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Project leader:	Angela Huckle, ADAS Boxworth
Report:	Final report, 31 March 2022
Previous report:	None
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Location of project:	Cornwall, Lincolnshire, Perthshire, Fife
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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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Associate Director

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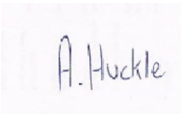
Signature Date 4/4/22



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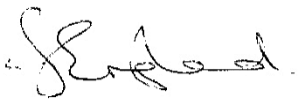
Signature  Date 4/4/22

1 Contents

1. Grower Summary

1.1 Headline

- Broccoli crops show a strong response to additional nitrogen (N) application, and this can have a significant impact on marketable yields per hectare.
- Existing N recommendations are robust, although care must be taken to ensure accurate determination of soil mineral nitrogen (SMN) is carried out when planning fertiliser applications.
- Care must be taken to avoid excess N applications to reduce the risk of spear rot or hollow stem incidence in susceptible varieties.

1.2 Background

Broccoli is a major UK crop, with significant customer demand for both traditional broccoli and purple sprouting varieties or newer Tenderstem. Although UK growers have access to specific recommendations for N provision to guide fertiliser management (Nutrient management guide, RB 209), growers are concerned about the influence of nitrogen on susceptible varieties of broccoli to spear/head rot. A wide range of recommendations are given in the literature, covering 112 – 450 kg N/ha depending on cultivation system and time of application (Bakker *et al*., 2008). Earlier editions of RB209 (8th Edition – 2008) did not differentiate between broccoli and cauliflower, giving the same recommendations for each crop, recommending 290 kg N/ha at soil nitrogen supply (SNS) Index 0 for summer/autumn plantings, and only recommending a 100 kg N/ha base dressing under conditions where poor establishment was likely. The 2010 update of the 8th edition of RB209 split broccoli from cauliflower, recommending a lower application of 235 kg N/ha at SNS Index 0 compared with 290 kg N/ha for cauliflower following an industry request due to the risk of head rot and assumptions that critical N content was lower for broccoli compared with cauliflower, although this remains to be tested. For Scotland, recommendations from SRUC for broccoli are higher than RB209, primarily as a result of a concern that lower rates would restrict some growers. A summary of current recommendations are given in below (Table 1).

Table 1. Summary of current recommendations for broccoli cultivation in the UK based on RB209 (England/Wales) and the SRUC Technical Note (TN – Scotland).

SNS Index (RB209)	0	1	2	3	4	5
N residue group (TN)	1	2	3	4	5	6
kg N/ha	<60	61-80	81-100	101-120	121-160	>160
RB209	235	200	165	135	80	0
SRUC TN	270	260	250	230	180	140

In addition to ensuring maximum yields which can be achieved, crop nutrient status can be linked with a number of postharvest quality indicators, including both physical (abiotic) and pathological (biotic) disorders. Hollow stem is the occurrence of an air-filled cavity within the stem below the head which is visible when the stem is cut at harvest. In addition to visible spoilage, the presence of the inner cavity can increase postharvest disease incidence to reduce yields further. The incidence of hollow stem is linked with rapid plant growth caused by wide plant spacing, high N levels, warm/moist weather or boron deficiency (Vigier & Cutcliffe, 1984). For instance, Moniruzzaman *et al.* (2007) demonstrated a three-fold increase in hollow stem area in broccoli when 200 kg N/ha was applied compared to 100 kg N/ha, although this effect showed a significant interaction with boron (B) application, where hollow stem incidence was reduced with increased B availability. Similarly, head rot, or spear rot, caused by infection in the broccoli head by a range of pathogens including *Pseudomonas* and *Erwinia* species can show increased incidence with greater nitrogen availability. Due to difficulties controlling head rot with pesticides this can lead to significant crop losses, especially under conditions of prolonged damp weather. For example, Everaarts (1994) reported an increase in head rot incidence from 39% at 0 kg N/ha to 88-90% at rates of 98 – 196 kg N/ha. As a result, it was considered relevant to include scoring of the incidence of spear rot and hollow stem in response to N application to test whether marketable yields can be adversely affected due to increased incidence of these conditions with greater N application.

Due to increasing incidence of head rot in Lincolnshire and Scotland in recent years, it was decided to review evidence to support N application recommendations for current UK varieties. This was addressed through a series of targeted trials at representative commercial sites in the east (Lincolnshire) and south (Cornwall) and in Scotland (Fife and Perthshire) to further examine the response of broccoli to nitrogen applications. The trials were established to test the following core objectives:

1. Determine economic optimum N rate for broccoli marketable yield.
2. Assess the impact of two different N application timings on broccoli marketable yields (Scotland only).
3. Assess the effect of N rate and timing on spear/head rot incidence.

1.3 Summary of 2021 Trials

Nitrogen application rates were chosen to test both existing recommendations and the rate ranges discussed above. Six application rates over two timings between 0 – 200 kg N/ha were used in Cornwall and Lincolnshire allowing full coverage of RB209 recommendations for those sites of 0 – 80 kg N/ha whilst allowing for testing of “luxury” application rates up to 200 kg

N/ha. Applications were split between two timings – once shortly after planting, followed by a second application one month later. For Scotland, seven application rates of 0 – 270 kg N/ha were tested covering recommendations of up to 250 kg N/ha in the SRUC technical notes. A base application one month pre-planting was only included at the 220 kg N/ha treatment, with the other treatments split between applications at planting, one month after planting and at heading. A summary of treatments is given in Table 2 and 3 below.

All other major nutrient requirements (P, K, Mg) were assessed and applied as necessary to RB209 recommendations to ensure no other nutrients were limiting. It was also ensured that the sites were at the correct soil pH. All other aspects of crop cultivation, including planting, and control of weeds, pests and diseases were carried out as per usual commercial practice by the host growers.

Nitrogen treatments were applied in triplicate to a randomised block design, with each block covering a 7m stretch of 3 beds, although harvest assessments were only taken from a 5m stretch of the central bed to prevent the influence of edge effects between treatments. A 20m buffer zone around the trial area was marked out to prevent N application from spreading into the trial plots when the commercial crop applications were made. Applications were made by hand with nitrogen applied as calcium ammonium nitrate (27%).

Table 2. Summary of treatments for Cornwall and Lincolnshire.

Treatment No	Timing 1 Just after planting	Timing 2 1 month later	Total N applied
	kg N/ha		
1 (Nil N)	0	0	0
2	60	0	60
3	60	30	90
4	80	40	120
5	100	60	160
6	120	80	200

Table 3. Summary of treatments for Fife and Perthshire, Scotland.

Trt No	Timing 1 Base	Timing 2 Just after planting	Timing 3 1 month later	Timing 4 At heading	Total N applied
	kg N/ha				
1 (Nil N)	0	0	0	0	0
2	0	60	0	0	60
3	0	60	60	0	120
4	0	80	80	20	180
5	0	100	80	40	220
6	0	120	100	50	270
7	100	0	80	40	220

Site Details

Trial sites were identified to achieve broad geographical spread across the UK, covering Truro, Cornwall, in the southwest, Lincolnshire in the east, and Fife and Perthshire in Scotland. Summary information for each site is given in Table 4 below. Soil analysis was carried out prior to planting to gain soil nitrogen status at 0, 60 and 90cm (although SMN sampling was performed only to 60cm at Cornwall due to shallower soils). This demonstrated a broad range of pre-trial soil N content across the trial sites with RB209 recommendations ranging from 0 – 165 kg N/ha, and these were used to decide N application treatments.

Table 4. Summary site details for trial sites. * A small amount of nitrogen may be needed if SMN levels are low in the top 30cm of soil. Numbers in Italics – Scottish Technical Note recommendations

Site	Soil Mineral Nitrogen (SMN) (kg N/ha)	Soil Nitrogen Supply (SNS Index)	Recommended N (RB209) (kg N/ha)	Planting Date	Harvest Date	Variety
Cornwall	184	6	0* (*140*)	27/4	23/7	Steel
Fife	127	4	80 (*180*)	2/6	19/8	Parthenon
Perthshire	89	2	165 (*250*)	10/6	20/8	Parthenon
Lincolnshire	156	4	80 (*180*)	9/8	15/11	Covina

1.4 Summary of Results

A response to increasing N applications was observed at all sites, but the level of response varied depending on the initial starting SMN (Figure 1). The response was weakest in Lincolnshire and Cornwall, where the high initial SMN reduced the crop response to supplementary N applications. The greatest response was seen in both Perthshire and Fife where marketable yields were increased by 10x/5x respectively with N applications up to 270 kg N/ha. However, increased N application showed a strong correlation with increasing postharvest quality reductions as a result of both hollow stem and spear rot. The increase in these conditions, coupled with the reduced N response at higher N applications saw a levelling off of yield between 120 – 220 kg N/ha.

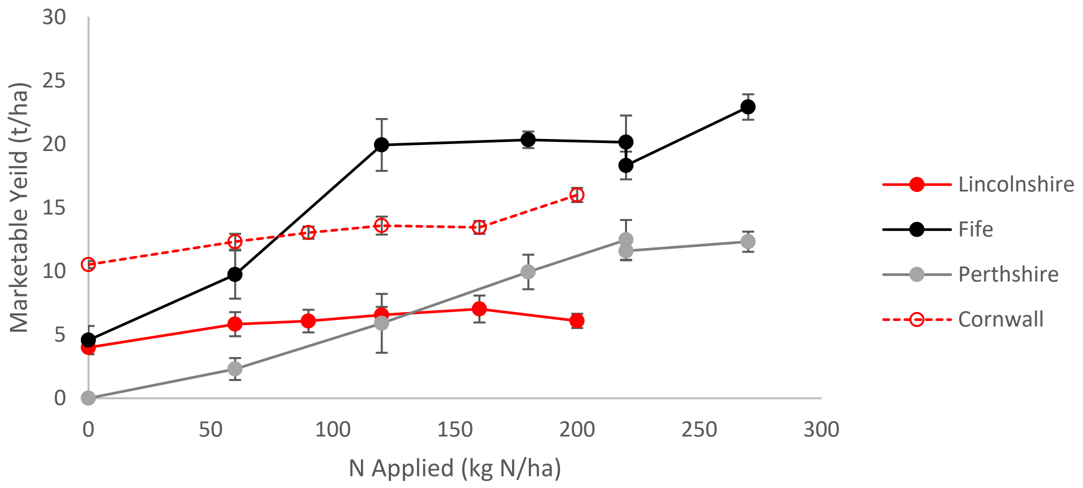


Figure 1. Marketable yield response to N application, 2021 trials.

Whilst increased N application did lead to greater yields, once the cost of current fertiliser costs and postharvest losses were taken into account diminishing returns were seen with increased N applications above 200 kg N/ha at the majority of sites examined (Figure 2). This was also mirrored by a general decline in nitrogen use efficiency with greater N application, demonstrating that greater proportions of available N were not being utilised by the crop.

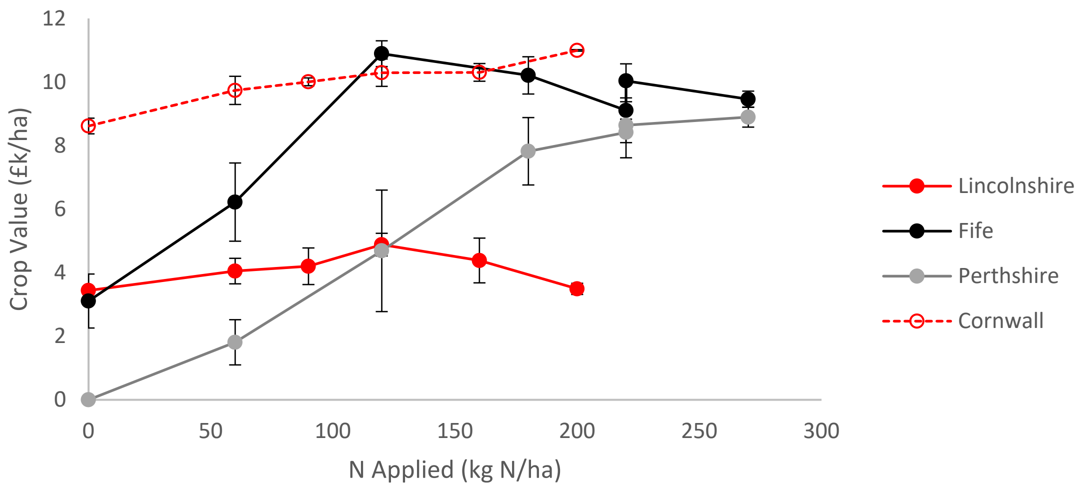


Figure 2. Summary figures for crop economic returns per ha.

Taking into account the increasing costs of N, levelling off of the yield responses and increased proportion of postharvest quality reductions, cost:benefit relationships for increased N application demonstrate a proportionate reduction in returns for higher N application (Figure 3). These relationships generally concur with current recommendations for broccoli taken from both RB209 and the Scottish Technical Notes.

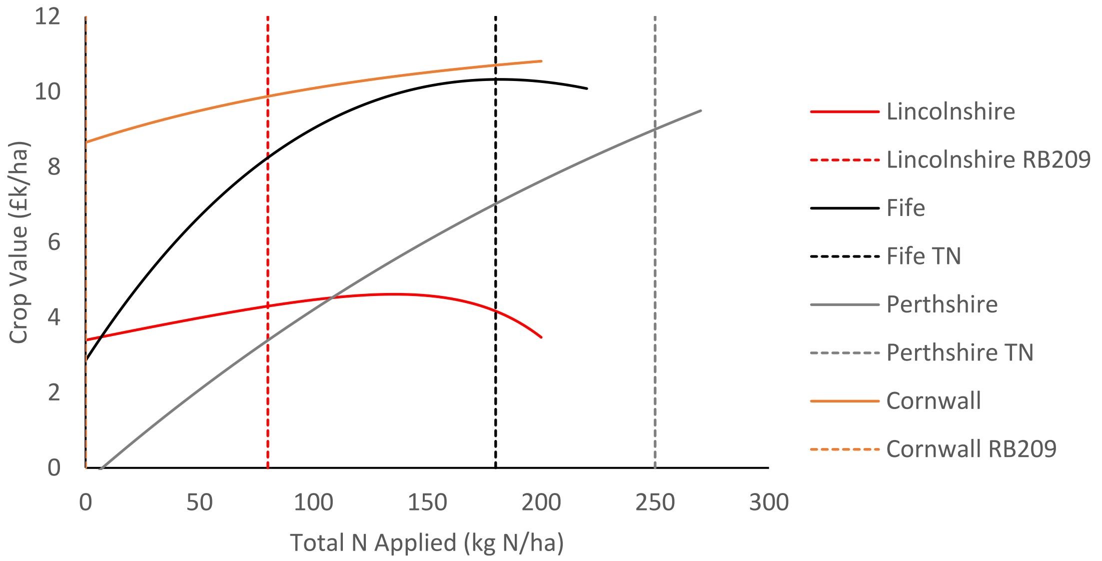


Figure 3. Fitted curves to economic optima for nitrogen application. RB209/Scottish Technical Note recommendations are by dashed lines.

In addition to testing the relationship between total N application and yield, a limited dimension of these trials assessed the relationship between base dressing and top dressing for the first N application. Results from Scotland indicated that base dressing prior to planting gave a significantly stronger yield response and brought harvest date forward due to faster early growth, especially where pre-planting SMN values were low. But, this also increased the risk of incidence of head rot.

In addition to supporting current recommendations for N application, these results support the careful use of soil analysis and SMN calculation to determine N applications – especially on soils that are likely to have high pre-planting N. This will ensure that N is not applied to excess and minimises both environmental and economic costs, whilst reducing the risk of postharvest losses.

1.5 Grower Action Points

- Ensure accurate soil analysis is taken, especially in situations where SMN may be uncertain or high, to enable accurate determination of crop N requirements.
- Promote existing soil N reserves to further reduce the need for supplementary N provision.

2 Science Section

2.1 Introduction

The provision of nitrogen (N) to a growing crop is one of the primary drivers of plant growth and yield output. Optimising N applications can be essential to ensure target yields are achieved whilst minimising the environmental impact of production (particularly through minimising nitrate leaching) and reducing costs. The latter is especially relevant to growers in 2022 given the recent increase in fertiliser costs and uncertainty surrounding the Ukrainian conflict, against a background of strong downwards price pressure from customers.

Broccoli is a major UK brassica crop, with over 8,750 ha planted in the UK producing 84 kt annually, with a further 128 kt of broccoli and cauliflower imported annually (Defra Hort Stats). The popularity of broccoli has benefitted further from high consumer demand for purple sprouting and Tenderstem varieties for which premium prices will be seen at the supermarket. However, only limited recent trials data is available to determine the optimum N requirements for a typical UK crop. The older RB209 (8th Edition – 2008) did not differentiate between broccoli and cauliflower, giving the same recommendations for each crop, recommending 290 kg N/ha at SNS Index 0 for summer/autumn plantings, and only recommending a 100 kg N/ha base dressing under conditions where poor establishment was likely. The 2010 update of the 8th edition of RB209 split broccoli from cauliflower, recommending a lower application of 235 kg N/ha at SNS Index 0 compared with 290 kg N/ha for cauliflower following an industry request due to the risk of head rot and assumptions that critical N content was lower for broccoli compared with cauliflower, although this remains to be tested. For Scotland, recommendations from SRUC for broccoli are higher than RB209, primarily as a result of a concern that lower rates would restrict some growers. A summary of current recommendations are given in below.

Table 5. Summary of current recommendations for broccoli cultivation in the UK based on RB209 (England/Wales) and the SRUC Technical Note (TN – Scotland).

SNS Index (RB209)	0	1	2	3	4	5
N residue group (TN)	1	2	3	4	5	6
kg N/ha	<60	61-80	81-100	101-120	121-160	>160
RB209	235	200	165	135	80	0
SRUC TN	270	260	250	230	180	140

In the wider literature a broad range of optimum N requirements have been published of 112 – 450 kg N/ha depending on cultivation system and time of application (Bakker *et al.*, 2008). The latter authors Bakker et al. (2008) investigated the effect of N fertiliser application rate (0, 50, 100, 150, 200, 300, 400 kg N/ha) on yield and quality of broccoli in two experiments (in 2001 and 2002) in Canada. Nitrogen was applied as ammonium nitrate prior to transplanting.

In both years, the economic optimum yield was achieved at around 300 kg N/ha. Similarly, Yoldas et al. (2008) investigated the effect of N fertiliser application rate (0, 150, 300, 450 and 500 kg N/ha) on yield of broccoli in a single experiment in Turkey. Nitrogen was applied as ammonium nitrate in three split equal applications at sowing, 20 days after sowing and after cutting main heads. Yields increased from 27 t/ha from the zero N control to 33 and 35 t/ha at the 150 and 300 kg N/ha application rates respectively, and then declined at the higher N application rates. Yoldas et al. (2008) concluded that the optimum N rate was 300 kg N/ha.

The PhD thesis by Vagen (2005) investigated the effects of three N fertiliser rates (0, 120, and 240 kg N/ha) and two planting times (May or late June/July) on yield and N use of the early cultivar 'Milady' and the late cultivar 'Marathon' of broccoli on three silty loam soils varying in SMN in southern Norway in 1999 and 2001. Vagen (2005) found that a supply of 200-250 kg N/ha from a combination of SMN and applied N fertiliser was necessary to achieve optimal yields. This is consistent with the RB209 (8th edition) recommendations of 235 kg N/ha at SNS Index 0.

As a result of these broad recommendations, there is little recent direct evidence using currently grown varieties to support recommendations for UK broccoli growers for optimum dosing strategies to either minimise the environment and economic costs of fertiliser provision, or to ensure that optimum yields of a high value crop can be achieved.

In addition to ensuring maximum yields can be achieved, crop nutrient status can be linked with a number of postharvest quality indicators, including both physical (abiotic) and pathological (biotic) disorders. Hollow stem is the occurrence of an air-filled cavity within the stem below the head which is visible when the stem is cut at harvest. In addition to visible spoilage, the presence of the inner cavity can increase postharvest disease incidence to reduce yields further. The incidence of hollow stem is linked with rapid plant growth caused by wide plant spacing, high N levels, warm/moist weather or boron (B) deficiency (Vigier & Cutcliffe, 1985). For instance, Moniruzzaman *et al.* (2007) demonstrated a three-fold increase in hollow stem area in broccoli when 200 kg N/ha was applied compared to 100 kg N/ha, although this effect showed a significant interaction with B application, where hollow stem incidence was reduced with increased B availability. Similarly, head rot, or spear rot, caused by infection in the crown by a range of pathogens including *Pseudomonas* and *Erwinia* species can show increased incidence with greater nitrogen availability. Due to difficulties controlling head rot with pesticides, this can lead to significant crop losses, especially under conditions of prolonged damp weather. For example, Everaarts (1994) reported an increase in head rot incidence from 39% at 0 kg N/ha to 88-90% at rates of 98 – 196 kg N/ha. As a result, it was considered relevant to include scoring of the incidence of spear rot and hollow stem in response to N application to test whether marketable yields can be adversely affected due to increased incidence of these conditions with greater N application.

As a result of these requirements, a series of trials were instigated at representative sites in the UK in the east (Lincolnshire) and south (Cornwall) and in Scotland (Fife and Perthshire) to further examine the response of broccoli to nitrogen application.

2.2 Project Objectives

This project has the following core objectives:

1. Determine economic optimum N rate for broccoli marketable yield.
2. Assess the impact of two different N application timings on broccoli marketable yields.
3. Assess the effect of N rate and timing on spear/head rot.

3 Methods and Materials

3.1 Trial Design

Trials were developed to be implemented as part of a commercial crop to ensure that cultivation conditions could be aligned with commercial norms.

N application rates were developed to test both existing recommendations and the rate ranges discussed above. Six application rates over two timings between 0 – 200 kg N/ha were used in Cornwall and Lincolnshire allowing full coverage of RB209 recommendations of 0 – 80 kg N/ha whilst allowing for testing of “luxury” dosage rates up to 200 kg N/ha. Applications were split between two timings – once shortly after planting, followed by a second application one month later. For Scotland, seven application rates of 0 – 270 kg N/ha were tested covering recommendations of up to 250 kg N/ha in the SRUC technical notes. A pre-planting base application was only included at the 220 kg N/ha treatment, with the other treatments split between applications at planting, one month after planting and at heading. A summary of treatments is given in Table 6 and Table 7 below.

All other major nutrient requirements (P, K, Mg) were assessed and applied as necessary to RB209 recommendations to ensure no other nutrients were limiting. It was also ensured that the sites were at the correct soil pH. All other aspects of crop cultivation, including planting, and control of weeds, pests and diseases were carried out as per usual commercial practice by the host growers.

Nitrogen treatments were applied in triplicate to a randomised block design, with each block covering a 7m stretch of 3 beds, although harvest assessments were only taken from a 5m stretch of the central bed to prevent the influence of edge effects between treatments. A 20m buffer zone around the trial area was marked out to prevent N application from spreading into the trial plots when the commercial crop applications were made.

3.2 Treatment Applications

Treatment applications were made by hand with nitrogen applied as calcium ammonium nitrate (27%).

Table 6. Summary of treatments for Cornwall and Lincolnshire.

Trt No	Timing 1 Just after planting	Timing 2 1 month later	Total N applied
	kg N/ha		
1 (Nil N)	0	0	0
2	60	0	60
3	60	30	90
4	80	40	120
5	100	60	160
6	120	80	200

Table 7. Summary of treatments for Fife and Perthshire, Scotland.

Trt No	Timing 1 Base	Timing 2 Just after planting	Timing 3 1 month later	Timing 4 At heading	Total N applied
	kg N/ha				
1 (Nil N)	0	0	0	0	0
2	0	60	0	0	60
3	0	60	60	0	120
4	0	80	80	20	180
5	0	100	80	40	220
6	0	120	100	50	270
7	100	0	80	40	220

Site Details

Trial sites were identified to achieve broad geographical spread across the UK, covering Truro, Cornwall in the southwest, Lincolnshire in the east, and Fife and Perthshire in Scotland. Summary information for each site is given in Table 8 below. Soil analysis was carried out prior to planting to gain soil nitrogen status at 0, 60 and 90cm (although SMN sampling was performed only to 60cm at Cornwall due to shallower soils). This demonstrated a broad range of pre-trial soil N content across the trial sites with RB209 recommendations ranging from 0 – 165 kg N/ha, and these were used to decide N application treatments.

Table 8. Summary site details for trial sites. * A small amount of nitrogen may be needed if SMN levels are low in the top 30cm of soil. Numbers in Italics – Scottish Technical Note recommendations

Site	Soil Mineral Nitrogen (SMN) (kg N/ha)	Soil Nitrogen Supply (SNS Index)	Recommended N (RB209) (kg N/ha)	Planting Date	Harvest Date	Variety
Cornwall	184	6	0* (*140*)	27/4	23/7	Steel
Fife	127	4	80 (*180*)	2/6	19/8	Parthenon
Perthshire	89	2	165 (*250*)	10/6	20/8	Parthenon
Lincolnshire	156	4	80 (*180*)	9/8	15/11	Covina

3.3 Experimental Methods

Trials were established to match with cultivation timings at each site as outlined in Table 8 above. Individual plots were marked out prior to planting at the Scotland sites to allow pre-planting base dressings to be applied prior to transplanting. The experimental areas had received no N fertiliser, digestate or organic manure before autumn 2020. Topsoil and soil analysis were undertaken at the start of the trial to ensure that no other nutrients were limiting, and to quantify total N availability for offtake calculations. A minimum of 8 cores from each sample depth (0-30cm, 30-60cm and 60-90cm) were taken per block, and combined into a single sample for each depth per block. Soil samples were refrigerated and sent for analysis by Lancrop Laboratories (sponsored by Yara) within 24 hours of collection. Communication was maintained with the host growers at each site to track application timings with growth stages.

Harvests were taken once at least 70% of the crop had reached marketable head size of >450g in weight, with the exception of the Lincolnshire site which was harvested slightly earlier and mean head weight was 325g. Four heads per plot were sampled for fresh weight, dry weight and N uptake determination, complete with whole plant biomass. Heads from a further 15 plants per plot were assessed for marketability criteria – size in weight, and head rot and hollow stem incidence. Samples for dry matter analysis were air dried at 80°C for a minimum of 48 hours before reweighing for dry matter content and being sent for foliar nutrient analysis.

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

4 Results & Discussion

4.1 Site 1 – Lincolnshire

Crop establishment was even in blocks 2 and 3 with a limited bare patch in block 1, but this could be accommodated as plots were large, and treatments and sampling were carried out as planned. The first application was made on 24 August 2021. At this time plants were well established but at an early growth stage with 3-4 true leaves expanded (GS13 – 14) and were still under fleece. A second application was made on 23 September 2021 (Figure 4), at which time plants had developed to 8-10 leaves per plant (GS18-20) and while general crop development was good one block had a limited bare areas – the plants were still fleeced at this stage. Plants were harvested on the 15 November 2021 when they were at maturity with most heads between 0.2-0.4kg (GS48 – 49).

SMN samples taken on 24 August 2021 indicated an average SMN of 156 kg N/ha (SNS Index 4 - Table 10), and topsoil nutrition analysis is given in Table 9 below. At SNS Index 4, this would be equivalent to a recommendation of 80 kg N/ha according to the RB209 recommendation for broccoli.

Figure 4. Lincolnshire trial area at application timing 2 showing the bare area in block 1, 23 September 2021.

Table 9. Topsoil analysis results - Lincolnshire

pH	Nutrient Content (ppm)												CEC	Org. Matter
	P	K	Mg	Ca	S	Mn	Cu	B	Zn	Mo	Fe	Na	(meg/100g)	DUMAS (%)
7.8	37	254	189	2690	7	88	6.9	2.11	5.9	0.03	1125	16	15	1.9

Table 10. SMN analysis at Lincolnshire, assuming a bulk density of 1.3g/cm3
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	Soil Mineral N (kg N/ha)			Mean SMN (0-90 cm)
Depth	Block 1	Block 2	Block 3	
0-30	69.03	78.39	75.27	
30-60	51.09	44.85	46.41	
60-90	43.29	26.52	33.15	
Total	163.41	149.76	154.83	**156**

Whole-plant biomass showed a positive response to N application, with whole plant biomass increasing from 31.8 t/ha at 0 kg N/ha to 45.6 t/ha at 200 kg N/ha, an increase of 43.5% (Figure 5). However, gross head biomass showed relative consistent biomass between treatments, increasing from 10.5 to 11.57 t/ha between 0 – 200 kg N/ha, therefore a lower increase of only 9.5%. This data would suggest that whilst increasing N application has increased biomass accumulation, this has driven vegetative foliar biomass increases without leading to increased head weight or yield.

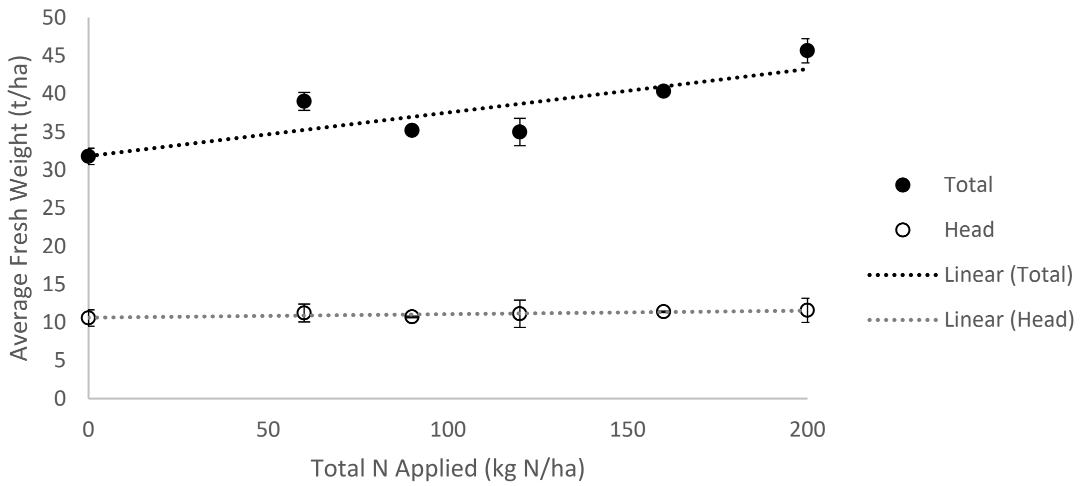

Figure 5. Average whole plant and gross head biomass per ha at harvest in Lincolnshire.

Head quality was relatively consistent between treatments, with gross and marketable head weight showing little variation between N applications (Figure 6). The proportion of marketable heads showed minor variation between treatments, increasing from 38% at 0 kg N/ha to 64% at 200 kg N/ha (Figure 7). There was no significant difference in marketable head number or weight per ha (p = 0.140/0.197 respectively) The increase in marketability was largely due to an increase in the percentage of heads over the minimum size threshold of 250g/head. No incidence of hollow stem was recorded across these treatments. Low levels of spear rot were recorded, however, which showed a small increase with increased N rate, although the overall difference between treatments was not significant (p = 0.455). Incidence of spear rot was 6.7 – 8.9% between 0 – 120 kg N/ha, and this increased to 13.3% and 17.8% at 160 and 200 kg N/ha respectively. Despite relatively consistent yields, the increased proportion of head rots led to a marked reduction in marketable yield with higher N applications (Figure 8) when scaled to an achieved planting density of 33000 from a density of 41900 at transplanting.

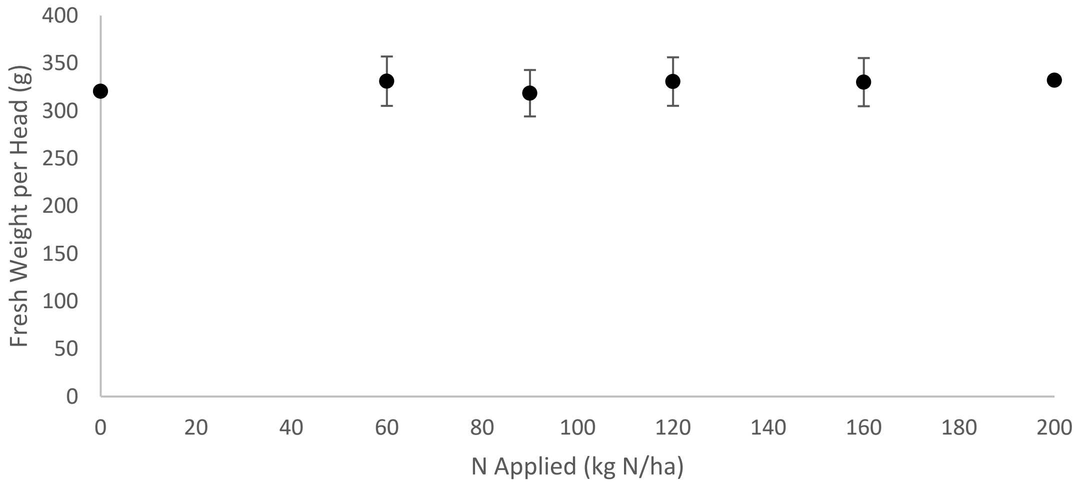

Figure 6. Average marketable head weight in response to N application, Lincolnshire.

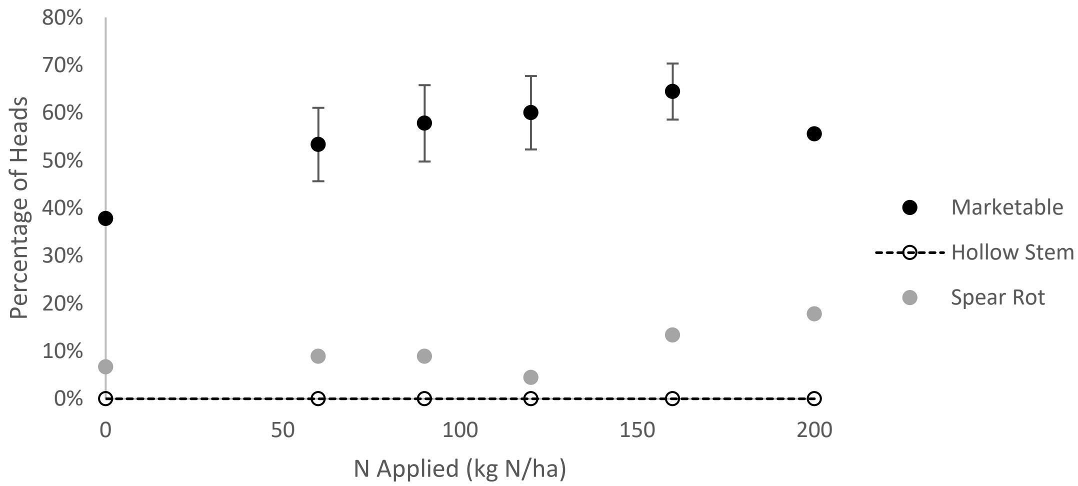

Figure 7. Average percentage of marketable heads, plotted with heads showing spear rot and hollow stem symptoms.

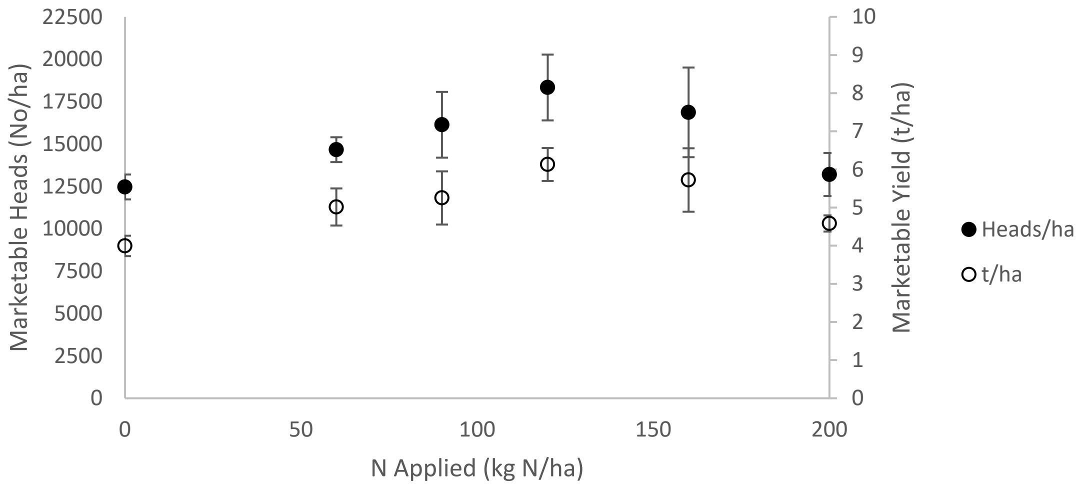

Figure 8. Marketable yield at Lincolnshire expressed at heads/ha and t/ha.

Average dry matter content was relatively consistent between treatments although the 0 kg N/ha had the least content (3.5% ± 0.5), with the highest seen at 120 kg N/ha (4.6 ± 0.2). When scaled up to the observed yield, there was an apparent positive increase in N offtake with increased N application, increasing from 128.4 kg N/ha at 0 kg N/ha, to 199.0 kg N/ha at 200 kg N/ha (Figure 9) although this increase was not significant (*p* = 0.208). However, nitrogen use efficiency (NUE) did not show a significant change between 90 – 200 kg N/ha which was relatively consistent between 35.9 – 36.6%, and there was no significant difference overall between treatments (*p* = 0.157). Taking into account fertiliser prices (assumed £1.45/N unit) there is not a significant economic return on increasing the N rate applied, with the greatest crop value (accommodating N cost) achieved at 120 kg N/ha (£4.9k/ha ± 0.36). There was no significant difference in crop value between treatments (*p* = 0.242).

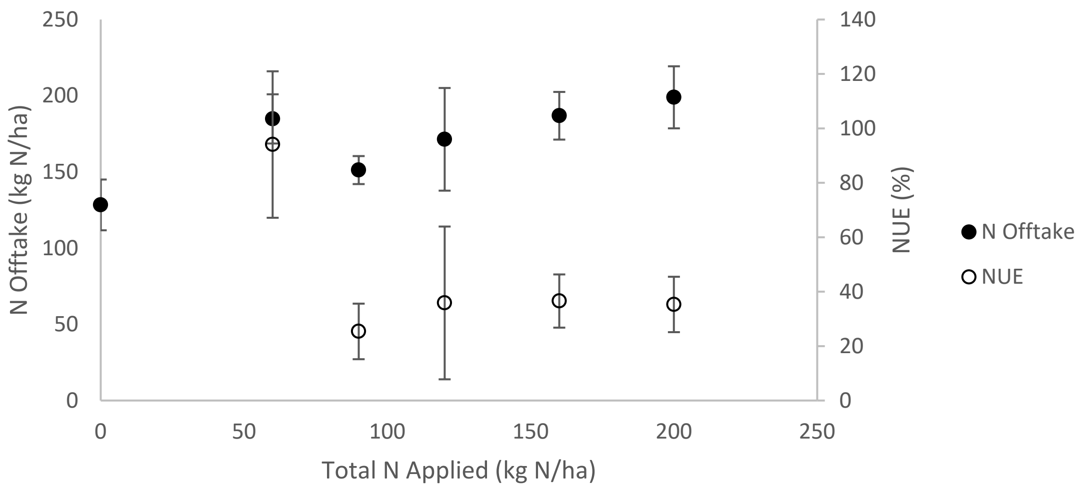

Figure 9. Nitrogen offtake and nutrient use efficiency (NUE) from the Lincolnshire trials.

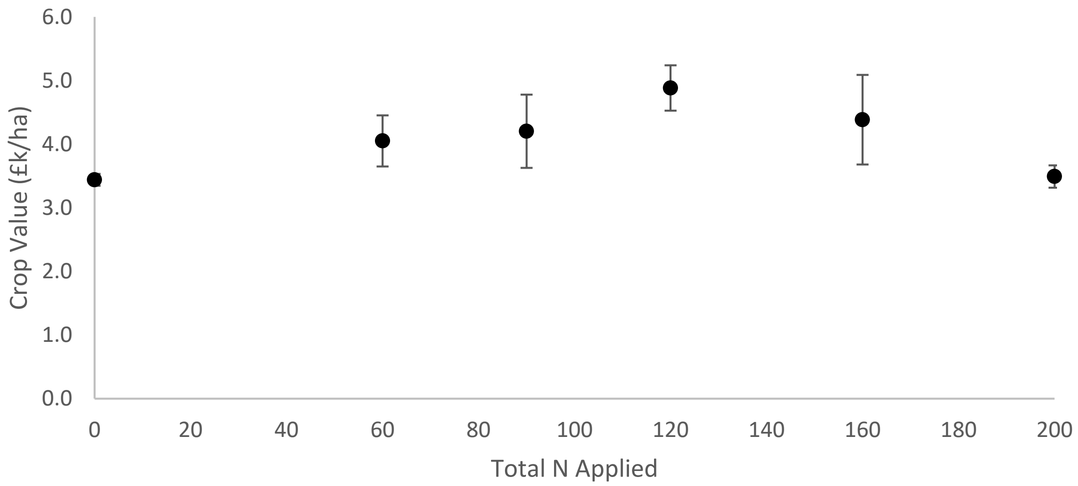

Figure 10. Crop value accommodating marketable yields and fertiliser price (assuming £1.45/unit), with produce marketed at £570/t (heads >550g)/ £825/t (heads 250 – 550g).

4.2 Site 2 – Cornwall

Good crop establishment was seen at the Cornish trial site (Figure 11), with applications made as planned on the 22 April 2021 and 1 June 2021, followed by assessment on the 23 July 2021 when the majority of heads were within 0.15-0.45g. Three harvests were taken on 22, 24 and 26 August by Bill Herring of Duchy College, results from the individual harvests are presented in Table 13.

SMN samples taken at the start of the trial indicated an average SMN of 184 kg N/ha, although samples were only collected to a depth of 60cm due to a shallow topsoil layer. At SNS Index 6 this would be equivalent to a recommendation of 0 kg N/ha from RB209, although a small application may be required if topsoil levels are low. SMN analysis results are given in Table 11 and Table 12 below.

Table 11. Topsoil analysis results - Cornwall

pH	Nutrient Content (ppm)												CEC	Org. Matter
	P	K	Mg	Ca	S	Mn	Cu	B	Zn	Mo	Fe	Na	(meg/100g)	DUMAS (%)
7.0	26	171	81	2726	4	56	12	1.03	6.9	0.02	715	45	16.2	5.9

Table 12. SMN analysis at Cornwall, assuming a bulk density of 1.3g/cm3.

	Soil Mineral N (kg N/ha)			**Mean SMN (0-60 cm)**
Depth	Block 1	Block 2	Block 3	
0-30	96.7	68.2	82.68	
30-60	82.7	92.8	91.6	
60-90	-	-	-	
Average	179.4	161.0	174.3	**184**

Table 13. Mean marketable percentage of heads and mean marketable weight at each harvest. 22, 24 and 26 July 2021

N applied (Kg N/ha)	Percentage marketable cut at each harvest (%)			Total % marketable	Average head weight per cut (grams)		
Date	**22/7**	**24/7**	**26/7**		**22/7**	**24/7**	**26/7**
0	12	43	25	80	440	424	416
60	22	40	26	88	498	433	413
90	28	36	25	89	515	466	424
120	39	20	34	93	494	426	447
160	32	33	25	90	493	474	451
200	46	37	14	97	567	503	461

Figure 11. Cornwall trial, 22 June 2021

At harvest, there was a small, but insignificant, positive trend in whole plant biomass with increasing N application rising from 31.4 t/ha at 0 kg N/ha to 40.7 kg N/ha at 160 kg N/ha, an increase of 26% (Figure 12). Gross head weight showed a similar (but also not significant) increase with greater N application, increasing from 11.7 t/ha at 0 kg N/ha to 14.6 t/ha at 200 kg N/ha, an increase of 24%.

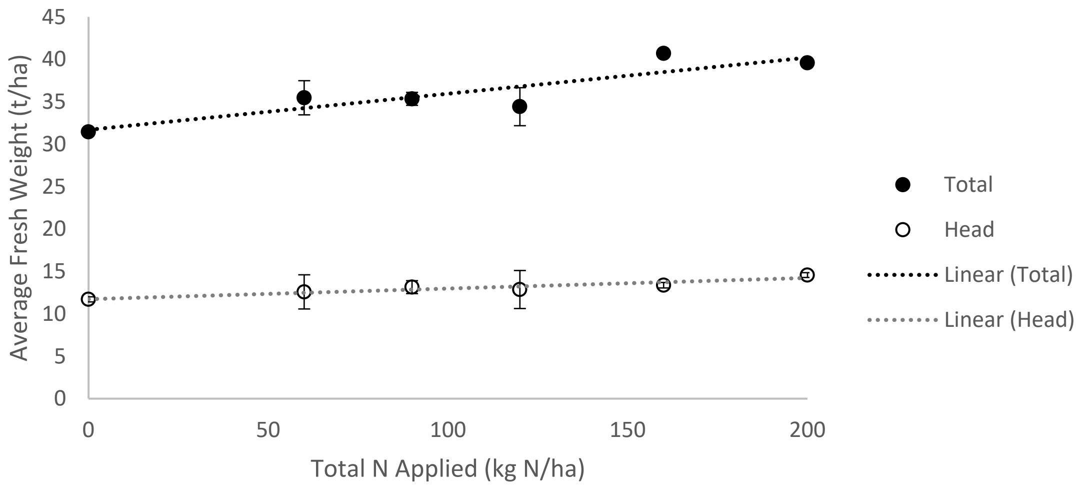

Figure 12. Average whole plant and gross head biomass per ha at harvest in Cornwall.

There was no incident of spear rot or hollow stem across the treatments, which is probably due to the variety grown (Steel) being resistant to head rot, and so the proportion of marketable heads varied only due to grade out of specification heads (Figure 13). Whilst the percentage of marketable heads at 0 kg N/ha was low compared with the other treatments, levels were relatively consistent between 60 – 160 kg N/ha (88.1 – 93.9%), although a significant increase was seen at 200 kg N/ha (97.6%), and there was a significant difference in the number of marketable heads/ha (p = 0.002). Average marketable head weight showed a small increase with increased N applied, reaching 520g at 200 kg N/ha (Figure 14), although this difference was significant (p <0.001).

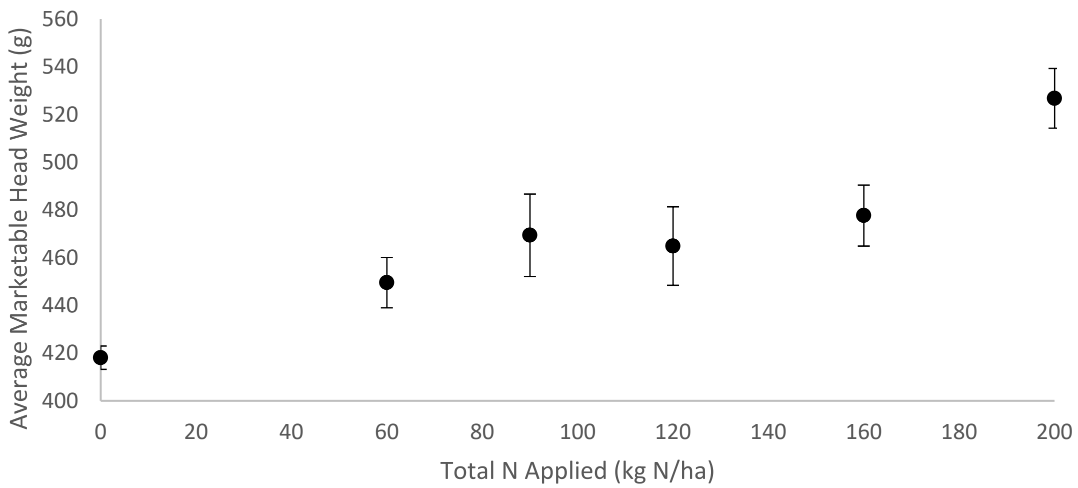

Figure 13. Average marketable head weight in response to N application, Cornwall.

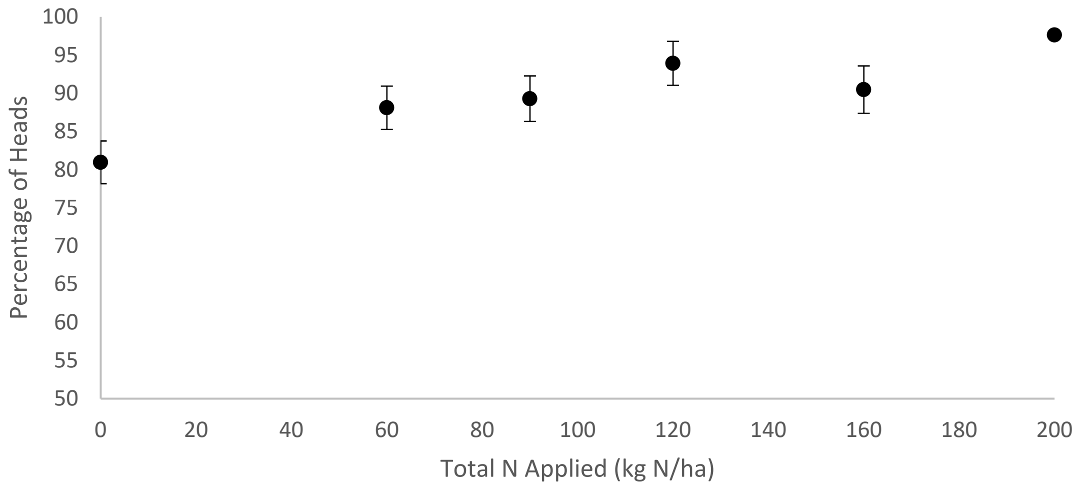

Figure 14. Average percentage of marketable heads harvested at Cornwall. No heads showed spear rot and hollow stem symptoms.

When viewed on a per ha basis, there is an apparent positive correlation between yield and N applications (Figure 15), and overall significant differences were seen between treatments (*p* <0.001). Yield increased from 9.5 t/ha at 0 kg N/ha to 12.1 kg N/ha at 120/160 kg N/ha. Yields show a further increase to 14.2 t/ha at 200 kg N/ha although given the absence of a positive trend before this level it is possible that this is due to experimental variability rather than a true effect, which would imply that peak N response is encountered between 120 – 160kg N/ha. There is a corresponding increase in head number which matches the trend in yields which correlates with the increase in average head weight seen between treatments in Figure 13.

As a result of these impacts, both whole plant N offtake and NUE efficiency show a positive relationship with increased N application (Figure 16), although there was not a significant difference between treatments (*p* = 0.469). N offtake increased from 66.4 kg N/a at 0 kg N/ha application to 138.9 kg N/ha at 200 kg N/ha, although the increase in NUE was less significant, increasing from 22.7% at 0 kg N/ha to 37.6% at 160 kg N/ha. Whilst crop value increased from £8.6k/ha at 0 kg N/ha to £10.0 - £10.3 kg N/ha at 90 – 160 kg N/ha, there was not a further substantial increase at 200 kg N/ha (£10.9k), indicating that diminishing returns are seen (Figure 17), although a significant difference was seen in crop value (*p* <0.001).

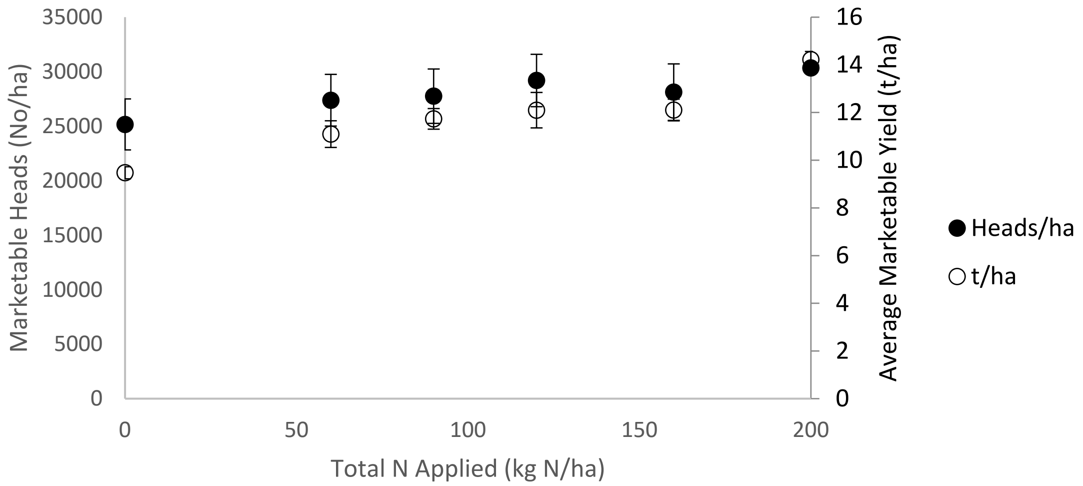

Figure 15. Marketable yield at Cornwall expressed at heads/ha and t/ha.

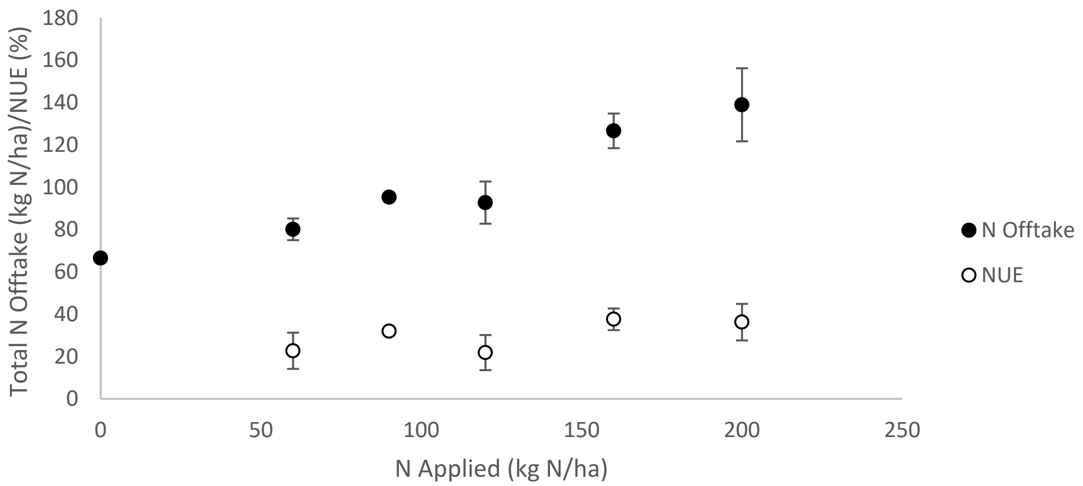

Figure 16. Nitrogen offtake and nutrient use efficiency (NUE) from the Cornwall trials.

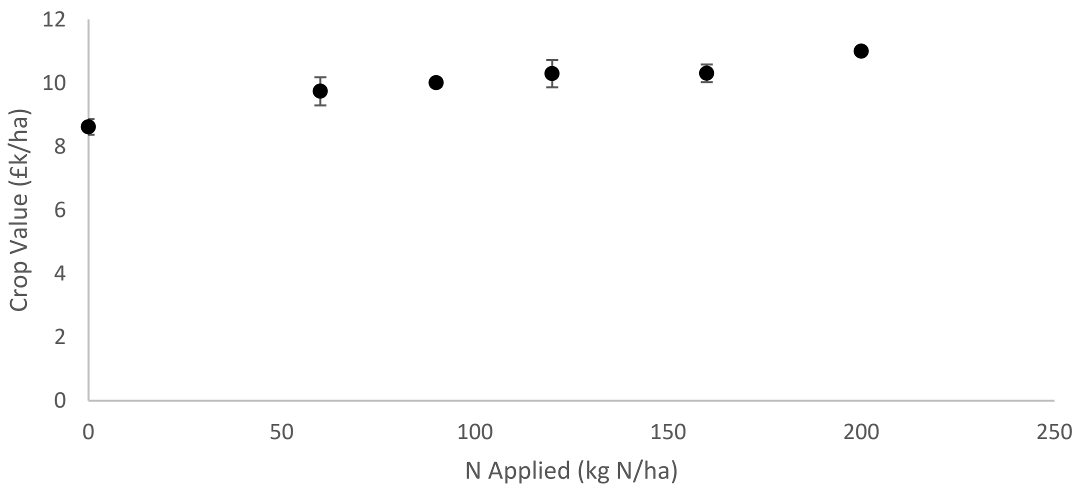

Figure 17. Crop value from the Cornwall trials accommodating marketable yields and fertiliser price (assuming £1.45/unit), with produce marketed at £570/t (heads >550g)/ £825/t (heads 250 – 550g).

4.3 Site 3 – Lochlands, Perthshire

The crop showed good establishment following the base applications on the 4-5 May 2021 prior to planting. Planting, and timing 2 treatments were applied during dry weather on 10 June 2021 when the plants showed three developed leaves (GS 13). Timing 3 applications were made on the 8 July 2021 a month later close to head initiation (Figure 18). Due to the dry weather following the 10 June 2021 applications, this prevented full uptake of timing 2 applications in the following month as granules were still visible on the soil surface at 8 July 2021, although rain the previous weekend ensured the soil was moist, and the granules were absorbed after this point. The grower applied the timing 4 applications on 19 July 2021. Heads were harvested and assessed on the 20 August 2021.

SMN samples taken at the start of the trial indicated an average SMN of 87 kg N/ha. At SNS Index 2 this would be equivalent to a recommendation of 165 kg N/ha from RB209 or 250 kg N/ha according to the Scottish Technical Note recommendations. SMN analysis results are given in Table 14 and Table 15 below.

Table 14. Topsoil analysis results - Lochlands

pH	Nutrient Content (ppm)												CEC	Org. Matter
	P	K	Mg	Ca	S	Mn	Cu	B	Zn	Mo	Fe	Na	(meg/100g)	DUMAS (%)
7.2	61	106	94	2104	15	67	9.1	1.06	5.9	0.01	1149	19	11.6	2.4

Table 15. SMN analysis at Lochlands, assuming a bulk density of 1.3g/cm3.

	Soil Mineral N (kg N/ha)			**Mean SMN (0-90 cm)**
Depth	Block 1	Block 2	Block 3	
0-30	42.90	40.56	7.41	
30-60	27.30	24.57	31.98	
60-90	23.40	23.40	39.39	
Average	93.60	88.53	78.78	**87**

Figure 18. Trial condition at application timing 3, 8 July 2021.

At harvest there was a strongly positive response to increasing N applications (Figure 19). Whole plant biomass increased from 14.3 t/ha at 0 kg N/ha to 47.4 t/ha at 270 kg N/ha, an increase of 231%. Gross head biomass showed a similar response – no heads were recovered at 0 kg N/ha, but gross yield increased from 10.0 t/ha at 60 kg N/ha to 15.3 t/ha at 270 kg N/ha, an increase of 49%. These data would suggest that whilst significant increases are seen in gross head yield, these are not proportionate with whole plant biomass increases. There was no significant difference between the two timing treatments at 220 kg N/ha when assessed as whole-plant biomass, gross head biomass was increased (but not significantly) in treatment 7 (pre-planting application of 100 kg N/ha) compared with treatment 5 (all post-planting).

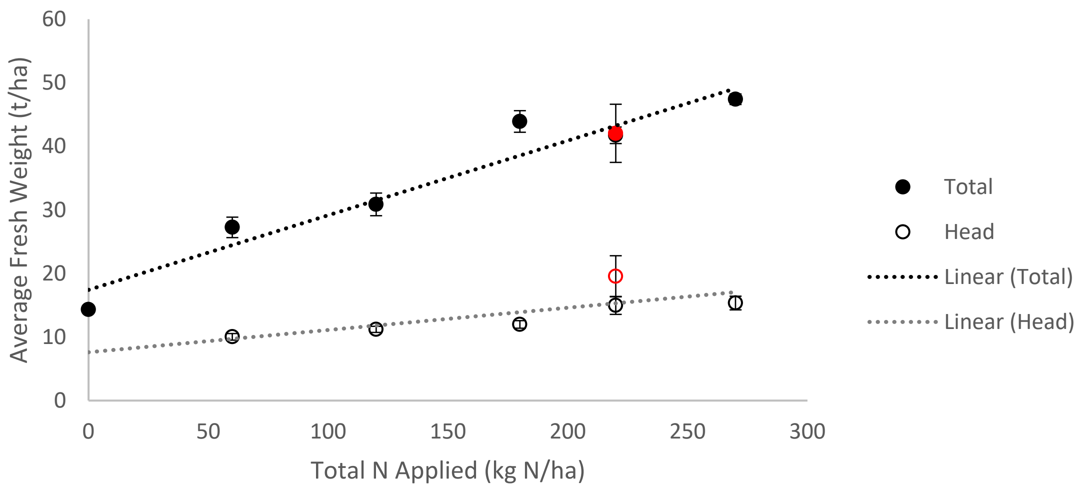

Figure 19. Average whole plant and gross head biomass per ha at harvest in Perthshire. Treatment 7 (220 kg N/ha with a 100 kg N/ha base dressing) points are given in **red**.

Average marketable head weight showed a similar increase with increasing N application rates (Figure 20), although there was no overall significant difference (p = 0.303). Marketable head weight increased from 303.9g at 60 kg N/ha to 431.7g at 270 kg N/ha, although the greatest marketable head weight was achieved at treatment 7 (220 kg N/ha with a 100 kg N/ha base dressing). The proportion of marketable heads also showed a strong response to N application, and this reached a maximum of 82 – 87% marketable at 180 kg N/ha (Figure 21). Relatively low numbers of head rot were seen, and although increases were seen at the higher rates of N application (220 – 270 kg N/ha) there was no overall significant difference (p = 0.844). Levels of hollow stem were proportionately greater, which increased from 2 and 7% at 60/120 kg N/ha to 38% at 270 kg N/ha although again no significant difference was observed (p = 0.259).

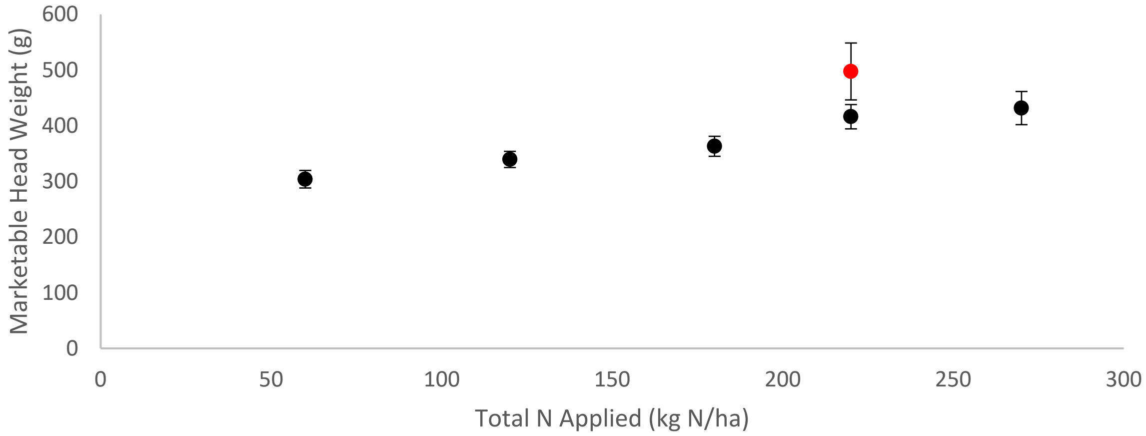

Figure 20. Average marketable head weight in response to N application, Perthshire. Treatment 7 (220 kg N/ha with a 100 kg N/ha base dressing) points are given in **red**.

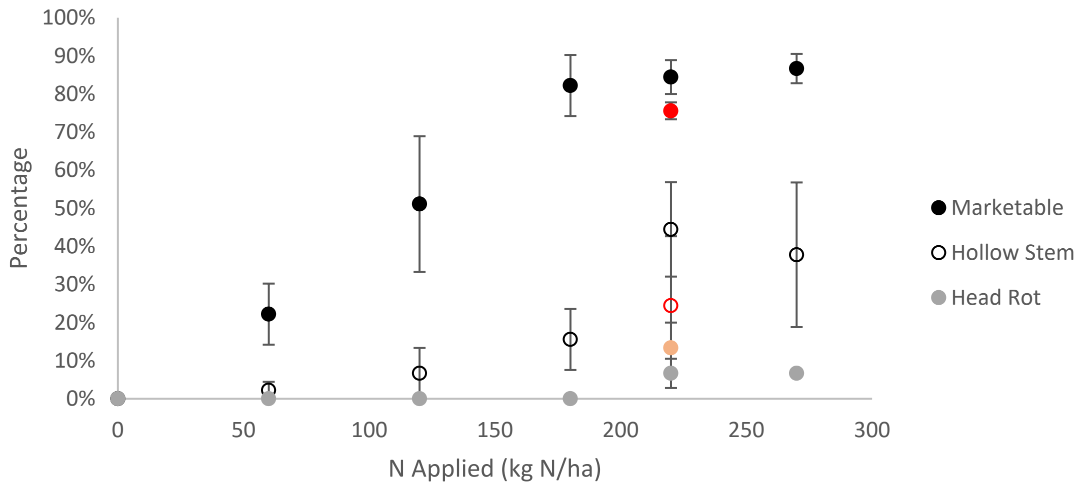

Figure 21. Average percentage of marketable heads, and heads showing hollow stem or head rots harvested in Perthshire. Treatment 7 (220 kg N/ha with a 100 kg N/ha base dressing) points are given in **red**.

When viewed on a per ha basis, there is an apparent positive correlation between yield and N applications (Figure 22) with strong significance ($p < 0.001$). Yield increased from 2.3 t/ha at 60 kg N/ha to 13.3 kg N/ha at 270 kg N/ha, although yields appeared to be levelling off at lower applications of 220 kg N/ha. However, it is noteworthy that the 220 kg N/ha treatment which included a pre-planting base dressing gave the greatest overall yield at 14.8 t/ha. Head number showed a comparable response ($p < 0.001$), except that greatest marketable head number was achieved at the post-planting 220 kg N/ha given the increase in rot/hollow stem number seen at higher applications and where the pre-planting base application was used.

Whilst a significant positive response to N application was seen in N offtake ($p < 0.001$), a relative decline in NUE was seen with increased N application (Figure 23) – overall NUE values were not significantly different ($p = 0.328$). N offtake increased from 100.2 kg N/a at 0 kg N/ha application to 246.7 kg N/ha at 270 kg N/ha. NUE was lowest at 220 kg N/ha at 35.9% compared with peak NUE seen at 60 kg N/ha (85.5%). Whilst crop value increased from £1.8k/ha at 60 kg N/ha to £8.6 – 8.9k/ha at 220 – 270 kg N/ha, although there was not a significant difference between these latter two dose rates (Figure 24).

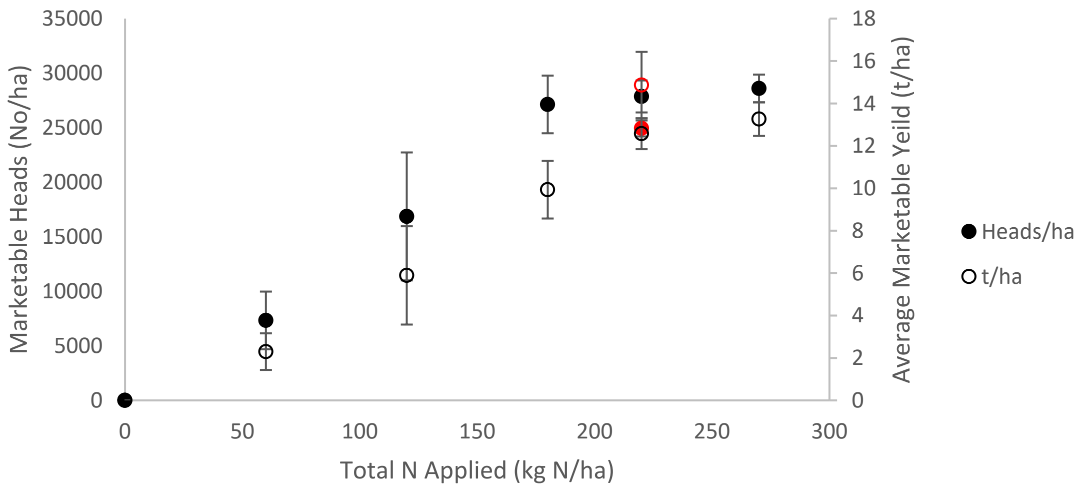

Figure 22. Marketable yield at Perthshire expressed at heads/ha and t/ha. Treatment 7 (220 kg N/ha with a 100 kg N/ha base dressing) points are given in **red**.

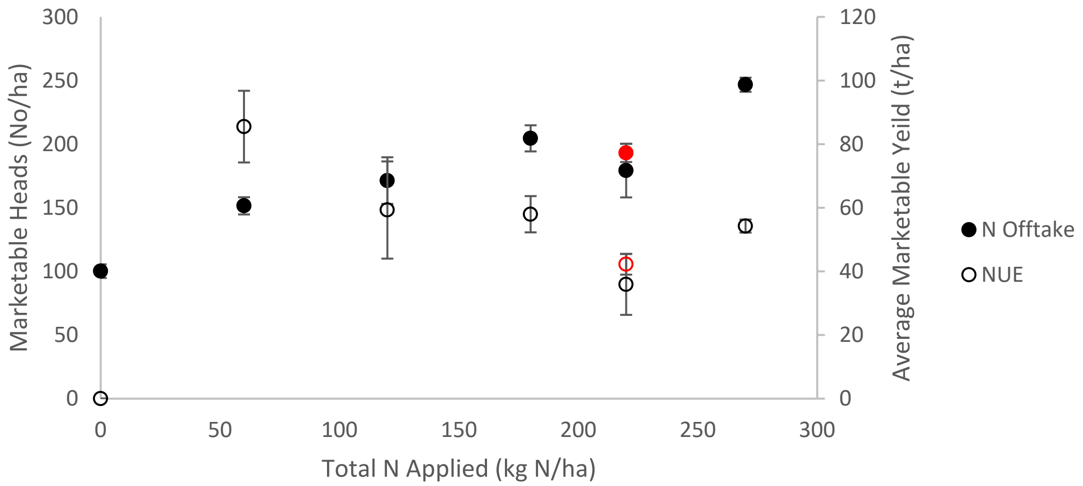

Figure 23. Nitrogen offtake and nutrient use efficiency (NUE) from the Perthshire trials. Treatment 7 (220 kg N/ha with a 100 kg N/ha base dressing) points are given in **red**.

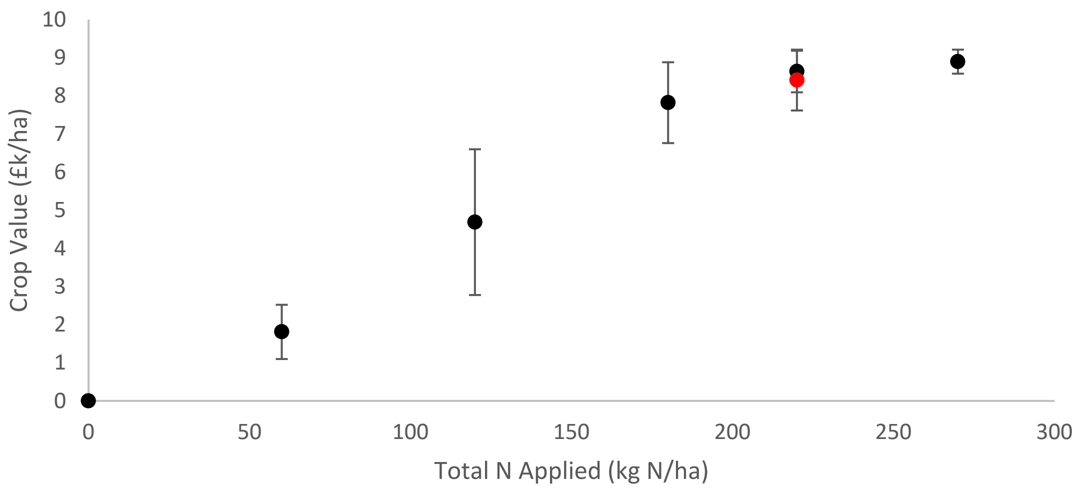

Figure 24. Crop value from the Perthshire trials accommodating marketable yields and fertiliser price (assuming £1.45/unit), with produce marketed at £570/t (heads >550g)/ £825/t (heads 250 – 550g). Treatment 7 (220 kg N/ha with a 100 kg N/ha base dressing) points are given in **red**.

4.4 Site 4 – Newington, Fife

The trial began with soil sampling and the base dressing application on the 6 May 2021 prior to planting on 3 June 2021. Timing 2 treatments were applied at this stage just after planting when the plants had three true leaves developed (GS 13). Timing 3 applications were made on 7 July 2021 when the crop was close to head initiation (Figure 25). Timing 4 applications were made by the grower a week later on 15 July at 10mm leading heads. Similar to the Perthshire site, the dry weather after Timing 2 applications meant that some granules were still visible on the soil surface at when Timing 3 was applied. However, rain over the previous weekend had resulted in damp soil at application of the Timing 3 treatments, and all granules dissolved quickly after this. At this point visible differences were seen between plants treated with the 0 kg N/ha, which were smaller and paler, with the T7 (220 kg N/ha with a 100 kg N/ha base dressing) treatments appearing the most forwards. Harvests and assessments were made of treatment 7 on 12 August 2021, with additional harvests made on the 14 August 2021 and 19 August 2021 of the remaining treatments due to delays in plots where a base application had not been applied reaching harvestable size. This demonstrates the effect that the base application had on bringing maturity forwards by a week at this site.

Figure 25. Trial condition at third timing application, 6/7/21.

SMN samples taken at the start of the trial indicated an average SMN of 127 kg N/ha. At SNS Index 4 this would be equivalent to a recommendation of 80 kg N/ha from RB209 or 180 kg N/ha according to the Scottish Technical Note recommendations. SMN analysis results are given in Table 13 and Table 14 below.

Table 13. Topsoil analysis results – Newington

pH	Nutrient Content (ppm)												CEC	Org. Matter
	P	K	Mg	Ca	S	Mn	Cu	B	Zn	Mo	Fe	Na	(meg/100g)	DUMAS (%)
6.6	46	397	145	2613	6	14	6.4	1.31	3.4	0.01	367	26	18.3	6.5

Table 14. SMN analysis at Newington, assuming a bulk density of 1.3g/cm3.

	Soil Mineral N (kg N/ha)			**Mean SMN (0-90 cm)**
Depth	Block 1	Block 2	Block 3	
0-30	44.8	34.7	88.9	
30-60	39.0	42.1	37.4	
60-90	38.2	32.4	24.2	
Average	122.07	109.2	150.54	**127.1**

At harvest, a strong positive response to N gave an increase in total biomass from 22.9 t/ha at 0 kg N/ha to 49.6 t/ha at 180 kg N/ha (an increase of 116%), although this showed a significant decline with higher applications, particularly at 220 kg N/ha (43.8 t/ha). Gross head weight showed a similarly positive response to increased N application in proportion with increases in biomass (Figure 26). Gross head biomass was 14.8 t/ha at 0 kg N/ha increasing to 29.5 t/ha at 270 kg N/ha (an 99.7% increase). Both of the 220 kg N/ha treatments showed a reduction in gross biomass compared to the other treatments, although head biomass only decreased in the treatment 7 plants which included in the 100 kg N/ha base dressing.

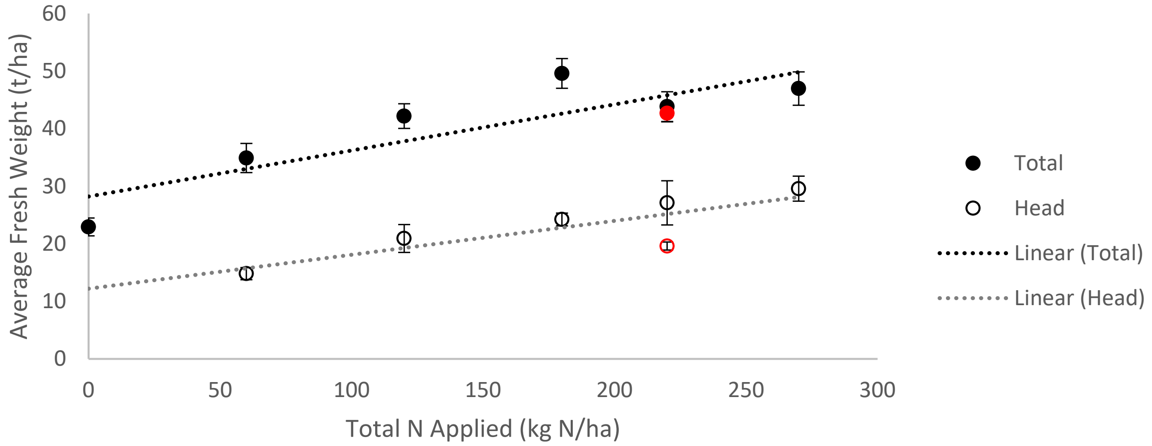

Figure 26. Average whole plant and gross head biomass per ha at harvest in Perthshire. Treatment 7 (220 kg N/ha with a 100 kg N/ha base dressing) points are given in **red**.

The percentage marketable yield increased from 35% at 0 kg N/ha to 96% at 120 kg N/ha, although there was a minor decrease at higher application rates. The reduction in marketable yield was greatest at 220 kg N/ha (76% - down from 96% at 120 kg N/ha), although this reduction was only seen in the post-planting treatment (Treatment 5) as the 100 kg N/ha pre-planting base dressing (Treatment 7) was comparable (93%). The reduction in marketable yield was due to a reduction in average size as well increased disease incidence – the number of heads within size specification increased from 2% to 60% between 0 – 120 kg N/ha, although reduced to 49% and 44% at 180 and 220 kg N/ha, although 270 kg N/ha showed a high marketable proportion at 67%.

Average marketable head weight showed a similar increase with increasing N application (Figure 27), with a strong significant difference (p <0.001). Marketable head weight increased from 303.9g at 60 kg N/ha to 431.7g at 270 kg N/ha, although the greatest marketable head weight was achieved at treatment 7 (220 kg N/ha with a 100 kg N/ha base dressing) with 497.5g heads. The proportion of marketable heads also showed a strong response to N application (Figure 28), although this reached a maximum of 82 – 87% marketable at 180 kg N/ha (Figure 27). Relatively low numbers of head rot were seen, although significant increases were seen at the higher rates of N application (220 – 270 kg N/ha). Levels of hollow stem were proportionately greater, which increased from 4% at 60 kg N/ha to 60% at 120 kg N/ha, reaching a maximum of 89% at 270 kg N/ha. The base-dressed 220 kg N/ha also showed a significant increase in hollow stem (89%) compared with the post-planting application (67%).

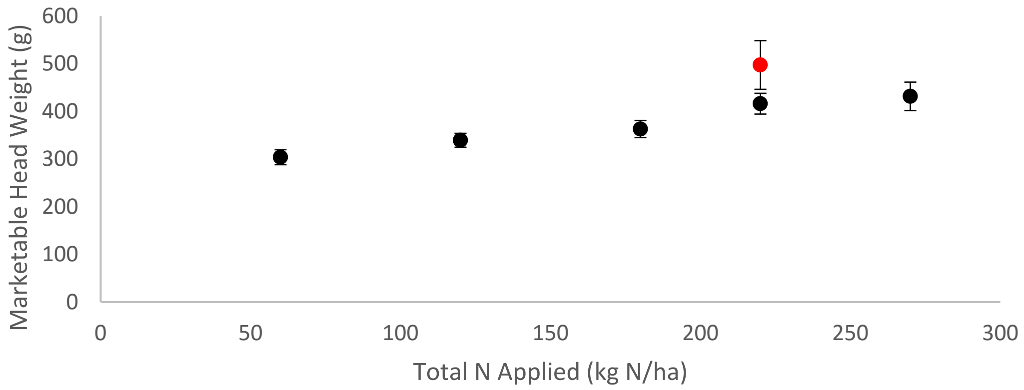

Figure 27. Average marketable head weight in response to N application, Fife. Treatment 7 (220 kg N/ha with a 100 kg N/ha base dressing) points are given in **red**.

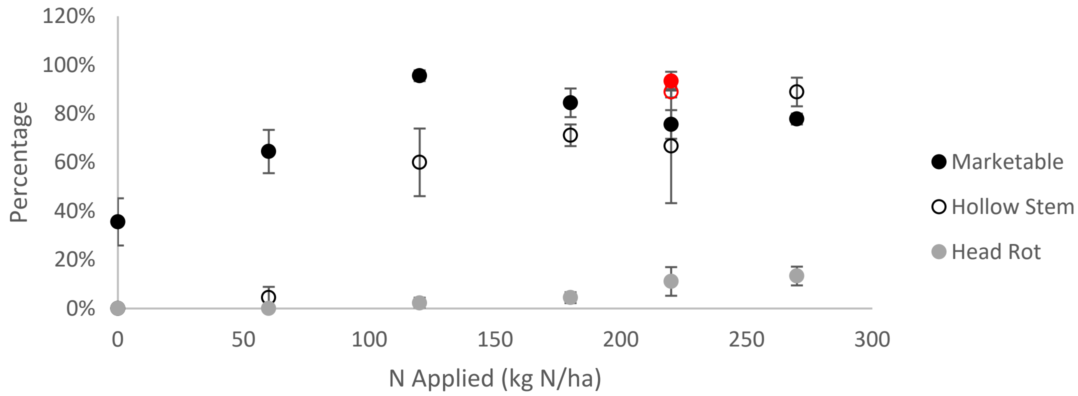

Figure 28. Average percentage of marketable heads, and heads showing hollow stem or head rots harvested in Fife. Treatment 7 (220 kg N/ha with a 100 kg N/ha base dressing) points are given in **red**.

Overall, there is a positive relationship between N application and yield between 0 – 120 kg N/ha in terms of both marketable head number and yield (Figure 29) increasing from 4.6 t/ha to 19.9 t/ha. Beyond this level marketable yield is relatively consistent, although there is a significant increase at 270 kg N/ha (22.9 t/ha). Head number showed a similar increase until 120 kg N/ha, reaching a peak of 31.5k heads/ha, although this subsequently declined with increased N content reaching 24.9/25.6 heads/ha at 220/270 kg N/ha, and there was no overall significant difference in marketable head number (p = 0.693). As such, the increase in marketable yield per ha at higher N rates was attributable to a greater average weight per head (as seen in Figure 27) which offset the reduction in marketable head number due in part to increased incidence of hollow stem/spear rot, giving a significant difference in head rot (p <0.001).

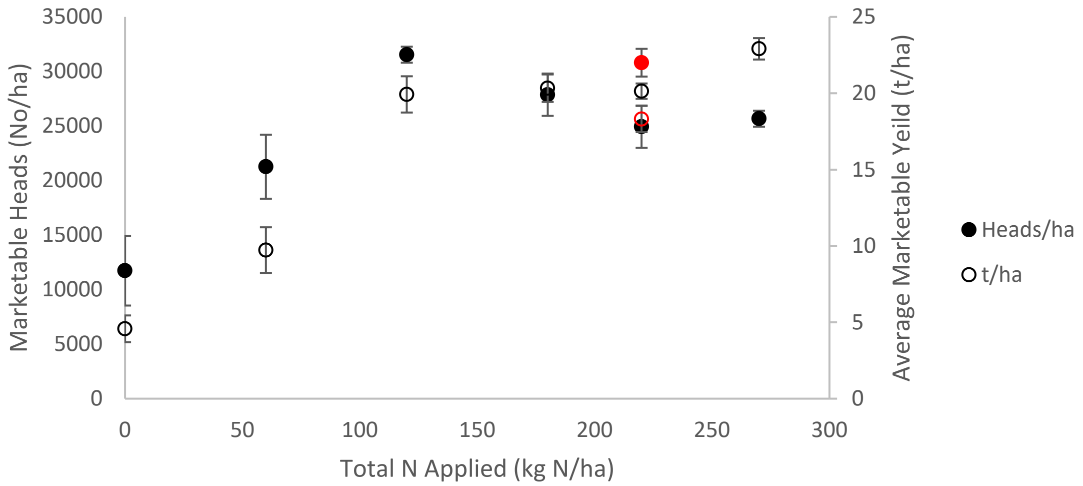

Figure 29. Marketable yield at Fife expressed at heads/ha and t/ha. Treatment 7 (220 kg N/ha with a 100 kg N/ha base dressing) points are given in **red**.

As a result in the strong proportionate increase in both gross head and whole plant biomass given in Figure 26 there is a positive influence on total N offtake which increased from 57 kg N/ha at 0 kg N/ha to 188 kg N/ha. It is noteworthy that the pre-planting base dressing at 220 kg N/ha achieved a lower N offtake (149 kg N/ha) than the full post planting treatment (174 kg N/ha). NUE was relatively consistent between treatments, and showed no significant differences. However, the lower N offtake in the base dressed 220 kg N/ha treatment gave a lower NUE of 41.8% compared with 53.0% in the full post-planting application (Figure 30). Whilst crop value increased from £3.1/ha at 0 kg N/ha to £10.8 at 120 kg N/ha, value declined at higher N rates beyond this point, although there was not a significant difference between either application rates at 220 kg N/ha (Figure 31).

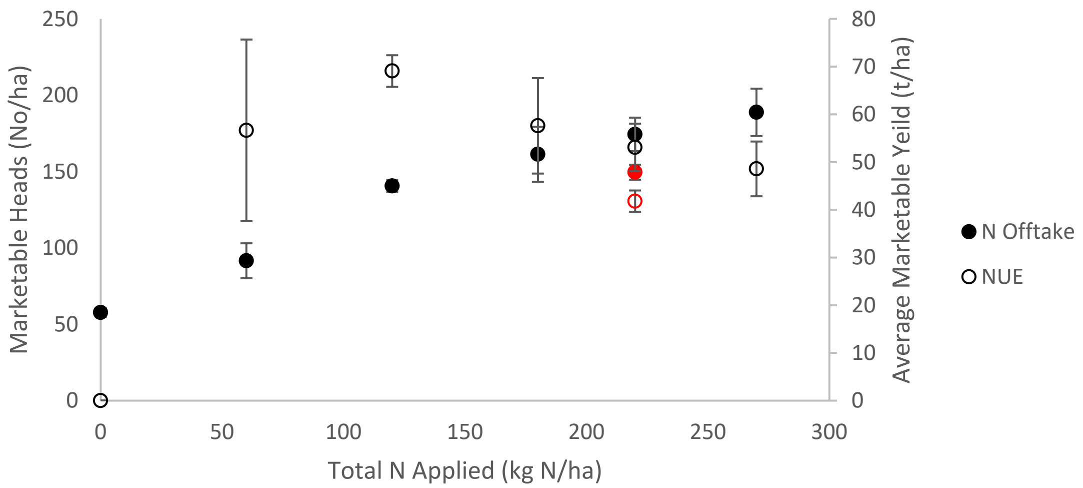

Figure 30. Nitrogen offtake and nutrient use efficiency (NUE) from the Fife trials. Treatment 7 (220 kg N/ha with a 100 kg N/ha base dressing) points are given in **red**.

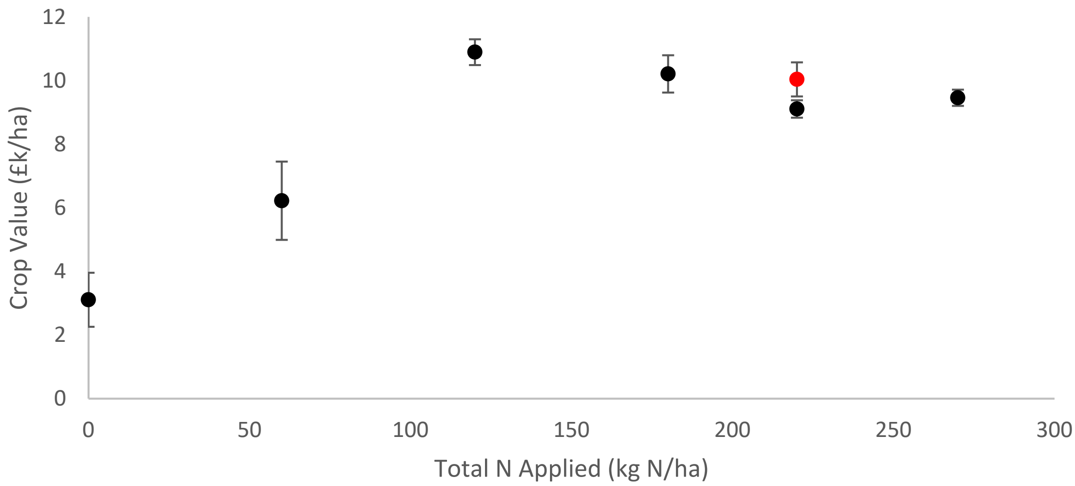

Figure 31. Crop value from the Fife trials accommodating marketable yields and fertiliser price (assuming £1.45/unit), with produce marketed at £570/t (heads >550g)/ £825/t (heads 250 – 550g). Treatment 7 (220 kg N/ha with a 100 kg N/ha base dressing) points are given in **red**.

4.5 Nitrogen Response - Summary

There was a strong whole crop N offtake response at all trial sites to increasing N application rates (Figure 32). The greatest response was seen at both Perthshire and Lincolnshire which showed comparable N offtake between 120 and 220 kg N/ha (c. 193 kg N/ha offtake), although the greatest N offtake was achieved at the 270 kg N/ha treatment at Perthshire (246.7 kg N/ha offtake). Lincolnshire and Perthshire were both later plantings (10th June and 9th August respectively) and so it is likely that greater temperatures gave a wider opportunity for overall N assimilation and growth.

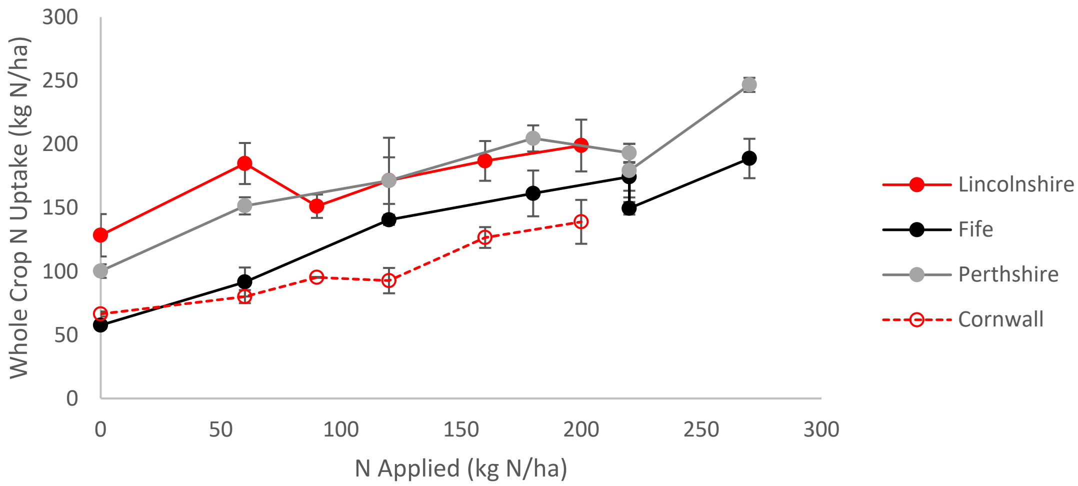

Figure 32. Summary of whole crop N uptake from the 2021 trials.

Despite the increase in N offtake, there was not an overall increase NUE with greater N application. There were no significant differences in NUE for the majority of applications between Perthshire, Cornwall and Lincolnshire, although NUE rates were increased (but not significantly at Fife (Figure 33), although even at this level the crop is only taking off at most 69% of the available nitrogen, so a considerable quantity of the applied N is going unutilised. With increasing N applications at Fife and Perthshire, a general reduction in NUE is seen with increased N application. For example, the greatest NUE at Fife was achieved at 120 kg N/ha (69.1%), but this declined to 48.5% at 270 kg N/ha.

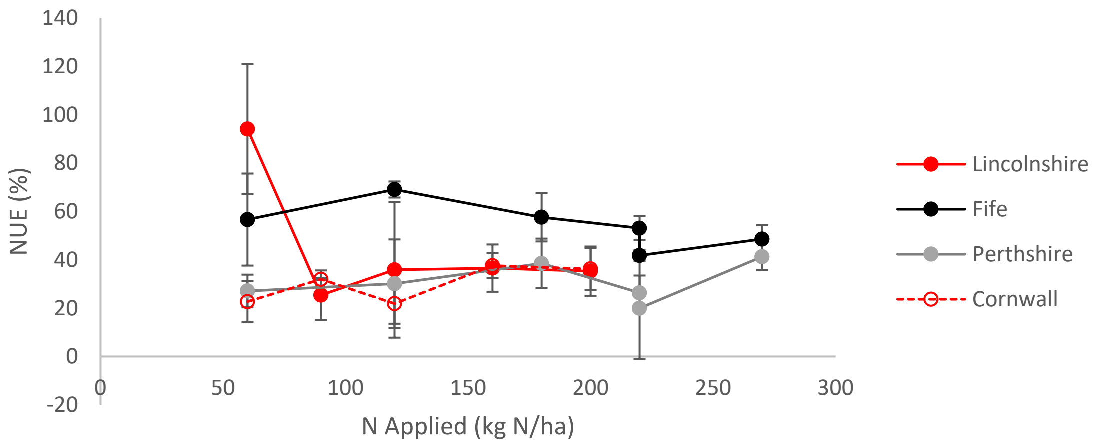

Figure 33. Summary NUE figures for the 2021 trials.

Marketable yields only showed a positive response to increasing rates of N up to a limited extent. At Lincolnshire marketable yield was relatively level at 5.8-7.1 t/ha, with an average head of 248g across the trial (compared with 476g at Fife) demonstrating the crop was harvested early. Conversely, the greatest yield response was seen at Fife where marketable yield increased from 4.5 t/ha at 0 kg N/ha to 22.9 kg t/ha at 270 kg N/ha. Perthshire also showed a strongly positive yield response, and whilst Cornwall showed marginal increases in marketable yield with increased N response this was not as strong as the two Scottish trials (Figure 34).

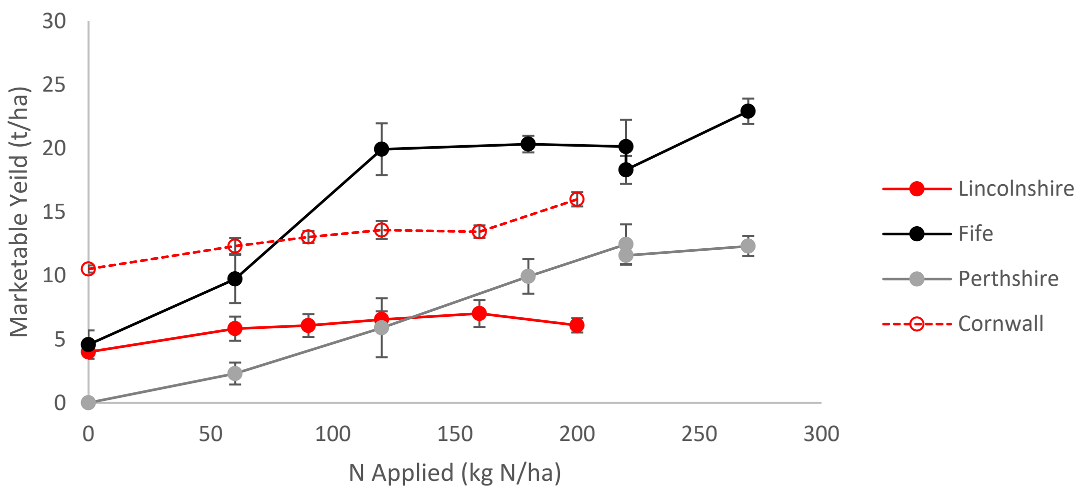

Figure 34. Summary figures for marketable yield responses in the 2021 trials.

The increase in marketable yield with greater N application was offset by an increased proportion of quality-related reductions at all sites. This was most notable at Lincolnshire where yield declines were seen above 150 kg N/ha. Spear rot was at relatively low levels at Lincolnshire, although this did increase after 120 kg N/ha to reach a maximum of 17.5% at 200 kg N/ha. Spear rot levels were lower at Perthshire, although levels were similarly increased at higher N application levels at 220 and 270 kg N/ha. Hollow stem also showed strong correlation with increased N application, particularly at Perthshire where levels reached 38% at higher N levels. Therefore, whilst higher N applications did increase the risk of these symptoms developing, overall increases in head weight still gave a positive influence of marketable yield per ha. Both Lincolnshire and Fife had high SMN at the start of the trial (156 and 127 kg N/ha respectively), and so it is likely that the higher incidence of spear rot and hollow stem at these sites correlated with the higher overall N availability. It is noteworthy, however, that no incidence of either spear rot or hollow stem was seen at Cornwall despite a high initial SMN of 184 kg N/ha. This is due to the use of a resistant variety, and indicates the benefit that this can give to the grower in reducing losses to spear rot. The lack of symptom development in Cornwall, and the absence of hollow stem in Lincolnshire, supports the idea that these conditions may be promoted by elevated N applications but are caused by a range of contributory factors, most likely including variety choice, rainfall, temperature and existing disease pressure.

Despite the increased incidence of quality-related symptoms, a strong correlation between increased N availability and marketable yield is seen. The strong N response was seen at Fife increasing from 4.6 t/ha at 0 kg N/ha to 22.9 kg N/ha at 270 kg N/ha, and this is likely to be as a result of the lower starting SMN (127 kg N/ha). A similarly strong positive response was seen at Perthshire which had the lowest starting SMN (89 kg N/ha). Conversely, Cornwall had the greatest initial SMN (184 kg N/ha) and show a relatively muted N response, although strong yields of 9.5 t/ha were seen at 0 N/ha application.

4.6 Economic Response

Given the economic and environmental impacts of N application, the N responses outlined above should be considered against the background of overall crop profitability. Taking into account fertiliser costs (assuming £1.45/unit, in November 2021) and crop value (assuming £825/t 250-550g, and £570/t >550g), a more muted response to N application is seen. Marginal increases with greater N application at Lincolnshire were seen until 120 kg N/ha (£4.9k/ha) although the combination of yield reduction and increased N costs caused a reduction in crop value to £3.5k/ha at 200 kg N/ha. In Scotland increases in crop value were sustained between 0 and 120 kg N/ha (Fife) and 0 and 220 kg N/ha (Perthshire), after which marketable yield reduced due to spear rot and increased fertiliser costs causing a reduction in overall returns. Given the differences in starting SMN between these sites, these results highlight the importance of identifying starting SMN levels and planning nitrogen applications accordingly to avoid reducing profitability either through excess N application which does not result in a proportionate yield return, or increases risk of quality reduction due to spear rot and hollow stem.

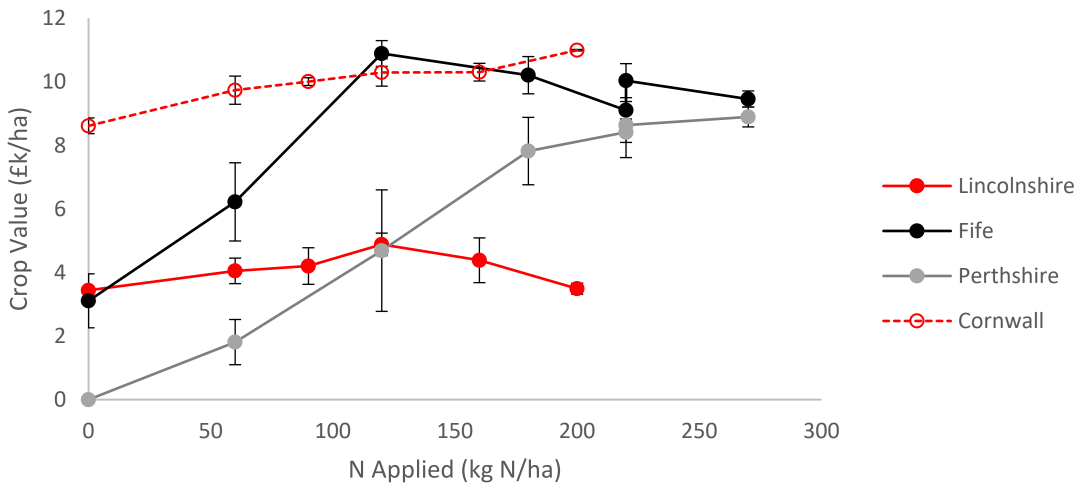

Figure 35. Summary figures for crop economic returns per ha.

Fitted curves applied to the economic returns can be used to test current recommendations (Figure 36). Current RB209 recommendations for Cornwall are 0 kg N/ha, although based on the continued increase in marketable yield applications of up to 200 kg N/ha could be justified economically. Current RB209 recommendations were sufficient for Lincolnshire, however, as applications beyond this level were unlikely to be economically justified. For both Scotland sites applications of 220 kg N/ha would be likely to return optimum yields.

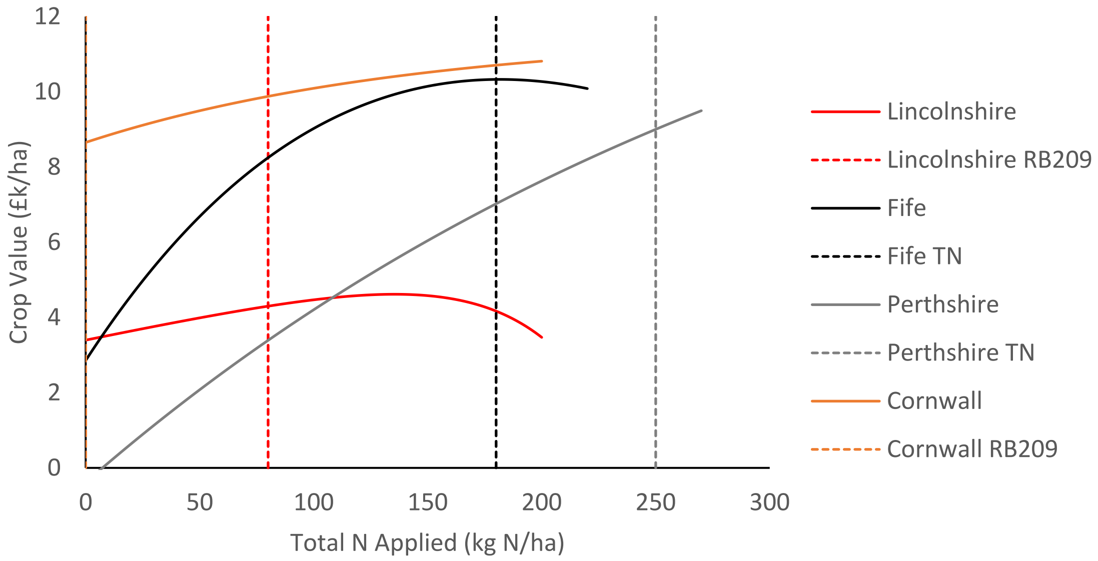

Figure 36. Fitted curves to economic optima for nitrogen application. RB209/Scottish Technical Note recommendations are by dashed lines.

4.7 Timing Responses

Whilst examined in a relatively minor way, the trials in Scotland tested the impacts of different N application timings at 220 kg N/ha:- either 100kg N/ha immediately after planting, followed by smaller applications of 80 and 40 kg N/ha at 1 month and at heading respectively (treatment 5) or 100 kg N/ha before planting followed by 80 and 40 kg N/ha 1 month after planting and at heading. Despite equal levels of N applied, the treatments yielded significantly different yields. At Perthshire the base dressing treatment gave a marketable yield of 14.8 t/ha, while the post-planting application gave a lower marketable yield (12.5 t/ha). In Fife, the base dressing treatment gave greater head number (30.8k heads/ha vs. 24.9k heads/ha) although lower marketable yield (18.31t/ha vs. 20.1 t/ha). However, the base dressed treatments were ready for harvest a week earlier (14/8 compared with 19/8 for the other trial) and so while the base dressing did not increase overall yield it brought forward the harvest window. It is also noteworthy that the greater benefit of base dressing was seen at Perthshire which had the lowest starting SMN (89 kg N/ha) compared with Fife (127 kg N/ha). This would indicate that base dressing is particularly beneficial in poorer soils with a lower SMN content to support early growth. However, in soils with a higher SMN content this application timing may show less benefit from base dressing as pre-existing N will be sufficient to drive early growth. It should be noted that the soil also had greater moisture at the timing of the base application, compared to drier conditions at the timing of the planting application. This could have influenced the ability of the plants to take up N after the fertiliser was applied and also needs to be considered.

5 Conclusions

The trials conducted in Cornwall, Lincolnshire and Fife and Perthshire have demonstrated a range of responses in broccoli to different N fertilisation strategies. There is a strong response to supplementary N application across a range of soil types and initial SMN levels, and whilst there is significant variability in the results trials broadly support existing RB209/Scottish Technical Note recommendations. Higher levels of N application are unlikely to translate into economically viable yield increases however, particularly as greater N application significantly increases the incidence of spear rot and hollow stem, reducing market yields overall. Furthermore, the increasing costs of N products (particularly due to the current geopolitical situation) as well as a desire to reduce the farm/crop greenhouse gas (GHG) footprint may promote growers to look closely at their N applications to try and ensure they apply the economic optimum N rate. The importance of targeted SMN analysis, particularly in soils where SMN is high or uncertain, has also been demonstrated to ensure that N fertiliser applications are based on the correct soil SNS Index (England)/ N residue group (Scotland)

6 Acknowledgements

Yara for funding analysis of soil and plant samples at Lancrop Laboratories, and also providing financial support of the trials. Bill Herring of Duchy College for assistance and harvest of the Cornwall site, as well as Alice Shrosbree of ADAS for assistance with harvest. Riviera Produce for hosting the site. James Rome of East of Scotland Growers for providing the trial sites and managing the agronomy of the Scottish sites. Elsoms Seeds Ltd., and Allium and Brassica Centre for the Lincolnshire site and agronomic trial management.

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8 Appendices – Experimental Data Summary

Site 1 – Lincolnshire

Plot	Block	Tment	N Rate	Mar. Yield (t/ha)	Mean Mar. Head Weight (g)	Mar. Heads (k/ha)	Marketable Heads (%)	Total Biomass FW (t/ha)	Total Head Biomass FW (t/ha)	Dry Matter %	N Uptake Whole Crop (kg N/ha)	NUE (%)	Hollow Stem (k/ha)	Head Rot (k/ha)	Gross Crop Value (£k/ha)	Crop Value - Net of N (£k/ha)
1	1	1	0	4.4	332.3	13.2	40.0	31.0	7.4	10.8	96.8		0	0.44	3.62	3.62
2	1	4	120	6.4	361.8	17.6	53.3	25.0	3.9	9.9	104.1	-20.2	0	0.22	5.25	5.08
3	1	2	60	5.6	363.3	15.4	46.7	36.3	7.2	10.4	165.6	62.1	0	0.22	4.62	4.53
4	1	6	200	4.5	341.1	13.2	40.0	37.5	6.6	10.7	158.9	15.3	0	0.44	3.71	3.42
5	1	3	90	4.1	310.9	13.2	40.0	37.5	7.1	10.8	136.0	8.5	0	0.44	3.39	3.26
6	1	5	160	4.4	283.2	15.4	46.7	40.3	7.5	10.8	157.7	18.4	0	0.22	3.60	3.37
7	2	6	200	5.0	323.7	15.4	46.7	56.7	11.8	10.2	225.3	48.5	0	0.44	4.11	3.82
8	2	5	160	5.6	422.2	13.2	40.0	42.4	7.7	10.5	211.3	51.8	0	0.88	4.28	4.05
9	2	1	0	4.1	311.4	13.2	40.0	28.9	7.2	10.5	135.0		0	0.22	3.39	3.39
10	2	3	90	6.5	328.9	19.8	60.0	36.0	6.8	11.0	167.7	43.7	0	0.44	5.37	5.24
11	2	4	120	6.7	305.9	22.0	66.7	39.2	8.1	10.5	208.3	66.6	0	0.22	5.55	5.38
12	2	2	60	4.0	306.7	13.2	40.0	45.7	11.2	10.8	216.9	147.5	0	0	3.34	3.25
13	3	3	90	5.1	333.7	15.4	46.7	32.0	7.1	10.6	149.9	24.0	0	0	4.24	4.11
14	3	6	200	4.3	387.4	11.0	33.3	42.6	10.8	10.8	212.6	42.1	0	0.88	3.52	3.23
15	3	4	120	5.3	343.6	15.4	46.7	40.7	10.0	10.3	201.8	61.2	0	0	4.37	4.19
16	3	2	60	5.4	350.9	15.4	46.7	35.0	8.4	10.8	171.9	72.6	0	0.66	4.46	4.37
17	3	5	160	7.2	328.8	22.0	66.7	38.3	7.9	11.0	191.5	39.5	0	0.22	5.97	5.74
18	3	1	0	3.5	316.8	11.0	33.3	35.4	10.5	11.2	153.3		0	0	3.31	3.31

Site 2 – Cornwall

Plot	Block	Tment	N Rate	Mar. Yield (t/ha)	Mean Mar. Head Weight (g)	Mar. Heads (k/ha)	Marketable Heads (%)	Total Biomass FW (t/ha)	Total Head Biomass FW (t/ha)	Dry Matter %	N Uptake Whole Crop (kg N/ha)	NUE (%)	Hollow Stem (k/ha)	Head Rot (k/ha)	Gross Crop Value (£k/ha)	Crop Value - Net of N (£k/ha)
1	1	5	160	11.3	453.2	27.8	89.3	41.0	10.3	11.3	114.8	30.2	0	0	10.03	9.80
2	1	4	120	10.9	452.5	27.6	88.9	34.8	7.4	12.1	74.5	6.7	0	0	9.61	9.44
3	1	3	90	11.4	455.8	27.8	89.3	34.7	9.8	11.4	95.9	32.7	0	0	10.12	9.99
4	1	2	60	10.3	448.3	25.5	82.1	32.8	11.1	11.7	72.0	9.1	0	0	9.11	9.02
5	1	1	0	9.4	427.8	24.4	78.6	32.9	7.4	11.2	63.3		0	0	8.44	8.44
6	1	6	200	14.3	528.0	30.0	96.4	48.1	12.7	10.9	171.3	52.4	0	0	11.28	10.99
7	2	1	0	9.9	414.2	26.6	85.7	32.3	6.3	11.5	70.0		0	0	9.10	9.10
8	2	3	90	12.6	503.7	27.8	89.3	37.1	10.7	11.2	94.8	31.5	0	0	10.36	10.23
9	2	5	160	12.1	483.2	27.8	89.3	38.1	10.3	10.7	122.8	35.2	0	0	10.59	10.35
10	2	2	60	12.2	468.4	28.9	92.9	38.1	17.2	10.6	89.6	38.5	0	0	10.64	10.55
11	2	6	200	14.8	547.8	31.1	100.0	36.0	11.7	10.3	112.2	22.9	0	0	11.25	10.96
12	2	4	120	13.4	497.4	30.0	96.4	39.6	14.7	10.4	108.9	35.3	0	0	10.98	10.80
13	3	2	60	10.8	431.9	27.8	89.3	35.5	11.3	9.3	78.7	20.4	0	0	9.72	9.63
14	3	5	160	12.9	496.4	28.9	92.9	43.0	11.3	10.9	142.3	47.4	0	0	10.99	10.76
15	3	4	120	12.0	444.6	30.0	96.4	28.9	8.6	10.9	94.7	23.5	0	0	10.81	10.64
16	3	1	0	9.1	412.3	24.4	78.6	29.1	6.9	11.6	66.1		0	0	8.31	8.31
17	3	3	90	11.2	448.6	27.8	89.3	34.2	8.1	11.4	94.9	31.6	0	0	9.94	9.80
18	3	6	200	13.6	504.5	30.0	96.4	34.6	12.4	10.8	133.3	33.4	0	0	11.33	11.04

Site 3 – Lochlands, Perthshire

Plot	Block	Tment	N Rate	Mar. Yield (t/ha)	Mean Mar. Head Weight (g)	Mar. Heads (k/ha)	Marketable Heads (%)	Total Biomass FW (t/ha)	Total Head Biomass FW (t/ha)	Dry Matter %	N Uptake Whole Crop (kg N/ha)	NUE (%)	Hollow Stem (k/ha)	Head Rot (k/ha)	Gross Crop Value (£k/ha)	Crop Value - Net of N (£k/ha)
106	1	1	0	0.0	0.0	0.0	0.0	14.2	1.3	18.7	108.8		0.0	0.0	0.0	0.0
206	2	1	0	0.0	0.0	0.0	0.0	13.9	1.6	20.2	90.4		0.0	0.0	0.0	0.0
307	3	1	0	0.0	0.0	0.0	0.0	14.8	1.8	18.1	101.3		0.0	0.0	0.0	0.0
102	1	2	60	2.9	327.4	0.0	26.7	29.0	3.7	12.6	140.7	67.5	0.0	0.0	2.4	2.3
202	2	2	60	0.6	274.0	8.8	6.7	24.0	4.8	15.9	149.9	82.8	0.2	0.0	0.5	0.4
304	3	2	60	3.4	310.3	2.2	33.3	28.7	4.6	12.8	164.0	106.2	0.0	0.0	2.8	2.7
103	1	3	120	3.5	320.2	11.0	33.3	27.3	3.9	12.8	137.8	31.3	0.0	0.0	2.9	2.7
201	2	3	120	3.6	330.0	11.0	33.3	33.0	6.3	12.0	175.4	62.7	0.7	0.2	3.0	2.8
302	3	3	120	10.5	368.0	11.0	86.7	32.3	5.3	12.2	200.9	83.9	0.0	0.0	8.7	8.5
101	1	4	180	7.2	328.5	28.6	66.7	40.7	7.5	10.2	218.3	65.6	2.0	0.2	6.0	5.7
204	2	4	180	11.1	388.7	22.0	86.7	46.5	9.9	9.7	210.8	61.5	0.0	0.0	9.2	8.9
303	3	4	180	11.5	372.0	28.6	93.3	44.5	14.5	10.0	184.5	46.8	0.0	0.0	9.1	8.8
105	1	5	220	11.0	384.3	30.8	80.0	43.2	9.5	8.6	206.8	48.5	0.4	0.7	8.0	7.7
207	2	5	220	12.5	406.3	26.4	93.3	39.1	11.1	10.5	192.9	42.2	0.9	0.0	9.9	9.6
301	3	5	220	14.2	457.9	30.8	80.0	42.9	13.1	9.5	137.9	17.1	0.0	0.2	8.9	8.6
107	1	6	270	14.9	485.0	26.4	86.7	48.9	10.4	9.5	235.9	50.2	0.0	0.0	9.9	9.5
205	2	6	270	12.6	382.1	28.6	93.3	46.1	12.7	9.7	250.0	55.5	1.8	0.0	9.1	8.7
306	3	6	270	12.2	427.8	30.8	80.0	47.3	11.5	10.0	254.2	57.0	2.0	0.4	8.9	8.5
104	1	7	220	9.7	399.2	26.4	73.3	33.0	8.4	9.9	179.0	35.8	0.7	0.0	7.6	7.3
203	2	7	220	16.0	522.0	24.2	73.3	47.8	20.4	9.0	198.3	44.6	0.7	0.0	8.3	8.0
305	3	7	220	18.9	571.1	24.2	80.0	45.4	13.8	9.8	202.2	46.4			10.3	10.0
FS 1	4	4	*180	12.5	407.1	26.4	93.3	31.3	7.7	12.3	154.8	30.3			9.9	9.7
FS 2	4	4	*180	14.1	448.4	30.8	86.7	41.3	8.9	11.7	194.2	52.2			9.8	9.6
FS 3	4	4	*180	13.4	436.2	28.6	93.3	35.0	9.2	10.9	163.5	35.2			10.09	9.83

Site 4 - Newlington, Fife

Plot	Block	Tment	N Rate	Mar. Yield (t/ha)	Mean Mar. Head Weight (g)	Mar. Heads (k/ha)	Marketable Heads (%)	Total Biomass FW (t/ha)	Total Head Biomass FW (t/ha)	Dry Matter %	N Uptake Whole Crop (kg N/ha)	NUE (%)	Hollow Stem (k/ha)	Head Rot (k/ha)	Gross Crop Value (£k/ha)	Crop Value - Net of N (£k/ha)
101	1	5	220	13.6	474.8	0.0	86.7	38.7	6.7	10.9	158.8	46.0	0.0	0.0	9.71	9.39
102	1	6	270	14.1	533.0	28.6	80.0	43.5	6.3	9.0	158.4	37.3	0.2	0.0	9.37	8.98
103	1	3	120	17.6	571.9	26.4	93.3	43.0	8.6	10.0	148.1	75.4	0.0	0.0	11.84	11.67
104	1	1	0	5.1	291.8	30.8	53.3	23.3	5.7	16.4	55.8		0.0	0.0	4.66	4.66
105	1	2	60	9.0	371.5	17.6	73.3	36.6	8.3	11.3	99.6	69.9	0.7	0.2	7.42	7.33
106	1	4	180	14.0	579.0	24.2	73.3	54.7	11.2	8.9	197.3	77.6	0.0	0.0	9.53	9.27
107	1	7	220	13.4	434.1	24.2	93.3	45.1	16.6	8.7	142.6	38.6	2.0	0.2	9.86	9.54
201	2	7	220	16.1	487.7	30.8	100.0	42.8	14.1	9.8	147.0	40.6	0.0	0.0	11.42	11.11
202	2	2	60	9.3	383.5	33.0	73.3	38.2	7.0	12.6	106.2	80.9	0.0	0.0	7.66	7.57
203	2	6	270	15.6	589.5	24.2	80.0	44.6	7.5	11.9	209.1	56.1	0.4	0.7	10.24	9.84
204	2	5	220	15.0	621.8	26.4	73.3	46.5	9.1	8.8	168.8	50.5	0.9	0.0	9.69	9.37
205	2	1	0	3.5	322.1	24.2	33.3	25.4	3.7	18.0	63.1		0.0	0.2	2.92	2.92
206	2	3	120	14.1	428.4	11.0	100.0	45.4	7.1	10.4	139.0	67.8	0.0	0.0	10.88	10.71
207	2	4	180	17.0	550.6	33.0	93.3	46.6	10.7	8.9	144.6	48.3	1.8	0.0	11.55	11.29
301	3	5	220	13.5	613.6	30.8	66.7	46.3	7.0	10.5	195.5	62.7	2.0	0.4	8.88	8.56
302	3	2	60	4.7	303.1	22.0	46.7	29.9	4.2	12.8	69.1	19.1	0.7	0.0	3.85	3.76
303	3	3	120	14.0	453.7	15.4	93.3	38.2	6.5	10.3	134.5	64.1	0.7	0.0	10.47	10.30
304	3	7	220	13.7	479.2	30.8	86.7	40.0	11.6	9.4	159.1	46.1	0.0	0.0	9.78	9.46
305	3	4	180	14.6	510.5	28.6	86.7	47.5	7.8	9.3	142.0	46.9	2.0	0.7	10.33	10.07
306	3	6	270	16.5	681.0	28.6	73.3	52.7	7.8	8.8	198.8	52.3	1.8	0.2	9.94	9.55
307	3	1	0	2.1	319.3	24.2	20.0	20.1	2.8	17.9	54.0		0.0	0.0	1.74	1.74
FS 1	4	FS	200	14.9	483.8	6.6	93.3	37.8	17.3	9.5	126.2	34.3			11.16	10.87
FS 2	4	FS	200	13.5	438.5	30.8	93.3	36.7	13.1	11.1	131.6	37.0			10.83	10.54
FS 3	4	FS	200	15.0	568.2	30.8	80.0	36.5	14.4	9.8	122.2	32.3			10.12	9.83