Shropshire Growers Discussion Group

Final Report 2021

Establishing Potato Cyst Nematode Trap Crops

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Summary and Key Points

Questions:

1. Can the PCN trap crops, *S. sisymbriifolium* and *S. scabrum*, be grown effectively when sown at the latest sowing period of late June in North Shropshire?
2. Do *S. sisymbriifolium* or *S. scabrum* need to be sown with additional nitrogen (50 kg or 100 kg N/ha) at planting?
3. Does 'priming' the seed of *S. sisymbriifolium* improve the establishment of the crop.
4. Do *S. sisymbriifolium* or *S. scabrum* grow well and compete in conventional and organic situations, without the use of herbicide weed control?
5. Do *S. sisymbriifolium* or *S. scabrum* reduce populations of PCN

Background:

1. Three sites in North Shropshire were planted with *Solanum sisymbriifolium* and *Solanum scabrum* at the end of June 2021.
2. The site at Edgmond utilised 6 replicates of each treatment and each plot was sampled for PCN population density, both Pi and Pf. The sites at Caynton and Ellerdine had three replicates but were not sampled for PCN population.
3. Two of the sites in North Shropshire, Caynton and Edgmond, would be classed as conventionally farmed and one, Ellerdine, is a registered 'organic' farm.
4. Crops were planted using commercial equipment.
5. Fertiliser N was applied by hand as Lawes organic 10% N pelleted fertiliser.

Answers:

1. Three trial sites were planted on the same day, 25th June 2021, but the establishment of the crops at all three field sites was quite variable, even within the individual trials. Rainfall did occur within 24hrs of planting suggesting that moisture for germination should not have been an issue. On the Caynton site, this was a second year of good establishment and growth from this sowing date. The Edgmond site was variable but gave indications that planting at this date was acceptable. At the Ellerdine site, it was difficult to judge the establishment as the site was quickly inundated with weeds. There is still further work required on the best method of establishing these crops, but they have now been successfully grown on some sites when planted in Late-June in North Shropshire.
2. The use of 100 kg N/ha, applied as organic pelleted fertiliser, appears to have improved the number of plants establishing and the canopy development, as is normal with nitrogen applications. Whether the crops would benefit from greater N or split applications would need to be further investigated.
3. Unfortunately, it was not possible to produce any primed seed in time for the planting of any of the trials.

4. The trial at the organic farm site quickly became inundated with fat hen, *Chenopodium album*, and although the crops did grow within the weeds they were always outcompeted. Consequently, this trial was terminated on 7th September, 74DAP, as no useful information could be gained. At the conventional farm site at Edgmond, both mayweed, *Matricaria chamomilla*, and fat hen, *Chenopdium album*, were problematic and needed significant hand weeding. The site at Caynton suffered from substantially less weed ingress and required only moderate weeding throughout. There is a significant need for effective pre- and or post-emergence herbicide during the establishment phase of these trap crops, once established both *S. sisymbriifolium* and *S. scabrum* can provide a good competitive canopy. In both the *S. sisymbriifolium* plots and in the commercial crop surrounding the trial at Caynton, there was very little weed growth suggesting a possible additional suppressive effect from the crop.
5. PCN samples were taken pre-planting (Pi) and at 130 days after planting (Pf). Initial populations ranged from 62 to 248 eggs/g air dried soil. PCR results identified the species as entirely *Globodera pallida*. The results suggest that both *S. sisymbriifolium* and *S. scabrum* reduced PCN populations by up to 56% of their initial value, range 38 – 55%. Individual plots of both *S. sisymbriifolium* and *S. scabrum* achieved PCN population reductions of 81% and 84% respectively, but the results were variable.

Please note: The date that the trap crops were sown is very much at the end of the recommended planting window as suggested by the seed suppliers (Produce Solutions), and the results from these trials cannot be seen as sowing recommendations. Please speak to the seed suppliers for further advice.

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1. Introduction

The potato cyst nematodes, PCN, *Globodera pallida* and *G. rostochiensis* are serious pests of potatoes causing an average of 35%, but up to 80%, yield losses along with associated losses to the sector of c. £26m. Consequently, some form of crop protection measure, or combination of measures, is required to enable long term potato production to be achieved. Although with many pests and diseases the first control measure can be the selection and use of resistant cultivars, there are very few commercially available cultivars with good resistance to the dominant PCN species, *G. pallida*. Similarly, as with other pests a suitable duration between potato crops often provides good agronomic control. Unfortunately, for PCN, rotation lengths greater than 7 years between potato crops are required to control the pest, making it financially unsustainable due to the investment required for the crop. Therefore, the most common means of control in current conventional agriculture is with the use of nematicides of which only Nemathorin (Syngenta) and Velum Prime (Bayer) remain in the market, albeit for an uncertain timescale. Consequently, organic, and conventional growers both need a suitable crop protection method to allow commercial potato production in PCN infested land to be sustainable. Although one option is the use of biofumigant crops, alternatives are the PCN trap crops *S. sisymbriifolium* and *S. scabrum,* which are grown to reduce PCN populations as they stimulate PCN hatch but prevent their reproduction. *Solanum sisymbriifolium* (Decyst, Produce solutions) has been grown in the UK as a 'PCN trap crop' for approximately 15 years, and worked well in rotations when used in the 'set-aside' system (1992 – 2008) as its ideal planting time is similar to maize. *Solanum scabrum* (Decyst Broadleaf) is an African leafy vegetable which is another potential PCN trap crop currently in development by Produce Solutions, but which lacks agronomic knowledge for use in the UK. Therefore, an understanding of latest safe sowing dates, establishment method and crop nutrition for both of these species is still in its infancy, despite *S. sisymbriifolium* having been commercially available for several years. Optimally these crops should be sown in mid-May to early-June as their growing requirements are similar to maize, but this conflicts with growing between traditional UK cash crops. The purpose of the field trials described in this report were therefore to investigate the effect of sowing these crops in late-June, which is at the end of the recommended window, mid-May to end-June. In addition, these trials were to investigate if the establishment and subsequent growth of the crops would be improved by the use of 50kg N/ha or 100kg N/ha applied at planting. A third component of these trials was to include the use of 'primed' seed to determine if this technique would aid the speed of emergence and establishment of the crops. However, although priming is used for crops such as sugar beet and various horticultural crops, the actual process of priming for *S. sisymbriifolium* and *S. scabrum* needs development. Also, within these trials, as there are currently no commercially available herbicides for weed control, the ability of these crops to outcompete any weed ingress was included to determine the weed problems in the absence of herbicides. Additionally, as an important aspect of this work is the effect of these crops on the resident PCN populations, the trial will investigate their effects on the PCN populations, to determine their ability to reduce PCN populations.

2. Materials and methods

Trial sites and trial design:
Trial sites in North Shropshire were: Edgmond (Organic Sandy loam), Ellerdine (Sandy clay loam), and Caynton (slightly stoney sandy loam), Figures 1, 2 and 3 respectively.
Caynton and Ellerdine were a standard Randomised Complete Block (RCB) with three replicates of all treatments. The Edgmond site utilised a stratified RCB design with 6 replicates, to ensure that each treatment was challenged by a similar PCN population. Plots were 4m wide x 10m long, with a 4m wide turning area between blocks, which was then over-drilled with *S. sisymbriifolium* or *S. scabrum*

Figure 1. Edgmond site pre-planting, surrounded by planted potato crop.

Figure 2. Ellerdine site at planting, within existing trap crop field crops.

Figure 3. Caynton site at planting, 25th June 2021.

Equipment:

All sites utilised the same Lemken solitair drill with 125mm spacing (Figure 4)

Figure 4. Planting equipment at Caynton, Lilyhurst and Tibberton. Lemken Solitair 9.

2.1 Planting dates and previous crops

Planting was achieved as early as possible after previous crop removal, Table 1a.

Table 1a. Planting dates and previous crops for the four trial sites involved in the Innovative Farmers trap crop trials 2020.

Site	Planting date	Previous crop	County
Caynton	25th June 2021	Forage rye	N. Shropshire
Edgmond	25th June 2021	Cereals	N. Shropshire
Ellerdine	25th June 2021	?	N. Shropshire

The area surrounding the trials at Caynton and Ellerdine were planted with commercial crops of *S. sisymbriifolium* and *S. scabrum*. The site at Edgmond was surrounded by maincrop potatoes.

2.2 Agronomy and Management

Seed

Certified seed was supplied by Produce solutions, Shropshire, UK:
Solanum sisymbriifolium (mixed with lentils) as DeCyst™ sown at a rate of 20 kg/ha. *Solanum scabrum* (mixed with lentils) DCyst broadleaf™, sown at 20 kg/ha. Seeds were planted at ≈1cm depth and pressed in with the drill press wheels.

Crop nutrition

All sites received either 50 or 100 kg/N ha as pelleted chicken manure, Lawes 10% N, within 2 days of planting. No other artificial synthetic fertilisers were used. Soil analysis was performed by Lancrop laboratories (York), Table 1b, where differences between the sites are highlighted, Table 1b.

Table 1b. Soil analysis results for Caynton and Edgmond trial sites. (Colour shading to highlight key variation from normal range)

	Caynton	**Edgmond**
pH	6.5	6.3
P index	4.3 V/high	2.1
K index	3.5 High	2.7
Mg index	4.1 V/high	4.4 V/high
Calcium	Low	Normal
Sulphur	V/low	Slightly low
Manganese	Slightly low	V/low
Molybdenum	0.03 (V low)	0.02 V low
Iron	985 ppm	1085
Copper	6.4	4.6
Boron	Slightly low	Normal
Zinc	High	Normal
Sodium	18 ppm V/low	25 V/Low
CEC	Slightly low	Normal

2.3 PCN populations

The effect of the trap crops on underlying PCN populations were to be determined at one site, Edgmond. Thirty cores were taken from a 2m wide strip running down the length of the plot for each of the initial population, *Pi*, and final population, *Pf*, counts. The cores were taken to approximately 20cm depth using a soil corer with a 15mm diameter, achieving approximately 1000g samples per plot. The samples were analysed by the Nematology Group at Harper Adams University, Shropshire, using the standard Fenwick can extraction method after air drying. PCN species were determined using PCR (adopted from Nakhla *et al*., 2010) and was found to be entirely *G pallida*. The initial PCN population densities ranged from 62 – 249 eggs/g air dried soil, Tables 2 and 3. The experiment was 'blocked' using a stratified design to ensure that all treatments were challenged by PCN densities of varying magnitude across the site, Table 3.

Table 2. Edgmond plot layout and initial PCN population densities, eggs/g air dried soil. (Plot numbers in red)

4 67	92	120	64	162	24 88
5m turning area					
121	249	92	80	117	169
5m turning area					
89	129	99	110	149	62
5m turning area					
1 160	144	78	168	100	21 174
Block 1	Block 2	Block 3	Block 4	Block 5	Block 6

Table 3. Edgmond site PCN population densities, eggs/g air dried soil, by replicate and crop species.

PCN Pi	Sisym	Scabrum
N 50 Rep1	62	64.17
N 50 Rep2	89.46	91.635
N 50 Rep3	92.12	99.45
N 50 Rep4	120.75	117.045
N 50 Rep5	160.205	161.59
N 50 Rep6	167.7	174
N100 Rep1	78.24	66.555
N100 Rep2	88.06	79.65
N100 Rep3	100.11	110.4
N100 Rep4	129.39	119.5
N100 Rep5	143.88	149.42
N100 Rep6	248.6	169.4

2.4 Emergence and ground cover assessments

The emergence counts were achieved by counting emerged plants at either side of a one metre rule in the centre of the plot, at 2m and 5m from the start of each plot. These counts were then converted to counts per m^{-2} for analysis.

Ground cover analysis was done using captured aerial imagery of each plot, taken from 14m AGL (above ground level) of the whole plot using a DJI Mavic 2 Pro with a 20MP Hasselblad camera. Images were cropped to analyse only the central 3m width of each individual plot to remove any overlap material from adjacent plots. Any non-crop green material (weed) was converted to black/brown within the image before being analysed. Analysis was done using the ‘Canopy cover’ software from the University of California. The pixels within each image are individually analysed for RGB and then a composite image is produced which segregates the ‘green area’ and converts it to Ground cover percentage, Figure 5.

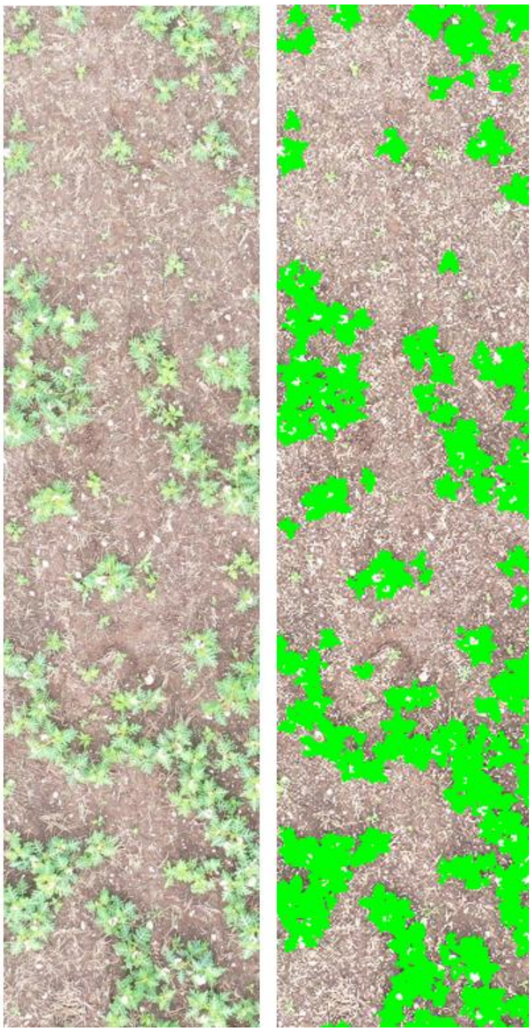

Figure 5. Aerial image from 14m AGL, 3m central section of plot 1 (left) and analysed/converted image (right), calculated at 12% GC.

2.5 Weed management

There are no herbicides specifically recommended for either *S. sisymbriifolium* or *S. scabrum* in the UK/EU. In the crops surrounding the trials, *S. sisymbriifolium* and *S. scabrum:* Ellerdine, flame weeding was used early post planting which did delay the weeds. This was followed up by topping the weeds above the height of the crop, but the crops could not compete. Once crops were established weeds did not pose an issue for either trap crop species but were still a considerable problem on the Ellerdine and Edgmond sites.

Irrigation

There were no applications of irrigation to any of the trials

2.6 Data analysis

All of the main data collected which included data for all plots within a trial, i.e., emergence and ground cover, were analysed as RCB factorial designs in RStudio (v. 1.4.1106). The results are presented as non-significant (N/S) when probability values were *P>0.05*. Where results were significant, the actual P values are given to show the level of significance. Analysis was initially done including interactions but where there was no interaction data was re-analysed without interaction to produce a greater number of df and thus a more robust analysis.

Observations

Rainfall was recorded, up to 40mm at Caynton, within 24 hours of planting. Rainfall records from Shawbury Met station show July 68mm, August 34mm, September 57mm, October 69mm, November 23mm. Mean temperatures per month were also taken from Shawbury Met station (North Shropshire) which indicate temperatures were below the optimum for this crop but similar to the 64 years mean, Figure 5a. Daylength and sun hours also show that the crop was sown when both daylength and the amount of sun hours were declining, which may be important, Figure 5a.

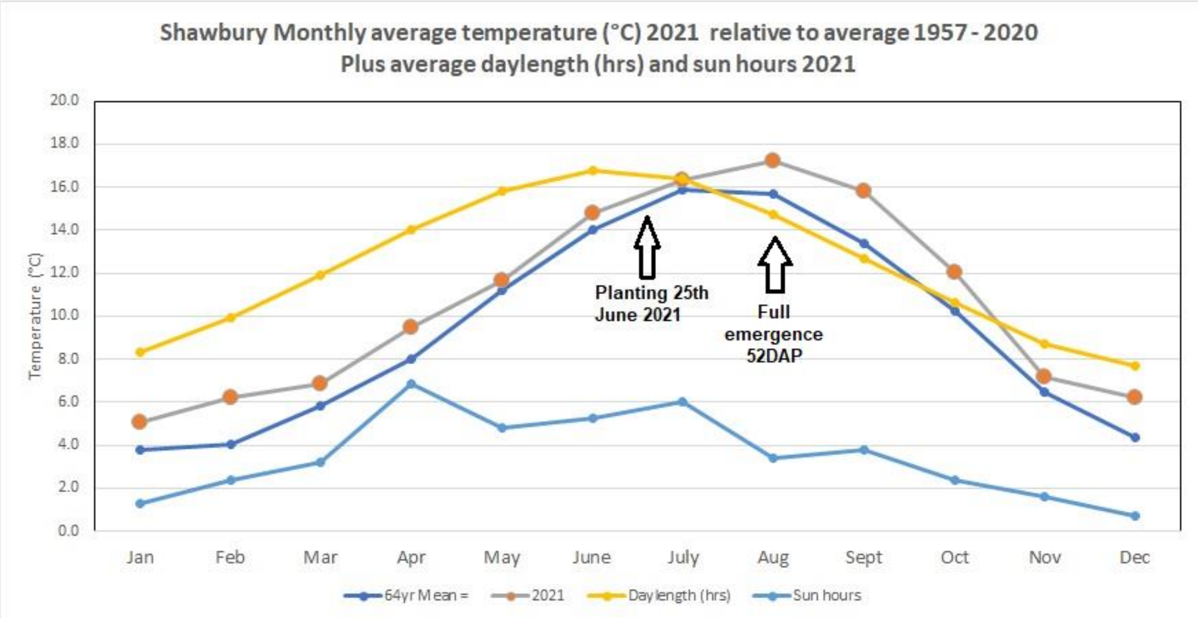

Figure 5a. Mean temperatures per month recorded at Shawbury (Adapted from Met office data)

3. Results

PCN populations at Edgmond site

There were significant initial PCN population, *Pi*, differences between blocks, *P <0.001*, which would be expected from a stratified trial design, but there were no significant treatment differences, Table 4. The population densities ranged from 62 – 249 eggs/g air dried soil, which would be classed as very high.

Table 4. Mean PCN initial population densities, eggs g/air dried soil, at Edgmond.

Edgmond site PCN Pi eggs g soil 2021				
	Sisym	Scabrum	Totals	
N50	115	118	**117**	
N100	131	116	**124**	N/S
Totals =	**123**	**117**		
	N/S		Interaction: N/S	

Final PCN population densities, *Pf*, taken at 130DAP were initially analysed as a three replicate balanced design due to poor crop establishment in some plots, Table 5a, but then as a single factor unbalanced anova, with variable replication, with the remaining plots used as a control (no crop), Table 5b. There were no differences between treatments for *Pf, Pf/Pi* or percentage population reductions using either analysis method.

Table 5a. Mean PCN final population densities at the Edgmond site 130DAP, eggs/g air dried soil, using a 3 replicate factorial balanced design.

Edgmond site PCN Pf eggs g soil 2021 (130DAP)				
	Sisym	Scabrum	Totals	CV = 46%
N50	75	54	**64.6**	
N100	64	53	**58.5**	N/S
Totals =	**69.5**	**53.6**		SED 28.6
	N/S		Interaction: N/S	

Table 5b. Mean PCN final population densities, *Pf/Pi* values and percentage population reductions at the Edgmond site 130DAP, eggs/g air dried soil, using a single factor unbalanced design with mixed replicate numbers.

Edgmond site PCN Pf, Pf/Pi and % reduction eggs g/soil 2021 (130DAP)				
Treatment	Eggs g soil	Pf/Pi	% PCN reduction	Reps
Control	89	0.74	26	5
Sisym 50	75	0.6	40	4
Sisym 100	64	0.62	38	5
Scabrum 50	54	0.53	47	6
Scabrum 100	53	0.44	56	4
		N/S	CV = 31%	

Crop Emergence

Crop emergence was slow to progress at all sites with little progress by 20 days after planting, DAP. All three sites had some patchy emergence by 27DAP and increased a little by 34DAP.

Edgmond (Sown 25th June 2021)

Plant emergence at Edgmond peaked at 52DAP with no significant differences. There were no further plants emerging by 60DAP, so the assessment switched to ground cover measurement after that date. Inspecting the plots identified that several appeared to have no crop plants. Consequently, three replicates containing crop plants were selected from each treatment to identify if any trends were in evidence, there were no significant effects, Table 6 and no trend should be inferred.

Table 6. Plant emergence at Edgmond at 52DAP taken from 3 reps only

EM52HAU3	Sisyn	Scabrum		
N50	8.0	9.3	*8.7*	
N100	16.0	12.0	*14.0*	N/S
	12.0	*10.7*		
	N/S		Interaction: N/S	

Caynton (Sown 25th June 2021)

Plant emergence at Caynton peaked at 52DAP, Figure 6, and a significantly greater plant emergence from application of 100 kg N/ha compared to 50 kg N/ha, *P = 0.003*, Table 7. There were no significant species differences. There were no further plants emerging by 60DAP and so the assessment switched to ground cover measurement after that date.

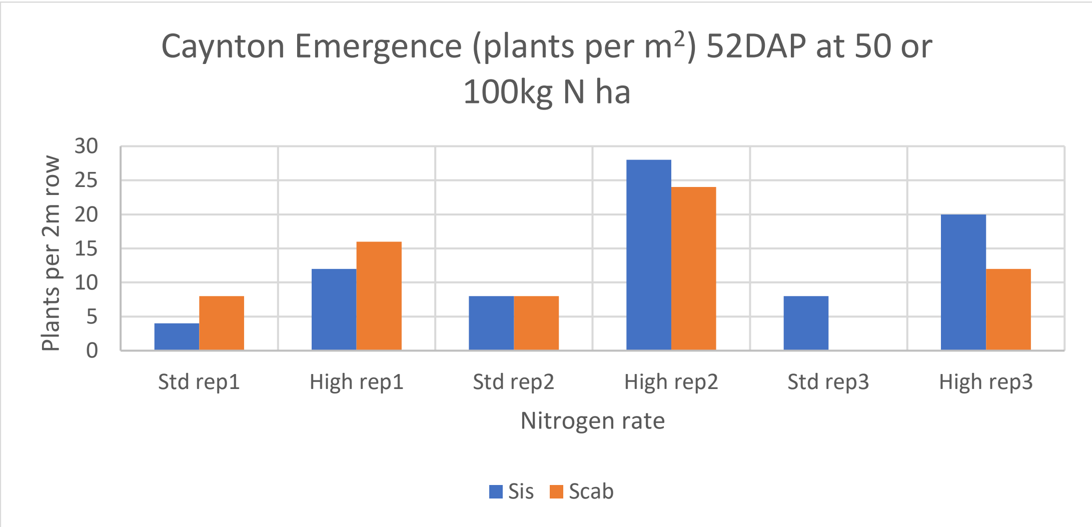

Figure 6. Emergence of crops, 52DAP, at the Caynton site.

Table 7. Emerged crop plants m^2 at 52DAP at the Caynton site

	Sisym	Scabrum		
50 kg N/ha	6.7	5.3	***6.0***	*P =*
100 kg N/ha	20.0	17.3	***18.7***	*0.003*
	13.3	***11.3***		
	N/S			

Ellerdine (Sown 25th June 2021)

Note: crops were over-sown into pre-existing *Solanum scabrum* crops which had already emerged. Unfortunately, this created problems when trying to determine speed of emergence of trial crops due to the pre-existing seed and plants, Figure 7.

Emergence was slow, with no emergence at 13DAP, Figure 8, or 21DAP, a few plants of both species were present by 27DAP, Figures 9 & 10, but weed emergence was significant Figures 11 and 12, and insufficient for data analysis. Crops could not be separated from the fast-emerging weeds even by 27DAP.

Figure 7.   Ellerdine IF trial site at drilling, 25th June 2021

Figure 8.   Ellerdine site 8th July, 13DAP, extensive growth of pre-drilled field crop.

Figure 9. Ellerdine site at 27DAP. Excessive weed growth and pre-existing crop.

Figure 10. Ellerdine IF site 27DAP, 22/7/2021, plant growth in and around trial.

As the trial continued the site became inundated with fat hen, *Chenopodium album*, and so assessments at 52DAP were implausible, Figures 11 & 12.

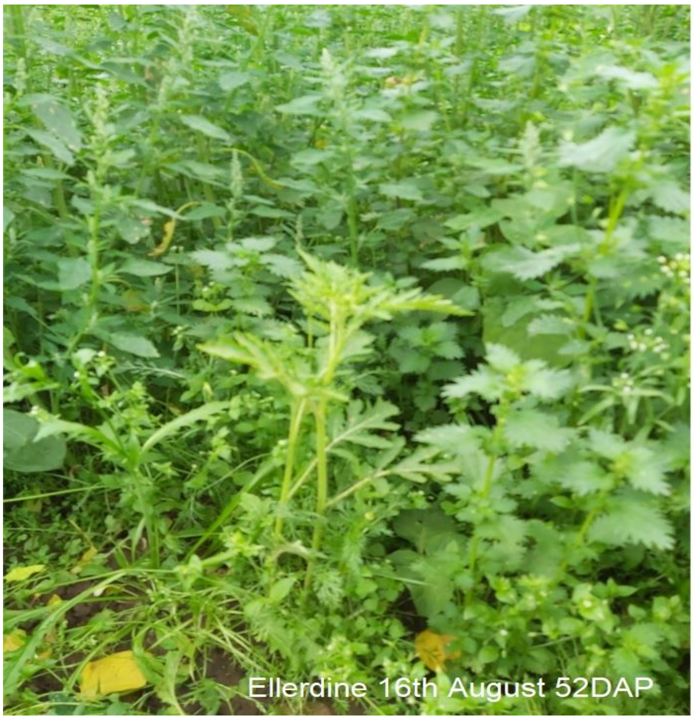

Figure 11. Within trial weed problems 52DAP, 16th Aug 2021, *S. Sisymbriifolium* within extensive fat hen and nettle.

Figure 12. Ellerdine site and surrounds at 52DAP (16th August 2021)

AT 60DAP the trial site continued to be impossible to assess and would have provided no useful data. At the site visit at 74DAP the trial had been topped to ground level and the surrounds cultivated and replanted.

Conclusions for Ellerdine

Due to the slow growth of these trap crops, the trial quickly became inundated with excessive weed growth, making it impossible to assess their development in relation to species or nitrogen application in any meaningful way. It is worthy of note that even in the surrounding field, where early single and double burning had occurred, the weed growth still eventually outcompeted the sown crops. Whether the weed growth would have affected the crops performance in control of PCN is difficult to assess. However, PCN control may still have occurred, and requires further investigation given that topping just above the *S. scabrum* height did allow the trap crops to grow. It is apparent from this trial that organic farms may face a difficult task of growing these initially slow growing trap crops when planted at this sowing time, late June. However, when planted in the preferred time of mid-May, this may allow the traps crops to establish faster and outcompete the weeds. Another alternative, discussed within the IF group, which may prove to be feasible, is the use of planting the trap crops as 'row crops' and then using inter-row weeding. As PCN are a significant issue for potato growers, the use of trap crops in an organic setting deserves further investigation.

Ground cover from the Edgmond site

Ground cover assessment at 82DAP showed no significant species or nitrogen rate differences, $P > 0.05$, Table 8, Figure 13, and there was considerable variation across the trial site.

Table 8. Mean ground cover percentage at the Edgmond site (all reps whole plot).

	Edgmond Mean % Ground cover 82DAP (6 rep)			
	Sisym	**Scabrum**		
Std N	7.88	8.00	***7.92***	**N/S (P=0.08)**
High N	28.35	8.52	***18.42***	
	18.12	***8.26***		
	N/S		**Interaction: N/S**	

However, it has been noted that several of the plots appear to have no plants emerged at all leading to an assumption of sowing failure, possibly due variable planting depth. This is highlighted by the ground cover in Figure 13. Consequently, a randomised subset of plots which could be confirmed as sown on the whole plot, was used in a 3-replicate analysis. This would remove the bias of unsown areas/plots within the analysis. The analysis of these results, Table 9, shows that *S sisymbriifolium* has significantly greater ground cover than *S. scabrum*. There were no other significant differences.

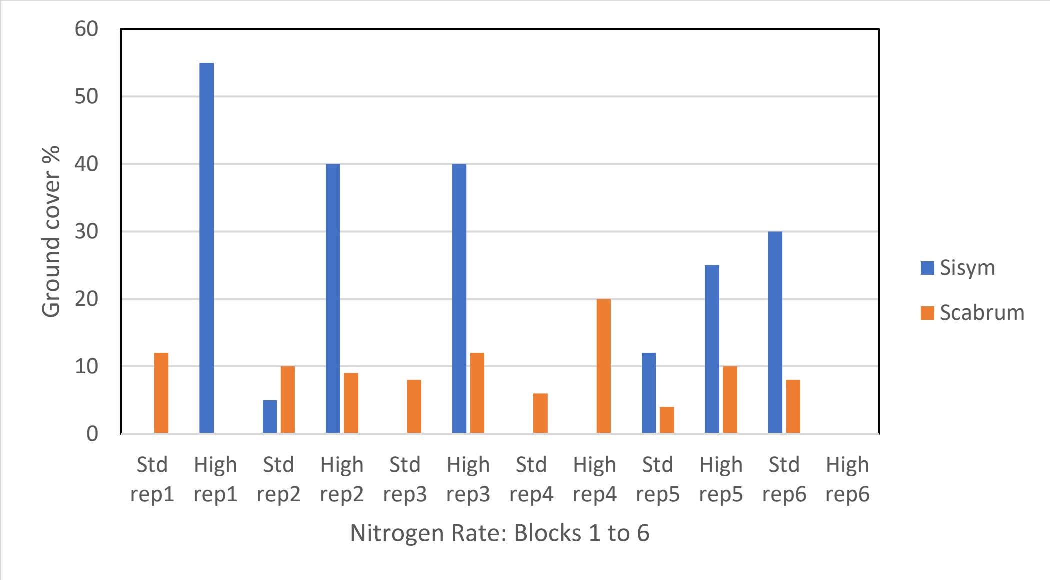

Figure 13. Ground cover % of *S. sisymbriifolium* and *S. scabrum,* Edgmond, 82DAP

Table 9. Three replicate ground cover percentage at the Edgmond site, 82DAP.

GC82HAU3	**S. Sisym**	**S. Scabrum**	Mean N	
N50	15.7	8.7	*12.2*	*N/S*
N100	40.0	14.0	*27.0*	
Mean	*27.8*	*11.3*		
	P = 0.045			

At 88DAP there were no significant differences between species or nitrogen rate, Table 9a, Figure 14.

Table 9a. Three replicate ground cover percentage at the Edgmond site, 88DAP.

GC88HAU3	**S, Sisym**	**S. Scabrum**		
N50	28.7	15.6	*22.2*	
N100	49.0	19.9	*34.5*	N/S
	38.9	*17.8*		
	N/S (P=0.08)			

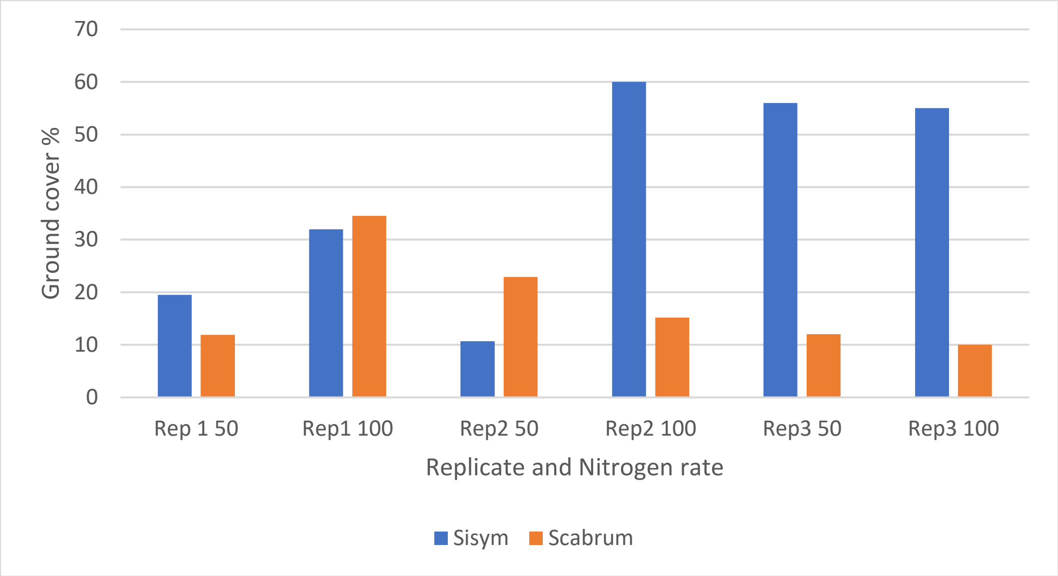

Figure 14. Edgmond Ground cover %, 3 replicates, (central 3m x 8m) 88DAP at 50 or 100kg N ha

At 109DAP, there were no significant ground cover differences between species or nitrogen rates, Table 10, Figure 15.

Table 10. Three replicate ground cover percentage at the Edgmond site, 109DAP.

Edgmond Mean % Ground cover 109DAP				
3 reps	**S. Sisym**	**S. Scabrum**		CV 56.8%
Std N	38	24	***31.0***	
High N	70	37	***53.3***	N/S
	53.7	***30.7***		SED 23.9
	N/S		Interaction: N/S	

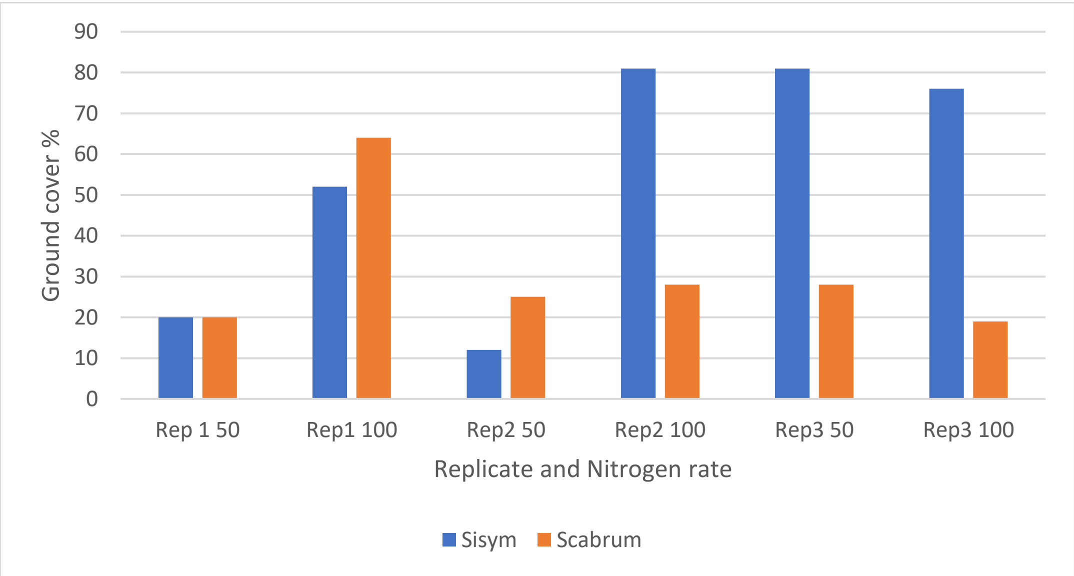

Figure 15. Edgmond GC % (central 3m x 8m) 109DAP at 50 or 100kg N ha

At 123DAP there were no significant ground cover differences between the species or as affected by nitrogen rate, Table 11, Figure 16.

Table 11. Three replicate ground cover percentage at the Edgmond site, 123DAP.

Edgmond	**Ground cover % 123DAP**			
Means	S Sisym	S Scabrum		CV 47%
Std N	36.7	41.8	***39.3***	
High N	77.7	49.7	***63.7***	***N/S***
	57.2	***45.7***		SED 24.19
	N/S		**Interaction N/S**	

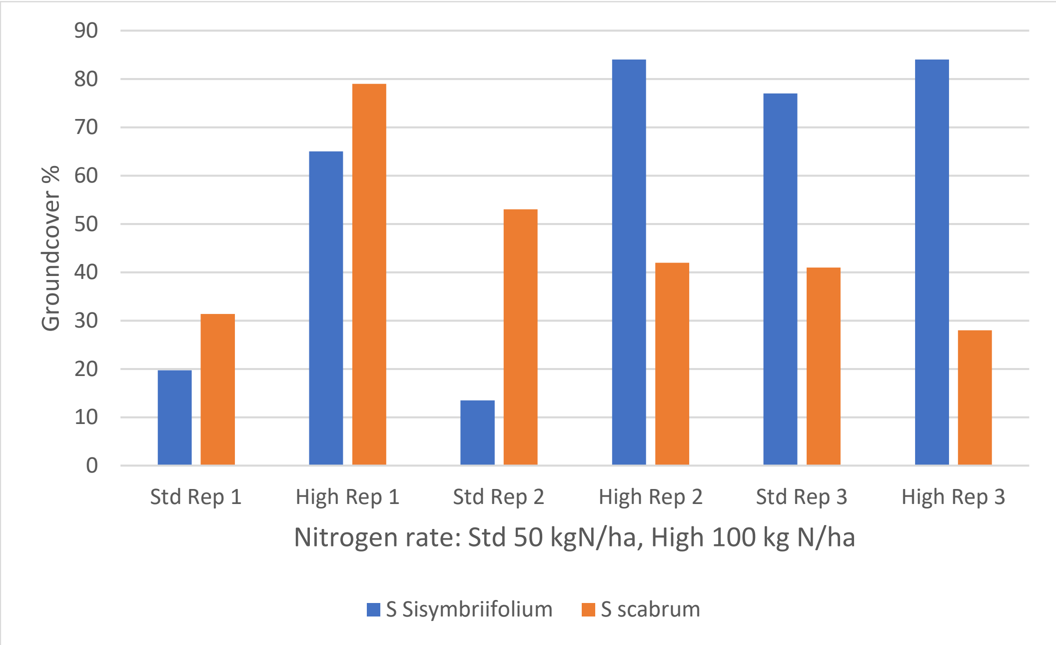

Figure 16. Edgmond GC % (central 3m x 8m) 123DAP at 50 or 100kg N ha

The final ground cover assessment at 147DAP continued the trend of no significant differences between species, nitrogen rates or interactions, Table 12, Figure 17.

Table 12. Three replicate ground cover percentage at the Edgmond site, 147DAP

Edgmond Mean % Ground cover 147DAP				
3 reps	**Sisym**	**Scabrum**		CV 54.6%
Std N	34.3	27.3	***30.8***	
High N	71.0	35.3	***53.2***	N/S
	52.7	***31.3***		SED 22.9
	N/S		Interaction N/S	

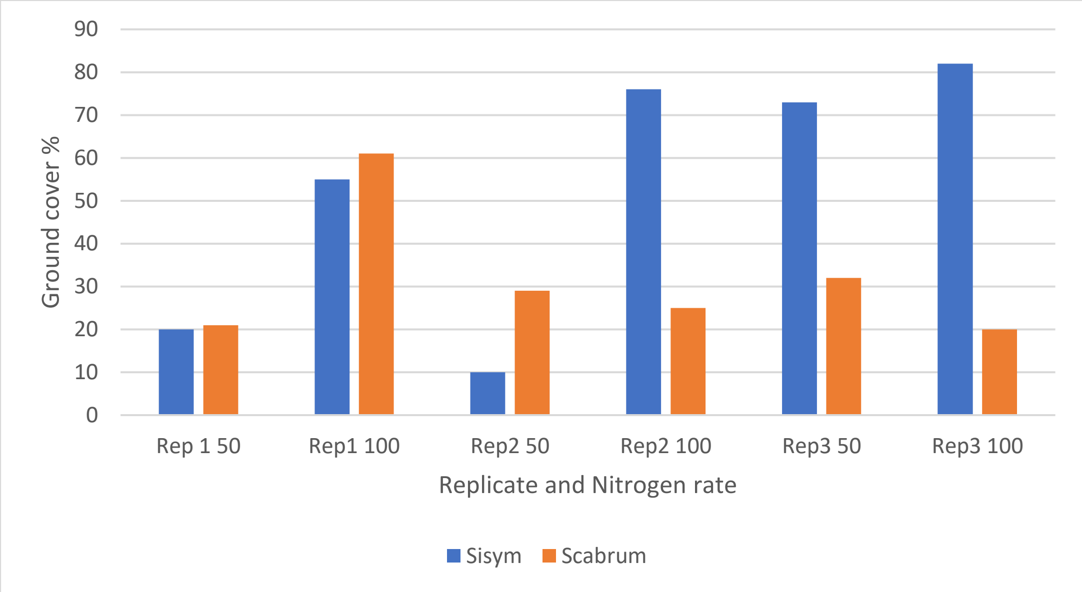

Figure 17. Edgmond GC % (central 3m x 8m) 147DAP at 50 or 100kg N ha

Plant Biomass assessments utilising 3 replicates at 123DAP

At 123DAP Edgmond plant biomass assessments were done on two plants per plot and converted to m^2 by utilising the plant numbers m^2 determined during the assessments.

Above ground biomass fresh-weight, FW, and dry-weight showed no significant differences between species or nitrogen rates, and no significant interactions, Tables 13 & 14, Figures 18 & 19. The very high CVs recorded demonstrate the variability of crop growth within and between the treatments.

Table 13. Above ground biomass FW (g) m^2 at the Edgmond site, 123DAP

Edgmond	**Above ground biomass FW g m2 123DAP**			
Means	S Sisym	S Scabrum		CV = 71.7%
Std N	1250.3	1394.7	***1322.5***	
High N	1437.9	1904.8	***1671.4***	***N/S***
	1344.1	***1649.8***		SED 1073.2
	N/S		**Interaction N/S**	

Table 14. Above ground biomass DW (g) m^2 at the Edgmond site, 123DAP

Edgmond	**Above ground dry matter 123DAP**			
Means	S Sisym	S Scabrum		CV = 79.2
Std N	232.6	179.9	***206.2***	
High N	267.5	245.7	***256.6***	***N/S***
	250.0	***212.8***		SED 183.35
	N/S		**Interaction N/S**	

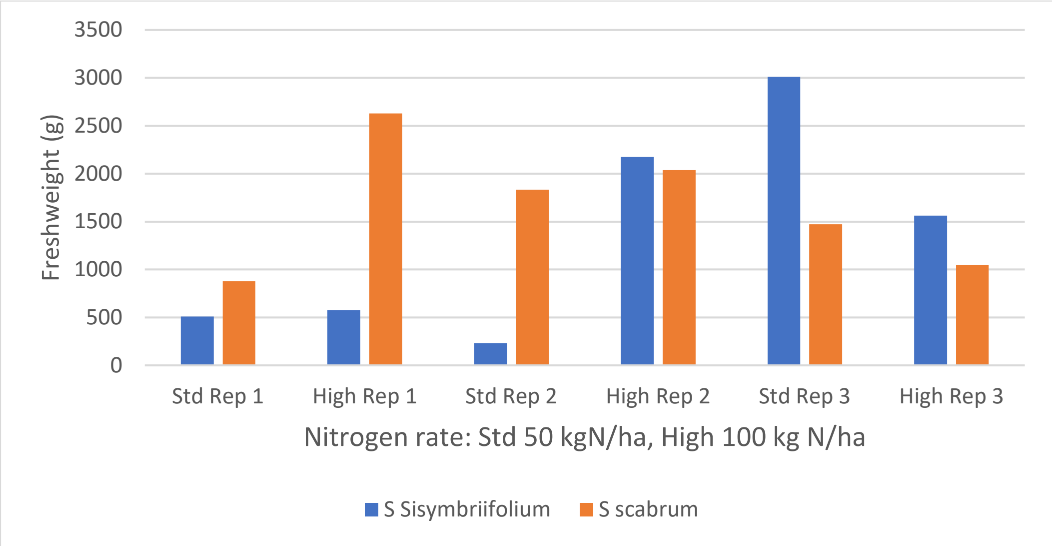

Figure 18. Edgmond above ground biomass (FW) m^2 123DAP

The amount of dry matter produced m^2 has been shown to be very important for *Solanum sisymbriifolium* in respect of its effect on PCN populations. None of the treatment means achieved greater than 267.5 g m^2, which is far below the desired 700g m^2, Table 14, Figure 19. This will be discussed further in the discussion chapter.

The mean number of plants m^2 were quite low at this site and no significant effects were recorded from the increased application of nitrogen or between species, although the latter was close to significance, $P = 0.058$, Table 15, Figure 20.

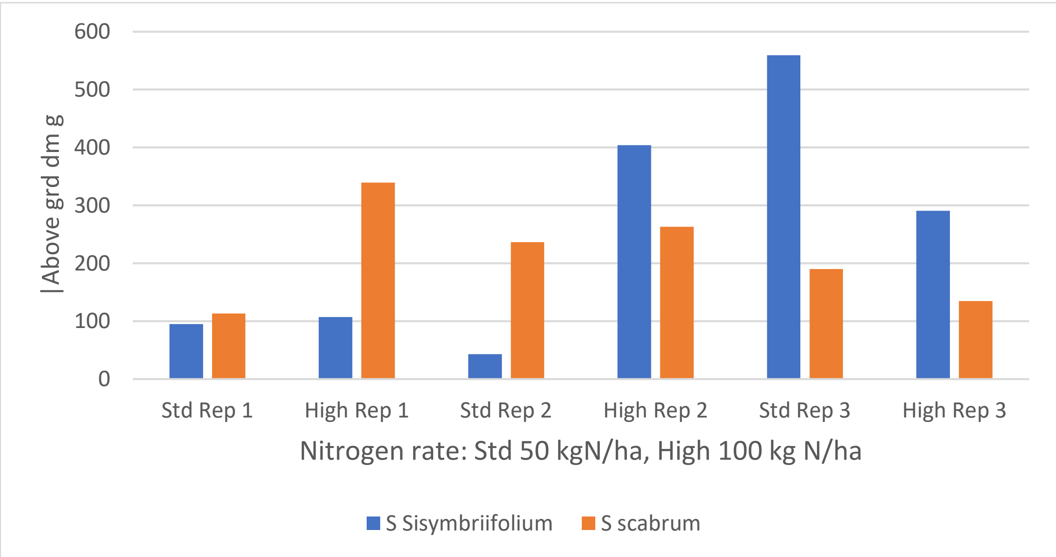

Figure 19. Edgmond above ground dry matter (g m^2)123DAP

Table 15. Plants m^2 at the Edgmond site, 123DAP

Edgmond	**Plants m^2 123DAP**			
Means	S Sisym	S Scabrum		CV = 54.6
Std N	4.5	2.5	***3.5***	
High N	7.8	3.2	***5.5***	***N/S***
	6.2	***2.8***		SED 2.46
	N/S (0.059)		**Interaction N/S**	

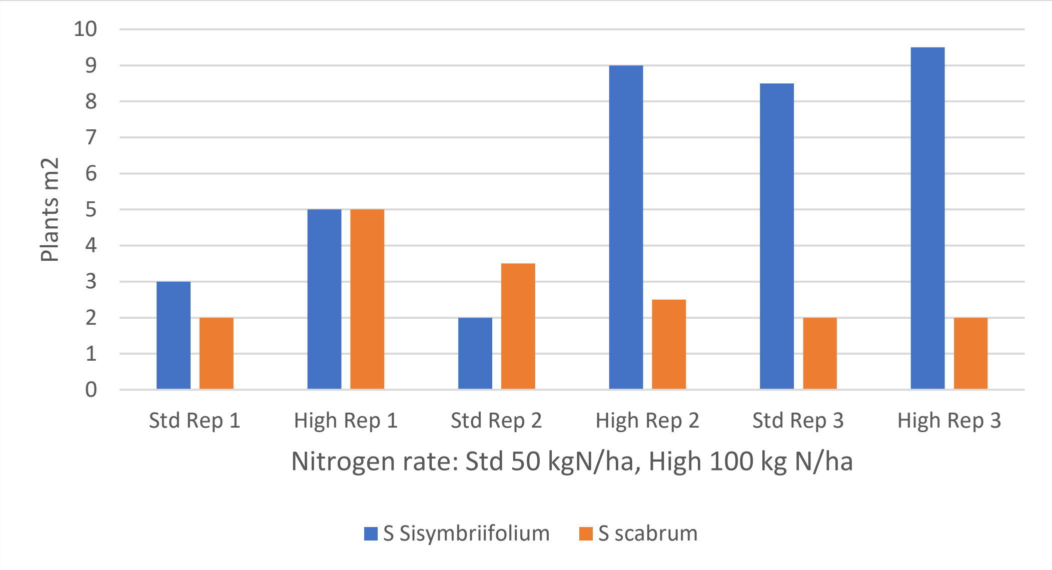

Figure 20. Plants m^2 at the Edgmond site, 123DAP

Average plant height, cm, was significantly greater where 100 kg N/ha had been applied. There were no significant species differences or interactions, Table 16, Figure 21.

Table 16. Average plant height, cm, at the Edgmond site, 123DAP.

Edgmond	**Height above ground 123DAP**			
Means	S Sisym	S Scabrum		CV = 13.4%
Std N	54.3	50.0	***52.2***	
High N	73.3	56.7	***65.0***	***P = 0.029***
	63.8	***53.3***		SED 7.83
	N/S (P = 0.059)		**Interaction N/S**	

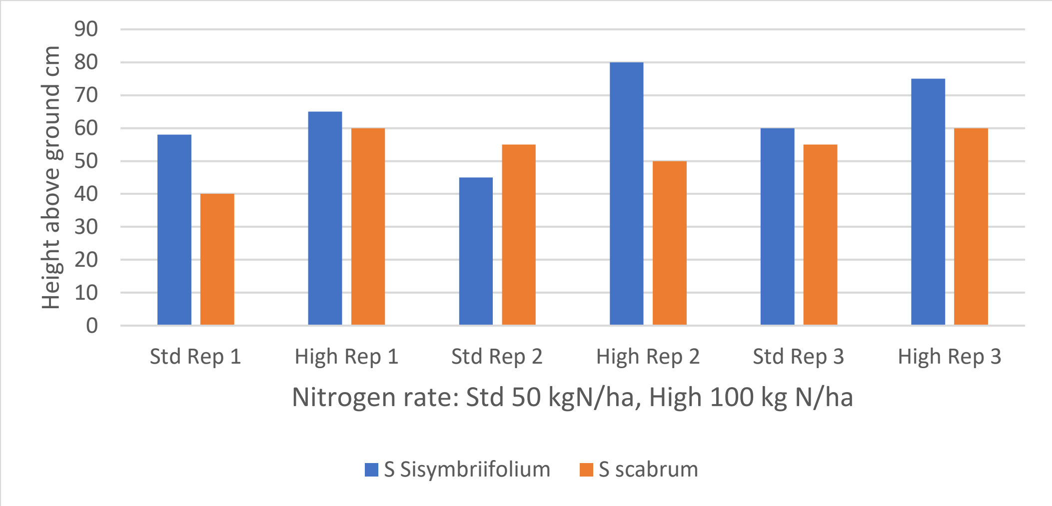

Figure 21. Plant height above ground, cm, 123DAP at the Edgmond site.

The length of the longest root showed no significant differences for Nitrogen rate, species and there were no interactions, Table 17, Figure 22. It should be noted however, that this assessment was limited by the difficulty in extracting roots without significantly disturbing roots of neighbouring plants.

Table 17. Longest root length, cm, for plants growing at the Edgmond site.

Edgmond	**Longest Root length, cm, 123DAP**			
Means	S Sisym	S Scabrum		CV = 30.6%
Std N	13.9	15.5	***14.7***	
High N	22.3	18.5	***20.4***	***N/S***
	18.1	***17.0***		SED 5.37
	N/S		**Interaction N/S**	

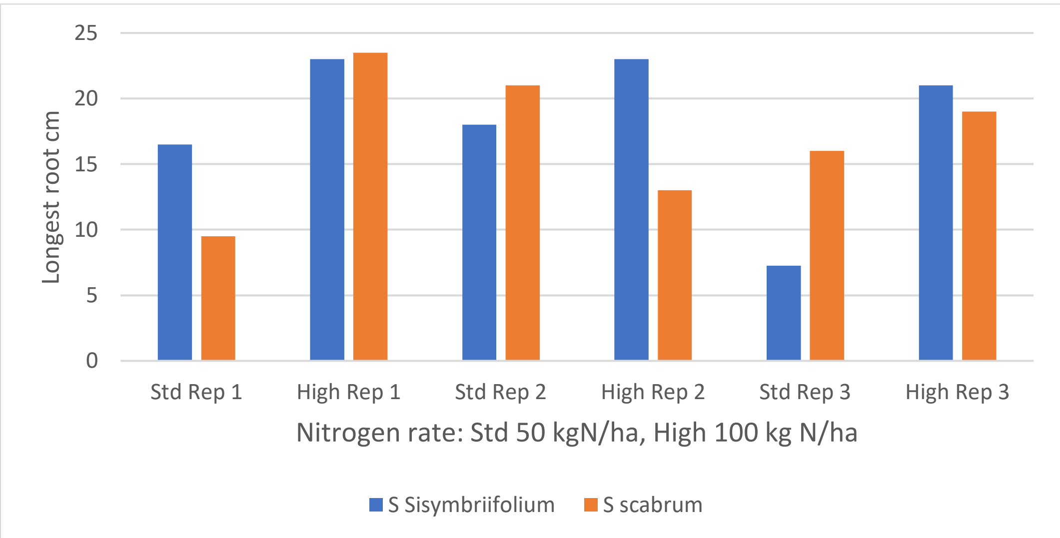

Figure 22. Longest root length of plants at the Edgmond site, 123DAP

The average weight (g) of roots <1mm per plant was significantly greater for *S scabrum* as compared to *S sisymbriifolium*. There were no significant effects of Nitrogen rate and there were no interactions, Table 18, Figure 23.

Table 18. Average weight (g) of roots <1mm per plant at the Edgmond site,123DAP.

Edgmond	**Fine root wt <1mm (g) 123DAP**			
Means	S Sisym	S Scabrum		CV = 42.6%
Std N	5.9	17.5	***11.7***	
High N	7.7	18.3	***13.0***	***N/S***
	6.8	***17.9***		SED 5.25
	P = 0.01		**Interaction N/S**	

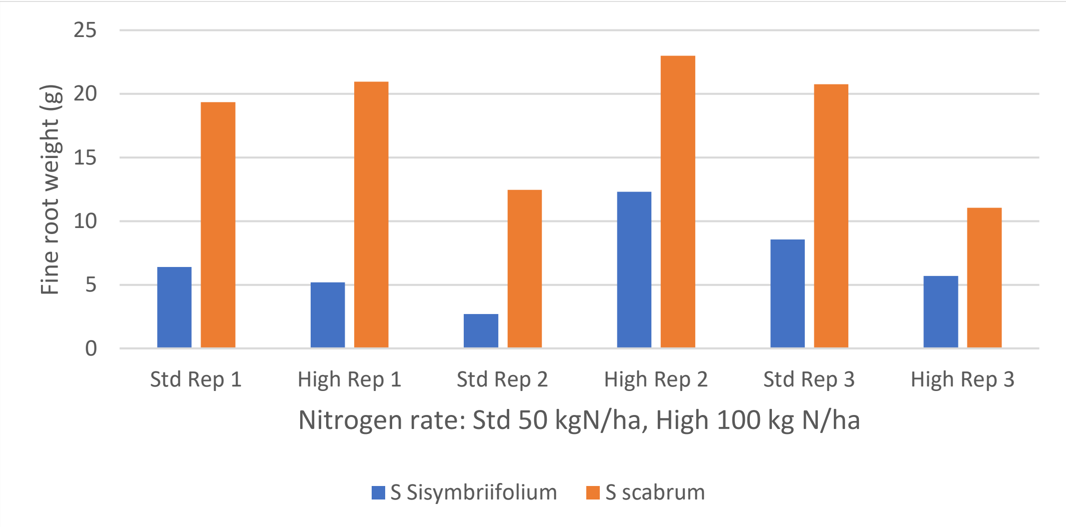

Figure 23. Average weight (g) roots <1mm per plant at the Edgmond site,123DAP

The weight of roots greater than 1mm were significantly greater for *S scabrum* than for *S sisymbriifolium*, *P = 0.01*. There were no significant effects of Nitrogen rate and no interactions, Table 19, Figure 24. These values did not include any root classed as a tap root.

Table 19. Average weight (g) of roots >1mm per plant at the Edgmond site,123DAP.

Edgmond	**Ave root wt (g) >1mm 123DAP**			
Means	S Sisym	S Scabrum		CV = 37.1%
Std N	17.8	35.5	***26.6***	
High N	16.6	43.3	***29.9***	***N/S***
	17.2	***39.4***		SED 10.48
	P = 0.01		**Interaction N/S**	

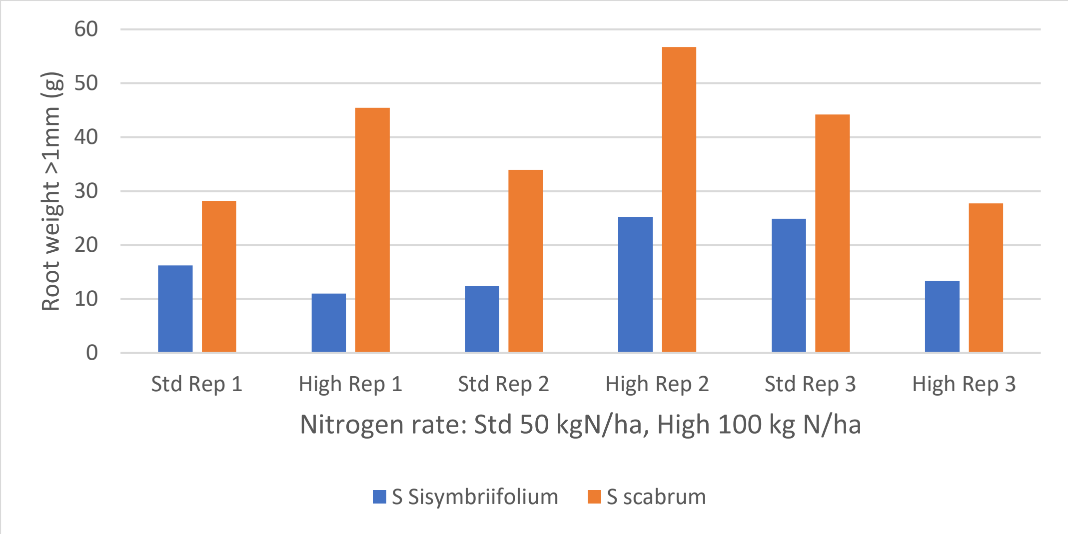

Figure 24. Average weight (g) roots >1mm per plant at the Edgmond site,123DAP

The lengths of the main root, taproots, showed no significant differences between species or nitrogen rate, and there were no interactions, Table 20, Figure 25.

Table 20. Average taproot length, cm, at the Edgmond site,123DAP

Edgmond	**Tap root length (cm)123DAP**			
Means	S Sisym	S Scabrum		CV = 30.6%
Std N	13.9	15.5	***14.7***	
High N	22.3	18.5	***20.4***	***N/S***
	18.1	***17.0***		SED 5.37
	N/S		**Interaction N/S**	

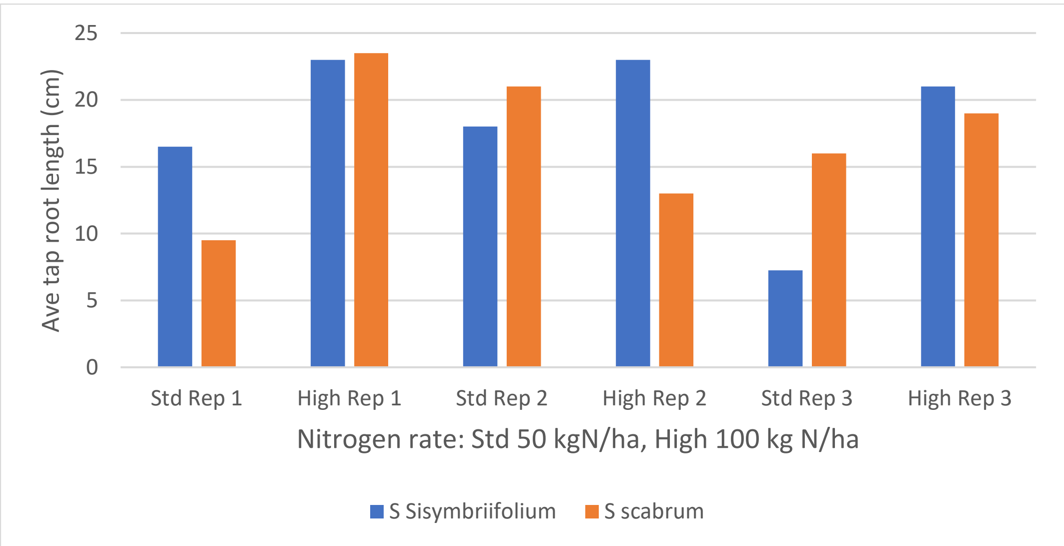

Figure 25. Average taproot length, cm, at the Edgmond site,123DAP

Investigating PCN Population relationships

The PCN population density assessments were displayed, Tables 3, 4, 5 a & b, and reported in relation to the basic statistical results. However due to the problems experienced within some plots, a modified balanced three replicate design was implemented. This meant that every species and nitrogen rate was replicated 3 times. Consequently, investigations of linear relationships could be based either on 6 results for species or nitrogen rate (ignoring N rate or species accordingly) or on 3 results which separated all treatment combinations. As many of the analyses produced no significant interactions however there is no statistical foundation for splitting the treatment combinations beyond species or nitrogen rate. Consequently, the following Figures are for interest only.

When potatoes are planted in PCN infested soil, one of the first indications of invasion into the plant is reduced emergence or poor early growth, dependent on the tolerance of the variety to damage. As *S. sisymbriifolium* and *S. scabrum* are solanaceous plants it is plausible to assume that they too may be affected by increasing PCN population densities. Figure 26 shows that at 67DAP a small ground cover decline as the PCN population density increases but the R^2 value of only 0.082 indicates a poor relationship and that only 8.2% of the variation in response is due to PCN population. Similarly, at 109DAP, there is no evidence that ground cover is affected by increasing PCN population density, Figure 27.

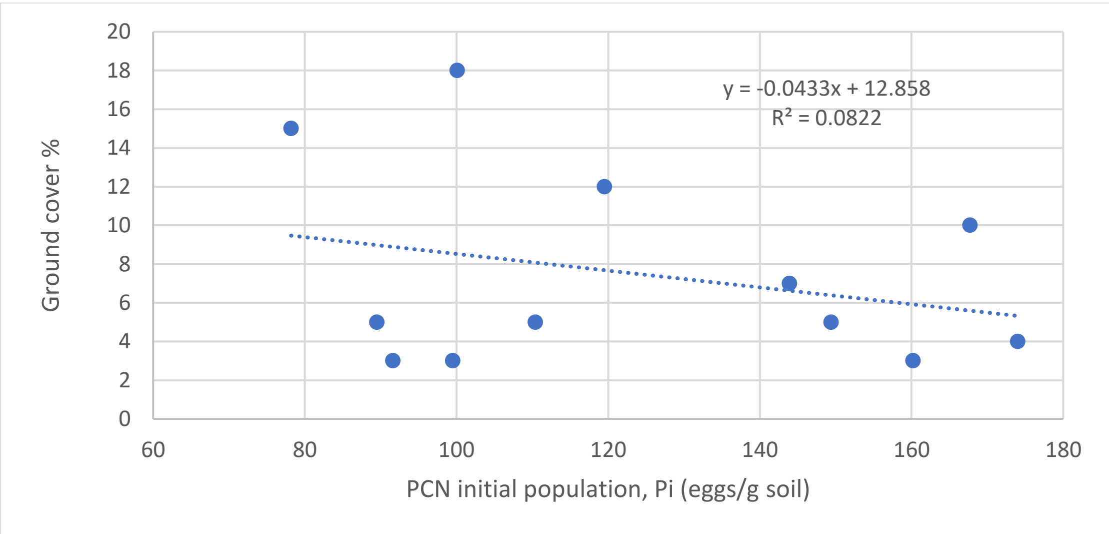

Figure 26. Relationship between PCN initial population density and GC% at 67DAP at the Edgmond site (3 replicate data)

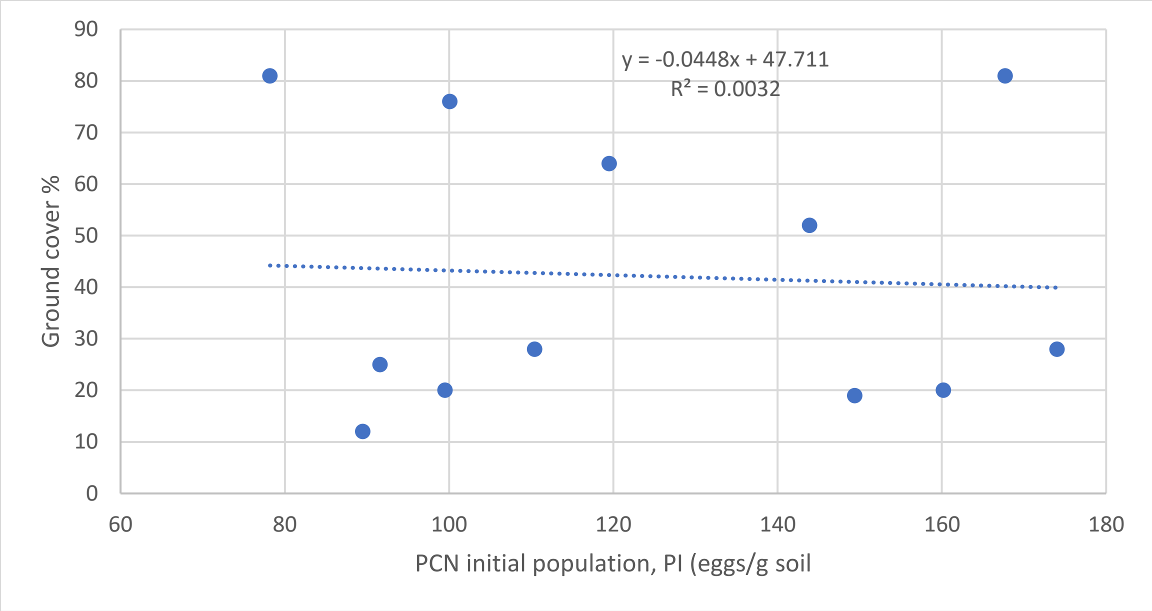

Figure 27. Relationship between PCN initial population density and GC% at 109DAP at the Edgmond site (3 replicate data)

As no statistically significant interactions were found in the analysis it was plausible to investigate the data further by analysis of effects of nitrogen rate but ignoring species, Figure 28. This suggests that as the PCN population density increases from just below 80 eggs g soil to approximately 150 eggs g soil, the ground cover declines when the nitrogen rate is 100 kg N/ha. In contrast, the ground cover apparently increases by a population increase from 90 – 175 eggs g soil, when crops receive only 50 kg N/ha. However, without the high leverage of the 168/81 data point there may be no effect of increasing Pi from the 50 kg N/ha application.

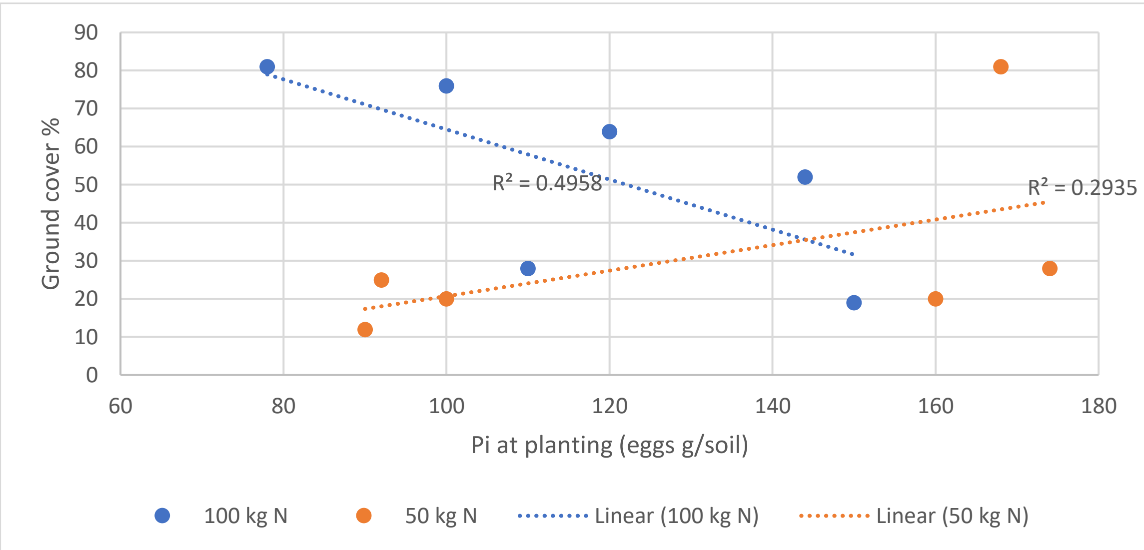

Figure 28. Ground cover response to N rate as affected by Pi at 109DAP, ignoring species (Edgmond site)

When investigating the different response of the crop species to increasing PCN population densities, ignoring N rate, no relationships were seen, Figure 29.

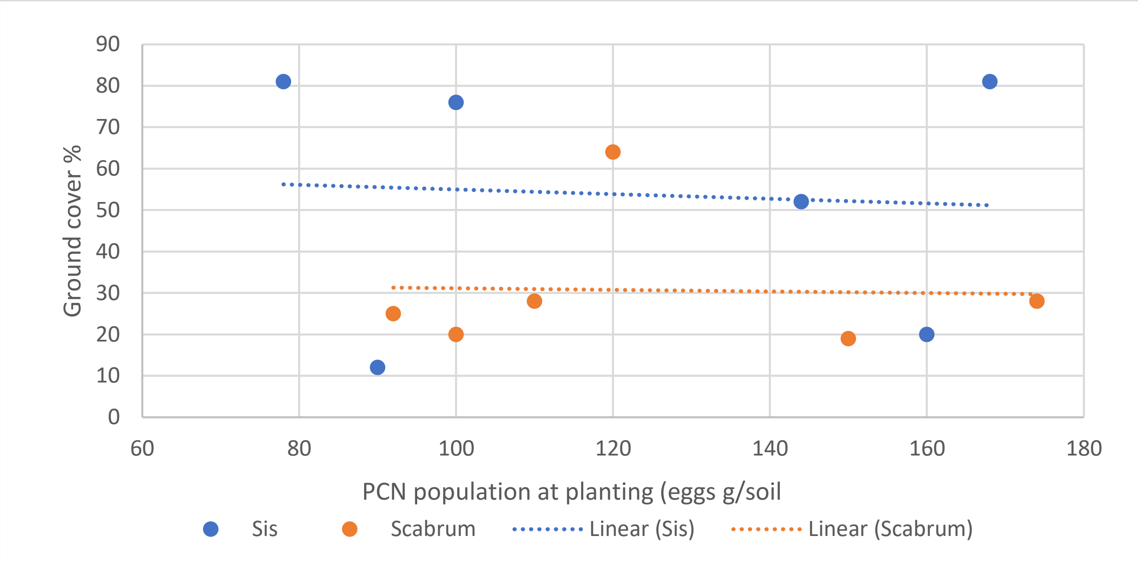

Figure 29. Ground cover response to species as affected by Pi at 109DAP, ignoring N (Edgmond site).

Caynton site

Ground cover percentage of whole plots (4m x 8m) at 67DAP showed only a significantly greater, P =0.03, ground cover with the high rate of Nitrogen (100 kg N ha), compared to the standard rate of 50 kg N/ha, Table 21. There were no other significant differences were seen but between *S scabrum* appears to be responding better at this site compared to the Edgmond site, Figure 30.

Table 21. Ground cover percentage of whole plots, 67DAP.

Caynton	**Mean % GC 67DAP**			
Means	S Sisym	S Scabrum		CV = 29.4%
Std N	**16.9**	**19.3**	***18.1***	*P = 0.03*
High N	**24.1**	**34.0**	***29.1***	
	20.5	***26.6***		SED 6.92
	N/S			

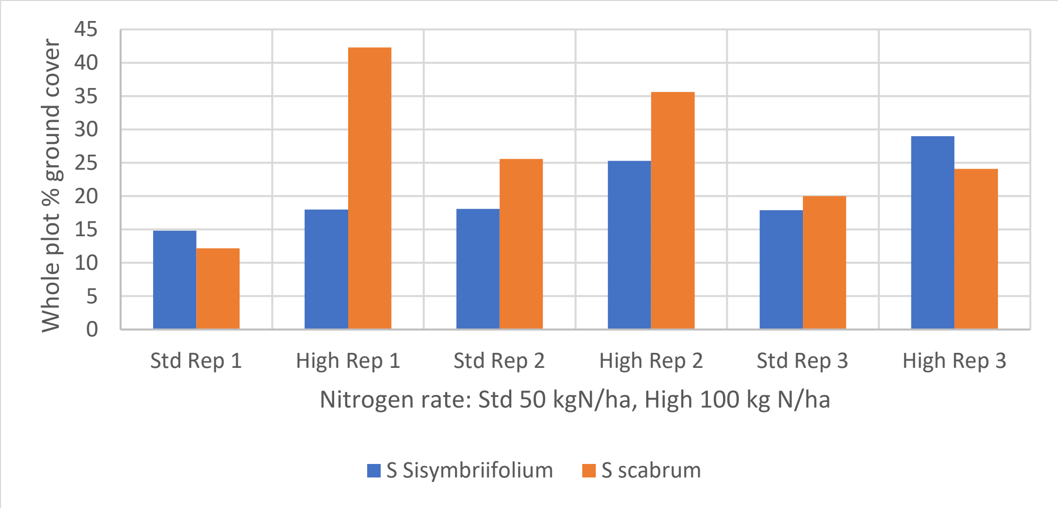

Figure 30. Ground cover % from aerial analysis at the Caynton site 67DAP.

Ground cover was assessed at 74DAP but there was no change in the canopy. By 82DAP the ground had increased substantially and it was possible to determine that there appeared to be some overlap of plant growth between plots. Consequently, it was decided that all further analysis would utilise the central 3m width of the plot rather than the 4m sown width. Application of 100 kg N/ha produced significantly greater ground cover compared to 50 kg N/ha, P = 0.013, Table 22, Figure 31.

Table 22. Ground cover percentage, on 3m x 8m plot, at Caynton 82DAP.

Caynton	**Mean % GC 82DAP**			
Means	S Sisym	S Scabrum		CV = 26.5%
Std N	**29.9**	**29.0**	*29.5*	*P = 0.013*
High N	**40.5**	**61.6**	*51.0*	
	35.2	*45.3*		SED 10.65
	N/S		Interaction: N/S	

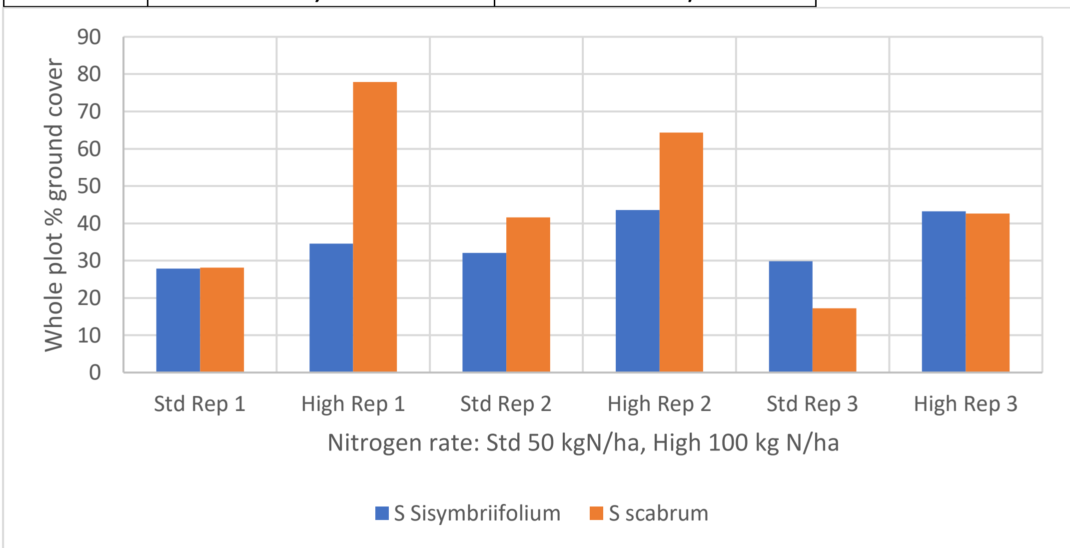

Figure 31. Caynton site ground cover percentage (3m x 8m), 82DAP.

At 88DAP the ground cover had continued to increase with a signifnificantly greater ground cover where 100kg N/ha (high) had been applied, Table 23 and Figure 32.

Table 23. Ground cover percentage, on 3m x 8m plot, at Caynton 88DAP.

Caynton	**Mean % GC 88DAP**			
Means	S Sisym	S Scabrum		CV = 22.9%
Std N	35.1	34.5	***34.8***	
High N	44.7	65.0	***54.9***	***P = 0.015***
	39.9	***49.8***		SED 10.28
	N/S			

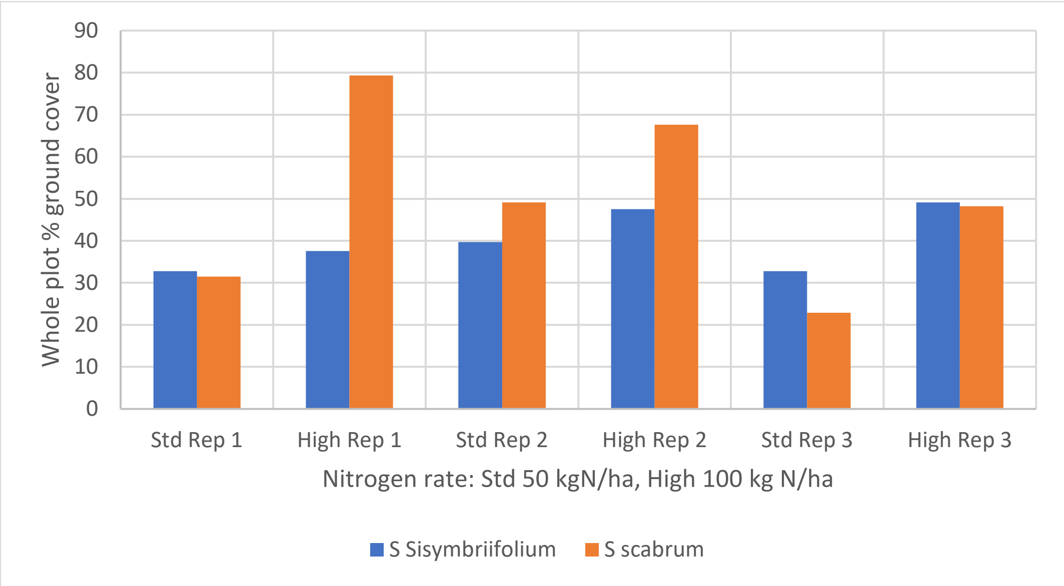

Figure 32. Ground cover percentage at the Caynton site (3m x 8m analysis), 88DAP

Caynton assessment 102DAP continued to demonstrate the significantly greater ground cover of *S scabrum* compared to the *S sisymbriifolium*, *P = 0.026*, and significantly greater ground cover from the application of 100kg N/ha for both species, *P = 0.018*, Figure 24, Table 33.

Table 24. Caynton Ground cover % (central 3m x 8m) 102DAP

Caynton	**Mean % GC 102DAP**			
Means	S Sisym	S Scabrum		CV =16.1%
Std N	46.7	55.3	***51.0***	
High N	57.0	81.3	***69.2***	***P = 0.018***
	51.8	***68.3***		SED 9.69
	P = 0.026		**Interaction N/S**	

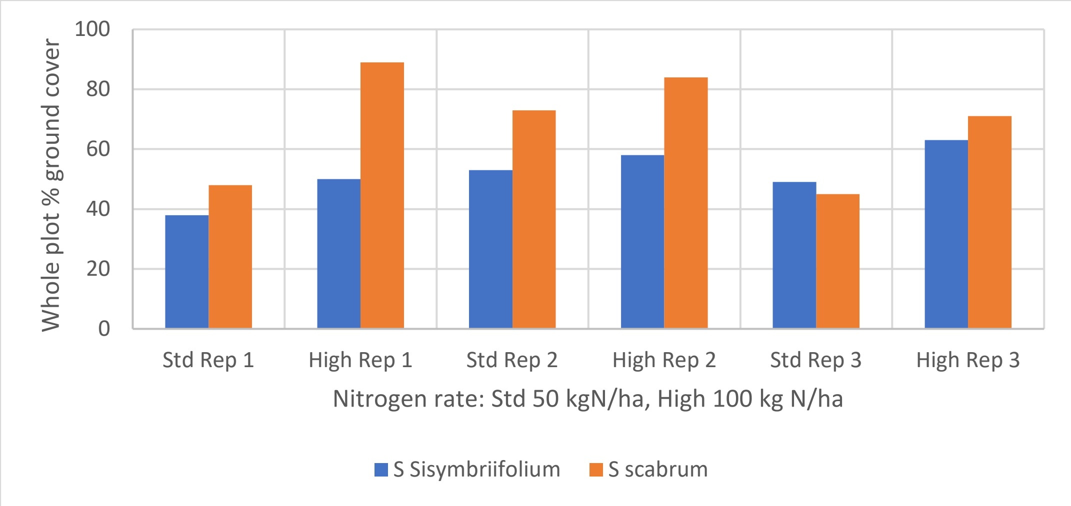

Figure 33. Caynton Ground cover % (central 3m x 8m) 102DAP

Root samples were inspected at 102DAP, examples of which are shown, Figure 34, which demonstrate differences of root architecture between *S sisymbriifolium* and *S scabrum*. Samples were taken from all plots for above and below ground biomass analysis for a more complete analysis at 122DAP.

Figure 34. Root archtecture for *S. sisymbriifolium* and *S. scabrum* at 102DAP grown at the Caynton trial site 2021

Canopy ground cover assessments at 109 DAP at Caynton demonstrated that *S. scabrum* had significantly greater ground cover than *S. sisymbriifolium*, *P = 0.01*, and significantly greater ground cover from application of 100 kg/N ha, *P = 0.03*, Table 25 and Figure 35.

Table 25. Caynton Ground cover % (central 3m x 8m) 109DAP at 50 or 100kg N ha

Caynton	**Mean % GC 109DAP**			
Means	S Sisym	S Scabrum		CV = 13.4%
Std N	51.7	64.3	***58.0***	
High N	60.3	84.0	***72.2***	***P = 0.0304***
	56.0	***74.2***		SED 8.71
	P = 0.0112		**Interaction N/S**	

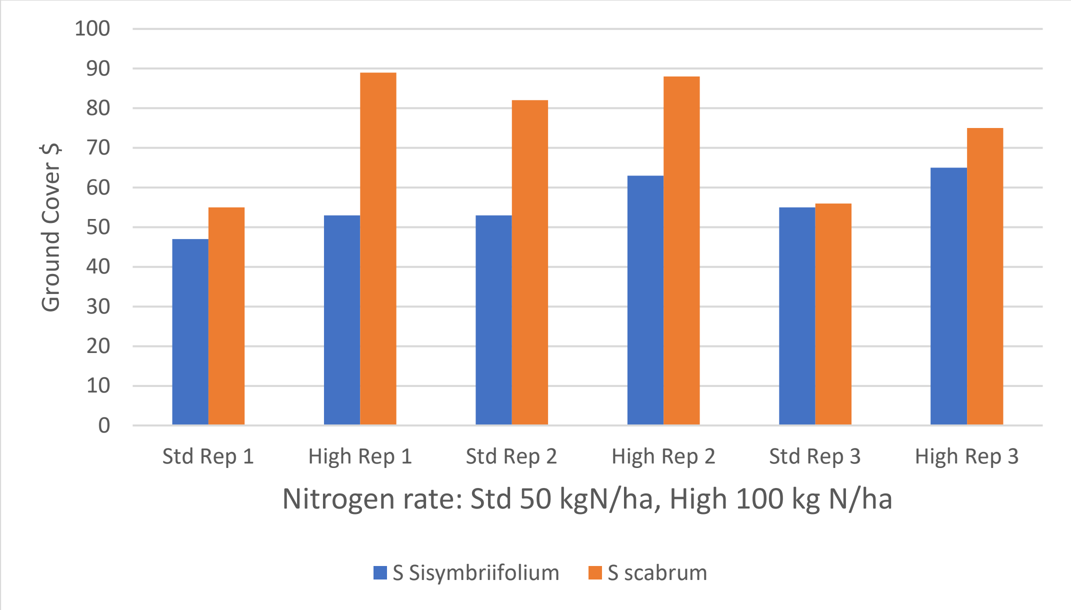

Figure 35. Caynton Ground cover % (central 3m x 8m) 109DAP at 50 or 100kg N ha

Canopy ground cover assessments at 122 DAP at Caynton demonstrated that *S scabrum* had significantly greater ground cover than *S sisymbriifolium*, *P = 0.009*, but similar ground cover between nitrogen, *P = 0.054*, Table 26 and Figure 36.

Table 26. Caynton Ground cover % (central 3m x 8m) 109DAP

Caynton	**Mean % GC 122DAP**			
Means	S Sisym	S Scabrum		CV =13.7%
Std N	55.2	67.2	***61.2***	
High N	60.0	87.9	***74.0***	***P = 0.054***
	57.6	***77.6***		SED 9.27
	P = 0.009		**Interaction N/S**	

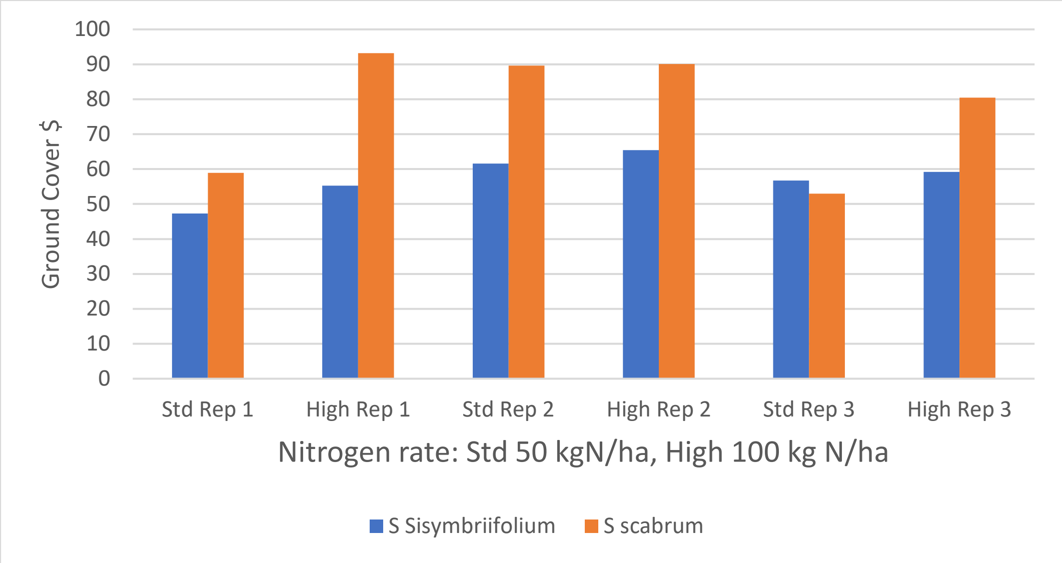

Figure 36. Caynton Ground cover % (central 3m x 8m) 122DAP

The progression of ground cover development, Figure 37, shows that *S. scabrum* benefited substantially from the application of 100 kg N/ha compared to the 50 kg N/ha application. Whereas the response of S sisymbriifolium to the 100 kg N/ha was less pronounced. The different responses by the species may be related to the leaf architecture; *S scabrum* is a larger leaf species than *S sisymbriifolium* and so more able to produce a greater leaf area.

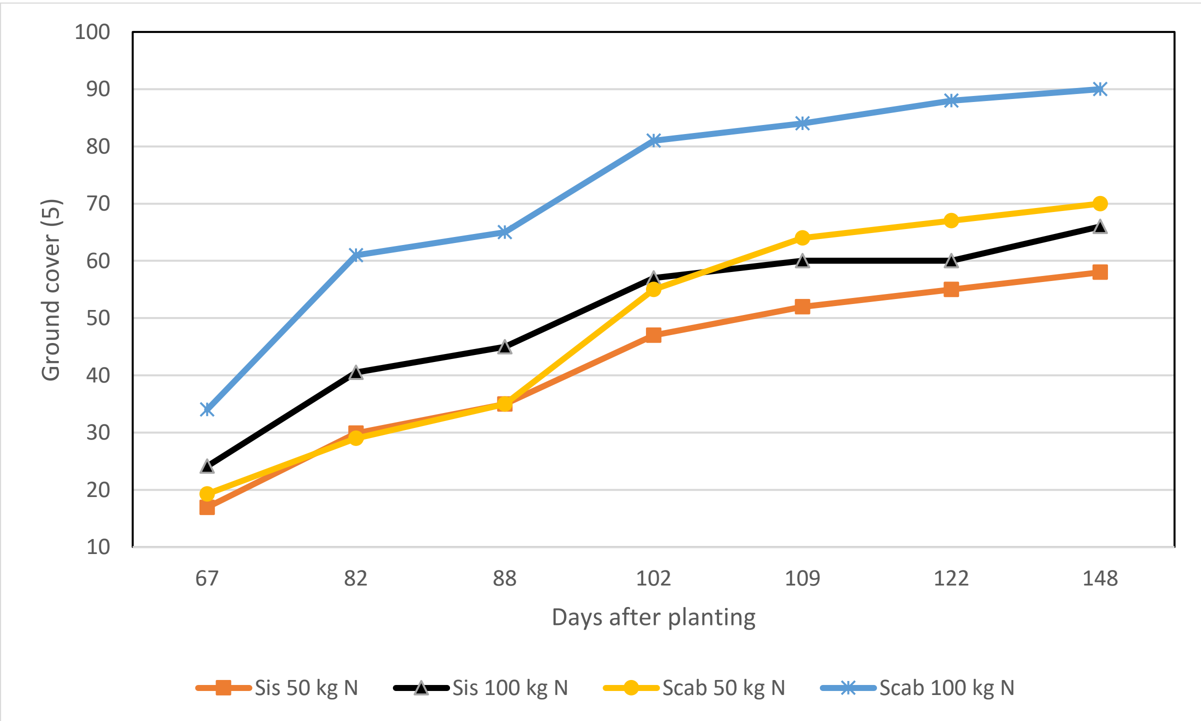

Figure 37. Caynton site ground cover (%) progression from 67 to 148 days after planting

Caynton site: Plant Biomass assessments at 122DAP

At 122DAP Caynton plant biomass assessments were done on two plants per plot and converted to m^2 by utilising the plant numbers m^2 determined during the assessments.

Above ground biomass fresh-weight (FW) and dry-weight (dm) were significantly greater where 100 kg N/ha was applied compared to 50 kg N/ha. There were no significant differences between species and no interactions, Tables 27 & 28, Figures 38 & 39. The very high CVs recorded demonstrate the variability of crop growth within and between the treatments.

Table 27. Caynton above ground biomass m^2, freshweight (g) at 122DAP

Caynton	**Above ground biomass FW g m^2 122DAP**			
Means	S Sisym	S Scabrum		CV = 56.1%
Std N	1808.8	1525.1	***1667.0***	
High N	2437.3	5806.3	***4121.8***	***P = 0.039***
	2123.1	***3665.7***		SED 1625.09
	N/S		**Interaction N/S**	

Table 28. Caynton above ground biomass m^2, dry matter (g) at 122DAP

Caynton	**Above ground dry matter (dm) m^2 122DAP**			
Means	S Sisym	S Scabrum		CV = 51.8%
Std N	336.4	196.7	***266.6***	
High N	453.3	749.0	***601.2***	***P = 0.041***
	394.9	***472.9***		SED
	N/S		**Interaction N/S**	

None of the S sisymbriifolium plots achieved 700g m2 dry matter, a benchmark, irrespective of nitrogen rate, Figure 34.

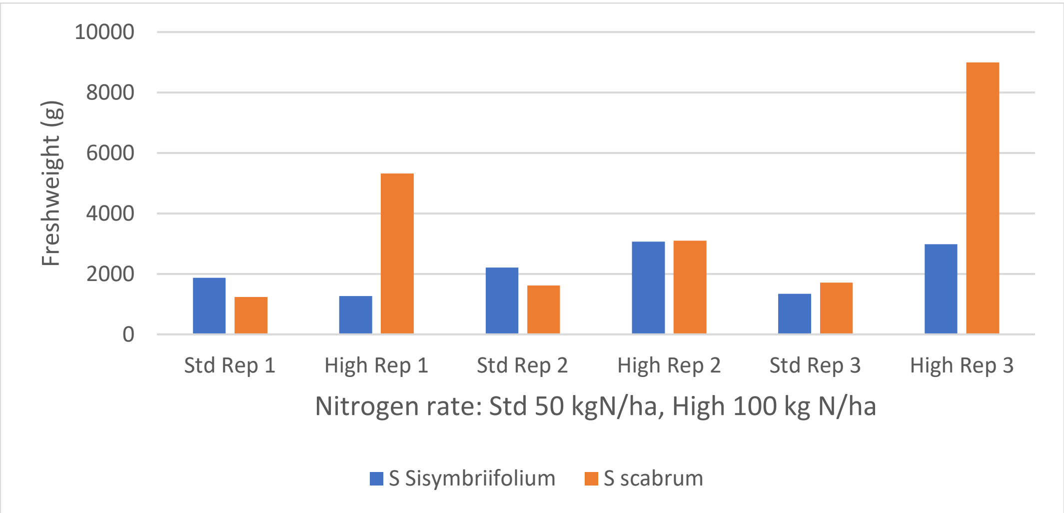

Figure 38. Caynton above ground biomass m^2, freshweight (g) at 122DAP

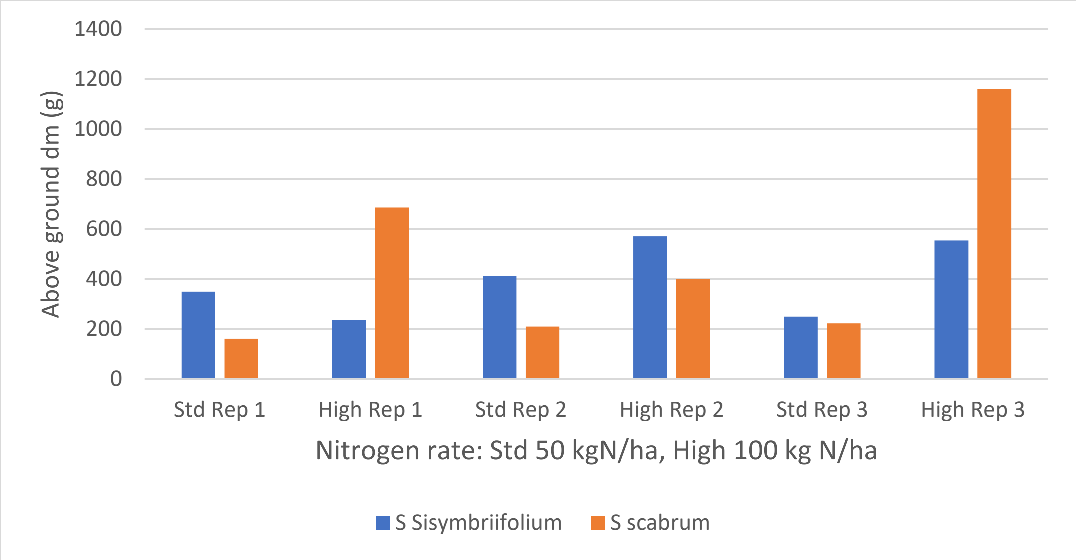

Figure 39. Caynton above ground biomass m^2, dryweight (g) at 122DAP

There were no significant plants m^2 differences between species, nitrogen applications or any interactions, Table 29, Figure 40.

Table 29. Plants m^2 at Caynton 122DAP

Caynton	**Plants m^2 122DAP**			
Means	S Sisym	S Scabrum		CV = 35.5%
Std N	6.8	4.5	***5.7***	
High N	8.5	9.8	***9.2***	***N/S***
	7.7	***7.2***		SED 2.63
	N/S		**Interaction N/S**	

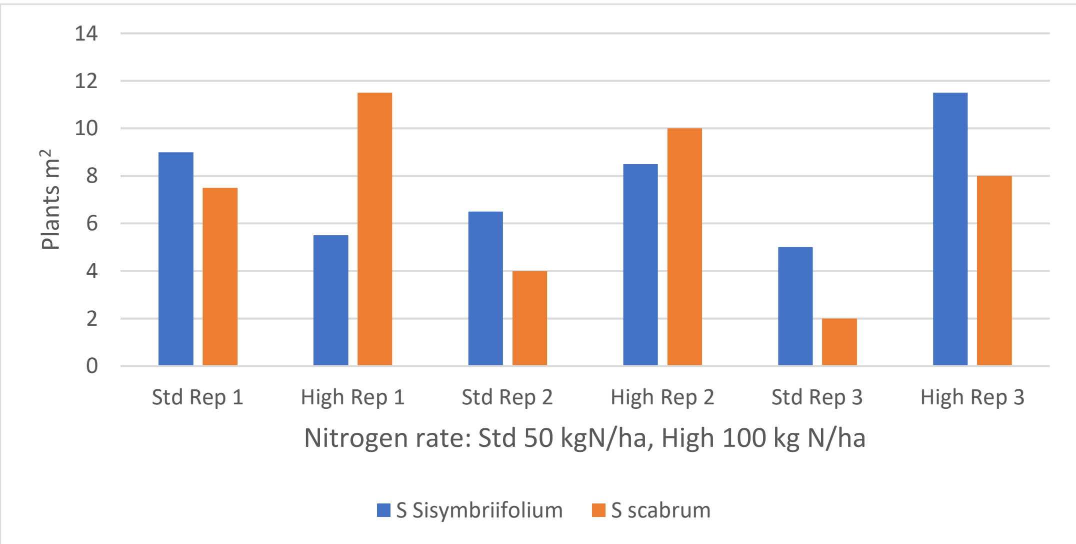

Figure 40. Plants m^2 at Caynton 122DAP

Plant height above ground ranged from 70 to 111.7cm. Although there were no significant species or nitrogen effects, there was a significant interaction, P = 0.003. The height of *S sisymbriifolium* was reduced by the higher rate of nitrogen in contrast to S scabrum which increased with the higher rate of nitrogen, Table 30, Figure 41.

Table 30. Plant height at Caynton in response to species and nitrogen rate 122DAP

Caynton	**Height above ground (cm) 122DAP**			
Means	S Sisym	S Scabrum		CV = 18.0%
Std N	76.0	70.0	***73.0***	
High N	70.0	111.7	***90.8***	***N/S***
	73.0	***90.8***		SED 14.75
	N/S		***P = 0.03***	

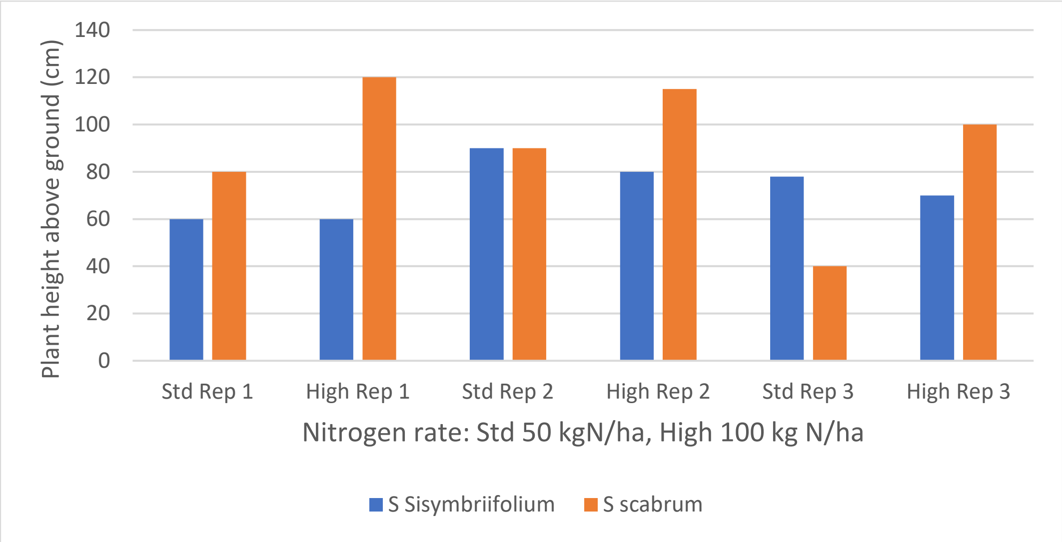

Figure 41. Plant height at Caynton in response to species and nitrogen rate 122DAP

There were no statistical differences in the length of the longest roots between crop species or as a result of nirogen application, and there were no interactions, Table 31, Figure 42.

Table 31. Length of longest root (cm) at Caynton 122DAP

Caynton	**Maximum root length (cm)**			
Means	S Sisym	S Scabrum		CV = 22.9%
Std N	27.5	24.8	***26.2***	
High N	26.2	23.0	***24.6***	***N/S***
	26.8	***23.9***		SED 58.21
	N/S		**Interaction N/S**	

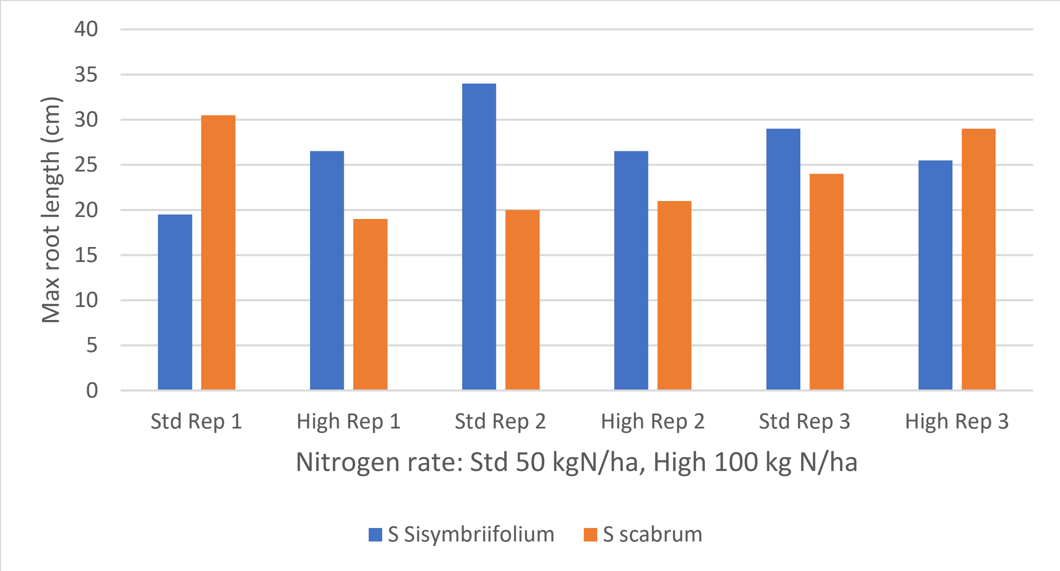

Figure 42. Length of longest root (cm) at Caynton 122DAP

The maximum length of the main (Tap) root was only 13.3cm. There were no statistical differences between species or nitrogen rates, and no interactions, Table 32. Figure 43.

Table 32. Maximum main/tap root length (cm) at Caynton 122DAP

Caynton	**Maximum tap root length (cm)**			
Means	S Sisym	S Scabrum		CV = 46.6%
Std N	12.3	7.9	***10.1***	
High N	13.3	12.7	***13.0***	***N/S***
	12.8	***10.3***		SED 5.39
	N/S		**Interaction N/S**	

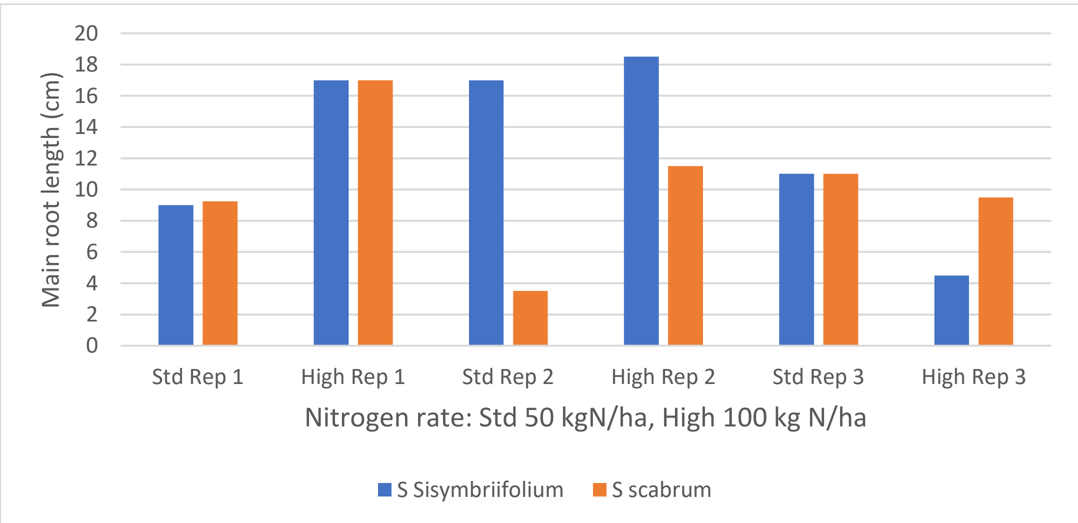

Figure 43. Maximum main/tap root length (cm) at Caynton 122DAP

The weight of fine roots, <1mm, were significantly greater for *S scabrum* than for *S sisymbriifolium, P =0.003*, but not between nitrogen rates. There were no significant interactions, Table 33, Figure 44.

Table 33. Weight of fine roots, <1mm, from plants at Caynton, 122DAP

Caynton	**Weight of roots <1mm 122DAP**			
Means	S Sisym	S Scabrum		CV = 32.0%
Std N	8.0	19.8	***13.9***	
High N	7.8	22.0	***14.9***	***N/S***
	7.9	***20.9***		SED 4.62
	P = 0.003		**Interaction N/S**	

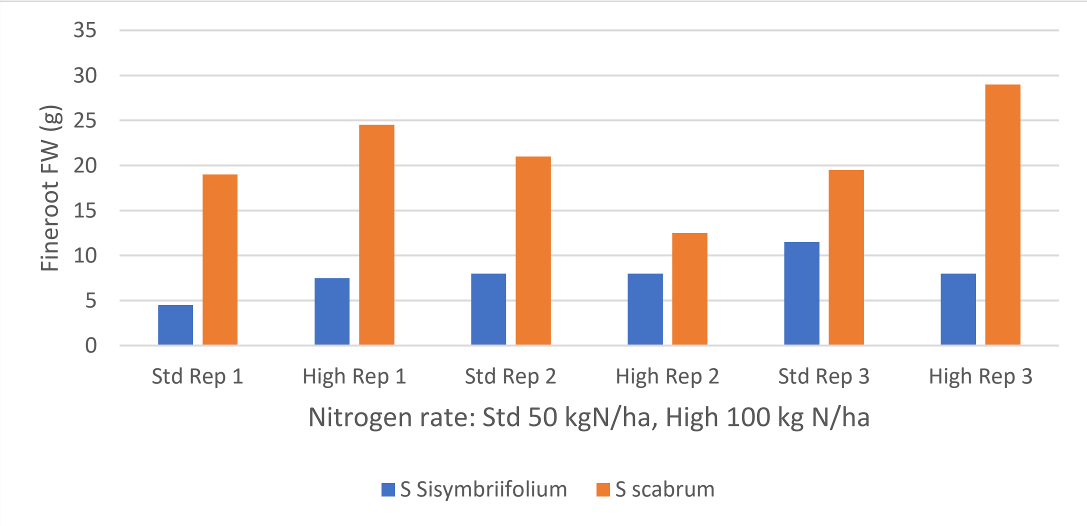

Figure 44. Weight of fine roots, <1mm, from plants at Caynton, 122DAP

There were no significant differences in the weight of roots >1mm between species or nitrogen rates, and no significant interactions, Table 34, Figure 45.

Table 34. Weight of roots >1mm, from plants at Caynton, 122DAP

Caynton	**Weight of roots >1mm 122DAP**			
Means	S Sisym	S Scabrum		CV = 14.1%
Std N	24.2	34.3	***29.3***	
High N	26.3	46.2	***36.3***	***N/S***
	25.3	***40.3***		SED 4.62
	N/S		**Interaction N/S**	

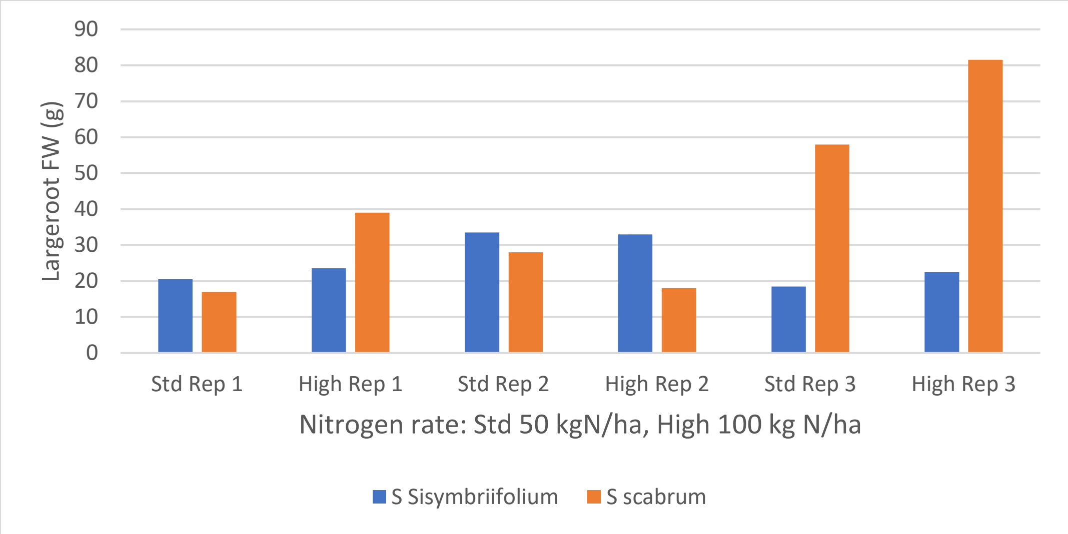

Figure 45. Weight of roots >1mm, from plants at Caynton, 122DAP

The final ground cover assessment at 148DAP showed a significantly greater canopy for *S scabrum*, 80%, compared to *S sisymbriifolium*, 62%, *P = 0.025*. The effect of nitrogen rate was substantial but not quite significant, *P* = *0.06*. There were no significant interactions, Table 35, Figure 46.

Table 35. Final ground cover (%) at Caynton 148DAP.

Caynton	**Mean % GC (3 x 8) 148DAP**			
Means	S Sisym	S Scabrum		CV = 14.9%
Std N	58.0	70.0	***64.0***	***N/S***
High N	66.0	90.0	***78.0***	***(P = 0.06)***
	62.0	***80.0***		SED 10.55
	P = 0.025		**Interaction N/S**	

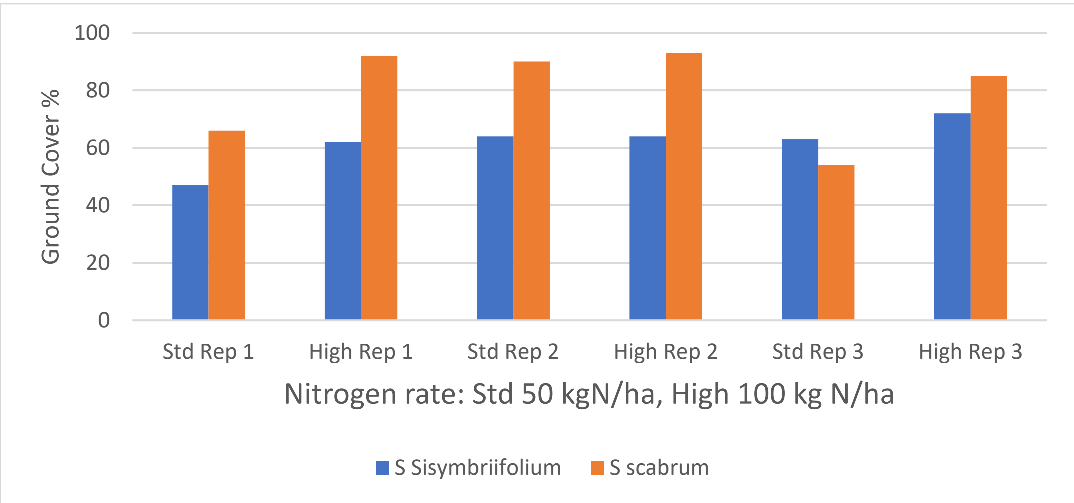

Figure 46. Final ground cover (%) at Caynton 148DAP.

4. Discussion

The trials undertaken in this IF project were designed to provide a better undertsanding of establishing and growing the PCN trap crops *S. sisymbriifolium* and *S. scabrum*. As often found in trials work, not everything goes to plan, and this is why several trials are required at different sites and over several years, and is a necessary requirement for a robust understanding. The following discussions will therefore start with the trial data and then the field performance of the crops.

The statistical analysis of data from the trial sites often showed coefficients of variation, CVs, that were substantially greater than would be desired (>15%) and demonstrates the variability of the growth both within and between treatments. The design of the Edgmond site included six replicates initially which helps to determine the validity of the results and the confidence in them, however, several plots failed to establish at this site which unfortunately affected two of the treatments more than the others. Consequently, although data was collected from as many plots as possible for the Edgmond site, data analsyses were mainly restricted to 3 replicates to maintain a balanced design, but as many replicates as possible where plausible to do so.

There are several significant factors which can affect the emergence and establishment of a crop within a given area, including, but not restricted to: soil temperature, moisture, chemical and structural composition, cultivation (tillage), method and depth of planting, viability of the seed, and the presence of pests and disease. As the equipment, the operator and day of planting were exactly the same the causes could be postulated to be differences in seedbed features and thus depth of drilling and seed consolidation, or soil physical and chemcial composition. The Edgmond site was an organic sandy soil and did have a 'fluffier' seedbed, which may have allowed the drill to sink lower into the soil than desired especially as results from the 2020 trials identified reduced emergence when sown at 3cm as opposed to 1.5cm.

The soil analysis for the sites were quite similar but did show some differences between the sites. Manganese, important for good crop establishment, was assessed as 'very low' for the Edgmond site, which is exacerbated on organic and sand soils with pH above 6.0 and where soils are fluffy, with the Edgmond site fitting most of these criteria, in contrast to the Caynton site which had slightly low manganese but was neither an organic or fluffy soil, it is palusible that manganese deficiency could have exacerbated the establishment problem. As the trials progressed there appeared to be different growth responses from the same species between the sites at Edgmond and Caynton; at the Caynton site *S. scabrum* grew substantially better than the *S. sisymbriffolium* whereas the reverse occurred at the Edgmond site. With the Edgmond site pH at 6.3 compared to 6.5 for Caynton, the pH itself, which is a logarithmic scale, could be influential as Scholte (2000) reported that both *S. sisymbriifolium* and S. *nigrum* grew much better at pH 4.8 than at pH 6.0. It should also be considered that, unlike the majortiy of mainstream arable crops, there are no actual fertiliser or nutrient recommendations derived from many years of reseach and, consequently, there are no guideline indices for the macro or the micro nutrients. The soil nutrient status for the sites and their associated suitability to potatoes, also solanaceae, did favour the Caynton site in many key aspects, so this may need to be the provisional starting requirement for both *S. sisymbriifolium* and *S. scabrum*.

Another issue which may be influential in comparing establishment with published work is the variation within the species genome. Currently there are several ‘varieties’ reported for *S. sisymbriifolium* including, White star, Pion, Sharp, Sis 4004 and Sis 6001, and studies often use one or more of these, or unspecified varieties, from which to draw results. Similarly, there are also local variations (within Africa) for *S. scabrum* as highlighted by Abukutsa-Onyango (2007) and Abukutsa-Onyango and Karimi (2007).

The difference in establishment of *S. sisymbriifolium* between studies, and from different countries, demonstrates the variability reported; Timmermans (2006) seminal work in the Netherlands details average emergence and establishment of 75% from several sites, including one at lattitude 52° 51’ which is similar latitude to the North Shropshire sites (c. 52.80’), but was influenced by seed rate where up to 84% was recorded from planting 50 seed^2 compared to only 57% at 400 seeds m^2. Dias *et al.* (2017) reported failed crops in Portugal from planting at temperatures of c. 25 - 28°C and low rainfall in one trial, whilst Scholte (2000) sowing 600 seeds m^2 in field trials, reported only that *S. sisymbriifolium* established quite poorly, but did not specify numbers or varieties.

For *S. scabrum* the establishment variability is compounded by significant variation of seed planting information, including reference to ‘spoons’ per area rather than seed weight or number. However, Abukutsa-Onyango (2007) gives average laboratory germination as 50% and 85% for field germination from 34 seed accessions of *S scabrum* but highlights that seed collection and management vary and can greatly affect seed viability. The expected germination is 60-65% germination for *S scabrum* and 40-50% for *S. sisymbriifolium* (Produce Solution, 2021).

At the Ellerdine site, there were considerable problems with weed ingress. By 27DAP it was impossible to distinguish crops from the weeds and by 60DAP the trial site remained impossible to assess due to the excessively fast and tall weed growth. As the site would provide no useful data the trial was terminated at 74DAP. For these reasons the Ellerdine trial will not be discussed further in these discussions.

As it can be seen from this background discussion, there is already considerable variation within the results reported for both *S. sisymbriifolium* and *S. scabrum* and this should be borne in mind for the following discussions.

The purpose of these trials were mainly two-fold

1) Determine if seedbed nitrogen would improve establishment
2) Determine if these trap crops would reduce PCN populations.

The use of seedbed nitrogen:

Nitrogen is a well researched area in crop nutrition, although not necessarily on these particular crops, and is classed as a major input for crops grown in most developed countries. Nitrogen has a major role as a component in proteins, amino acides, amino enzymes, nucleic acids, chlorphyll, alkoloids and purine bases, all of which are essential for plant growth. The main effects of nitrogen on growth of *S. scabrum*, over the range of 0 – 100 kg N/ha ,were reported as increased height, leaf and branch number, with an optimum of c. 40 kg N/ha (Abukutsa-Onyango and Karimi, 2007). This is similar to potatoes where increased leaf and shoot growth, and total leaf number occur (Vos & Biemond, 1992) and most higher plants (Leghari et al., 2016). The actual effect of nitrogen on establishment of *S. scabrum*, rather than crop growth post-emergence is however, less well reported, and similarly very little information is available concerning root growth. In other crops, Khan *et al.* (2011) demonstrated that increased seedbed N increased emerging wheat plant numbers, and similarly maize (Khan *et al.*, 2009).

Emergence and plant numbers

Emergence of both plant species at all three trial sites was slow, with little emergence at 20 or 27DAP, or 34DAP and then progressed slowly. At 52DAP the emergence/establishment at Edgmond showed no statistical difference between species or nitrogen rate, though plants m^2 were greater, 14, in the 100 kg N/ha compared to the 50 kg N/ha, 8.7, treatment. In contrast, plant numbers at the Caynton site were significantly greater, P=0.003, in the 100 kg N/ha treatment, 18.7 compared to 6 in the 50 kg N/ha treatment. This corresponds to work by Dias *et al.* (2012) who also reported 20-21 plants m^2 for crops planted in two regions in Portugal, acheived from a seed rate of 400 seeds m^2, giving just 5% establishment. At 122DAP plant numbers had declined at Caynton to a range of 5.7 – 9.2 m^2, showed no real differences between species or nitrogen rate. Although this work is similar to that of Dias *et al.* (2012), it disagrees with Timmermans et al. (2006), where 228 plants m^2 established at 400 seeds m^2 and greater numbers established when sown at 200, 100 and 50 seeds m^2. Timmermans *et al.* (2006) suggested that there appeared to be no benefit from sowing at greater than 100 seeds m^2 and so the seed rate used in our nitrogen/species trials, equivalent to approximately 240 seeds m2, was potentially unhelpful to establishment and plant growth.

Overall however, it does appear that nitrogen applied at 100 kg N/ha did promote better emergence for both species and establishment especially in *S sisymbriifolium*.

Ground cover development

Ground cover, GC, development at the Caynton site followed a weekly incremental improvement from 82DAP until the final assessment as 148DAP. *S. scabrum* showed the greatest improvement to the increase of seedbed nitrogen, where values rose from 34% to 90% GC at 100 kg N/ha, compared to 20% to 70% at 50 kg N/ha. Although the response to greater nitrogen also followed an increasing trend for *S. sisymbriifolium*, the actual difference was substantially less, values rose from 24% to 67% GC at 100 kg N/ha, compared to 18% to 58% at 50 kg N/ha. It is unsurprising that *S. scabrum* achieved overall greater GC% and gave greater responses to nitrogen, at these plants densities, as in comparison to *S. sisymbriifolium*, the plant branches more profusely and, as a broad leaf crop, better able to facilitate leaf expansion. At a final trial visit in early December, 164DAP, the *S. sisymbriifolium* was still green and showing no sesescence, whereas the *S. scabrum* was dying back due to frost damage, at both sites. The Edgmond ground cover progression was in stark contrast to Caynton in that it favoured *S. sisymbriifolium* development, especially in response to nitrogen, where it reached a maximum ground cover of 71% at 147DAP.

S. scabrum, responded positively to 100 kg N/ha but only marginally better than at 50 kg N/ha, reaching a maximum of 49.7% GC at 123DAP. These findings are similar to those reported for the response of *S. scabrum* to nitrogen by Abukutsa-Onyango and Karimi (2007) but their work does suggest that no significant benefit was seen to nitrogen rates greater than 40 kg N/ha. It is worth noting however, that the work by Abukutsa-Onyango and Karimi (2007) was on sites located on the equator, 34° 37' E and 0° N at an altitude of about 1560 metres above sea level, and therefore climatic effects on growth would have been substantially different from this work and that by Timmerman (2006) and Scholte (2000).

In order to determine if the soil population densities of PCN, Pi, had affected the growth of the crops at the Edgmond site, linear relations were investigated. There was no relationship between Pi and ground cover at 67DAP, when analysed as a whole data set. Similarly there was not relationship between Pi and GC at 109DAP when analysed as a whole data set or when analysed as separate species, ignoring nitrogen rates. However, when analysed as nitrogen rates, ignoring species, as Pi increased the GC increased positively in the 50 kg N/ha treatment, whereas as Pi increased the GC decreased in the 100 kg N/ha treatment. Looking at Figure 28 however, the GC response at 50 kg N/ha has high leverage from data point Pi 168 GC 81, in whose absence the trend would be horizontal. In contrast to this the GC response at 100 kg N/ha, is predominantly negative and without clear leverage points. A factor influencing this trend could be linked to the effect of nitrogen, where increased nitrogen can lead to a high concentration of soluble N which increases the osmotic potential of the soil solution, causing reduction in water uptake by the plant roots (Marschner, 1995) and potentially reducing ground cover in a plant already stressed by PCN invasion. It should be noted that as there are only 6 data points per set, the effect of one or two erroneous data points can lead to false conclusions and so care should be used when considering these apparent effects.

Overall, it does therefore appear that nitrogen applied at 100 kg N/ha does promote better ground cover for both species but especially for *S. scabrum* at the plant densities achieved.

Biomass assessments

Above ground dry matter: One of the key elements for control of PCN by *S. sisymbriifolium* is the development of sufficient above ground biomass, as this correlates to below ground biomass, potential to stimulate hatch and PCN from root exudates and reduce PCN soil population densities. Timmermans (2005) and Timmermans *et al.* (2006) suggested that 700g dry matter m^2 appeared to be the minimum biomass required to achieve this purpose, measured at 14 weeks post emergence. Unfortunately no such benchmark is available as yet for *S. scabrum*. At the Caynton site there was a significant response, *P* = 0.041, to nitrogen application, where an average of 601g dm m^2 from both species resulted from 100 kg N/ha, in comparison to only 266g dm m^2 for the 50 kg N/ha treatment. *S. sisymbriifolium* achieved a maximum of 453g dry matter m^2, at 100 kg N/ha, compared to only 336.4 from 50 kg N/ha. *S. scabrum* achieved 749g dm m^2 at 100 kg N/ha compared to only 196.7g at 50 kg N/ha. The responses to nitrogen were smaller at Edgmond and lacked statistical significance: *S. sisymbriifolium* increased from 232.6g at 50 kg N, to 267.5g at 100 kg N, whereas *S. scabrum* increased from 179.9g at 50 kg N to 247.7g at 100 kg N/ha.

Planting dates for our trial sites were also within an acceptable range for good biomass production, as the planting date of 25th June 2021 corresponded well to the results of Timmerman *et al.* (2006), for that planting time, but it is probable that the substantially lower plant density in our trials reduced the biomass production in comparison. The establishment issues at the Edgmond site severely disadvantaged the development of the biomass but no clear reason can be identified at this point.

Root growth: at both sites the weight of fine and larger roots, <1mm and > 1mm, was significantly and substantially better in *S. scabrum* than *S. sisymbriifolium,* demonstrating a potentially important difference between these species for PCN control. The greater nitrogen application did improve root weights, but this was not significant. An extensive root system was suggested by Scholte (2000) to be a necessary and favourable trait, in order to promote good PCN hatching, but also suggested that this trait was only beneficial if their was concomitant production of sufficient and suitable exudates. Testing a wide range of solanaceae genera and related species for PCN hatch stimulation, Scholte (2000) demonstrated that exudates from both *S. sisymbriifolium* and *S. scabrum* were similarly effective to potato cultivars but that *S. scabrum* was the most effective, though lacked full resistance to PCN. This therefore suggests that the extensive root system developed by *S. scabrum* in our trials should be very effective at PCN hatch stimulation and additional nitrogen may be still be beneficial.

Overall, these results suggest that that both of these crop species responded favourably to the increase of nitrogen from 50 to 100 kg N/ha.

The effect of *S. sisymbriifolium* and *S. scabrum* on PCN population densities.

PCN populations were only studied at the Edgmond site and revealed populations ranging from 62 to 248 eggs/g air dried soil, which would be classed as very high and unsuitablle for planting potatoes, even with the use of nematicides. The PCN soil sampling methods and intensity of sampling was in accordance with good practice and should have provided a good representation of the PCN populations present both pre-planting and after 130DAP. In a fully funded research project it would have been useful to also determine the PCN population post-Winter, to determine any continued effect after trap crop death. As this process is quite expensive it was not possible to facilitate the further work. In terms of discussion of these results, only percentage reductions will be covered as the Pf/Pi ratio used within nematology is perhaps less useful in this type of report.

The effect of both of the trap crop species was to reduce the populations to quantities lower than found in the fallow plots where they were reduced by an average of 26%, range 0% to 30%, from 127 down to 90 eggs/g soil. This is in complete agreement with the average 26% decline rate for *G. pallida,* in the absence of a host, as reported by Trudgill *et al.* (2014). *S. sisymbriifolium* reduced PCN populations by 40%, from 135 down to 75 eggs/g soil in the 50 kg N treatment, and 38%, from 108 down to 62 eggs/g soil in the 100 kg N/ha treatment. Whilst *S. scabrum* reduced population densities by 48%, from 118 down to 62 eggs/g soil in the 50 kg N/ha treatment, and by 56%, from 115 down to 49 eggs/g soil in the 100 kg N/ha treatment. There were plots which recorded 85% population reductions but variability within treatments was quite high, which is why there were no statistically significant differences between treatments.

One of the interesting aspects of these results is the different PCN population reductions seen between the species, although it should be stressed that there were no statistically different effects. As discussed, *S. scabrum* gave the greatest PCN population reductions and this may well be linked to the findings of its greater root mass and thus its potential to stimulate PCN hatch. The evidence in this work that the significantly greater root growth from *S. scabrum* in both <1mm and >1mm sizes, could have stimulated PCN hatch due to the number or density of roots and the presence of the finer, more active, roots, which could have increased exudate release and thus hatch stimulation.

The effect of *S. sisymbriifolium* grown in the field, as opposed to glasshouse studies, has been shown by several authors to reduce populations of one or both species of PCN in the Netherlands (Timmermans, 2005), Portugal (Dias *et al.* 2017) and USA (Dandurand & Knudsen, 2016). Dias *et al.* (2017) also grew the potato cultivar Melody, resistant to *G. rostochiensis* but susceptible to *G. pallida*, which reduced the PCN population less than *S. sisymbriifolium* at a site with *G pallida,* but greater than *S. sisymbriifolium* at a site containing *G. rostochiensis*, which would be expected. The work by Dandurand & Knudsen (2016) included treatments with and without biocontrol fungi and reported that *S. sisymbriifolium* produced no new cysts when grown in infested soil, showing its resistance to *G. pallida*, and that *Pf/Pi* could be reduced by up to 99%.

Overall, the results suggest that *S. sisymbriifolium* and *S. scabrum* when sown at this 'late' timing, both reduced PCN population densities, but that the rate of fertiliser N did not appear to affect this directly.

5. Conclusions

The potato cyst nematode is a significant pest of potatoes in the UK, and around the world, but with the availability of chemcial control options diminishing the use of specialised trap crops, *S. sisymbriifolium* and *S. scabrum,* to reduce PCN populations, would be useful. Unfortunately, growing these trap crops sucessfully normally requires planting times within existing cropping windows, thus meaning the loss of a cash crop to achieve it. However, planting the trap crops in late-June in North Shropshire, on sandy loam soils, was shown to be feasible in 2020 and again in 2021, but not without establishment issues. When seedbed nitrogen was added at 50 or 100 kg N/ha the latter was shown to be more beneficial to overall canopy development, confirming its need for these crops. Both *S. sisymbriifolium* and *S. scabrum* showed potential for reduction of the *G. pallida* population, up to twice that seen in fallow plots, with *S. scabrum* providing substantially greater root growth for PCN hatch stimulation. Further work is still needed to clarify best practice for sowing and seedbed consolidation of these crops, especially when sown at the end of the recommended sowing dates, but this work confirms their potential to reduce PCN populations and the benefit of additional nitrogen.

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