessed 12/6/19.

Culpepper, C. W., & Caldwell, J. S. (1932). Relation of age and of seasonal conditions to composition of root, petiole, and leaf blade in rhubarb. *Plant Physiology* **7**(3): 447.

Forest, B. (1958). Acidity of rhubarb petioles as influenced by stage of maturity, season and partial shading. *Canadian Journal of Plant Science*, **38**(4): 387-393.

Helsel, D., Marshall, D., Zandstra, B. (1981) *Rhubarb: Cultural Guidelines for Michigan* Extension Bulletin E-1577, Michigan State University http://www.canr.msu.edu/foodsystems/uploads/files/rhubarb.pdf accessed 16/6/19.

Jaeger C. H., Monson R. K., Fisk M., Schmidt S.. Seasonal partitioning of nitrogen by plants and soil microorganisms in an alpine ecosystem, *Ecology*, 1999, vol. 80 (pg. 1883-1891)

Lipson D., Bowman W. D., Monson R. K.. Luxury consumption and storage of nitrogen in the alpine herb, Bistorta bistortoides, *Ecology*, 1996, vol. 77 (pg. 1277-1285)

Rhubarb (2004) Oregon State University Extension Service www.horticulture.oregonstate.edu/oregon-vegetables/rhubarb-0. Accessed 16/9/19.

Schrader, W.L. (2000) *Rhubarb Production in California* University of California Division of Agriculture and Natural Resources www.anrcatalog.ucanr.edu/pdf/8020.pdf accessed 12/6/19

Shen, N., Cui, Y., Xu, W., Zhao, X., & Yang, L. (2017). Impact of phosphorus and potassium fertilizers on growth and anthraquinone content in *Rheum tanguticum* Maxim. ex Balf. *Industrial Crops and Products*, **107**: 312-319.

Warncke, D, Christenson, D., Jacobs, L., Vitosh, M., Zandstra, B. (1998) *Fertilizer Recommendations for Vegetable Crops in Michigan* Extension Bulletin E-550B, Michigan State University www.hortintl.cals.ncsu.edu/articles/fertilizer-recommendations-vegetable-crops-michigan accessed 14/6/19.

Xiong, F., Nie, X., Zhao, X., Yang, L., & Zhou, G. (2019). Effects of different nitrogen fertilizer levels on growth and active compounds of rhubarb from Qinghai plateau. *Journal of the Science of Food and Agriculture,* **99**(6): 2874-2882.

5.6 Appendices