Final Report

To investigate the potential of both native and non-native *Solanum* species as PCN trap crops

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Report Authors: Steve Ellis, ADAS, High Mowthorpe, Sarah Cook ADAS, Boxworth & Denis Buckley, Highfield Lodge Agronomy

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1. SUMMARY

1.1. Aim

The overall aim of the project was to investigate the potential of both native and non-native *Solanum* species as Potato Cyst Nematode (PCN) trap crops and to provide guidelines on how they can be integrated within current arable rotations. This aim was addressed through three objectives:

a) To review relevant literature (UK and Europe) to highlight knowledge gaps and determine candidate species
b) To identify the most likely species as potential trap crops for PCN under UK conditions
c) To quantify the agronomic requirements for growing and destroying the trap crop

The project was joint-funded by AHDB Potatoes and Defra.

1.2. Methodology

The project used pot experiments to investigate:

- the efficacy of a range of potential trap crop species against PCN
- the establishment of trap crop species at a range of sowing dates
- the susceptibility of trap crop species to herbicides

The efficacy of trap crops to control PCN was compared at a range of sowing dates, four soil types (peaty loam, silt, loamy sand and sandy loam) and at a range of plant populations (one to six plants/5 litre pots). In year one, seven potential trap crops (2 samples of black nightshade, 2 samples of sticky nightshade, thorn-apple, woody nightshade, and a *Solanum* species (species name yet to be confirmed and referred to as "unspecified *Solanum* spp" throughout this report) were compared. In year two this was reduced to black nightshade, sticky nightshade and the unspecified *Solanum* spp. In the final year only black nightshade and the unspecified *Solanum* spp were studied.

Herbicide treatment is important to supress weed growth and improve trap crop establishment. The herbicide screen was also done in three soil types (silt loam, loamy sand and sandy loam).

1.3. Results

Over three years of the project black nightshade and the unspecified *Solanum* spp were most effective at controlling PCN. Tables a, b, c, below summarise a subset of the data for one site (High Mowthorpe, North Yorkshire) where trials were carried out over the three years of the project. The trap crop plants were grown in 5 litre pots housed in a poly tunnel.

Effectiveness of control of PCN was assessed by calculating the mean initial (Pi) and final (Pf) number of PCN eggs/gram soil in each treatment. The mean number of eggs at the end of the trial is expressed as a percentage of the initial population for each of the soil types studied. If PCN levels declined the percentage is less than 100 and if levels increased the values are above 100. *[The Pi is shown in brackets]. For some trap crop species two samples (grown from seed sourced from different locations) were evaluated.

The tables provide an indication of the variation in control that was seen between different soil types and years of the project.

Table a. Summary results for the trap crop plants evaluated in year 1.

Trap crop	Month sown	Days grown	Plants/ pot**	Mean eggs/g soil as % of initial population [ ]*		
				Silt loam	Loamy sand	Peaty loam
Black nightshade 1	April	220	4	21% [148]	70% [64]	26% [636]
Black nightshade 2	April	220	4	33% [140]	35% [104]	3% [819]
Sticky nightshade 1	April	220	4	79% [172]	10% [83]	44% [690]
Sticky nightshade 2	April	220	4	117% [124]	47% [69]	55% [576]
Unspecified *Solanum* spp	April	220	4	35% [170]	40% [84]	14% [717]

[ ]* = initial (Pi) number of PCN eggs/g soil
** target number of plants/pot. See Table 14 for the mean number of plants that were established for each trap crop species.

Table b. Summary results for the trap crop plants evaluated in year 2.

Trap crop	Month sown	Days grown	Plants/ pot	Mean eggs/g soil as % of initial population [ ]*
				Silt loam
Black nightshade 1	April	226	6	26% [32]
Sticky nightshade 2	April	226	6†	60% [30]
Unspecified *Solanum* spp	April	226	6	63% [27]

† on average only 3 plants established per pot.

Table c. Summary results for the trap crop plants evaluated in year 3.

Trap crop	Month sown	Days grown	Plants/ pot	Mean eggs/g soil as % of initial population [ ]*		
				Silt loam	Loamy sand	Sandy loam
Black nightshade	May	180	6	61% [55]	38% [101]	24% [75]
Unspecified *Solanum* spp	May	180	6	61% [60]	82% [103]	33% [75]

1.4. Summary of main conclusions

- Black nightshade (*Solanum nigrum*) and the unspecified *Solanum* spp showed good potential as trap crops over the three years of the project and gave best control of PCN. Black nightshade reduced PCN egg numbers by between 76% and 45% and the unspecified *Solanum* spp by between 65% and 45%.

- The optimum period for sowing trap crops appears to be in the period from late April to mid-July, when temperatures are high. Later sowings (August and September) are prone to failure. In practical terms, it may be possible to drill trap crops immediately after winter barley if the ground is cleared quickly, but better results are more likely in the late spring as a whole season crop.

- The longer the growing season for the trap crop the greater the reduction in the PCN population. This was reflected in root dry weight with the earliest sowings producing the highest root dry weight.

- Sticky nightshade (*Solanum sisymbriifolium*) was less effective as a candidate trap crop species than black nightshade or the unspecified *Solanum* spp in the pot trials of this project. Sticky nightshade reduced PCN egg numbers by 34% over Years 1 and 2 whereas the comparable figure for black nightshade was 60%.

- Thorn-apple (*Datura stramonium*) and woody nightshade (*Solanum dulcamara*) were difficult to establish and also had significantly less impact on PCN than black nightshade, the unspecified *Solanum* spp and sticky nightshade and should be omitted from any future trap crop work.

- It was not possible to demonstrate differences in PCN control based on either one or six plants per pot. The effect of the higher plant population was to reduce dry weight per plant as a result of plant-to-plant competition. Field work is required to determine the optimum established plant population for maximum PCN reduction.

- Getting candidate trap crop species to reliably germinate is a problem requiring investigation; a solution must be found if they are to successfully establish under field conditions. Black nightshade was the worst in this regard, showing variations in germination which could not be explained. The unspecified *Solanum* spp showed the highest and most consistent level of germination.

- The impact of soil type on the efficacy of trap crops was variable. There was limited evidence to suggest that different species may perform best in particular soil types.

- There was some evidence to suggest that PCN cyst numbers increased in the presence of trap crops in year three although egg numbers were still reduced. This suggests that any new cysts contained few eggs or that the eggs had hatched almost immediately. It has been reported elsewhere that entry into dormancy at the end of the first generation is not obligatory for PCN (see AHDB Potatoes project R433).

- In practical terms, although black nightshade was most effective at reducing PCN levels it may be that other species are better candidate trap crops as their establishment is more reliable and their canopies are more vigorous and give better weed suppression.

- None of the herbicides tested were entirely crop-safe.

- Soil type had a significant effect on the phytotoxicity of the herbicides tested. Both black nightshade and the unspecified *Solanum* spp were killed to a greater extent when grown in the loamy sand and sandy loam soils than in the silt loam.

- Black nightshade was relatively tolerant of clomazone and metribuzin applied pre-emergence, and metribuzin, rimsulfuron, MCPA applied post-emergence.

- The unspecified *Solanum* spp had a similar spectrum of herbicide tolerance to that of black nightshade, with the exception of metribuzin, to which it was intolerant.

- The herbicides pendimethalin (Stomp Aqua), prosulfocarb (Defy) and metribuzin + flufenacet (Artist), all applied in Year 2, and metobromuron (Praxim) in Year 3, were particularly phytotoxic to black nightshade. The same herbicides were a little less phytotoxic to the unspecified *Solanum* spp but not sufficiently so to conclude that any of them would be safe when used in the field.

- In the herbicide screening work in Year 2, which included sticky nightshade, the emergence was so poor that it is not possible to draw firm conclusions as regards herbicide tolerance. Further screening work is required to refine possible herbicide programmes.

- All work in the current project has been done in pots and future studies should seek to evaluate trap cropping in the field. Trap crop agronomy and risks associated with deployment of the novel trap crops (e.g., if they are hosts for potato pests and diseases) should be studied in addition to field-based assessments of trap crop efficacy.

2. INTRODUCTION

Potato cyst nematodes (PCN), *Globodera pallida* and *Globodera rostochiensis*, are the most economically serious pests of potatoes in Great Britain with losses estimated to be in the region of £25.9 million per annum. Since the mid-1970's, PCN management has relied on a combination of resistant varieties, rotation and nematicides. This has been only moderately successful as the pressure to grow potatoes on the best ground, usually with irrigation, often means adopting tighter rotations than optimal for controlling the pest. In addition, nematicides are currently under regulatory pressure within the EU. Both Temik (aldicarb) and Telone (1,3-dichloropropene) are no longer approved and other products are receiving greater scrutiny. It has been estimated that losses due to PCN would rise to £58.2 million per annum if currently available nematicides were to be lost as a result of regulatory changes relating to the approval of pesticides. Prompted by the potential for loss of nematicides, alternative control measures against PCN have attracted interest.

Trap cropping involves growing a crop specifically to induce PCN to hatch, the plants used are not suitable hosts for the nematodes and the PCN larvae ultimately die and so are unable to multiply, reducing the PCN population in the field. An alternative approach is use a suitable host (potato crop) but harvest the crop before the nematodes multiply. Research into the life cycles of PCN in the field suggests this method may be more hazardous than first thought because of climate change affecting the time of formation of cysts, making identification of the "correct" time to harvest the crop difficult to determine.

The overall aim of the project was to investigate the potential of both native and non-native *Solanum* species (which are not hosts for PCN) as PCN trap crops and to provide guidelines on how they can be integrated within current arable rotations. This aim was addressed through three objectives:

a) To review relevant literature (UK and Europe) to highlight knowledge gaps and determine candidate species.
b) To identify the most likely species as potential trap crops for PCN under UK conditions.
c) To quantify the agronomic requirements for growing and destroying the trap crop

Ultimately this project aimed to identify the best trap crops, optimum plant density, sowing date, destruction date and herbicide strategies to prevent infestation by other weed species.

3. MATERIALS AND METHODS

3.1. Year 1: 2013/2014

Pot experiments were used to identify the best candidate PCN trap crops but also to investigate aspects of agronomy, particularly timing of establishment, the optimum seed rate for effective PCN control, when trap crops should be destroyed to prevent return of seed to the soil and the potential for trap crop volunteers to infest the following potato crop. Any obvious impacts of the trap crops on potato diseases were also recorded.

There were two experiments in year 1. These were all done in pots either in a polytunnel (High Mowthorpe) or on a hard-standing area exposed to ambient conditions (Boxworth).

3.1.1. Experiment 1. To identify the most likely candidates as potential trap crops for PCN under UK conditions (ADAS, High Mowthorpe)

Seven potential trap crops were screened using field soils in which the PCN infestation was known and compared with a cereal crop as a control. The eight crops were sown on 30 April 2013 and grown in 5 litre pots containing three soil types (silt loam, loamy sand or peaty loam) at ADAS High Mowthorpe, North Yorkshire and were monitored daily and watered as necessary.

The full list of trap crops is given in Table 1 below.

Table 1. Trap crop species and source

Trap Crop		**Source**
Common name	**Latin name**	
Black nightshade 1	*Solanum nigrum*	Field collected, Shropshire
Black nightshade 2	*S. nigrum*	Field collected, Swindon, Wiltshire
Sticky nightshade 1	*Solanum sisymbriifolium*	Originally sourced from Chiltern Seeds
Sticky nightshade 2	*S. sisymbriifolium*	CN seeds, supplied through GreenvaleAP by Barworth Agriculture.
Thorn-apple	*Datura stramonium*	Herbiseed
Woody nightshade	*Solanum dulcamara*	Herbiseed
Unspecified *Solanum* spp	To be confirmed	Supplied by Barworth Agriculture
Spring barley (cv Solstice): used as a non-trap crop control	*Hordeum vulgare*	commercial seed

The experiment used a 8 x 3 factorial treatment structure arranged in a randomised block design. There were three replicates of each treatment giving 72 x 5 litre pots in total.

Test soils were collected from fields known to have a moderate to high level of PCN infestation (at least 11 eggs/g soil) and sieved to remove any large stones. The soil for each soil type was then mixed in a cement mixer to ensure even distribution of PCN cysts. After mixing, 24 pots were filled with one of each of the three soil types. The pots were filled to the rim, then tipped back on to a tray and a random 200 g sample taken for PCN extraction. This extraction provided the initial PCN population (Pi). The remaining soil was then returned to the pot. Trap crops were sown directly into the pots at a rate of ten seeds per pot and housed in a polytunnel. Once seedlings had established they were thinned to leave four plants per pot. There were nine replicate pots of each candidate crop. Some of the trap crops (thorn-apple and woody nightshade) showed very poor germination. Additional seeds were therefore sown in pots of compost to aid germination and seedlings transplanted to the experimental pots.

The pots were arranged in a polytunnel in a randomised block design, monitored daily and watered as and when necessary.

Pots remained in the poly tunnel for 220 days after which a 2 cm diameter x 15 cm deep cheese corer was used to take five soil cores from each. This soil was air dried and extracted to give the final PCN population (Pf).

3.1.1.1. PCN extraction

PCN samples were extracted using the Fenwick can (Fenwick, 1940). Initially it was intended to extract 200g of air dried soil from each experimental pot. However, cyst numbers in the test soils were very high and it was unnecessarily time consuming to count all those extracted. Therefore, samples of only 50g of soil were used. The cysts were collected on filter papers and the numbers assessed using a Fidler turntable (1963). Up to 100 cysts were picked off to provide a sub-sample and the number of eggs and larvae counted in the suspension; the remainder of the cysts were counted and recorded.

Cysts from the sub-sample were cut open using a needle and an oculist's scalpel to release all the eggs and larvae from each cyst. The free eggs and larvae were washed into a 100 ml conical flask in 50 ml of water. The conical flask was placed on a magnetic stirrer and three separate 1 ml aliquots of the suspension were pipetted into Hawksley counting slides. The number of eggs and larvae in each 1 ml aliquot was counted and the mean of the three results calculated to give the mean per ml of suspension. This mean was multiplied by the quantity of water used in the suspension and divided by the weight of the soil sample extracted to give numbers per gram of soil. A correction factor was applied if more than 100 cysts were counted.

3.1.2. Experiment 2. To quantify some of the agronomic requirements for growing and destroying the trap crop (ADAS, Boxworth)

The establishment of the trap crops was compared at six sowing dates in a silt loam soil infested with PCN at ADAS Boxworth, Cambridgeshire. Soil was sieved to remove large stones then 3 litre pots were filled with sieved soil and sown with 60 seeds in rows. *Datura stramonium* seed were soaked in warm water prior to sowing and all seeds were covered with a thin layer of soil. Six trap crops (Table 2) were sown on each of six dates: 22 April, 20 May, 20 June, 19 July, 21 August and 20 September 2013.

The experiment comprised a total of 144 pots with six trap crops, six sowing dates and four replicates.

Table 2. Trap crop species and source

Trap crop		Source
Common name	**Latin name**	
Black nightshade 1	*Solanum nigrum*	Shropshire
Black nightshade 2	*S. nigrum*	Swindon
Sticky nightshade 1	*S. sisymbriifolium*	Chiltern seeds
Sticky nightshade 2	*S. sisymbriifolium*	GVAP
Thorn-apple	*Datura stramonium*	Herbiseed
Woody nightshade	*S. dulcamara*	Herbiseed

The candidate crops were the same as used in Experiment 1 but without spring barley or the unspecified *Solanum* spp.

The experiment used a 6 x 6 factorial treatment structure arranged in a randomised block design. Plants were grown in pots and placed on hard standing, where they were open to the elements but protected from birds and vermin. Pots were monitored regularly and additional irrigation applied as necessary.

Seedling emergence was assessed as in Table 3. A final assessment was done on all pots on 14 January 2014 and the number of live and dead plants was recorded.

Table 3. Dates of emergence assessments

Sowing date	13-May	06-Jun	26-Jun	11-Jul	02-Aug	21-Aug	11-Sep	09-Oct	18-Oct	05-Nov	12-Dec
22 Apr	✓	✓	✓	✓							
20 May		✓	✓	✓	✓	✓					
20 Jun				✓	✓	✓	✓	✓			
19 Jul					✓	✓	✓	✓			
21 Aug							✓	✓		✓	
20 Sep									✓	✓	✓

3.2. Year 2: 2014/2015

Pot experiments were used to assess the establishment and effectiveness of trap crops at a range of sowing dates (Experiment 1) and also the selectivity (crop safety) of a range of herbicides on the trap crop species (Herbicide screen, Experiment 2). Experiment 1 was done at both Boxworth and High Mowthorpe and Experiment 2 at Boxworth only. These were all done in pots either in a polytunnel (High Mowthorpe) or on a hard-standing area exposed to ambient conditions (Boxworth).

3.2.1. Experiment 1. Evaluation of optimum sowing date and seed rate for trap crops (ADAS, High Mowthorpe and Boxworth).

The efficacy of three trap crop species (the three species which gave most effective control of PCN in Year 1) was compared over five sowing dates and at three seed rates in a single soil type at Boxworth and High Mowthorpe. This was important in trying to determine the potential of trap crops for late summer/early autumn establishment following combinable crops. The experiment used a soil type (silt loam) in which potatoes are commonly grown in the UK. The soil was collected from a site naturally infested with a moderate PCN population.

The soil was sieved prior to sowing to remove any large stones. The experiment comprised 135, 5 litre pots in total with three trap crops, three seed rates, five sow dates (April – mid-September) and three replicates [3 x 5 x 3 factorial treatment structure arranged in a randomised block design]. A soil sample of approximately 2 kg was taken from the site at which the soil was collected and extracted using the Fenwick can to determine the PCN population (for method see section 3.1.1.1).

The full list of trap crops is given in Table 4 below.

Table 4. Trap crop species and source

Trap Crop		**Source**
Common name	**Latin name**	
Black nightshade 1	*Solanum nigrum*	Field collected, Bratton Shropshire, 2013
Sticky nightshade 2	*Solanum sisymbriifolium*	Ex GVAP
Unspecified *Solanum* spp	To be confirmed	Supplied by Barworth Agriculture

The experiment continued until 4 December 2013 at High Mowthorpe and 28 January 2014 at Boxworth. This meant that plants from each sowing date were exposed to PCN for differing periods of time at each site. These are listed in Table 5 below.

Table 5. Sowing date and exposure period (days) during which trap crops were exposed to PCN for each sowing date at Boxworth and High Mowthorpe.

Sowing date	**Boxworth**	**High Mowthorpe**
22 April	281	226
4 June	238	183
10 July	202	147
26 August	155	100
22 September	128	*

* Sowing failed

Once the experiment was stopped, the number of trap crops in each pot was counted, the plants cut off at the soil surface and the contents of each pot tipped on to a plastic tray. The roots were separated from the soil and dried in an oven at 100°C for 24 hours. Root dry weight was measured and the root dry weight per plant calculated. The soil was then thoroughly mixed and a sub-sample of just over 100 g taken. These samples were air dried and extracted to give the final PCN population (Pf).

PCN extraction and egg counting was done as in year 1 (section 3.1.1.1).

3.2.2. Experiment 2. Herbicide screen (ADAS, Boxworth)

This experiment investigated the selectivity (crop safety) of a range of herbicides on the trap crop species *Solanum nigrum*, *S. sisymbriifolium* and the unspecified *Solanum* spp. The unsterilised silt loam soil was sourced from a commercial potato producer and had a large weed seedbank.

Herbicides were chosen on the basis of their current or previous use in potatoes. This was because the trap crop species all belong to the same botanical family as potato (Solanaceae). Of the herbicides chosen, all except MCPA are currently approved for use in potatoes, although both metribuzin and bentazone have label restrictions on certain potato cultivars.

Two rates of herbicide were chosen:

1. Those typically used in potatoes on this soil type (silt loam). This was usually less than the full rate for a pre-emergence treatment.
2. 50% of the above rate.

The use of two application rates, and in particular the lower rate, was justified as it allowed the sensitivity of the trap crop species to the herbicide to be determined and also whether this response was dose-related. Also it is well-known that potato crops grown from small 'seed' (tubers) are more sensitive to herbicides than those grown from large 'seed' (tubers). As the trap crops were grown from true seed, which is very small relative to potato 'seed' tubers it might be expected that they would be particularly sensitive to herbicides. Additionally experimental experience indicates that crops grown in pots are more sensitive to herbicides than those grown in fields.

Canopy development of trap crops is likely to be much slower than that of a potato crop due the difference in seed size. Trap crops will therefore be much less effective at smothering weeds than commercial potatoes. As a result it is highly unlikely that pre-emergence herbicide application alone will be sufficiently broad spectrum or persistent to provide commercially acceptable weed control. It was therefore considered very important to test herbicides which can be applied post-emergence of the trap crop, and the most common potential products were selected for this experiment.

Of the main herbicides used in potatoes, only linuron was excluded, because the maximum rate currently approved (600 g/ha a.i.) is only a fraction of that used commercially in the past under its old approval (1,250 - 1,650 g/ha a.i.). As a result, linuron is now only used in mixtures with other residual herbicides, rather than as a stand-alone treatment so it was not included in this screen.

The experiment was done in one litre pots filled with a silt loam soil known to be infested with PCN. There were three trap crop species, 19 herbicide treatments and four replicates providing 228 pots in total. The experiment was located on an open hard standing area at ADAS Boxworth.

The full list of trap crop species and herbicide treatments is given in Tables 6 and 7.

Table 6. Trap crop species

Treatment	**Species**	**Seed source**
1	*S. nigrum 1*	Bratton, Shropshire 2013
2	*S. sisymbriifolium 2*	Ex GVAP
3	Unspecified *Solanum* spp	Barworth Agriculture

Pots of soil were prepared for sowing on 14 June 2014 and the trap crops were sown on 20 June. Any weeds which emerged in the test soil were removed on 20 June and the pre-emergence herbicides applied on 23 June. By 6 July the trap crops had reached the two leaf stage and the post-emergence sprays ware applied on 17 July. Details of the spray applications are given in Table 8. The effects of both the pre- and post-emergence herbicides were assessed on 14 August. This was 52 days after the pre-emergence application and 28 days after the post emergence application. The numbers of different weed species were also noted. The use of herbicides pre- and post-emergence were analysed as two separate experiments.

Table 7. Herbicide treatments

	Pre – emergence 3-5 days after sowing		**Post – emergence 2-4 expanded leaves**	
	Product	**Product Rate**	**Product**	**Product Rate**
1	Untreated	-	-	-
2	Untreated	-	-	-
3	Centium 360 CS	0.18 L/ha	-	-
4	Shotput	0.5 kg/ha	-	-
5	Stomp Aqua	3.0 L/ha	-	-
6	Defy	4.0 L/ha	-	-
7	Artist	2.0 kg/ha	-	-
8	Centium 360 CS	0.09 L/ha	-	-
9	Shotput	0.25 kg/ha	-	-
10	Stomp Aqua	1.5 L/ha	-	-
11	Defy	2.0 L/ha	-	-
12	Artist	1.0 kg/ha	-	-
13	-	-	Titus + Activator 90	50 g/ha + 0.2 L/ha
14	-	-	Basagran SG Grounded	1.0 kg/ha + 1.5 l/ha
15	-	-	Shotput	0.25 kg/ha
16	-	-	Agroxone	1.7 L/ha
17	-	-	Titus +Activator 90	25 g/ha + 0.2 L/ha
18	-	-	Basagran SG +Grounded	0.5 kg/ha + 1.5 L/ha
19	-	-	Shotput	0.125 kg/ha
20	-	-	Agroxone	0.85 L/ha

Product name	**Active substance**
Agroxone	MCPA 500 g/L
Artist	Flufenacet 240 g/kg + Metribuzin 175 g/kg
Basagran SG	Bentazone 87%
Centium 360 CS	Clomazone 360 g/L
Defy	Prosulfocarb 800 g/L
Shotput	Metribuzin 70%
Stomp Aqua	Pendimethalin 400 g/L
Titus + Activator 90	Rimsulfuron 25%

Table 8. Spray details (both sprays were applied indoors in the equivalent of 200 L water/ha using a pot sprayer.)

Date	**23 June 2014**
Crop growth stage:	Pre-emergence of trap crop
Soil condition:	Surface: damp, subsoil: damp
Temperature at application	23°C

Date	**17 July 2014**
Crop growth stage:	Trap crop at 4-6 leaves
Soil condition:	Surface: damp, subsoil: damp
Temperature at application	25°C

3.3. Year 3: 2015/2016

Pot experiments were done at ADAS Boxworth and ADAS High Mowthorpe and used to assess the establishment and effectiveness of trap crops at a range of sowing dates (Experiment 1) and also the selectivity (crop safety) of a range of herbicides on the trap crop species (Herbicide screen, Experiment 2). Experiment 1 was done in a polytunnel at High Mowthorpe and on a hard standing area at ADAS Boxworth. Experiment 2 was done at Boxworth only and was located on a hard standing area.

3.3.1. Experiment 1. Confirmation of optimum seed rates and sowing dates for most effective trap crop species

The efficacy of two trap crop species (*S. nigrum* and the unspecified *Solanum* spp*)* was compared over three sowing dates (5 May, 3 July, 13 August at Boxworth 15 May, 15 June, 31 July at High Mowthorpe), at two seed rates (one or six plants/pot) in three soil types (loamy sand, sandy loam, silt loam). The three sowing dates were included to determine the potential of establishing trap crops from spring until early summer. The three soil types are typical of those in which potatoes are commonly grown in the UK.

The experiment used a 2 x 2 x 3 x 3 factorial treatment structure arranged in a randomised block design. There were three replicates of each treatment giving 108 x 5 litre pots in total at each site. A soil sample of approximately 2 kg was taken from the site at which the soil was collected and extracted using the Fenwick can to determine the PCN population (for method see 3.1.1.1)

The experiment was stopped on 11 November at High Mowthorpe and 11 December at Boxworth. This enabled an assessment to be made of the length of time trap crops need to be exposed to PCN in order to stimulate egg hatch and reduce pest levels. This is important in determining the optimum sowing date for trap crops in the field. The full list of trap crops is given in Table 9 below.

Table 9. Trap crop species and source

Trap Crop		**Source**
Common name	**Latin name**	
Black nightshade	*Solanum nigrum*	Field collected, Holme Fen Norfolk, 2014
Unspecified *Solanum* spp	To be confirmed	Supplied by Barworth Agriculture

The test soils were collected from fields known to have a moderate level of PCN infestation (at least 11 eggs/g soil) and sieved to remove any large stones as in previous years. The soil was sieved, prepared and sub-sampled to determine the initial PCN population (Pi) as in previous years. There were two target plant populations for each trap crop: one plant per pot and six plants per pot. Trap crop seed was initially germinated in compost in a Petri-dish by Highfield Lodge Agronomy. A Petri-dish of each trap crop species was sent to both Boxworth and High Mowthorpe approximately two weeks before the planned sowing date. The seedlings were transferred to a seed tray containing multi-purpose compost and allowed to grow on. Ultimately the established seedlings were transferred from the compost to the pots of soil on the pre-determined sowing date. This method ensured that the correct number of seedlings were present in each pot. Where seedlings failed to grow on they were quickly replaced by others from the stock growing in seed trays. There were 54 replicate pots of each trap crop species. The pots were arranged in a randomised block design, monitored daily and watered as and when necessary.

The experiment continued until 11 November at High Mowthorpe and 11 December at Boxworth. This meant that plants from each sowing date were exposed to PCN for differing periods of time at each site. These are listed in Table 10 below.

Table 10. Sowing date and exposure period (days) during which trap crops were exposed to PCN for each sowing date at Boxworth and High Mowthorpe. Plants harvested 11 November at High Mowthorpe and 11 December at Boxworth.

Site	**Sowing date (2015)**	**Exposure period**
Boxworth	5 May	220
	3 July	161
	13 August	120
High Mowthorpe	15 May	180
	15 June	149
	31 July	103

Once the experiment was stopped, the number of trap crops in each pot was counted, the plants cut off at the soil surface and the contents of each pot tipped on to a plastic tray. The roots were separated from the soil and dried in an oven at 100ºC for 24 hours. Root dry weight was measured and the root dry weight per plant calculated. The soil was then thoroughly mixed and a sub-sample of just over 100 g taken. These samples were air dried and extracted (section 3.1.1.1) to give the final PCN population (Pf).

3.3.2. Experiment 2. Herbicide screen (ADAS, Boxworth)

In 2015, an experiment was set up to look at the selectivity (crop safety) of a range of herbicides on the *S. nigrum* and the unspecified *Solanum spp* in three soil types silt loam, sandy loam and loamy sand. The soil used was sourced from commercial potato producers, was unsterilised and had a large natural weed seedbank.

Herbicides were chosen from those tested in a similar experiment in 2014. All except Agroxone (MCPA) are currently approved for use in potatoes by CRD, although both metribuzin and bentazone have label restrictions on cultivar tolerance. In the past, MCPA was used as an emergency post-emergence treatment for fat hen control in potatoes. Praxim (metobromuron) gained approval for pre-emergence use in the 2015 potato crop and was included in this experiment.

The selectivity of five herbicides applied either pre or post emergence on two trap crop species in three soil types was compared (Table 11). Pre- and post-emergence applications were considered as separate experiments for each trap crop species giving four experiments in total. There were three pre-emergence and three post-emergence herbicide applications plus an untreated control in each experiment. This resulted in 4 x 3 factorial treatment structure arranged in a randomised block design with three replicates per treatment giving a total of 36 pots per experiment and 144 pots in total. Each experiment was done in three litre pots. Pots were located outdoors on a hard-standing area at ADAS Boxworth.

Table 11. Herbicide treatments

	Pre – emergence 3-5 days after sowing		**Post – emergence 2-4 expanded leaves**	
	Product	**Product Rate**	**Product**	**Product Rate**
1	Untreated	-	-	-
2	Centium 360 CS	0.18 L/ha	-	-
3	Shotput	0.25 kg/ha	-	-
4	-	-	Shotput	0.125 kg/ha
5	-	-	Titus	25 g/ha + 0.2 L/ha Activator 90
6	-	-	Agroxone	0.85 L/ha
7	Praxim	1.5 L/ha	-	-

Product name	**Active substance**
Agroxone	MCPA 500 g/L
Centium 360 CS	Clomazone 360 g/L
Shotput	Metribuzin 70%
Titus	Rimsulfuron 25%
Praxim	Metobromuron 500gLl

A total of 48 pots were filled with one of the three soil types and each sown with 40 seeds of either *S. nigrum* or the unspecified *Solanum* spp on 29 July, 2015. This provided sufficient pots for all four experiments. Pre-emergence spray treatments were applied on 5 August 2015. Emergence of *S. nigrum* was slower than of the unspecified *Solanum* spp therefore it was decided to spray the post-emergence treatments to the *S. nigrum* pots later than for the Unspecified *Solanum* spp to try and allow further seedlings to emerge. The unspecified *Solanum* spp were sprayed on 28 August 2015 and *S. nigrum* on 1 September 2015. All sprays were applied indoors in 200 L water/ha using a pot sprayer. Details of the crop growth stage, temperature and soil conditions on each spray date are given in Table 12. The high temperatures at spraying were due to the sprayer being located inside a polytunnel. Plants were located in this area for the minimum of time necessary.

Plant counts were done to assess the phytotoxicity of the herbicide treatments to the trap crops. These were on 7, 14 and 21 days post treatment. For pre-emergence treatments the assessment dates were 12, 19 and 26 August. For post-emergence treatments they were 4, 15 and 22 September. The final plant population was assessed in each pot on 16 September for pre-emergence treatments and 13 October for post-emergence treatments.

Any weed species that emerged in the pots other than the trap crop species were removed by hand. Pots were watered as necessary.

Table 12. Crop growth stage, temperature and soil conditions at the time of pre- and post-emergence herbicide application

Pre-emergence treatments	
Date	5 August 2015
Crop growth stage:	Pre-emergence of trap crop
Soil condition:	Surface: damp, subsoil: damp
Temperature at application	29.4°C
Post-emergence treatments	
Unspecified *Solanum* spp	
Date	28 August 2015
Crop growth stage:	4-6 leaves
Soil condition:	Surface: damp, subsoil: damp
Temperature at application	36.9°C
S nigrum	
Date	1 September 2015
Crop growth stage:	4-6 leaves
Soil condition:	Surface: damp, subsoil: damp
Temperature at application	21.6°C

3.4. Statistical analysis

The parametric analysis of variance (ANOVA) was used for statistical analysis. PCN populations were expressed in numbers of eggs/g of soil. The number of eggs within an individual PCN cyst can be very variable so to help take account of this it was decided to present data on the impact of trap cropping on PCN egg numbers as the ratio of the final population (Pf) to the initial population (Pi). This value was then multiplied by 100 i.e. ((Pf/Pi) x100. These data are nominally percentage values and are sometimes transformed before being subjected to the analysis of variance. However, extreme values (outliers) were removed (see page 34) leaving a relatively consistent dataset making transformation unnecessary. In addition the analysis of variance is a relatively robust statistical test which is able to cope with most datasets. To test this some datasets were transformed using the log transformation and subjected to the analysis of variance. The conclusions from this transformed data were the same as from the original data confirming that transformation was unnecessary. This also meant that it was possible to present the original data rather than transformed data and the equivalent back-transformed values. This avoided any possible confusion over the back-transformed means which would have been different from the means of the original data.

4. Results

4.1. Year 1: 2013/14

4.1.1. Experiment 1. To identify the most likely candidates as potential trap crops for PCN under UK conditions (ADAS, High Mowthorpe).

PCN populations in the three soil types collected from the field are summarised in Table 13.

Table 13. Pre-cropping PCN populations (eggs/g soil & cysts/100g soil) in the three soil types collected from the field

Soil type	Eggs/g soil			Cysts/100g soil		
	Mean	Max	Min	Mean	Max	Min
Silt loam	145	234	87	55	78	34
Loamy sand	75	123	13	102	150	70
Peaty loam	725	1153	459	406	430	322

Mean egg counts were in the ADAS high category (>60 eggs/g soil) in all three soil types. If these soils had been received as advisory samples from farmers the advice would have been to avoid cropping with potatoes. These PCN populations had potential to provide a very robust test of the trap crops.

The mean number of trap crop plants in each pot is shown in Table 14. The intention was to establish four plants per plot, but this was only possible for the spring barley. Of the trap crop species tested, black nightshade, sticky nightshade (1) and the unspecified *Solanum* spp established best and all had at least three plants per pot. Thornapple and woody nightshade were most difficult to establish, despite trying to germinate extra seeds in compost. Both these species only had a mean of 1.4 plants per pot and this poor viability cast doubts of their suitability as trap crops.

Table 14. Mean number of trap crop plants per pot in August 2013 (target = 4)

Trap crop	Soil type			
	Silt loam	Loamy sand	Peaty loam	Mean
Black nightshade 1	3.3	3.0	2.7	3.0
Black nightshade 2	3.7	4.0	4.0	3.9
Sticky nightshade 1	3.0	3.7	3.3	3.3
Sticky nightshade 2	1.0	1.7	3.7	2.1
Thornapple	0.7	2.0	1.7	1.4
Woody nightshade	0.7	2.7	1.0	1.4
Unspecified *Solanum* spp	4.0	4.0	3.7	3.9
Spring barley	4.0	4.0	4.0	4.0
Mean	2.5	3.1	3.0	

Initial (Pi) and final (Pf) PCN populations were calculated for each experimental pot (Table 15a – c).

The initial PCN populations (Pi) and final populations (Pf) for each soil type and trap crop are shown below as
(a) mean number of PCN cysts/100g soil
(b) mean number of PCN eggs/g soil
(c) mean number of PCN eggs/cyst

Table 15(a). Pi and Pf values: Mean numbers of PCN cysts/100g soil for each combination of trap crop and soil type

Trap crop	**Soil type**					
	Silt loam		**Loamy sand**		**Peaty loam**	
	Pi	**Pf**	**Pi**	**Pf**	**Pi**	**Pf**
Black nightshade 1	54	53	91	86	390	373
Black nightshade 2	62	64	107	101	433	371
Sticky nightshade 1	60	61	109	89	400	368
Sticky nightshade 2	48	58	101	94	373	434
Thornapple	53	59	97	104	411	397
Woody nightshade	50	116	92	110	406	367
Unspecified *Solanum* spp	65	59	119	102	396	245
Spring barley	48	57	103	82	437	409

Table 15(b). Pi and Pf values: Mean numbers of PCN eggs/g soil for each combination of trap crop and soil type

Trap crop	**Soil type**					
	Silt loam		**Loamy sand**		**Peaty loam**	
	Pi	**Pf**	**Pi**	**Pf**	**Pi**	**Pf**
Black nightshade 1	148	31	64	3	636	55
Black nightshade 2	140	49	104	20	819	15
Sticky nightshade 1	172	131	83	6	690	60
Sticky nightshade 2	124	131	69	11	576	236
Thornapple	140	136	66	43	666	385
Woody nightshade	146	187	64	94	931	128
Unspecified *Solanum* spp	170	57	84	35	717	61
Spring barley	116	175	62	39	761	516

Table 15(c). Pi and Pf values: Mean numbers of PCN eggs/cyst soil for each combination of trap crop and soil type

Trap crop	**Soil type**					
	Silt loam		**Loamy sand**		**Peaty loam**	
	Pi	**Pf**	**Pi**	**Pf**	**Pi**	**Pf**
Black nightshade 1	274	59	68	27	164	40
Black nightshade 2	227	88	99	37	195	7
Sticky nightshade 1	291	217	75	8	172	66
Sticky nightshade 2	255	229	69	30	153	69
Thornapple	263	229	67	42	163	110
Woody nightshade	291	220	70	70	230	70
Unspecified *Solanum* spp	262	93	72	35	180	39
Spring barley	239	305	60	49	175	132

The impact of the trap crops on PCN numbers was determined by calculating the Pf values as a percentage of the equivalent Pi value (Table 16). This ensured that all values were positive. If PCN levels declined the percentage was less than 100 and if levels increased the values were above 100.

There was a significant difference in final cyst number/100 g as a percentage of the initial population between soil types (P<0.05, Table 16). The presence of the trap crops reduced the numbers of cysts in the peaty loam by about 7% and in the loamy sand by about 3%. In the silt loam cyst numbers increased by approximately 21%. Although cyst numbers did not differ significantly between trap crops (P=0.052) the lowest numbers of cysts were recorded where the unspecified *Solanum spp* had been grown.

Table 16. Mean PCN cyst number/100 g soil as a percentage of the initial population

Trap crop	**Soil type**			
	Silt loam	**Loamy sand**	**Peaty loam**	**Mean**
Black nightshade 1	98	98	100	99
Black nightshade 2	103	95	89	96
Sticky nightshade 1	102	86	93	94
Sticky nightshade 2	126	105	117	116
Thornapple	110	107	97	105
Woody nightshade	210	120	91	140
Unspecified *Solanum* spp	97	88	80	82
Spring barley	121	80	94	98
Mean	121	97	93	

SED (46 df) for comparison of soil type means = 10.3
SED (46 df) for comparison of trap crop means = 16.9
SED (46 df) for comparisons within the body of the table = 29.3

PCN egg numbers/g soil differed significantly between both soil types and trap crops (P<0.001 in each case, Table 17). Egg numbers declined in all soil types in the presence of trap crops. The impact was greatest in the peaty loam where egg numbers decreased on average by 62% over the duration of the study. In the silt loam and loamy sand the equivalent figures were 17% and 38%, respectively.

Table 17. Mean PCN egg number/g soil as a percentage of the initial population

Trap crop	**Soil type**			
	Silt loam	**Loamy sand**	**Peaty loam**	**Mean**
Black nightshade 1	21	70	26	39
Black nightshade 2	33	35	3	24
Sticky nightshade 1	79	10	44	44
Sticky nightshade 2	117	47	55	73
Thornapple	97	78	66	80
Woody nightshade	129	137	27	98
Unspecified *Solanum* spp	35	40	14	30
Spring barley	155	76	72	101
Mean	83	62	38	

SED (46 df) for comparison of soil type means = 11.4
SED (46 df) for comparison of trap crop means = 18.6
SED (46 df) for comparisons within the body of the table = 32.3

Data on the number of eggs/g soil as a percentage of the initial population for each replicate of the four best trap crops (36 values) are given in Table 18. The analysis of variance did not indicate any statistically significant interactions between soil type and trap crops, but data in Table 18 suggest that some trap crops are most effective in particular soil types. Sticky nightshade (ex Chiltern seeds) was most effective in loamy sand and black nightshade (both sources) in peaty loam.

Table 18. Mean PCN egg number/g soil as a percentage of the initial population for individual replicates for the four best trap crop species

Trap crop	**Replicate**	**Soil type**		
		Silt loam	**Loamy sand**	**Peaty loam**
Black nightshade 1	1	37	4	27
	2	20	115	11
	3	8	62	34
Black nightshade 2	1	6	47	1
	2	61	33	3
	3	31	28	7
Sticky nightshade 1	1	87	14	93
	2	62	11	8
	3	80	8	36
Unspecified *Solanum* spp	1	18	67	13
	2	38	33	27
	3	47	44	27

The number of PCN eggs/cyst differed significantly between soil type (P<0.01) and trap crop (P<0.001,Table 19). In the peaty loam the number of eggs per cyst decreased by 61% over the duration of the study. The equivalent figures for the silt loam and the loamy sand were 31% and 41%, respectively.

Table 19. Mean number of PCN eggs/cyst as a percentage of the initial population

Trap crop	**Soil type**			
	Silt loam	**Loamy sand**	**Peaty loam**	**Mean**
Black nightshade 1	22	60	24	35
Black nightshade 2	36	36	4	25
Sticky nightshade 1	76	11	46	44
Sticky nightshade 2	93	42	46	60
Thorn-apple	88	72	68	76
Woody nightshade	75	108	29	71
Unspecified *Solanum* spp	34	48	22	35
Spring barley	130	96	76	101
Mean	69	59	39	

SED (46 df) for comparison of soil type means = 8.7
SED (46 df) for comparison of trap crop means = 14.3
SED (46 df) for comparisons within the body of the table = 24.7

Black nightshade 2 (ex Swindon) was again the most effective trap crop and reduced egg numbers per cyst by approximately 75%. This was followed by the unspecified *Solanum* spp and black nightshade 1 (ex Shropshire), both showing reductions of 65%

4.1.2. To quantify some of the agronomic requirements for growing and destroying the trap crop (ADAS, Boxworth)

There was a wide variation in the emergence of the trap crops (Table 20). Sticky nightshade 1 had the highest level of emergence and thornapple the lowest.

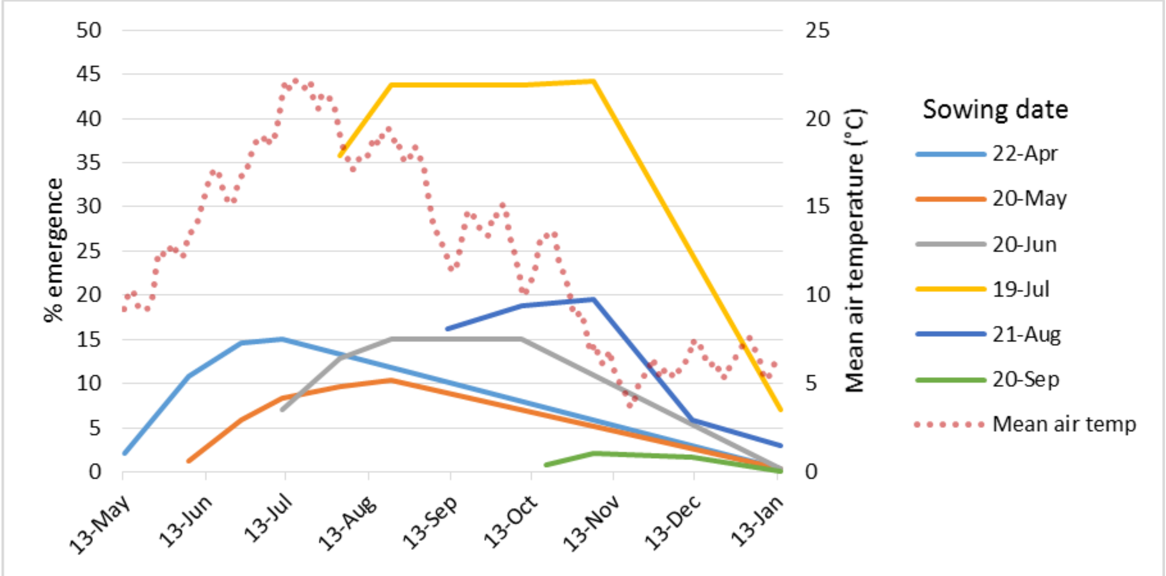
Table 20. Maximum % emergence of trap crops

Trap crop		**Source**	**Maximum emergence (%)**
Common name	**Latin name**		
Black nightshade 1	*Solanum nigrum*	ex Shropshire	44
Black nightshade 2	*S. nigrum*	ex Swindon	41
Sticky nightshade 1	*S. sisymbriifolium*	ex Chiltern seeds	66
Sticky nightshade 2	*S. sisymbriifolium*	Barworth Agriculture	31
Thorn-apple	*Datura stramonium*	Herbiseed	4
Woody nightshade	*S. dulcamara*	Herbiseed	12

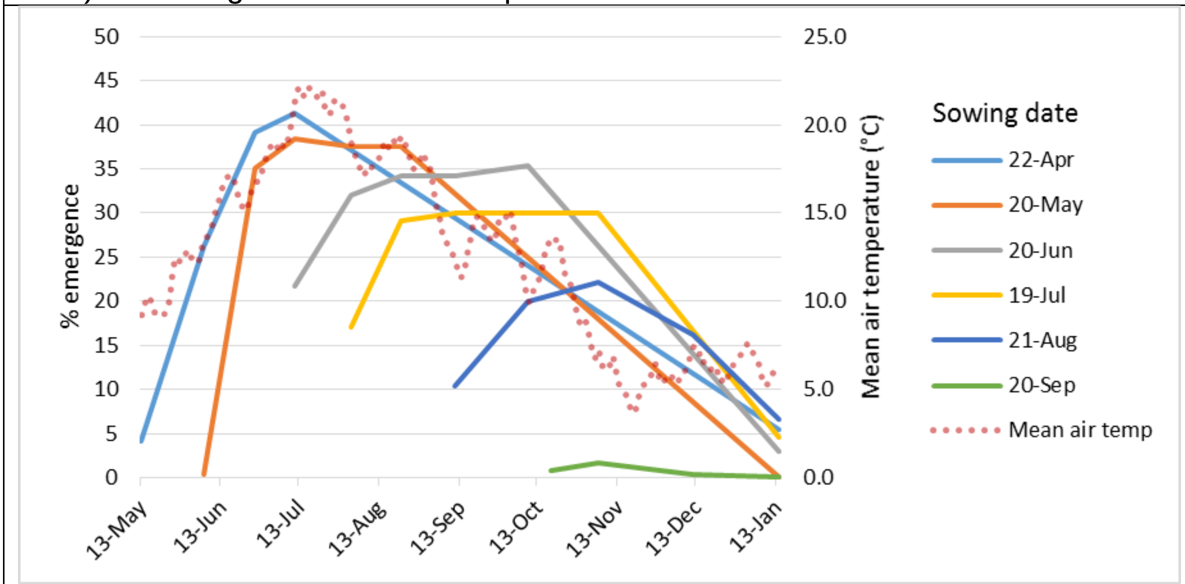
In the following figures, percentage emergence and mean air temperature were plotted against time for all of the species tested.

Black nightshade

There was a wide variation in emergence between the seed lots of black nightshade (Figure 1). Emergence of the seed lot from Shropshire was less than that from Swindon. Emergence from the Shropshire seed lot was variable and did not correspond well to mean air temperature (Figure 1a). In contrast, emergence of the ex-Swindon seed lot declined as sowing date became later (Figure 1b) and this correlated well with mean air temperature.



a) Black nightshade – ex Shropshire

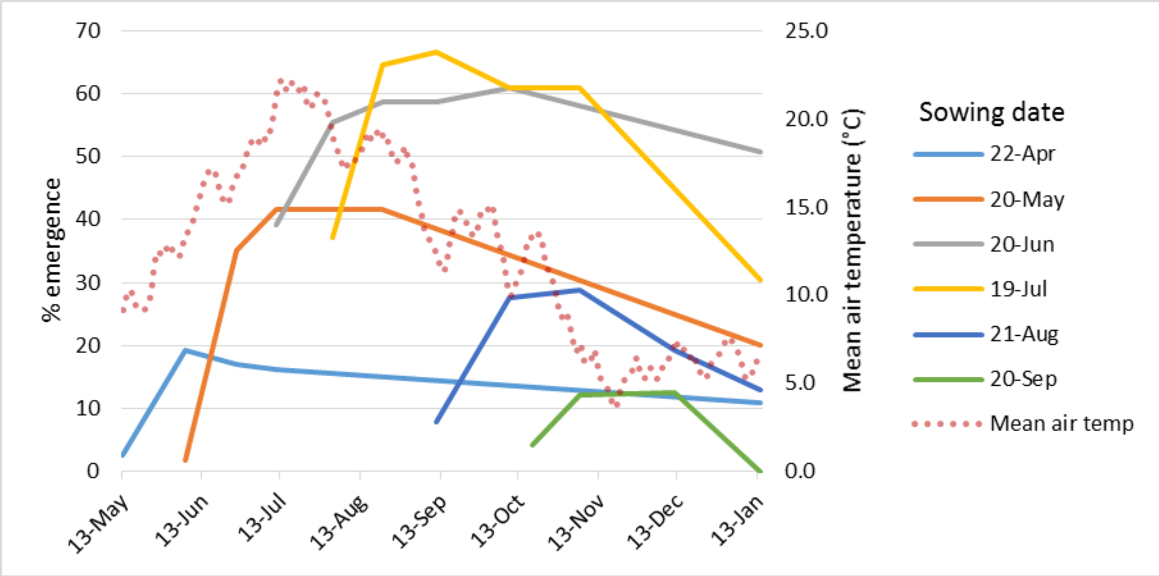


b) Black nightshade – Ex Swindon

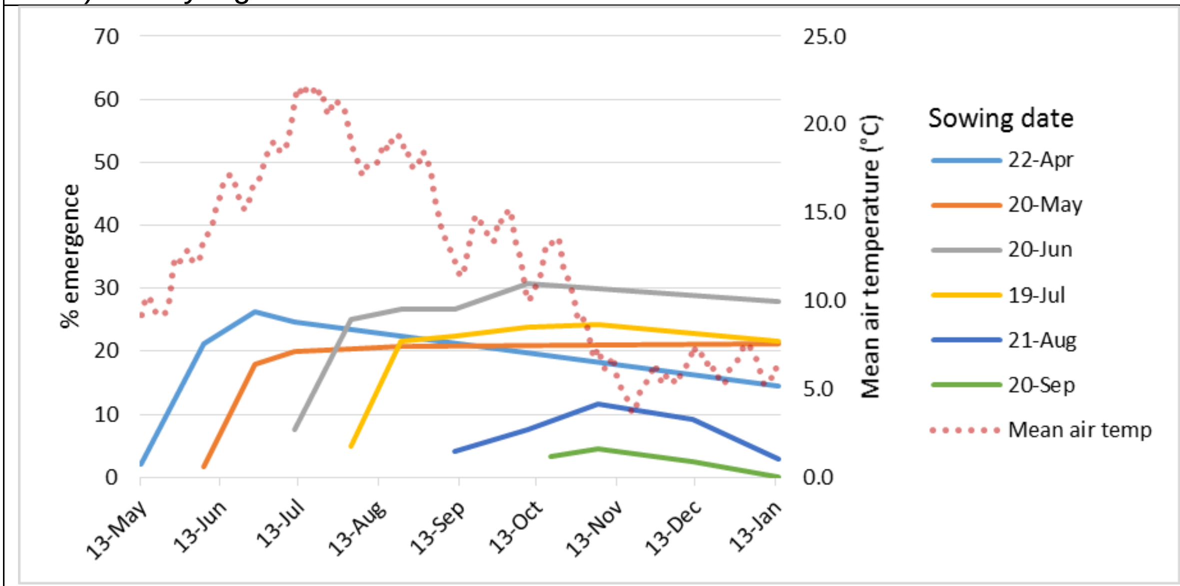
Figure 1. Emergence of black nightshade (*Solanum nigrum*)

Sticky nightshade

Emergence of the ex-Chiltern sticky nightshade was the highest of all the trap crop species. Emergence reached a peak (approximately 70%) at the July sowing but then declined rapidly at the August and September drillings (Figure 2a). There was a degree of correlation between emergence and mean air temperature. The Barworth Agriculture sticky nightshade was less viable than that from Chiltern with maximum emergence (approximately 30%) at the June sowing date (Figure 2b).



a) Sticky nightshade – ex Chiltern



b) Sticky nightshade – Barworth Agriculture

Figure 2. Emergence of sticky nightshade (*Solanum sisymbriifolium*)

Thornapple

Emergence of thorn-apple was poor and never exceeded 4% of seed sown. There was no obvious correlation with mean air temperature (Figure 3).

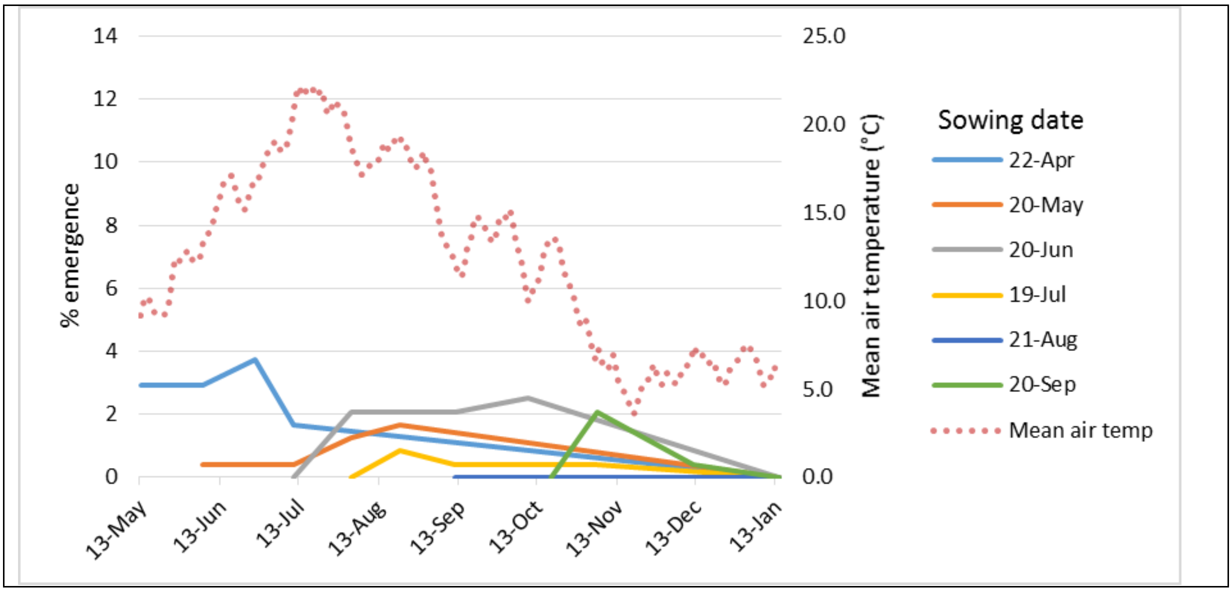


Figure 3. Emergence of thorn-apple (*Datura stramonium*).

Woody nightshade
Emergence of woody nightshade was also poor and did not exceed 12% of seed sown. Emergence appeared to correlate with mean air temperature (Figure 4).

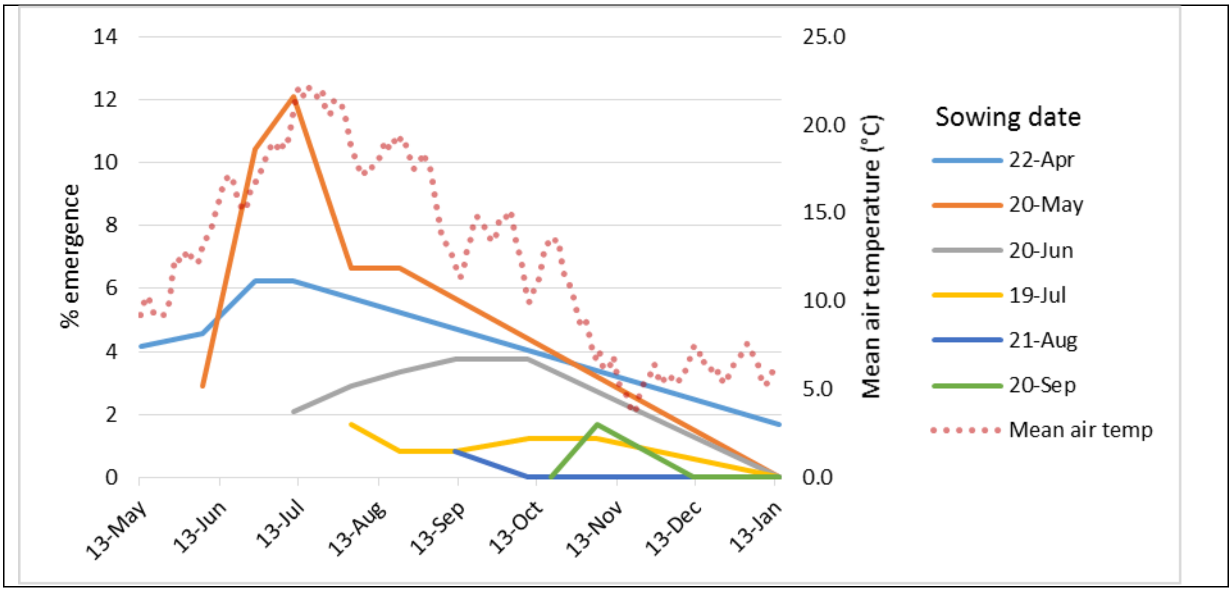


Figure 4. Emergence of Woody nightshade (*Solanum dulcamara*)

All species
The rate of emergence of each species was calculated and related to the mean air temperature for the period of maximum emergence (Table 21). For the majority of the black and sticky nightshade seed lots the period of maximum emergence corresponded to an average temperature of 21.5°C, the one exception was the Swindon black-nightshade for which maximum emergence was at 16.5°C.

Table 21. Maximum emergence rate (plants/day) and mean air temperature for this period °C)

Trap crop		Source	Max rate of emergence plants/day	Av temp at which this occurs (°C)
Common name	**Latin name**			
Black nightshade 1	*S. nigrum*	Ex Shropshire	1.63	21.5
Black nightshade 2	*S. nigrum*	Ex Swindon	5.76	16.9
Sticky nightshade 1	*S. sisymbriifolium*	Ex Chiltern seeds	2.56	21.5
Sticky nightshade 2	*S.sisymbriifolium*	Barworth Agriculture	2.71	21.5
Thornapple	*Datura stramonium*	Herbiseed	Too few seeds emerged	
Woody nightshade	*S. dulcamara*	Herbiseed	1.25	16.9

Winter survival

Sticky nightshade had the highest percentage of surviving plants over winter (Table 22). Only a small percentage of late sown black nightshade plants survived and no thornapple or woody nightshade. However, winter 2013-2014 was relatively mild with few frosts so could not be considered typical for the area (Boxworth, Cambridgeshire; Figure 5).

Table 22. Percentage of plants remaining alive on 14 January 2014

Trap crop		Source	Sowing date					
Common name	**Latin name**		**22 Apr**	**20 May**	**20 Jun**	**19 Jul**	**21 Aug**	**20 Sep**
Black nightshade 1	*S. nigrum*	Ex Shropshire	0	0	0	4	2	0
Black nightshade 2	*S. nigrum*	Ex Swindon	4	0	2	3	4	0
Sticky nightshade 1	*S. sisymbriifolium*	Ex Chiltern seeds	7	12	31	20	8	0
Sticky nightshade 2	*S. sisymbriifolium*	Barworth Agriculture	9	15	17	13	2	0
Thornapple	*Datura stramonium*	Herbiseed	0	0	0	0	0	0
Woody nightshade	*S. dulcamara*	Herbiseed	0	0	0	0	0	0

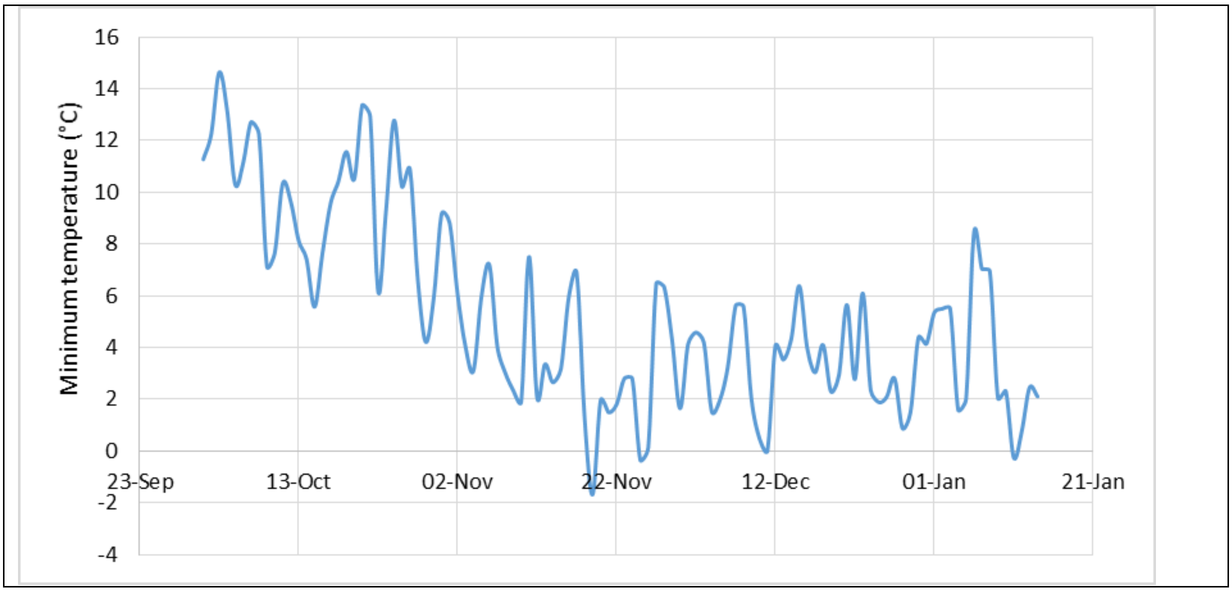


Figure 5. Minimum temperatures at ADAS Boxworth September 2013 to January 2014

4.2. Year 2: 2014/15

4.2.1. Experiment 1. Evaluation of optimum sowing date and seed rate for trap crops (ADAS, High Mowthorpe and Boxworth).

The PCN population in the silt soil used at both High Mowthorpe and Boxworth had a mean of 41 eggs/g soil and 27 cysts/100g. This count is in the ADAS moderate category (11-60 eggs/g soil) and provided a robust test of the trap crops.

Proportion of trap crops that established at each sowing date
Black nightshade and the unspecified *Solanum* spp generally established better than sticky nightshade at both Boxworth and High Mowthorpe (Table 23, 24).

Table 23. Mean number of trap crop plants of each species established across all sowing dates and target populations at Boxworth

Species	**Sowing date**	**Target population (plants/pot)**		
		1	**3**	**6**
Black nightshade	April	1.0	3.0	5.0
	June	1.0	2.3	6.0
	July	0.7	2.7	4.7
	August	1.0	2.7	4.0
	September	0.3	2.0	2.7
Sticky nightshade	April	0.7	2.3	5.0
	June	0.3	1.7	1.7
	July	0.7	0.3	1.0
	August	0.3	2.0	5.0
	September	0.3	1.7	4.0
Unspecified *Solanum* spp	April	1.0	2.0	6.0
	June	1.0	3.0	4.0
	July	1.3	2.3	2.7
	August	0.7	2.0	2.3
	September	1.0	0.3	4.0

Table 24. Mean number of trap crop plants of each species established across all sowing dates and target populations at High Mowthorpe

Species	**Sowing date**	**Target population (plants/pot)**		
		1	**3**	**6**
Black nightshade	22 April	1.0	3.0	6.0
	4 June	1	3	5
	10 July	0.3	1.0	2.0
	26 August	1.0	2.7	5.3
Sticky nightshade	22 April	1.0	2.0	2.7
	4 June	0.3	1.7	1.0
	10 July	0	1.0	1.3
	26 August	1.0	3.0	5.7
Unspecified *Solanum* spp	22 April	1.0	3.0	6.0
	4 June	1.0	3.0	5.3
	10 July	0	0	1.0
	26 August	1	1.7	5.0

Trap crops were sown at three seed rates to achieve a target of 1, 3 or 6 plants per plot. The percentage of trap crops that ultimately established in relation to the target population was calculated and subjected to the analysis of variance. The final sowing date at High Mowthorpe in September 2014 was omitted from the analysis as so few plants established.

At Boxworth trap crop establishment differed significantly between sowing dates and trap crop species ($P<0.01$ in each case, Tables 25 and 26). Establishment was best in

April and June and worst in September. Both black nightshade and the unspecified *Solanum* spp established better than sticky nightshade.

Table 25. Mean trap crop species establishment as a percentage of the target population for each trap crop across all target plant populations and sowing dates at Boxworth

Species	**Sowing date**	**Target population (plants/pot)**			**Mean**	**Mean species**
		1	**3**	**6**		
Black nightshade	April	100	100	83.3	94.4	79.6
	June	100	77.8	100	92.6	
	July	66.7	88.9	77.8	77.8	
	August	100	88.9	66.7	85.2	
	September	33.3	66.7	44.4	48.1	
	Mean	80.0	84.4	74.4		
Sticky nightshade	April	66.7	77.8	83.3	75.9	51.9
	June	33.3	55.6	27.8	38.9	
	July	66.7	11.1	16.7	31.5	
	August	33.3	66.7	83.3	61.1	
	September	33.3	55.6	66.7	51.9	
	Mean	46.7	53.3	55.6		
Unspecified *Solanum* spp	April	100	66.7	100	88.9	74.8
	June	100	100	100	100	
	July	100	77.8	44.4	74.1	
	August	66.7	66.7	38.9	57.4	
	September	66.7	11.1	66.7	48.1	
	Mean	86.7	64.4	73.3		
	Mean target population	71.1	67.4	67.8		

SED (70 df) for comparison of trap crop species means = 8.19
SED (70 df) for comparison of target population means = 8.19
SED (70 df) for comparison of trap crop species within sow date = 18.32
SED (70 df) for comparison of trap crop species within target population = 14.19
SED (70 df) for comparison within the body of the table = 31.73

Table 26. Mean trap crop species establishment as a percentage of the target plant population across all sowing dates and target populations at Boxworth

Sowing date	Target population (plants/pot)			Mean
	1	3	6	
April	88.9	81.5	88.9	86.4
June	77.8	77.8	81.5	79.0
July	77.8	59.3	46.3	61.1
August	66.7	74.1	63.0	67.9
September	44.4	44.4	59.3	49.4

SED (70 df) for comparison of sow date means = 10.58
SED (70 df) for comparison of sow date means within target populations = 18.32

At High Mowthorpe there was a significant interaction between trap crop species and sowing date (P<0.001, Tables 27 & 28). The ranking of percentage establishment varied between trap crop species across sowing dates. Black nightshade and the unspecified *Solanum* spp showed the best establishment in April and June (there was no sowing date in May). In contrast, sticky nightshade showed best emergence in August.

For all species, plant establishment was much lower in July than at all other sowing dates.

Table 27. Mean trap crop species establishment as a percentage of the target population for each trap crop, target plant populations and sowing dates at High Mowthorpe

Species	**Sowing date**	**Target population (plants/pot)**			**Mean**	**Mean species**
		1	**3**	**6**		
Black nightshade	April	100	100	100	100	80.1
	June	100	100	83.3	94.4	
	July	33.3	33.3	33.3	33.3	
	August	100	88.9	88.9	92.6	
	Mean	83.3	80.6	76.4		
Sticky nightshade	April	100	66.7	44.4	70.4	55.6
	June	33.3	55.6	16.7	35.2	
	July	0	33.3	22.2	18.5	
	August	100	100	94.4	98.1	
	Mean	58.3	63.9	44.4		
Unspecified *Solanum* spp	April	100	100	100	100	70.4
	June	100	100	88.9	96.3	
	July	0	0	16.7	5.6	
	August	100	55.6	83.3	79.6	
	Mean	75.0	63.9	72.2		
	Mean target population	72.2	69.4	64.4		

SED (70 df) for comparison of trap crop species means = 4.88
SED (70 df) for comparison of target population means = 4.88
SED (70 df) for comparison of trap crop species within sow date = 9.76
SED (70 df) for comparison of trap crop species within target population = 8.45
SED (70 df) for comparisons within the body of the table = 16.90

Table 28. Mean trap crop species emergence as a percentage of the target population across all sowing dates and target populations at High Mowthorpe

Sowing date	**Target population (plants/pot)**			**Mean**
	1	**3**	**6**	
April	100.0	88.9	81.5	90.1
June	77.8	85.2	63.0	75.3
July	11.1	22.2	24.1	19.1
August	100.0	81.5	88.9	90.1

SED (70 df) for comparison of sow date means = 5.63
SED (70 df) for comparison of sow date means within target populations = 9.76

Root dry weight per plant

At Boxworth, there was a significant interaction in root dry weight between trap crop species, sowing date and target population (P<0.05, Table 29 & 30). This was probably due to a highly significant interaction between trap crop species and sowing date (P<0.001), a highly significant interaction between trap crop species and target population (P<0.001) and a significant interaction between sowing date and target population (P<0.01). Root dry weight tended to decrease as sowing date became later, and with increasing target population, and the unspecified *Solanum* spp had a higher root dry weight than sticky nightshade which in turn had a higher dry weight than black nightshade. However, these rankings were not consistent when compared across trap crop species, sowing date and target population.

Table 29. Mean root dry weight of trap crop species/plant across all trap crop species, target populations and sowing dates at Boxworth

Species	**Sowing date**	**Target population (plants/pot)**			**Mean**	**Mean species**
		1	**3**	**6**		
Black nightshade	April	1.56	0.42	0.47	0.82	0.75
	June	3.74	0.87	0.45	1.69	
	July	0.88	0.59	0.66	0.71	
	August	0.04	0.42	0.05	0.17	
	September	0.75	0.28	0.00	0.35	
	Mean	1.39	0.52	0.33		
Sticky nightshade	April	2.75	4.37	1.49	2.87	1.38
	June	2.05	2.32	2.36	2.24	
	July	1.48	3.02	1.43	1.98	
	August	0.00	0.16	0.08	0.00	
	September	0.00	0.28	0.00	0.00	
	Mean	1.12	2.03	1.00		
Unspecified *Solanum* spp	April	18.13	8.20	3.05	9.79	5.12
	June	17.66	7.53	5.12	10.10	
	July	6.16	5.01	4.33	5.17	
	August	1.26	0.42	0.00	0.54	
	September	0.10	0.00	0.00	0.00	
	Mean	8.66	4.19	2.49		
	Mean target population	3.73	2.25	1.27		

SED (70 df) for comparison of trap crop species means = 0.501
SED (70 df) for comparison of target population means = 0.501
SED (70 df) for comparison of trap crop species within sow date = 1.120
SED (70 df) for comparison of trap crop species within target population = 0.868
SED (70 df) for comparison within the body of the table = 1.941

Table 30. Mean trap crop root dry weight/plant across all sowing dates and target populations at Boxworth

Sowing date	**Target population (plants/pot)**			**Mean**
	1	**3**	**6**	
April	7.48	4.33	1.67	4.49
June	7.82	3.57	2.64	4.58
July	2.84	2.87	2.14	2.41
August	0.27	0.34	0.02	0.21
September	0.23	0.13	0	0.07

SED (70 df) for comparison of sow date means = 0.647
SED (70 df) for comparison of sow date means within target populations = 1.120

At High Mowthorpe, there were highly significant interactions between trap crop species and sowing date, trap crop species and target population, sowing date and target population and trap crop species, sowing date and target population ($P<0.001$ in each case, Tables 31 & 32). There was no consistent ranking of root dry weight of trap crop species across sowing dates and the root dry weight of the unspecified *Solanum* spp was much higher than for both other trap crops. In general, the unspecified *Solanum* spp had the highest root dry weight followed by black nightshade and sticky nightshade. Root dry weight tended to decrease with increasing plant population and root dry weight at the August sowing was much lower than at other sowing dates.

Table 31. Mean root dry weight of trap crop species/plant across all trap crop species, target populations and sowing dates at High Mowthorpe

Species	Sow date	Target population (plants/pot)			Mean	Mean species
		1	3	6		
Black nightshade	April	2.61	1.48	0.78	1.62	1.84
	June	3.47	1.37	0.95	1.93	
	July	2.22	4.93	2.98	4.60	
	August	0.23	0.31	0.69	0.41	
	Mean	2.14	2.02	1.35		
Sticky nightshade	April	3.06	1.93	0.95	1.98	1.13
	June	1.75	2.24	2.50	3.62	
	July	0	0.31	0.30	0.11	
	August	0.20	0.16	0.21	0.19	
	Mean	1.25	1.16	0.99		
Unspecified *Solanum* spp	April	32.24	16.11	4.56	17.84	8.76
	June	28.99	6.94	2.34	12.76	
	July	0	0	11.40	23.57	
	August	0.73	1.26	0.57	0.85	
	Mean	15.49	6.08	4.71		
	Mean target popn	6.29	3.09	2.35		

SED (70 df) for comparison of trap crop species means = 1.122
SED (70 df) for comparison of target population means = 1.122
SED (70 df) for comparison of trap crop species within sow date = 2.244
SED (70 df) for comparison of trap crop species within target population = 1.943
SED (70 df) for comparisons within the body of the table = 3.887

Table 32. Mean trap crop root dry weight/plant across all sowing dates and target populations at High Mowthorpe

Sowing date	Target population (plants/pot)			Mean
	1	3	6	
April	12.64	6.51	2.09	7.08
June	11.41	3.52	1.93	5.62
July	0.74	1.75	4.89	2.46
August	0.39	0.57	0.49	0.48

SED (70 df) for comparison of sow date means = 1.296
SED (70 df) for comparison of sow date means within target populations = 2.244

Analysis of PCN levels

Initial (Pi) and final (Pf) PCN populations were determined for each experimental pot (Tables 33-36). Some data points were omitted from the analysis of variance and treated as missing values if the initial PCN egg or cyst count was 10 or less. This was because any change in the final value would have a disproportionately high impact on the calculation of Pf/Pi x 100. If the Pf/Pi x 100 for cyst numbers was also over 200%, this value was omitted from the analysis and considered as a missing value.

At Boxworth, the initial counts of PCN cysts/100g soil varied between 5 and 58 cysts/100g soil. It was particularly noticeable that the cyst counts were higher for the September sowing than for all others. Final cyst counts varied between 6 and 64 cysts/100g of soil with the final sowing date again having the highest count.

Table 33. Pi and Pf values: Mean numbers of PCN cysts/100g soil for each combination of trap crop, sowing date and target plant population at Boxworth

Species	**Sow date [E]***	**Target population (plants/pot)**					
		1		**3**		**6**	
		Pi	Pf	Pi	Pf	Pi	Pf
Black nightshade	April [281]	14	12	13	7	17	8
	June [238]	12	11	17	9	14	7
	July [202]	12	6	7	10	12	9
	August [155]	7	7	9	8	9	9
	Sept [128]	43	49	39	54	35	40
Sticky nightshade	April [281]	19	11	17	9	13	12
	June [238]	11	11	15	16	14	10
	July [202]	8	12	13	11	10	6
	August [155]	10	11	13	16	8	10
	Sept [128]	36	38	33	38	28	32
Unspecified *Solanum* spp	April [281]	17	7	14	8	16	12
	June [238]	13	9	12	6	12	8
	July [202]	12	10	9	9	13	12
	August [155]	7	10	12	11	5	11
	Sept [128]	48	44	58	64	24	24

[E]* = exposure period in days (see Table 5 for details)

At Boxworth, the number of eggs/g soil varied between 16 and 107 eggs/g soil for the Pi counts and between 2 and 108 eggs/g soil for the Pf counts (Table 34). In 42 of 45 (93%) of paired combinations of Pi and Pf values, the Pf value was lower than the Pi value. As expected in view of the high cyst counts, egg counts at the final sowing in September were higher than for all other sowing dates.

Table 34. Pi and Pf values: Mean numbers of PCN eggs/g soil for each combination of trap crop, sowing date and target population at Boxworth

Species	**Sowing date**	**Target population (plants/pot)**					
		1		**3**		**6**	
		Pi	**Pf**	**Pi**	**Pf**	**Pi**	**Pf**
Black nightshade	April	21	5	23	4	24	3
	June	16	9	35	8	32	3
	July	33	8	31	12	29	9
	August	21	16	27	19	25	20
	September	78	108	94	93	88	61
Sticky nightshade	April	31	12	35	11	28	12
	June	33	9	28	12	29	15
	July	23	18	21	22	28	9
	August	30	27	51	31	28	24
	September	71	70	76	57	78	45
Unspecified *Solanum* spp	April	33	6	26	6	28	7
	June	30	10	32	6	23	7
	July	38	2	21	21	28	17
	August	25	16	38	21	29	24
	September	107	64	88	67	38	49

At High Mowthorpe, numbers of cysts varied between 4 and 14 cysts/100 g soil for both Pi and Pf values (Table 35). There was little difference between the initial number of cysts and the final number in most paired combinations of trap crop species, sowing date and target population.

Table 35. Pi and Pf values: Mean numbers of PCN cysts/100g soil for each combination of trap crop, sowing date and target population at High Mowthorpe

Species	**Sow date [E]***	**Target population (plants/pot)**					
		1		**3**		**6**	
		Pi	**Pf**	**Pi**	**Pf**	**Pi**	**Pf**
Black nightshade	April [226]	13	12	11	9	13	8
	June [183]	8	11	6	7	14	16
	July [147]	8	4	14	8	14	7
	August [100]	4	6	6	6	7	8
Sticky nightshade	April [226]	9	8	11	10	11	12
	June [183]	11	6	12	8	8	8
	July [147]	7	4	12	10	12	7
	August [100]	7	10	6	7	5	8
Unspecified *Solanum* spp	April [226]	10	12	15	10	7	10
	June [183]	10	9	9	8	10	9
	July [147]	8	9	14	14	12	11
	August [100]	7	7	4	7	8	10

At High Mowthorpe, the number of eggs/g soil varied between 14 and 40 eggs/g soil for the Pi counts and between 12 and 24 eggs/g soil for the Pf counts (Table 36). In 31 of 35 (86%) of paired combinations of Pi and Pf values the Pf value was lower than the Pi value.

Table 36. Pi and Pf values: Mean numbers of PCN eggs/g soil for each combination of trap crop, sowing date and target population at High Mowthorpe

Species	**Sow date**	**Target population**					
		1		**3**		**6**	
		Pi	**Pf**	**Pi**	**Pf**	**Pi**	**Pf**
Black nightshade	April	27	16	33	11	32	8
	June	33	22	20	16	28	23
	July	23	6	35	17	31	9
	Aug	23	17	30	13	32	18
Sticky nightshade	April	20	12	24	13	30	18
	June	32	14	30	19	16	17
	July	22	11	20	21	28	22
	Aug	31	23	20	20	14	18
Unspecified *Solanum* spp	April	23	15	40	17	27	15
	June	31	22	22	21	29	11
	July	21	12	30	24	29	17
	Aug	25	14	27	14	21	21

At Boxworth, cyst number, as a percentage of the initial population, differed significantly between sowing dates ($P<0.001$, Table 37, 38). Cyst numbers increased compared with the initial population for both August and September sowings.

Table 37. Mean PCN cyst numbers/100g soil as a percentage of the original population (Pi/Pf x 100) for each trap crop species, target plant population and sowing dates at Boxworth

Species	**Sowing date**	**Target population (plants/pot)**			**Mean**	**Mean species**
		1	**3**	**6**		
Black nightshade	April	97	58	46	67	89
	June	95	56	50	67	
	July	48	135	78	87	
	August	108	91	104	101	
	Sept	116	129	119	121	
	Mean	93	94	79		
Sticky nightshade	April	56	59	67	60	92
	June	70	45	58	58	
	July	131	89	103	108	
	August	102	122	138	121	
	Sept	103	113	120	112	
	Mean	92	86	97		
Unspecified *Solanum* spp	April	43	63	73	60	99
	June	68	76	88	77	
	July	85	103	95	95	
	August	208	102	170	160	
	Sept	96	115	102	104	
	Mean	100	92	105		
	Mean target population	95	90	94		

SED (70 df) for comparison of trap crop species means = 8.7
SED (70 df) for comparison of target population means = 8.7
SED (70 df) for comparison of trap crop species within sow date = 19.4
SED (70 df) for comparison of trap crop species within target population = 15.0
SED (70 df) for comparisons within the body of the table = 33.6

Table 38. Mean PCN cyst numbers/100 g soil as a percentage of the original population (Pi/Pf x 100) across all sowing dates and target populations at Boxworth

Sowing date	**Target population (plants/pot)**			**Mean**
	1	**3**	**6**	
April	65	60	62	62
June	78	59	65	67
July	88	109	92	96
August	139	105	137	127
September	105	119	113	113

SED (70 df) for comparison of sow date means = 11.2
SED (70 df) for comparison of sow date means within target populations = 19.4

At High Mowthorpe, cyst number as a percentage of the initial population did not differ significantly between species or target population (Table 39). There was a trend for numbers of cysts in pots of the unspecified *Solanum* spp to be higher than in pots of black or sticky nightshade.

Table 39. Mean PCN cyst numbers/100 g soil as a percentage of the original population (Pi/Pf x 100) for each all trap crop species, target plant population and sowing date at High Mowthorpe

Species	**Sowing date**	**Target population (plants/pot)**			**Mean**	**Mean species**
		1	**3**	**6**		
Black nightshade	April	102	80	70	84	95
	June	123	124	114	120	
	July	56	57	53	55	
	August	134	97	129	120	
	Mean					
Sticky nightshade	April	98	98	107	101	93
	June	55	71	108	78	
	July	53	84	62	67	
	August	138	113	125	125	
	Mean					
Unspecified *Solanum* spp	April	136	74	142	117	111
	June	86	86	91	88	
	July	97	119	110	109	
	August	103	154	130	129	
	Mean					
	Mean target population	98	96	104		

SED (70 df) for comparison of trap crop species means = 8.4
SED (70 df) for comparison of target population means = 8.4
SED (70 df) for comparison of trap crop species within sowing date = 16.7
SED (70 df) for comparison of trap crop species within target population = 14.5
SED (70 df) for comparisons within the body of the table = 29.0

There was a significant interaction between cyst numbers as a percentage of the final population between trap crop species and sowing date (P<0.05, Table 40). There was no consistent ranking of cyst number as a percentage of the initial population for trap crop species across the four sowing dates.

Table 40. Mean PCN cyst numbers/100 g soil as a percentage of the original population (Pi/Pf x 100) across all sowing dates and target populations at High Mowthorpe

Sowing date	**Target population (plants/pot)**			**Mean**
	1	**3**	**6**	
April	112	84	106	101
June	88	94	104	95
July	69	87	75	77
August	125	121	128	125

SED (70 df) for comparison of sowing date means = 9.7
SED (70 df) for comparison of sowing date means within target populations = 16.7

At Boxworth, egg number as a percentage of the initial population differed significantly between sowing dates (P<0.001, Tables 41 & 42). The efficacy of control of PCN declined the later the trap crops were sown. There was no statistically significant effect of trap crop species or target population on reduction of PCN egg numbers.

Table 41. Mean PCN egg numbers/g soil as a percentage of the original population (Pi/Pf x 100) for each trap crop species, target plant populations and sowing dates at Boxworth.

Species	**Sowing date**	**Target population (plants/pot)**			**Mean**	**Mean species**
		1	**3**	**6**		
Black nightshade	April	23	25	14	21	55
	June	53	23	11	29	
	July	24	39	30	31	
	August	74	108	84	89	
	Sept	127	92	93	104	
	Mean	**60**	**58**	**46**		
Sticky nightshade	April	37	33	47	39	66
	June	36	48	69	51	
	July	85	113	44	81	
	August	88	70	89	82	
	Sept	102	71	64	79	
	Mean	**70**	**67**	**63**		
Unspecified *Solanum* spp	April	19	25	27	24	54
	June	39	21	37	32	
	July	0	110	69	59	
	August	81	54	66	67	
	Sept	62	79	126	89	
	Mean	**40**	**58**	**65**		
	Mean target population	57	61	58		

SED (70 df) for comparison of trap crop species means = 7.4
SED (70 df) for comparison of target population means = 7.4
SED (70 df) for comparison of trap crop species within sowing date = 16.5
SED (70 df) for comparison of trap crop species within target population = 12.8
SED (70 df) for comparisons within the body of the table = 28.6

Table 42. Mean PCN egg numbers/g soil across all three trap crop species as a percentage of the original population (Pi/Pf x 100) across all sowing dates and target populations at Boxworth

Sowing date	Target population (plants/pot)			Mean
	1	3	6	
April	26	27	30	28
June	42	31	39	37
July	36	87	48	57
August	81	78	80	80
September	97	81	94	91

SED (70 df) for comparison of sowing date means = 19.1
SED (70 df) for comparison of sowing date means within target populations = 33.1

At High Mowthorpe, egg numbers as a percentage of the initial population differed significantly between trap crop species (P<0.05, Table 43). Black nightshade reduced egg numbers by 45% compared with 27% for the unspecified *Solanum* spp and 23% for sticky nightshade. There was no statistically significant effect of sowing date or target population, nor any interaction between these variables for egg number as a percentage of the initial population.

Table 43. Mean PCN egg numbers/g soil as a percentage of the original population (Pi/Pf x 100) across all trap crop species, target populations and sowing dates at High Mowthorpe.

Species	Sowing date	Target population (plants/pot)			Mean	Mean species
		1	3	6		
Black nightshade	April	80	32	26	46	55
	June	78	78	85	80	
	July	28	79	34	37	
	August	73	45	56	58	
	Mean	**64**	**51**	**50**		
Sticky nightshade	April	69	56	60	62	77
	June	36	73	107	72	
	July	33	107	80	73	
	August	76	96	132	101	
	Mean	**53**	**83**	**95**		
Unspecified *Solanum* spp	April	68	72	63	67	73
	June	86	95	38	73	
	July	58	107	65	77	
	August	70	50	100	73	
	Mean	**70**	**81**	**67**		
	Mean target population	63	72	71		

SED (70 df) for comparison of trap crop species means = 8.5
SED (70 df) for comparison of target population means = 8.5
SED (70 df) for comparison of trap crop species within sowing date = 16.9
SED (70 df) for comparison of trap crop species within target population = 14.7
SED (70 df) for comparisons within the body of the table = 29.3

4.2.2. Herbicide screen (ADAS, Boxworth)

When assessed on 14 August, sown trap crop species (Table 44) were present in the relevant pots but were supplemented with plants that had germinated from the soil seed bank. Establishment of the unspecified *Solanum* spp and *S*. *sisymbriifolium* was poor

Weeds present included thornapple (*Datura stramonium),* brome *(Bromus spp),* annual meadow grass *(Poa annua),* bittercress *(Cardamine spp.),* sow thistle *(Sonchus spp.),* groundsel *(Senecio vulgaris),* willow herb *(Epilobium spp.)* and fat hen *(Chenapodium album).* Table 45 shows the weed spectrum and population on 14 August in the untreated pots. There were very few weeds (<1/m²) in the treated pots.

Where numbers of *S nigrum* seedlings were higher than the number of seeds sown this was due to seed present in the natural seedbank.

Table 44. Trap crop species count in the untreated pots (plants/m², 14 August 2014)

Species	Mean number per pot	Maximum number per pot
S. nigrum	20.0	57
Unspecified *Solanum* spp	8.4	16
S sisymbriifolium	0.8	9

Table 45. Untreated weed count (plants/m^2, 14 August 2014)

Species		Mean number per pot	Maximum number per pot
S. nigrum	Black nightshade	20.0	57
Unspecified *Solanum* spp		8.4	16
S sisymbriifolium	Sticky nightshade	0.8	9
Datura stramonium	Thorn apple	0.7	4
Bromus spp	Brome	0.4	2
Poa annua	Annual meadow grass	0.3	2
Cardamine spp.	Bittercress	0.0	2
Sonchus spp.	Sow thistle	0.1	1
Senecio vulgaris	Groundsel	0.1	1
Epilobium spp.	Willowherb	0.2	2
Chenapodium album	Fat hen	0.2	4

S. nigrum

This species did not survive application of Stomp Aqua, Defy or Artist. Shotput applied post emergence, and pre-emergence at the high rate (0.5 kg/ha), reduced survival by approximately 20% compared to that applied pre-emergence at 0.25 kg/ha.

High rates of Titus, Agroxone and Basagran reduced survival by 30%, 40% and 10% respectively compared with the lower rates. There was 100% survival at both rates of Centium 360 CS.

Unspecified *Solanum* spp

This species had a different tolerance to herbicides than *S. nigrum*. There was a greater level of survival following treatment with Stomp Aqua, Defy or Artist than that demonstrated by *S. nigrum* and there were clear rate responses; survival was greater at the lower doses.

Plant survival after the application of Shotput was similar whether the product was applied pre- or post-emergence. Doubling the application rate reduced survival by 50%. There was no difference in survival between the rates of Titus and Basagran. Agroxone at the higher rate reduced survival by 40% compared to the lower rate. There was 100% survival at the lower rate of Centium 360 CS, whilst increasing the rate reduced survival by 10%.

S. sisymbriifolium

Populations of this species were too low to draw any meaningful conclusions on the effectiveness of herbicides.

Table 46. Plant counts of *S. nigrum*, the unspecified *Solanum* spp *and S. sisymbriifolium* in the herbicide treatments (plants/pot) 14 August 2014

Timing	**Herbicide**	**Rate**	***S. nigrum***	**Unspecified *Solanum* spp**	***S. sisymbrifolium***
	Untreated		20.0	8.4	0.8
Pre	Centium 360 CS	0.09 L/ha	20.3	8.3	3.5
Pre	Centium 360 CS	0.18 L/ha	19.8	7.3	2.5
Pre	Shotput	0.25 kg/ha	23.5	6.5	5.0
Pre	Shotput	0.5 kg/ha	16.5	2.3	1.5
Post	Shotput	0.125 kg/ha	17.8	6.0	1.0
Post	Shotput	0.25 kg/ha	15.0	1.5	0.5
Pre	Stomp Aqua	1.5 L/ha	4.8	5.0	2.8
Pre	Stomp Aqua	3.0 L/ha	2.0	0.8	3.0
Pre	Defy	2.0 L/ha	3.0	4.0	4.3
Pre	Defy	4.0 L/ha	4.3	1.0	1.0
Pre	Artist	1.0 kg/ha	2.8	2.5	0.8
Pre	Artist	2.0 kg/ha	1.0	0.5	1.0
Post	Titus	25 g/ha	19.5	3.3	0.5
Post	Titus	50 g/ha	13.8	4.0	1.5
Post	Basagran SG	0.5 kg/ha	27.0	5.8	2.3
Post	Basagran SG	1.0 kg/ha	17.8	6.8	1.3
Post	Agroxone	0.85 L/ha	20.3	2.5	0
Post	Agroxone	1.7 Ll/ha	11.5	6.3	1.8
	F Probability		<0.001	0.011	0.004
	LSD		11.26	4.47	2.14

Table 47. Percent survival of *S. nigrum* and the unspecified *Solanum* spp assessed on 14 August 2014, compared to the untreated, following the herbicide treatments

Timing	**Herbicide**	**Rate**	***S. nigrum***	**Unspecified *Solanum* spp**
	Untreated		100	100
Pre	Centium 360 CS	0.09 L/ha	101	98
Pre	Centium 360 CS	0.18 L/ha	99	87
Pre	Shotput	0.25 kg/ha	118	78
Pre	Shotput	0.5 kg/ha	83	27
Post	Shotput	0.125 kg/ha	89	72
Post	Shotput	0.25 kg/ha	75	18
Pre	Stomp Aqua	1.5 L/ha	24	60
Pre	Stomp Aqua	3.0 L/ha	10	9
Pre	Defy	2.0 L/ha	15	48
Pre	Defy	4.0 L/ha	21	12
Pre	Artist	1.0 kg/ha	14	30
Pre	Artist	2.0 kg/ha	5	6
Post	Titus	25 g/ha	98	39
Post	Titus	50 g/ha	69	48
Post	Basagran SG	0.5 kg/ha	135	69
Post	Basagran SG	1.0 kg/ha	89	81
Post	Agroxone	0.85 L/ha	101	30
Post	Agroxone	1.7 L/ha	58	75
	F pr		<0.001	0.011
	LSD		56.31	53.36

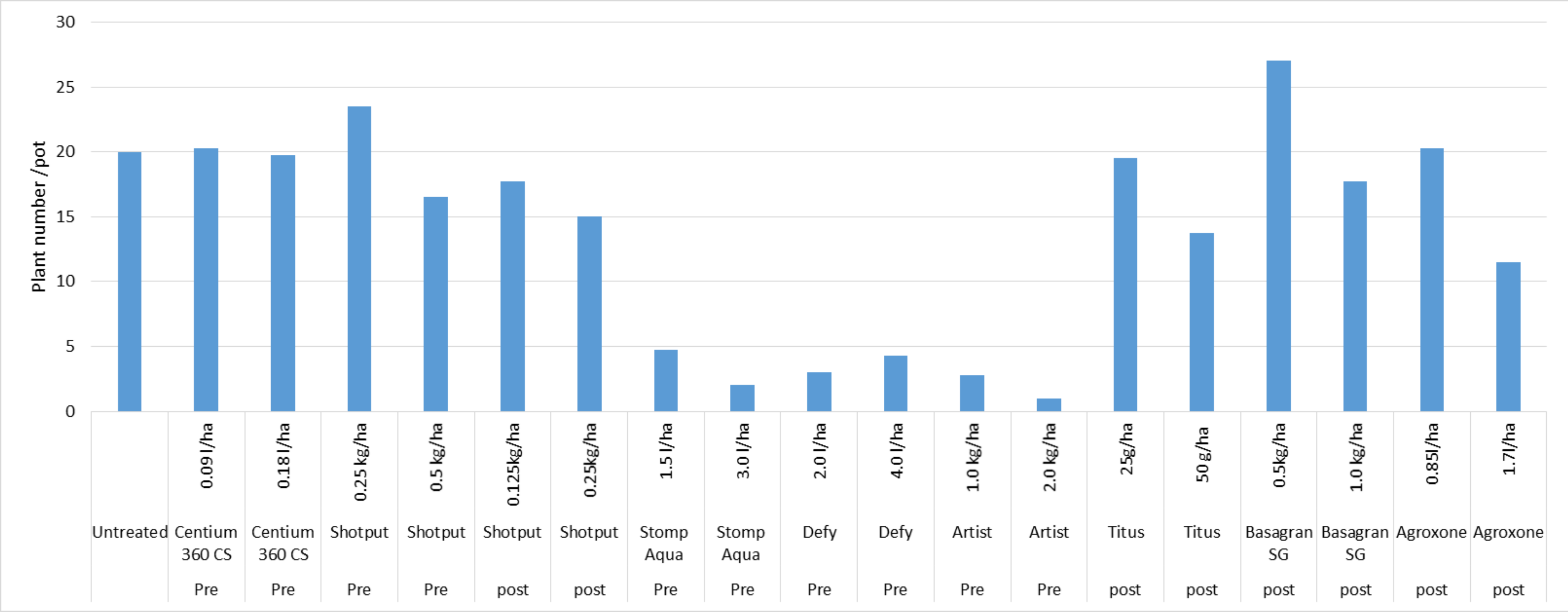


Figure 6. Plant number per pot of *Solanum nigrum* on 14 August 2014

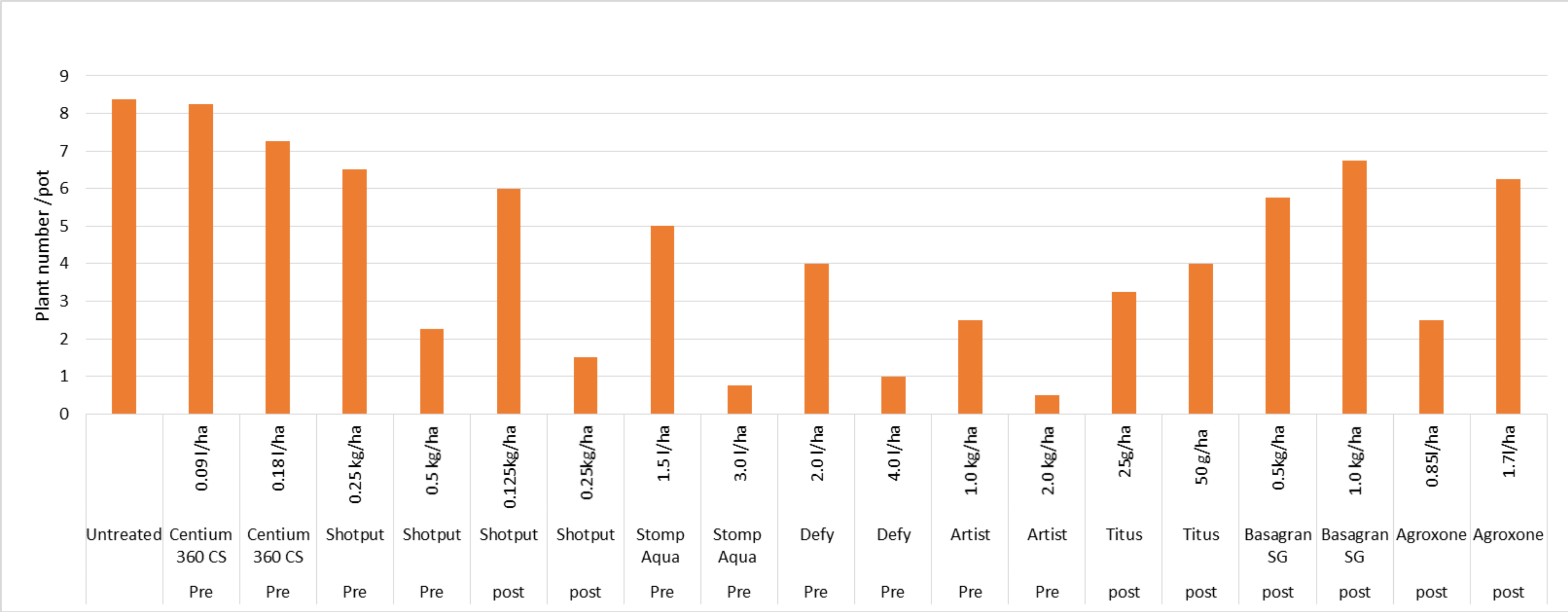


Figure 7. Plant number per pot of the unspecified *Solanum* spp on 14 August 2014

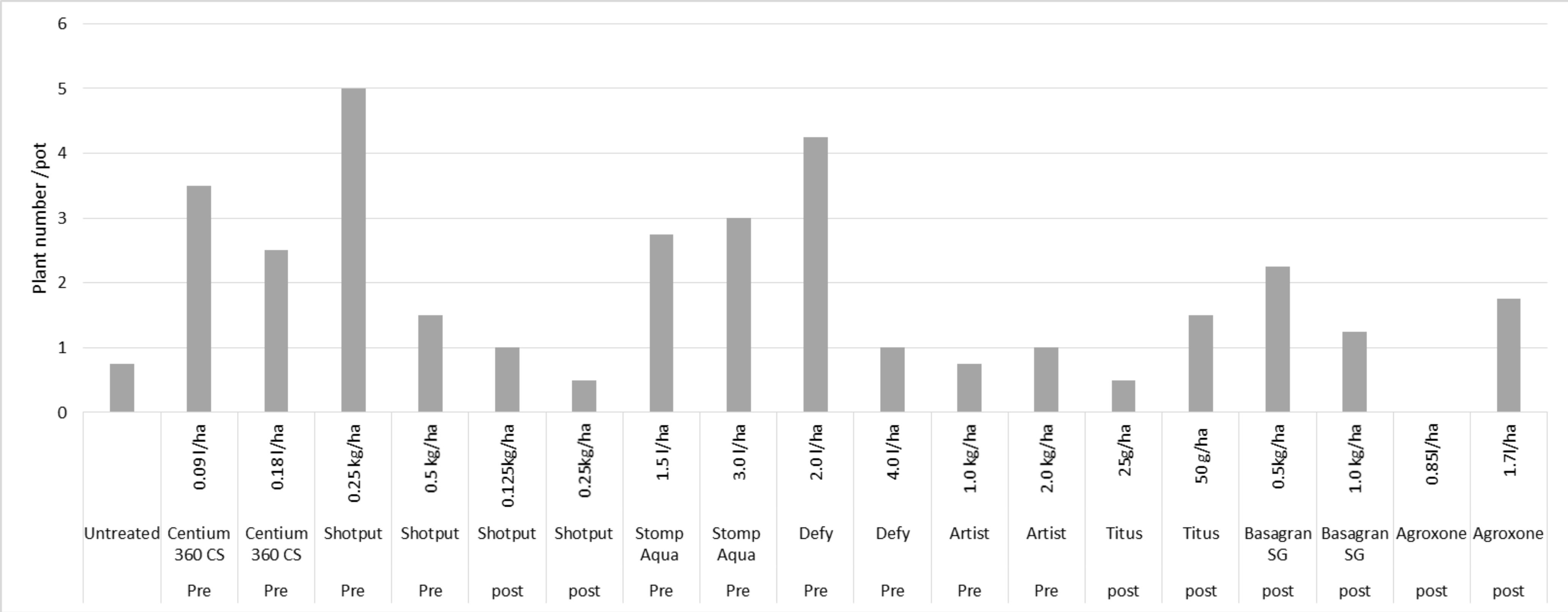


Figure 8. Plant number per pot of *Solanum sisymbriifolium* on 14 August 2014

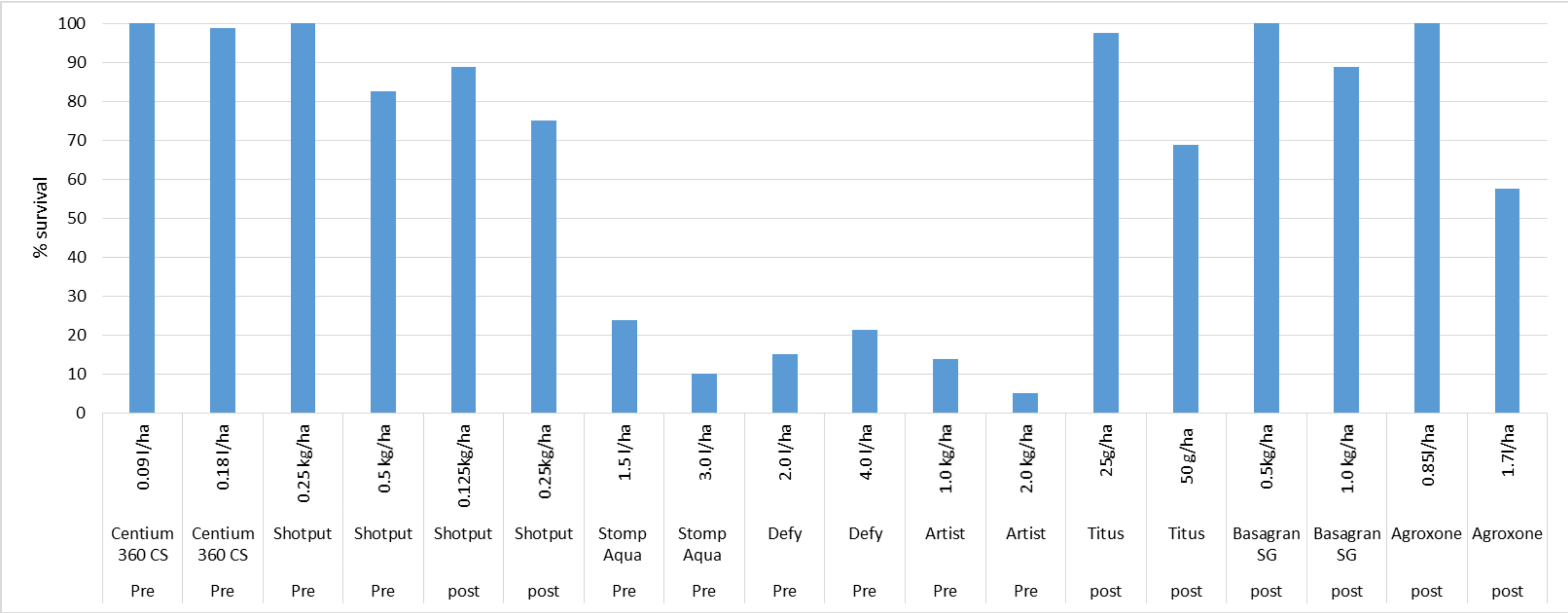


Figure 9. Plant survival of *Solanum nigrum* on 14 August 2014 (%)

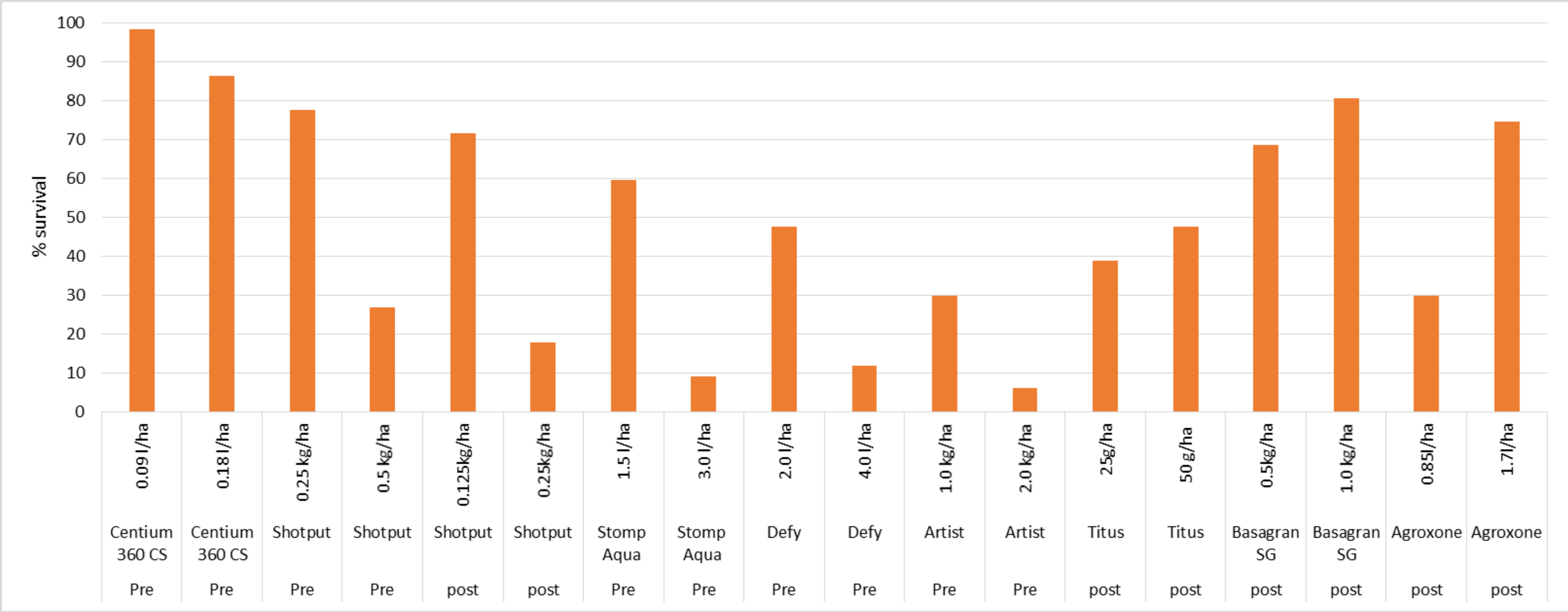


Figure 10. Plant survival of the unspecified *Solanum* spp on 14 August 2014 (%)

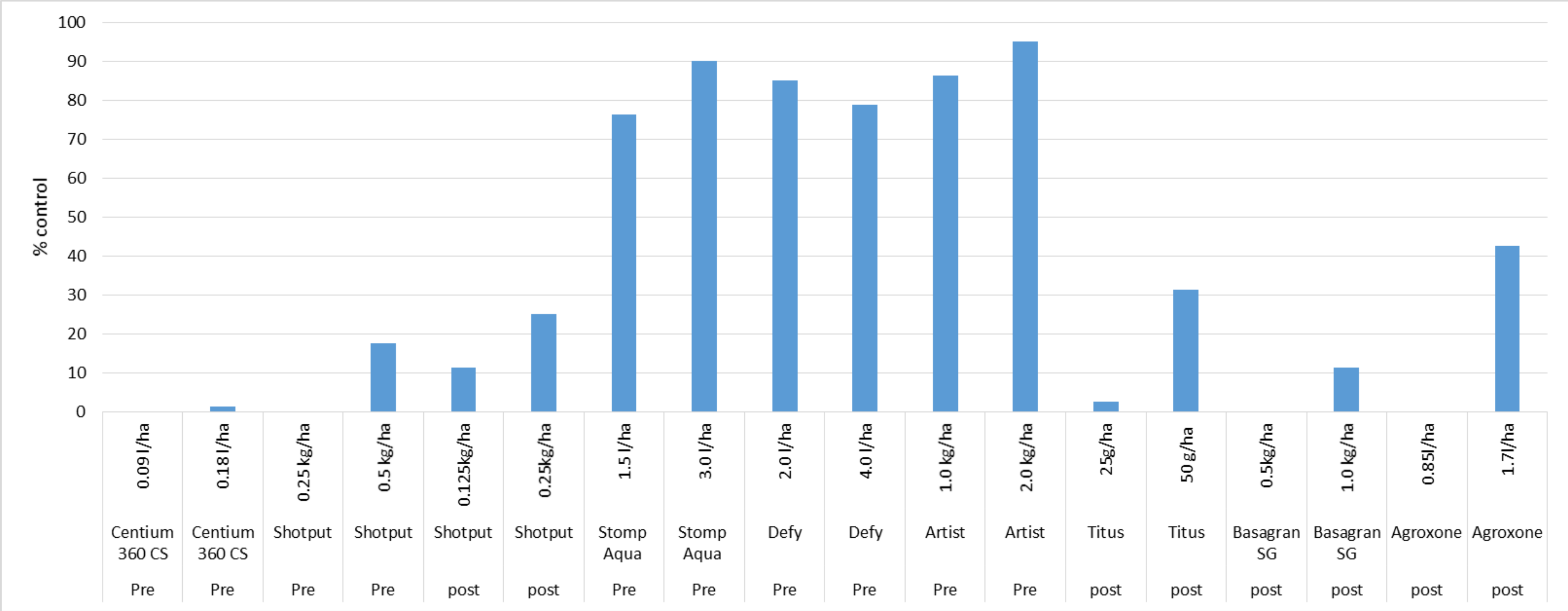


Figure 11. Percent control of *Solanum nigrum* on 14 August 2014

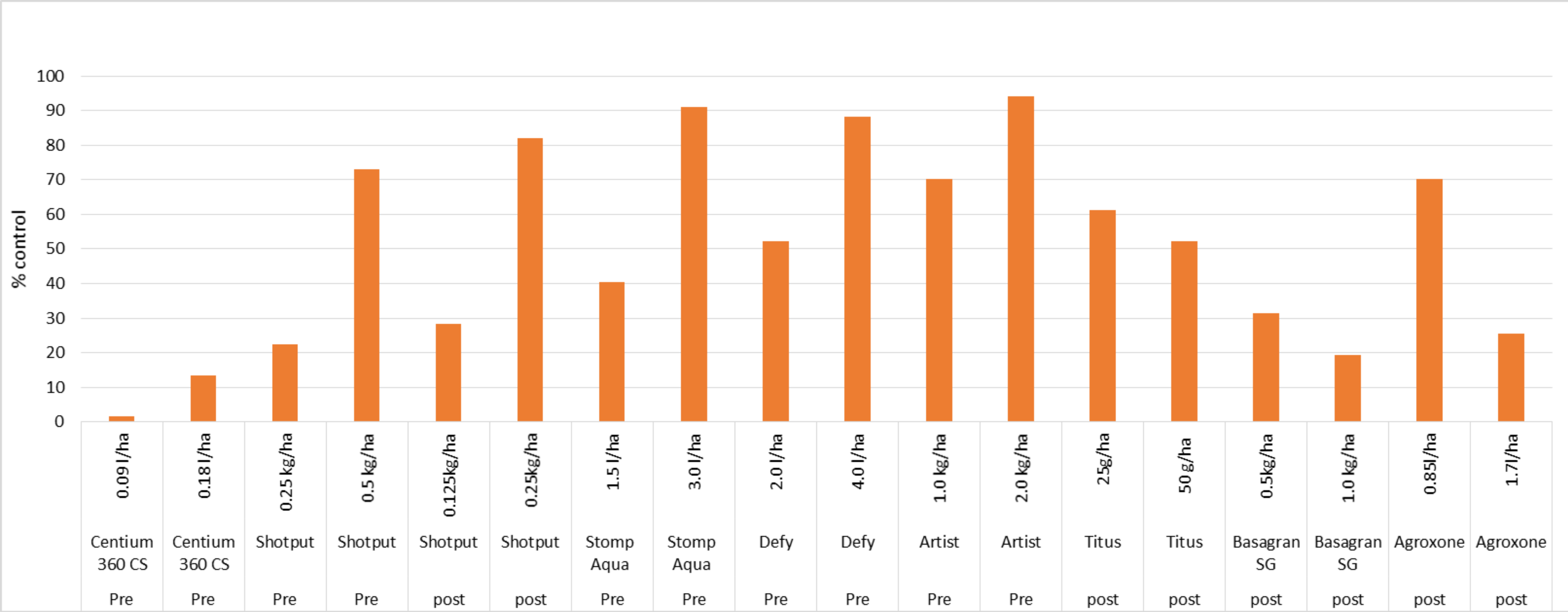


Figure 12. Percent control of the unspecified *Solanum* spp on 14 August 2014

4.3. Year 3: 2015/16

4.3.1. Experiment 1. Confirmation of optimum seed rates and sowing dates for most effective trap crop species

Three soil types were used in the Year 3 experiments, a loamy sand, a sandy loam and a silt loam. The PCN population in each of these soils was a mean of 110 eggs/g soil and 97 cysts/100 g soil in the loamy sand, a mean of 69 eggs/g soil and 65 cysts/100 g soil in the sandy loam and a mean of 68 eggs/g soil and 41 cysts/100 g soil in the silt loam. All three egg counts are in the ADAS high category (>60 eggs/g soil) and normal advice would be not to grow potatoes in this land. Therefore the PCN levels in each soil type provided a very robust test of the trap crops. Data for each variate are tabulated for each combination of sowing date, trap crop species, target population and soil type. Further tables are also provided to help illustrate any statistically significant results.

Proportion of trap crops that established at each sowing date

Trap crop establishment at Boxworth was generally good. The target plant population of one plant per pot was achieved on 52/54 replicates (96%) and the target plant population of six plants/pot was achieved on 31/54 replicates (57%) with a further 12 replicates having five plants/pot (80% of replicates with five or more plants/pot. At High Mowthorpe trap crop establishment was also good with 53/54 (98%) replicates with the target population of one plant/pot and 43/54 replicates with the target population of six plants/pot (80%). Where this was not achieved seven replicates had five plants/pot so that in total 50/54 (93%) had five or more plants/pot.

Root dry weight per plant

Data for both Boxworth and High Mowthorpe are summarised in Tables 48 and 49, respectively.

At Boxworth, there was a significant interaction in root dry weight between sowing date and trap crop (P<0.001, Table 50) and sowing date and seed rate (P<0.05, Table 51). The interaction between sow date and trap crop was probably because at the last sowing in August the difference in root dry weight between trap crop species was much smaller than at the May and July sowing. The interaction between sow date and seed rate was probably because the difference in root dry weight between one or six plants/pot was much smaller at the August sowing than in May or July.

At High Mowthorpe, there was a significant interaction in root dry weight between sowing date and trap crop species (P<0.001, Table 52), sowing date and target population (P<0.001, Table 53) and trap crop species and target population (P<0.05, Table 54). There was little difference in root dry weight between the May and June sowings for black nightshade whereas the root dry weight of the unspecified *Solanum* spp was much lower at the June sowing than in May. Also the unspecified *Solanum* spp produced a much higher dry weight than black nightshade at the first two sowing dates but not in July.

The root dry weight per plant at one plant per pot was also much higher than at six plants/pot for the May and June sowing whereas in July there was little difference between the trap crop species (Table 53). The difference in root dry weight between the two target populations was much greater for the unspecified *Solanum* spp than for black nightshade (Table 54).

Table 48. Mean root dry weights/plant (g) all sowing dates, trap crop species, target populations and soil types at Boxworth

Sowing date	Species	Target population	Soil type		
			Loamy sand	Sandy loam	Silt
5 May	*S. nigrum*	1	8.77	6.00	5.87
	S. nigrum	6	1.58	2.76	2.21
	Unspecified *Solanum* spp	1	18.53	35.03	24.53
	Unspecified *Solanum* spp	6	7.68	7.08	21.35
3 July	*S. nigrum*	1	9.37	4.60	5.57
	S. nigrum	6	1.76	2.29	1.16
	Unspecified *Solanum* spp	1	18.63	19.03	11.40
	Unspecified *Solanum* spp	6	5.80	7.11	5.77
13 August	*S. nigrum*	1	0.67	0.53	0.43
	S. nigrum	6	0.57	0	0.11
	Unspecified *Solanum* spp	1	3.03	0.67	1.73
	Unspecified *Solanum* spp	6	2.81	0.94	0.75

SED (67 DF) for comparison within the body of the table = 5.567

Table 49. Mean root dry weights/plant (g) all sowing dates, trap crop species, target populations and soil types at High Mowthorpe

Sowing date	Species	Target population	Soil type		
			Loamy sand	Sandy loam	Silt
15 May	*S. nigrum*	1	9.10	6.56	11.88
	S. nigrum	6	1.83	1.80	1.97
	Unspecified *Solanum* spp	1	37.27	16.76	26.98
	Unspecified *Solanum* spp	6	12.47	17.53	3.67
15 June	*S. nigrum*	1	9.71	10.05	4.99
	S. nigrum	6	1.98	2.40	1.04
	Unspecified *Solanum* spp	1	24.33	20.53	11.43
	Unspecified *Solanum* spp	6	4.73	4.72	3.21
31 July	*S. nigrum*	1	1.01	0.83	2.09
	S. nigrum	6	1.03	0.62	0.90
	Unspecified *Solanum* spp	1	1.28	3.08	1.37
	Unspecified *Solanum* spp	6	1.45	1.17	0.81

Table 50. Mean root dry weight (g) of trap crop species at each of the three sowing dates at Boxworth

Sowing date	**Trap crop species**	
	Black nightshade	Unspecified *Solanum* spp
5 May	4.53	19.04
3 July	4.13	11.29
13 August	1.66	1.66

SED (67DF) for comparisons within the body of the table = 2.273

Table 51. Mean root dry weight (g) of trap crop species for each target population at each of the three sowing dates at Boxworth

Sowing date	**Target population (plants/pot)**	
	One	Six
15 May	16.46	7.11
15 June	11.43	3.98
31 July	1.18	0.84

SED (67DF) for comparisons within the body of the table = 2.273

Table 52. Mean root dry weight (g) of trap crop species at each of the three sowing dates at High Mowthorpe

Sowing date	**Trap crop species**	
	Black nightshade	Unspecified *Solanum* spp
15 May	5.52	19.12
15 June	5.03	11.49
31 July	1.08	1.53

SED (70DF) for comparisons within the body of the table = 2.103

Table 53. Mean root dry weight (g) of trap crop species for each target population at each of the three sowing dates at High Mowthorpe

Sowing date	**Target population (plants/pot)**	
	One	Six
15 May	18.09	6.54
15 June	13.50	3.01
31 July	1.61	1.00

SED (70DF) for comparisons within the body of the table = 2.103

Table 54. Mean root dry weight (g) of trap crop species at each target population at High Mowthorpe

	Target population (plants/pot)	
	One	Six
S. nigrum	6.24	1.51
Unspecified *Solanum* spp	15.89	5.53

SED (70DF) for comparisons within the body of the table = 1.717

Analysis of PCN levels

Boxworth
At Boxworth, the mean Pf value for number of cysts was lower than the Pi value in all loamy sand samples and higher than the Pi value in all sandy loam samples. In the silt the Pf value was higher than the Pi value in 7 out of 12 treatment combinations (Table 55). Where the Pf was higher than the Pi it is possible that PCN was able to reproduce on the trap crop roots.

Mean initial egg numbers (Pi) ranged between 54 and 113/g soil in comparison with 222 and 126 eggs/g soil for the final egg count (Pf) (Table 56). The mean Pf egg count was lower than the Pi count for each of the 36 treatment comparisons.

Table 55. Pi and Pf values: Mean numbers of PCN cysts/100 g soil for each combination of trap crop, sowing date and target plant population at Boxworth

Sowing date	**Species**	**Target popn**	**Soil type**					
			Loamy sand		**Sandy loam**		**Silt**	
			Pi	Pf	Pi	Pf	Pi	Pf
5 May	*S. nigrum*	1	85	34	113	124	98	67
	S. nigrum	6	54	22	87	126	79	74
	Unspecified *Solanum* spp	1	70	40	96	117	60	75
	Unspecified *Solanum* spp	6	72	34	45	109	72	73
3 July	*S. nigrum*	1	80	31	75	108	96	96
	S. nigrum	6	101	40	77	115	70	76
	Unspecified *Solanum* spp	1	61	38	88	119	81	79
	Unspecified *Solanum* spp	6	89	42	57	105	67	86
13 August	*S. nigrum*	1	75	49	89	116	93	89
	S. nigrum	6	77	43	71	103	74	83
	Unspecified *Solanum* spp	1	62	48	91	126	60	86
	Unspecified *Solanum* spp	6	88	42	59	105	69	72

Table 56. Pi and Pf values: Mean numbers of PCN eggs/g soil for each combination of trap crop, sowing date and target plant population at Boxworth

Sowing date	**Species**	**Target popn**	**Soil type**					
			Loamy sand		**Sandy loam**		**Silt**	
			Pi	Pf	Pi	Pf	Pi	Pf
5 May	*S. nigrum*	1	82	10	114	17	114	15
	S. nigrum	6	64	6	127	18	78	12
	Unspecified *Solanum* spp	1	70	20	105	43	59	23
	Unspecified *Solanum* spp	6	80	12	50	30	60	25
3 July	*S. nigrum*	1	78	16	70	48	82	32
	S. nigrum	6	121	15	83	28	58	15

	Unspecified *Solanum* spp	1	54	19	69	52	78	39
	Unspecified *Solanum* spp	6	100	25	90	42	85	33
13 August	*S. nigrum*	1	76	45	89	71	90	56
	S. nigrum	6	103	37	77	66	83	55
	Unspecified *Solanum* spp	1	73	44	97	94	75	61
	Unspecified *Solanum* spp	6	77	34	75	60	95	34

At Boxworth, final cyst number as a percentage of the initial population differed significantly between trap crops ($P<0.05$) and soil type ($P<0.001$, Table 57). Cyst numbers increased compared with the initial population for both trap crop species but the effect was most marked with the unspecified *Solanum* spp. Pf cyst numbers were 175% of the Pi value in the loamy sand and 128% of the Pi value in the sandy loam. They decreased by 36% in the silt soil.

Table 57. Mean PCN cyst numbers/100 g soil as a percentage of the original population (Pi/Pf x 100) across all sowing dates, trap crop species, target plant populations and soil types at Boxworth

Sowing date	Species	Target popn	Soil type			Trap crop mean
			Loamy sand	Sandy loam	Silt	
May	*S. nigrum*	1	42	110	80	107
May	*S. nigrum*	6	46	184	103	
May	Unspecified *Solanum* spp	1	58	142	179	138
May	Unspecified *Solanum* spp	6	52	282	119	
July	*S. nigrum*	1	43	148	99	
July	*S. nigrum*	6	41	159	132	
July	Unspecified *Solanum* spp	1	86	138	100	
July	Unspecified *Solanum* spp	6	82	239	168	
Aug	*S. nigrum*	1	100	163	107	
Aug	*S. nigrum*	6	57	176	138	
Aug	Unspecified *Solanum* spp	1	89	140	158	
Aug	Unspecified *Solanum* spp	6	72	228	151	
	Mean		64	176	128	

SED (70DF) for comparison of trap crop means = 13.8
SED (70DF) for comparison of soil type means = 16.9

At Boxworth, final PCN egg numbers as a percentage of the initial number (Pf/Pi x 100) differed significantly between sowing date (P<0.001), trap crop (P<0.05) and soil type (P<0.01, Table 58). Black nightshade decreased PCN egg numbers on average by 59% in comparison with 43% for the unspecified *Solanum* spp. Reduction in PCN egg numbers decreased the later trap crops were sown. At the May sowing egg numbers were reduced by 72%, at the July sowing by 57% and at the August sowing by 24%.

In the silt PCN egg numbers were reduced on average by 64% in the loamy sand by 35% and in the sandy loam by 54%.

Table 58. Mean PCN egg numbers/g soil as a percentage of the original population (Pi/Pf x 100) across all sowing dates, trap crop species, target plant populations and soil types at Boxworth

Sow date	**Species**	**Target population**	**Soil type**			**Sowing date mean**	**Trap crop mean**
			Loamy sand	**Sandy loam**	**Silt**		
5 May	*S. nigrum*	1	12	15	17	28	41
	S. nigrum	6	11	15	15		
	Unspecified *Solanum* spp	1	29	53	40		57
	Unspecified *Solanum* spp	6	17	66	43		
3 July	*S. nigrum*	1	20	69	40	43	
	S. nigrum	6	12	36	27		
	Unspecified *Solanum* spp	1	42	77	50		
	Unspecified *Solanum* spp	6	51	53	39		
13 Aug	*S. nigrum*	1	86	81	66	76	
	S. nigrum	6	43	97	71		
	Unspecified *Solanum* spp	1	61	95	87		
	Unspecified *Solanum* spp	6	53	121	54		
	Soil type mean		36	65	46		

SED (70DF) for comparison of trap crop species = 6.6
SED (70DF) for comparison of soil type means = 8.0
SED (70Df) for comparison of sowing date means = 8.0

High Mowthorpe

At High Mowthorpe, the Pf value for number of cysts/100 g soil was greater than the Pi value in 22/36 (61%) of the paired combinations of sowing date, trap crop species, target population and soil type. This suggest that PCN were able to reproduce to some extent on the trap crop roots.

Table 59. Pi and Pf values: Mean numbers of PCN cysts/100 g soil for each combination of trap crop, sowing date and target population at High Mowthorpe

Sowing date	**Species**	**Target population**	**Soil type**					
			Loamy sand		**Sandy loam**		**Silt**	
			Pi	Pf	Pi	Pf	Pi	Pf
15 May	*S. nigrum*	1	94	84	67	68	31	49
	S. nigrum	6	89	96	78	63	38	47
	Unspecified *Solanum* spp	1	85	90	71	76	32	38
	Unspecified *Solanum* spp	6	89	115	66	62	41	46
15 June	*S. nigrum*	1	84	87	58	72	37	43
	S. nigrum	6	93	91	58	72	39	47
	Unspecified *Solanum* spp	1	96	75	80	81	49	49

	Unspecified *Solanum* spp	6	92	77	64	80	43	33
31 July	*S. nigrum*	1	91	76	71	66	40	31
	S. nigrum	6	80	67	80	82	38	37
	Unspecified *Solanum* spp	1	87	83	78	75	40	51
	Unspecified *Solanum* spp	6	85	91	68	70	39	42

At High Mowthorpe egg numbers varied between 43 and 117 eggs/g soil for the Pi value and 17 and 87 eggs/g soil for the Pf value (Table 60). The Pf value for the number of eggs/g soil was lower than the Pi value in 35/36 (97%) of the paired combinations.

Table 60. Pi and Pf values: Mean numbers of PCN eggs/g soil for each combination of trap crop, sowing date and target population at High Mowthorpe

Sowing date	**Species**	**Target popn**	**Soil type**					
			Loamy sand		**Sandy loam**		**Silt**	
			Pi	Pf	Pi	Pf	Pi	Pf
15 May	*S. nigrum*	1	113	30	73	25	56	38
	S. nigrum	6	101	37	75	17	55	25
	Unspecified *Solanum* spp	1	95	56	93	27	43	25
	Unspecified *Solanum* spp	6	103	81	75	27	60	33
15 June	*S. nigrum*	1	102	56	60	30	52	30
	S. nigrum	6	99	57	59	19	70	47
	Unspecified *Solanum* spp	1	102	60	91	45	67	47
	Unspecified *Solanum* spp	6	117	61	69	27	66	40
31 July	*S. nigrum*	1	108	83	86	66	71	40
	S. nigrum	6	110	82	87	61	63	59
	Unspecified *Solanum* spp	1	106	87	78	77	59	74
	Unspecified *Solanum* spp	6	81	71	73	69	67	59

The data for final cyst number as a percentage of the initial cyst number at High Mowthorpe are summarised across all 36 treatment comparisons in Table 61. There was a significant interaction in cyst number between sowing date and trap crop species ($P<0.05$, Table 62). This was probably because there was little difference in cyst numbers between trap crop species on 15 May whereas marked differences were recorded on 15 June and 31 July. On 15 June more cysts were present where there was one plant/pot compared with six plants per pot but on 31 July the ranking was reversed.

There was a significant interaction in cyst number between sowing date and soil type ($P<0.05$, Table 63). This was probably because the ranking of sowing date means varied between soil types. The difference in cyst number between the sandy loam and the silt was also much smaller on 31 July than at other sowing dates.

Table 62. Mean PCN cyst numbers/100 g soil as a percentage of the original population (Pi/Pf x 100) across all sowing dates, trap crop species, target plant populations and soil types at High Mowthorpe

Sow date	Species	Target population	Soil type			Sowing date mean	Trap crop mean
			Loamy sand	Sandy loam	Silt		
May	Black nightshade	1	90	99	160	112	106
May	Black nightshade	6	110	80	129		
May	Unspecified *Solanum* spp	1	107	108	124		106
May	Unspecified *Solanum* spp	6	129	95	113		
June	Black nightshade	1	105	129	124	107	
June	Black nightshade	6	99	123	121		
June	Unspecified *Solanum* spp	1	83	109	101		
June	Unspecified *Solanum* spp	6	85	125	77		
July	Black nightshade	1	85	97	80	100	
July	Black nightshade	6	84	104	99		
July	Unspecified *Solanum* spp	1	96	98	124		
July	Unspecified *Solanum* spp	6	113	105	109		
	Soil type mean		99	106	113		

SED (70DF) for comparison of trap crop species = 5.4
SED (70DF) for comparison of soil type means = 6.7
SED (70Df) for comparison of sowing date means = 6.7

Table 63. Mean cyst number/100 g soil as a percentage of the original population (Pi/Pf x 100) for trap crop species at each of the three sowing dates at High Mowthorpe

Sowing date	Target population (plants/pot)		Mean
	One	Six	
15 May	111	113	112
15 June	117	97	107
31 July	91	108	100
Mean	106	106	

SED (70DF) for comparisons within the body of the table = 9.5

Table 64. Mean cyst number/100 g soil as a percentage of the original population (Pi/Pf x 100) for sowing dates in each soil type at High Mowthorpe

Sowing date	Soil type			Mean
	Loamy sand	Sandy loam	Silt	
15 May	109	96	131	112
15 June	93	121	106	107
31 July	95	101	103	100
Mean	99	106	113	

SED (70DF) for comparisons within the body of the table = 11.65

At High Mowthorpe, final PCN egg number as a proportion of the initial number did not differ significantly between trap crop species. Black nightshade reduced PCN

populations by 40% compared with 32% for the unspecified *Solanum* spp. Egg numbers differed significantly between sowing dates (P<0.001, Table 65) with the degree of PCN control declining the later the trap crops were sown. There was also a significant difference in PCN control between soil types. The greatest reduction in egg numbers was in the sandy loam (43.8%), followed by the loamy sand (36.6%) and the silt (24.6%).
Table 65. Mean PCN egg numbers/g soil as a percentage of the original population (Pi/Pf x 100) across all sowing dates, trap crop species, target populations and soil types at High Mowthorpe

Sow date	Species	Target population	Soil type			Mean
			Loamy sand	Sandy loam	Silt	
15 May	*S. nigrum*	1	29.5	35.4	74.6	49.1
	S. nigrum	6	38.1	23.8	60.5	
	Unspecified *Solanum* spp	1	58.0	32.9	59.8	
	Unspecified *Solanum* spp	6	81.7	33.4	60.8	
15 June	*S. nigrum*	1	54.4	55.0	77.7	57.8
	S. nigrum	6	56.4	32.3	68.4	
	Unspecified *Solanum* spp	1	58.7	55.6	72.3	
	Unspecified *Solanum* spp	6	53.3	39.5	69.8	
31 July	*S. nigrum*	1	78.0	102.0	62.5	88.2
	S. nigrum	6	78.4	68.8	93.2	
	Unspecified *Solanum* spp	1	84.3	96.4	117.5	
	Unspecified *Solanum* spp	6	89.6	99.7	87.8	
Mean			63.4	56.2	75.4	

SED (70DF) for comparison of sowing date means = 6.98
SED (70DF) for comparison of soil type means = 6.98

4.3.2. Experiment 2. Herbicide screen (ADAS, Boxworth)

Plant count data for the pre-emergence herbicide treatments is given in Table 67.

Any germinating weeds were removed by hand so that they did not compete with the trap crops and distort the results. Establishment of black nightshade was poorer than of the unspecified *Solanum* spp*.*

At the final assessment there was a significant interaction between pre-emergence herbicide treatment and soil type (P<0.01, Table 66) in the level of control of black nightshade*.* This was probably due to the lower number of seedlings emerged in the loamy sand compared with the other soil types and the variable effects of different herbicides within the three soil types. For example Shotput decreased numbers of black nightshade in the sandy loam but had no impact in the silt loam.

Error! Reference source not found. There was also a significant interaction between oil types and pre-emergence herbicide treatments for the unspecified *Solanum* spp at the final plant count (P<0.01, Table 67). There was a trend for all herbicides to reduce trap crop numbers but all herbicides killed more trap crop seedlings in the sandy loam and the loamy sand than in the silt loam.

At the final assessment of the post-emergence herbicide trial numbers of black nightshade plants differed significantly between soil types (P<0.01, Table 68) and herbicide treatments (P<0.05). Numbers of plants in the loamy sand were much lower than in either the silt loam or the sandy loam. All herbicides reduced the trap crop populations in comparison with the untreated control. Agroxone reduced numbers by 65%, Shotput by 61% and Titus by 39%.

Numbers of the unspecified *Solanum* spp differed significantly between post-emergence herbicide treatments at the final plant count (P<0.001, Table 69). All herbicides reduced the number of plants but the greatest effect was due to Shotput which reduced numbers by 67%.

A summary of the percentage survival and kill following both pre and post-emergence herbicide treatments of both trap crop species is given in Tables 70 and 71.

Table 66. Plant counts (number seedlings/pot) of black nightshade following pre-emergence herbicide applications (PT = Post treatment)

Product	**Soil type**			**Mean**
	Silt loam	**Sandy loam**	**Loamy sand**	
7 days PT				
Untreated	1.7	6.3	4.3	4.1
Centium 360 CS	6.0	5.7	1.7	4.4
Shotput	10.7	6.3	0.3	5.8
Praxim	6.3	8.0	1.0	5.1
Mean	6.2	6.6	1.8	
SED (22 DF) for comparison of herbicide means = 1.49				
SED (22 DF) for comparison of soil type means = 1.29				
SED (22 DF) for comparisons within the body of the table = 2.58				
14 days PT				
Untreated	6.3	7.0	3.7	5.7
Centium 360 CS	10.0	8.3	1.0	6.4
Shotput	14.7	6.0	1.3	7.3
Praxim	8.7	2.3	1.7	4.2
Mean	9.9	5.9	1.9	
SED (22 DF) for comparison of herbicide means = 1.39				
SED (22 DF) for comparison of soil type means = 1.21				
SED (22 DF) for comparisons within the body of the table = 2.41				
21 days PT				
Untreated	5.3	7.7	3.3	5.4
Centium 360 CS	9.0	7.7	0	5.6
Shotput	12.7	6.3	1.3	6.8
Praxim	5.0	1.7	1.7	2.8
Mean	8.0	5.8	1.6	
SED (22 DF) for comparison of herbicide means = 1.12				
SED (22 DF) for comparison of soil type means =0.97				
SED (22 DF) for comparisons within the body of the table = 1.93				

Final plant count				
Untreated	3.3	6.3	3.0	4.2
Centium 360 CS	4.7	7.7	0	4.1
Shotput	9.3	3.7	1.0	4.7
Praxim	5.0	0.3	0.3	1.9
Mean	5.6	4.5	1.1	
SED (22 DF) for comparison of herbicide means = 1.06				
SED (22 DF) for comparison of soil type means = 0.92				
SED (22 DF) for comparisons within the body of the table = 1.83				

Table 67. Plant counts (number seedlings/pot) of the unspecified *Solanum* spp following pre-emergence herbicide applications (PT = Post treatment)

Product	**Soil type**			**Mean**
	Silt loam	**Sandy loam**	**Loamy sand**	
7 days PT				
Untreated	16.7	27.3	26.7	23.6
Centium 360 CS	27.7	24.7	21.3	24.6
Shotput	21.7	8.3	23.7	17.9
Praxim	22.0	24.0	12.7	19.6
Mean	22.0	21.1	21.1	
SED (22 DF) for comparison of herbicide means = 2.57				
SED (22 DF) for comparison of soil type means = 2.23				
SED (22 DF) for comparisons within the body of the table = 4.45				
14 days PT				
Untreated	23.7	26.7	25.7	25.3
Centium 360 CS	30.0	26.7	21.7	26.1
Shotput	24.7	5.3	3.7	11.2
Praxim	24.7	8.3	15.0	16.0
Mean	25.8	16.8	16.5	
SED (22 DF) for comparison of herbicide means = 2.05				
SED (22 DF) for comparison of soil type means = 1.78				
SED (22 DF) for comparisons within the body of the table = 3.55				
21 days PT				
Untreated	28.0	27.3	27.0	27.4
Centium 360 CS	31.0	22.7	18.3	24.0
Shotput	20.3	4.7	3.3	9.4
Praxim	22.3	7.0	16.3	15.2
Mean	25.4	15.4	16.3	
SED (22 DF) for comparison of herbicide means = 2.09				
SED (22 DF) for comparison of soil type means =1.81				
SED (22 DF) for comparisons within the body of the table = 3.62				
Final plant count				
Untreated	22.3	27.3	25.0	24.9
Centium 360 CS	21.0	11.0	13.0	15.0
Shotput	16.7	1.0	1.7	6.4
Praxim	18.3	1.3	9.3	9.7
Mean	5.6	4.5	1.1	
SED (22 DF) for comparison of herbicide means = 2.04				

SED (22 DF) for comparison of soil type means = 1.77
SED (22 DF) for comparisons within the body of the table = 3.54

Table 68. Plant counts (number seedlings/pot) of the black nightshade following post-emergence herbicide applications (PT = Post treatment)

Product	**Soil type**			**Mean**
	Silt loam	**Sandy loam**	**Loamy sand**	
Pre-treatment				
Untreated	4.3	8.0	3.3	5.2
Shotput	8.0	2.7	4.0	4.9
Titus	7.0	3.0	1.7	3.9
Agroxone	6.3	6.0	1.3	4.6
Mean	6.4	4.9	2.6	
SED (22 DF) for comparison of herbicide means = 1.29				
SED (22 DF) for comparison of soil type means = 1.12				
SED (22 DF) for comparisons within the body of the table = 2.24				
7 days PT				
Untreated	5.3	6.3	3.0	4.9
Shotput	3.7	0	1.7	1.8
Titus	4.0	2.3	0	2.1
Agroxone	5.3	3.7	1.0	3.3
Mean	4.6	3.1	1.4	
SED (22 DF) for comparison of herbicide means = 0.76				
SED (22 DF) for comparison of soil type means = 0.66				
SED (22 DF) for comparisons within the body of the table = 1.31				
14 days PT				
Untreated	3.3	6.3	3.0	4.2
Shotput	4.0	0.7	0.7	1.8
Titus	3.7	2.3	0	2.0
Agroxone	5.3	3.7	1.0	3.3
Mean	4.1	3.3	1.2	
SED (22 DF) for comparison of herbicide means = 0.73				
SED (22 DF) for comparison of soil type means =0.64				
SED (22 DF) for comparisons within the body of the table = 1.27				
21 days PT				
Untreated	3.3	6.7	3.0	4.3
Shotput	4.0	0.7	0.7	1.8
Titus	3.7	2.3	0.0	2.0
Agroxone	4.3	1.7	1.0	2.3
Mean	3.8	2.8	1.2	
SED (22 DF) for comparison of herbicide means = 0.77				
SED (22 DF) for comparison of soil type means = 0.67				
SED (22 DF) for comparisons within the body of the table = 1.33				

Table 68. cont.

Product	Soil type			Mean
	Silt loam	Sandy loam	Loamy sand	
Final plant count				
Untreated	2.7	5.3	2.3	3.4
Shotput	2.7	0.7	0.7	1.3
Titus	4.0	2.3	0	2.1
Agroxone	1.7	1.7	0.3	1.2
Mean	2.8	2.5	0.8	
SED (22 DF) for comparison of herbicide means = 0.69				
SED (22 DF) for comparison of soil type means = 0.60				
SED (22 DF) for comparisons within the body of the table = 1.20				

Table 69. Plant counts (number seedlings/pot) of the unspecified *Solanum* spp following post-emergence herbicide applications (PT = Post treatment)

Product	**Soil type**			**Mean**
	Silt loam	**Sandy loam**	**Loamy sand**	
Pre-treatment				
Untreated	26.7	27.0	26.0	26.7
Shotput	23.7	22.7	26.3	24.2
Titus	21.0	22.3	23.7	22.3
Agroxone	24.7	22.3	22.7	23.2
Mean	24.0	23.6	24.7	
SED (22 DF) for comparison of herbicide means = 1.83				
SED (22 DF) for comparison of soil type means = 1.59				
SED (22 DF) for comparisons within the body of the table = 3.17				
7 days PT				
Untreated	22.3	26.0	24.0	24.1
Shotput	21.3	21.3	26.7	23.1
Titus	18.7	20.3	25.3	21.4
Agroxone	22.0	17.7	21.3	20.3
Mean	21.1	21.3	24.3	
SED (22 DF) for comparison of herbicide means = 1.68				
SED (22 DF) for comparison of soil type means = 1.46				
SED (22 DF) for comparisons within the body of the table = 2.91				
14 days PT				
Untreated	22.3	27.3	25.0	24.9
Shotput	10.3	4.0	12.3	8.9
Titus	19.0	23.7	27.7	23.4
Agroxone	24.0	20.3	22.7	22.3
Mean	18.9	18.8	21.9	
SED (22 DF) for comparison of herbicide means = 2.30				
SED (22 DF) for comparison of soil type means =1.99				
SED (22 DF) for comparisons within the body of the table = 3.98				

Table 69 cont.

Product	Soil type			Mean
	Silt loam	Sandy loam	Loamy sand	
21 days PT				
Untreated	21.7	26.0	24.7	24.1
Shotput	10.0	4.0	11.3	8.4
Titus	18.0	21.3	28.0	22.4
Agroxone	22.3	17.7	21.7	20.6
Mean	18.0	17.3	21.4	
SED (22 DF) for comparison of herbicide means = 2.23				
SED (22 DF) for comparison of soil type means = 1.93				
SED (22 DF) for comparisons within the body of the table = 3.86				
Final plant count				
Untreated	24.3	28.0	25.7	26.0
Shotput	10.0	4.3	11.7	8.7
Titus	15.3	17.3	26.0	19.6
Agroxone	21.7	16.3	19.3	19.1
Mean	17.8	16.5	20.7	
SED (22 DF) for comparison of herbicide means = 2.40				
SED (22 DF) for comparison of soil type means = 2.07				
SED (22 DF) for comparisons within the body of the table = 4.15				

Table 70. Percent survival and percent kill, compared to the untreated, of black nighshade and the unspecified *Solanum* spp by the pre-emergence herbicide treatments on 16 September 2015

Herbicide	Rate	% survival		% kill	
		Black nightshade	***Unspecified* Solanum sp**	***Black nightshade***	***Unspecified* Solanum sp**
Silt loam					
Centium 360 CS	0.18 l/ha	140	94	0	6
Shotput	0.25 kg/ha	280	75	0	25
Praxim	1.5 l/ha	150	82	0	18
Sandy loam					
Centium 360 CS	0.18 l/ha	121	40	0	60
Shotput	0.25 kg/ha	58	4	42	96
Praxim	1.5 l/ha	5	5	95	95
Loamy sand					
Centium 360 CS	0.18 l/ha	0	52	100	48
Shotput	0.25 kg/ha	33	7	67	93
Praxim	1.5 l/ha	11	37	89	63

Table 71. Percent survival and percent kill, compared to the untreated, of *Solanum. nigrum* and the unspecified *Solanum* spp by the post-emergence herbicide treatments on 16 September 2015

Herbicide	**Rate**	**Survival**		***% kill***	
		Black nightshade	**Unspecified *Solanum* spp**	***Black nightshade***	**Unspecified *Solanum* spp**
Silt loam					
Shotput	0.125 kg/ha	0	59	100	41
Titus	25 g/ha + 0.2 L/ha Activator 90	0	37	150	63
Agroxone	0.85 l/ha	38	11	63	89
Sandy loam					
Shotput	0.125 kg/ha	88	85	13	15
Titus	25 g/ha + 0.2 L/ha Activator 90	56	38	44	62
Agroxone	0.85 L/ha	69	42	31	58
Loamy sand					
Shotput	0.125 kg/ha	71	55	29	45
Titus	25 g/ha + 0.2 L/ha Activator 90	100	0	0	101
Agroxone	0.85 L/ha	86	25	14	75

5. Discussion

5.1. Efficacy of trap crops for PCN control

Trap crop species

Over the life of the project a total of five species were evaluated for their ability to act as a trap crop for PCN. These were:

- black nightshade (*S nigrum*): 3 different accessions collected from different regions in GB
- sticky nightshade (*S. sisymbriifolium*): 2 different commercial seed sources
- thorn-apple (*D. stramonium*),
- woody nightshade (*S dulcamara*)
- unspecified *Solanum* spp

In Year 1, all five candidate trap crop species were evaluated in large pots in a poly tunnel at High Mowthorpe . Three different soil types were studied with a target of four plants per pot (seeds sown in April). PCN control differed significantly between the trap crop species. The most effective trap crop, as assessed by the reduction in numbers of PCN eggs, was black nightshade 2 (ex-Swindon) closely followed by the unspecified *Solanum* spp. Overall, these trap crops reduced egg numbers by 76% and 65%, respectively. Black nightshade 1 (ex-Shropshire) was the next most effective trap crop and reduced egg numbers on average by 61%.

There were no significant differences in the reduction of PCN levels (eggs/g soil) between soil types. However, within individual replicates there were some very high levels of reduction of PCN egg numbers by different trap crop species in different soil types. Black nightshade 2 reduced egg numbers by as much as 99% in the peaty loam, and both black nightshade 1 and sticky nightshade 1 reduced egg numbers by 92% in the silt loam and loamy sand, respectively.

In Year 2 black nightshade 1, sticky nightshade 2 and the unspecified *Solanum* spp were again evaluated in large pots. There were two locations at which the trials were carried out. One involved the pots being placed in a polytunnel (as in year 1 [High Mowthorpe]) and at the second site [Boxworth] the pots were placed outdoors on hard standing. A single soil type (silt loam) was used and a range of plant densities and sowing dates were compared.

The level of control was lower than in Year 1. At High Mowthorpe, there was a significant difference in trap crop efficacy between the species. The most effective trap crop was black nightshade which reduced PCN egg populations by 45%. It was significantly better than either sticky nightshade or the unspecified *Solanum* spp which reduced egg numbers by 23% and 27%, respectively. At Boxworth there was no significant difference in PCN control between trap crop species, although there was a trend for both black nightshade and unspecified *Solanum* spp to reduce egg numbers more than sticky nightshade. The levels of PCN control were 45%, 46% and 34%, respectively.

Previous work with sticky nightshade showed that a reduction of up to 80% of the soil population of PCN could be achieved (Scholte, 2000b; Scholte & Vos, 2000). In the current study sticky nightshade was less effective and reduced PCN egg numbers by between 23% and 56% over two years of experimentation.

In year 3, only black nightshade (collected in Norfolk in 2014) and the unspecified *Solanum* spp were included in pot experiments. There were two locations at which the trials were carried out. One involved the pots being placed in a poly tunnel (as in years 1 and 2 [High Mowthorpe]) and at the second site [Boxworth] the pots were placed outdoors on hard standing [as in year 2]. Three soil types were used and the target trap crop populations were 1 or 6 plants per pot.

At Boxworth, final PCN egg numbers as a percentage of the initial population differed significantly between sowing date, trap crop and soil type. Black nightshade reduced PCN numbers on average by 59% in comparison with 43% for the unspecified *Solanum* spp. At High Mowthorpe there was no significant difference in trap crop efficacy between the species. Black nightshade decreased PCN egg numbers by 40% and the corresponding reduction for the unspecified *Solanum* spp at High Mowthorpe was 32%.

Black nightshade has long been known as a potential trap crop for PCN (Russell *et al* 1949, Doncaster 1957). Scholte (2000) and Scholte & Vos (2000) compared it to potato and sticky nightshade. Results showed that two separate populations of black nightshade were not as effective in reducing PCN populations in the soil as sticky nightshade and true potato, although all trap crops tested still resulted in a greater PCN reduction than non-host crop control. Unpublished data (Denis Buckley, Highfield Lodge Agronomy) suggested that black nightshade was more effective than sticky nightshade reducing PCN level by 80-90% compared with 70% for sticky nightshade. The results from this study suggest that overall black nightshade is the most effective trap crop in terms of its effect on the numbers of PCN eggs/g soil.

Impact of soil type on trap crop efficacy

The four soil types studied over the three years of this project were: a silt loam, a loamy sand, a sandy loam and a peaty loam. In Year 3, there was a significant difference in the level of PCN control between soil types at both Boxworth and High Mowthorpe. However, there was no consistent ranking between soil types across both sites. At Boxworth the reduction in PCN levels was greatest in the silt loam (64%) followed by the sandy loam (54%) and the loamy sand (35%). At High Mowthorpe the greatest reduction in PCN egg numbers was in the sandy loam (44%) followed by the loamy sand (37%) and the silt loam (25%).

It is interesting that in Year 1 the impact of the trap crops was most noticeable in the peaty loam. It is possible that roots were able to grow in this soil type more easily than in the silt loam or loamy sand and therefore able to permeate the pot and have a greater influence on PCN levels. This hypothesis is supported by Timmermans (2005) and Timmermans *et al*. (2006) who found that PCN reduction was positively correlated to root length density (the length of roots per volume of soil). PCN reduction ranged from 42.6% at 0.26 cm cm^3 root length density to 85.3% at 5.8 cm cm^3 root length density (Timmermans *et al.*, 2006).

Soil type will be an important consideration when choosing candidate trap crops and limited evidence from this project suggests that different species may perform best in particular soil types. It may also be possible to use blends of trap crop species for particular situations.

Impact of root mass on trap crop efficacy

Root length density is believed to influence the efficacy of trap crops for PCN control as discussed above. As a result, root dry weight was measured in Years 2 and 3 of the project to determine how this was affected by trap crop species, sowing date and target population. At Boxworth in Year 2, it was difficult to draw any conclusions on the effect of trap crop species, sowing date and target population on root dry weight due to highly significant interactions between these variables. Rankings of root dry weights were not consistent across trap crop species, sowing date and target population. This was at least in part because the number of plants that established in each pot was not necessarily the intended target population. In general, there was a trend for root dry weight to decrease with later sowing date and also with increased plant population as might be expected. The unspecified *Solanum* spp tended to have the highest root dry weight followed by sticky nightshade and black nightshade. Increasing plant number would be expected to decrease root dry weight due to competition between plants for a limited volume of soil. Also if plants are sown later their roots would have less time to establish than when sown earlier. At up to 1.5 m high, the unspecified *Solanum* spp was about 4-5 times taller than either black nightshade or sticky nightshade so would necessarily have had a much larger root system in order to support the foliage.

At High Mowthorpe, any clear conclusions on the impact of trap crop species, sowing date and target population were again complicated by significant interactions between these variables. The unspecified *Solanum* spp tended to have the highest root dry weight which tended to decrease with later sowing date. However, there was no consistent ranking of root dry weight of trap crop species across sowing dates. Also root dry weight was very low following the August sowing so it was difficult to determine differences between sowing dates and trap crop species.

In Year 3 the root dry weights recorded for *S. nigrum* at Boxworth were higher than those recorded in year 2 in the silt loam. There were again interactions between the various variables at both Boxworth and High Mowthorpe which made it difficult to interpret the impact of sowing date, trap crop species, target population and soil type on root dry weight. However, there was a trend for the unspecified *Solanum* spp to have the highest root dry weight and for root dry weight to decrease the later trap crops were sown as might be expected. Also the root dry weight for a single plant tended to be higher than for six plants per plot no doubt due to competition between plants.

Impact of plant population on trap crop efficacy

The effect of plant population on trap crop efficacy was assessed in both Years 2 and 3 of the project. In Year 2 the target population for each trap crop was one, three or six plants per pot. In Year 3 two plant populations were studied, one or six plants per pot. There was no effect of target population on the efficacy of trap crops at either Boxworth or High Mowthorpe in either Year 2 or Year 3. This result suggests that the roots were able to permeate the soil within the pots irrespective of the number of plants that established. The volume of soil able to be colonised by trap crop species will be important in determining seed rates for their establishment in the field.

Impact of sowing date on trap crop efficacy

At Boxworth in Years 2 and 3 and at High Mowthorpe in Year 3, the efficacy of trap crops decreased the later they were sown; best PCN control was for pots sown in April and the worst for those sown in September. This result might be expected as with later sowings the pest is less exposed to trap crop roots than in early sowings also plants are likely to establish less well the later they are sown in the year. The root system at the final sowing was very small whereas at earlier sowings it permeated the whole pot. There was no effect of sowing date on trap crop efficacy at High Mowthorpe in Year 2. However, the April sowing was most effective at reducing PCN while the September sowing failed. The High Mowthorpe pots were maintained in a poly tunnel and it is possible that ambient weather conditions were more uniform at this site, which may have helped plants to establish more quickly than at Boxworth where pots were exposed to the environment. At Boxworth the trap crops were exposed to PCN for between 128 and 281 days in Year 2 and 120 and 220 days in year 3. At High Mowthorpe trap crops were exposed to PCN for between 100-226 days in Year 2 and 103-180 days in Year 3. It is interesting that at High Mowthorpe, PCN egg counts were reduced by an average of 23% even when in the presence of traps crops for only 100 days in Year 2 and by 17% when in the presence of trap crops in Year 3. This would suggest that the impact of the trap crops can be relatively rapid and this warrants further investigation.

If trap crops are to be adopted on a wide scale it is likely that different sowing dates will be required to fit with different rotations. This may in turn mean the use of different species to suit different situations. Therefore the ability of trap crop species to establish at different times of the year and the speed with which they can influence PCN populations will be areas that require future research.

The potential for trap crops to act as a host for PCN
Some evidence of the potential for trap crops to be a host of PCN is available from the comparison of PCN cyst numbers pre- and post-growing of the trap crops. Generally there was little difference in cyst numbers between the start and end of the experiment in Years 1 and 2, suggesting that the trap crops prevent the production of new cysts. However, it is unclear whether juveniles are prevented from invading the roots, or are able to invade but unable to develop further. In Year 3 cyst number at the end of the experiment at Boxworth and High Mowthorpe tended to be higher than the initial cyst number. At Boxworth this was most evident with the unspecified *Solanum* spp which had about 40% more cysts than at the start of the experiment. However, egg numbers at both sites were generally lower in the Pf samples than the Pi samples suggesting that any new cysts had few eggs. The potential for trap crops act as a host for PCN and potato diseases such as potato late blight (*Phytophthora infestans*) and verticillium wilt (*Verticillium dahliae*) will need to be studied in more detail in order allay any fears from growers.

Experimental methodology
Throughout the life of the project there were some changes to the initial experimental methodology in experiments to assess the efficacy of trap crop species as discussed below.

In Year 1, soil samples to determine Pf PCN populations were obtained by taking five 15cm deep, 2cm diameter cheese corer cores per pot. It is likely that this would not provide as representative as sample as tippling the entire contents of the pot on to a tray, mixing it thoroughly and taking a random 100g sample. As a result in both Years 2 and 3 the soil coring method was abandoned for determination of Pf populations and replaced by sub-sampling from the entire contents of the pot. At Boxworth in Year 2, it was noticeable that at sowings in August and September cyst numbers were higher than at other sowing dates. This was because there was insufficient of the silt soil collected for Year 2 experiments to fill all pots so silt soil from the Year 1 experiment was used which had a higher PCN cyst population.

In Year 1, trap crop seeds were sown directly into the soil of the test pots, as it was thought that this would best reflect field conditions. However, there were problems with seed germination, requiring supplementary transplanting of seedlings. In Years 2 and

3 experiments it was decided that where the efficacy of PCN control was being compared, seeds should initially be sown in compost and a defined number transplanted to each test pot. This ensured that each pot had identical numbers of plants. Although it was not always possible to establish the target populations of plants per pot, the numbers of plants of the best trap crop species were similar. It is therefore unlikely that any difference in plant numbers impacted on the efficacy of the trap crops. Despite transplanting seedlings in year two establishment of all trap crops in July at High Mowthorpe was poor in comparison with other months. There is no obvious explanation for this anomaly but it is likely that it was due to environmental conditions and irrigation. It will be important to determine the optimum conditions for establishment in order to create trap crop populations that are capable of providing significant control of PCN.

5.2. Trap crop agronomy

Trap crop emergence

Black-nightshade (*Solanum nigrum*) is a common arable weed, generally located in the south of Britain predominantly in fields with spring cropping in the rotation. Roberts & Lockett (1978) recorded that field emergence began in May, reached a peak in late May or June and declined in July and August. Their germination tests indicated that 20°C was necessary for appreciable germination which agreed with the results found here (16.9-21.5°C).

Timmermans *et al*, (2007) working with sticky nightshade (*Solanum sysimbrifolium*) in the Netherlands showed that time to emergence increased from 12 days at 21.8°C to 24 days at 16.5°C to 39 days at 13.0°C and more than 90 days at 9.1°C. There was no germination below 9°C. Sticky nightshade sold as Decyst and Foil-sis are recommended to be sown during May/June to ensure optimal establishment. The results of this study suggest an optimum mean air temperature for emergence of 21.5°C which is slightly higher than for black nightshade.

Sticky nightshade was the only species to survive overwinter. Sticky nightshade is not reported to be sensitive to frost (Timmermanns *et al*., 2007, Scholte, 2000), but this winter was probably not a good test as there were few frost periods.

In summary, both black and sticky nightshade need relatively high temperatures for good establishment limiting the period during which they can be sown. Black nightshade has a lower temperature requirement than sticky nightshade. There was variation in germination between the seed lots. Both woody nightshade and thorn-apple were difficult to establish and do not appear to be suitable candidate as trap crop species.

Sticky nightshade was the least effective trap crop, reducing PCN levels by 26% at High Mowthorpe and 34% at Boxworth. This trap crop was also more effective in Year 1 of the project when PCN levels were reduced by an average of 56%. The level of efficacy of sticky nightshade in Year 2 was lower than in previous work with this species. Scholte, (2000) and Scholte & Vos (2000) showed that a reduction of up to 80% of the soil population of PCN could be achieved.

Establishment of trap crop species

At Boxworth, trap crop establishment decreased with later sowing dates. Plants emerged well in April and June but poorly in September. In general, black nightshade and the unspecified *Solanum* spp established better than sticky nightshade. At High

Mowthorpe, the different species of trap crop established best at different sowing dates accounting for the significant interaction between these variables. Black nightshade established best in July and August and the unspecified *Solanum* spp established best in June and sticky nightshade established best in August. There was very poor establishment of all species in July and September. Overall black nightshade tended to show the best establishment of all trap crop species at High Mowthorpe.

In Year 1 of the project, pot experiments showed that, for the majority of the black and sticky nightshade seed lots, the period of maximum emergence corresponded to an average temperature of 21.5°C. This tended to be recorded in early July. In Year 2, results at Boxworth and High Mowthorpe suggest that it is possible to establish the trap crops earlier in the season (April and June). This increases the flexibility of when trap crop species can be grown before sowing a potato crop. It was encouraging that trap crops showed good establishment in April at Mowthorpe as this site is approximately 170 miles further north and generally cooler than Boxworth.

5.3. Susceptibility of trap crops to herbicides

Herbicide treatment is a vital component of establishing trap crop species as it allows suppression of potential competing weed species. It is important to be able to treat trap crops pre- or post-emergence with herbicide treatments that have minimal impact on the trap crops but maximal impact on other weed species.

Following the herbicide screen in Year 2 there are a number of trends worthy of comment and further investigation although it must be borne in mind that the results are for a single site in a single year and on a single soil type only. Furthermore, the experiment was done in pots rather than in the field.

Black nightshade (S. nigrum)
Black nightshade appeared to be relatively tolerant of clomazone (Centium), because at both rates tested, there was little difference in plant survival. This is despite the fact that the Centium label suggests black nightshade is ‘moderately sensitive’ when this product is used as a herbicide in a potato crop. The strengths of clomazone are cleavers (*Galium aparine*) and fool’s parsley (*Aethusa cynapium*) and it provides useful additional control of speedwell (*Veronica* spp.), black bindweed (*Polygonum convolvulus*) and fat hen.

The tolerance of black nightshade to metribuzin (Shotput) applied pre-emergence was to be expected, because black nightshade is a well-known weakness of this herbicide. It also appears to be relatively tolerant of post-emergence application.

The effect of pendimethalin (Stomp Aqua) was unclear. The label suggests black nightshade is a susceptible weed, but implies that if application is followed by dry conditions, or when high weed populations occur, then a follow-up treatment may be required. Data from the current project indicate that black nightshade is very susceptible to pendimethalin, and therefore, this active ingredient can be omitted from further herbicide screening.

Similarly black nightshade was very susceptible to both prosulfocarb (Defy) and flufenacet + metribuzin (Artist). The susceptibility to Artist is particularly disappointing, because field experience indicates that this broad spectrum product works well in potatoes on a wide range of mineral soil types and under a wide range of soil moisture conditions.

Post-emergence rimsulfuron (Titus) showed a dose-response effect, indicating some sensitivity of black nightshade to this product. When used on potatoes in the field, rimsulfuron tends to stunt the growth of black nightshade rather than kill it, allowing the potatoes to subsequently smother the weed. The strengths of rimsulfuron include brassica species such as oilseed rape volunteers and charlock (*Sinapsis arvensis*), annual nettle (*Urtica urens*) and cleavers (*Chenapodium album*), and so to use it post-emergence would be very useful. The apparent dose-response of black nightshade to this herbicide indicates that further work is required to refine its use in order to avoid significant damage to the trap crop.

The tolerance of black nightshade to bentazone (Basagran) is at variance with the label, where it is rated as susceptible. It should be noted that the field activity of bentazone can be very inconsistent, depending on high temperatures (above 20°C) and high light intensities at the time of application for good herbicidal effect. The activity of rimsulfuron is more consistent, but it still requires at least moderate temperatures (above 14°C) and high humidity to show good herbicide activity.

Of the three post-emergence treatments tested, MCPA (Agroxone) showed the greatest dose-response. From the mid-1950s to mid-1980s, MCPA was occasionally used in potatoes as an emergency treatment to control fat hen but, when European regulation of pesticides was adopted in the mid-1980s, such use was no longer permitted. Interestingly, the Weed Control Handbook (Fryer and Makepiece 1978) lists *S. nigrum* as being resistant to MCPA at the 'young plant' stage of growth, so further screening work is necessary to clarify the susceptibility.

Unspecified *Solanum* spp.

As with black nightshade, the unspecified *Solanum* spp was quite tolerant of clomazone (Centium). It showed strong dose-response, both pre- and post-emergence, to metribuzin (Shotput), pendimethalin (Stomp Aqua), prosulfocarb (Defy) and flufenacet + metribuzin (Artist). However, with pendimethalin, prosulfocarb and flufenacet + metribuzin the dose-response was so great that these products present too great a risk for commercial use, especially on a lighter soil type. Of the post-emergence treatments, bentazone (Basagran) appeared to be the safest to the trap crop.

Of the three trap crop species tested, the unspecified *Solanum* spp was by far the most vigorous in its canopy growth, and therefore most likely to smother weeds once it becomes well established. Nevertheless, it is unrealistic to expect to grow this trap crop without herbicides, so further weed control experimentation is required to confirm its potential.

Sticky nightshade (S. sisymbriifolium)

The poor establishment of the sown seeds of this species prevents firm conclusions from being drawn regarding its susceptibility to herbicides. This is despite a laboratory test of a seed sample from this batch indicating entirely satisfactory germination (44%). However, when sticky nightshade was used commercially as DeCyst, GreenvaleAP, recommended clomazone (Centium) at 0.25 l/ha of product, or pendimethalin (Stomp) at 2 l/ha of product to help establish the trap crop and reduce competition from other weeds. In practice, pendimethalin (Stomp) at 2.0 l/ha could not be expected to provide sufficient pre-emergence weed control, especially in a dry season. For post-emergence herbicide options, limited field experience in Holland indicates that rimsulfuron (Titus) at 15 g/ha of product with a wetter, or rimsulfuron (Titus) at 15 g/ha of product + MCPA (Agroxone) at 0.3 l/ha of product without an added wetter could be used post-emergence. As an alternative, a low dose programme of metribuzin (rates not specified) could be used once the crop had reached three pairs of true leaves. In 2007, field experience with rimsulfuron (Titus) at 15 g/ha of product with a wetter proved to be harsh on *S. sisymbriifolium*, effectively stopping its growth for several weeks.

Timmermans (2005) considered that the period between emergence and 50% light interception is the period where weeds can out-compete sticky nightshade and potentially prevent trap crop establishment. Field experience in the relatively cool, wet growing season of 2007 support this. It is possible that in this experimental herbicide screen, the untreated control was swamped by weeds which caused poor establishment of sticky nightshade. Timmermans (2005) also suggested that for best weed control the period from emergence to 50% light interception should be as short as possible, and that drilling in May and June should be preferred over earlier or later drilling.

In Year 3, the susceptibility of trap crop species to both pre- and post-emergence herbicides was investigated in three soil types, a silt, a loamy sand and a sandy loam.

Soil type had a significant effect on the effectiveness of the herbicides. Both *Solanum* species were killed to a greater extent when grown in the loamy sand and sandy loam soils than the silt.

Every herbicide used resulted in some level of kill of the *Solanum* species. In other words, none was entirely crop safe. When looking at the overall means of soil types, of the pre-emergence treatments, Praxim gave the highest level of kill of black nightshade, whereas Centium and Shotput were safer. Shotput appeared to be particularly phytotoxic to the unspecified *Solanum* spp when applied as a pre-emergence herbicide, with Centium being least phytotoxic.

Kill from pre-emergence treatments was higher than from post-emergence treatments. Although the poor percent emergence of black nightshade may have affected the results, Titus did appear to be the most crop-safe on this species. However, one should bear in mind that Titus can stunt plants rather than kill them, and plant size was not recorded in this experiment. Shotput again appeared to be very phytotoxic to the unspecified *Solanum* spp. The fact that this occurred on all three soil types indicates that the phytotoxicity is due to leaf uptake only rather than from a combination of root and leaf uptake. If root uptake played a significant role in the phytotoxicity of this herbicide, one would have expected a gradation of least phytotoxicity on the silt, intermediate on the sandy loam and most on the loamy sand, but this was not evident in the results. On average, Titus and Agroxone showed little phytotoxicity to the unspecified *Solanum* spp, but this result could also have been affected by poor emergence of the trap crop. It is interesting to compare these results with those from the Year 2 experiment. Then, Centium showed little phytotoxicity to either species (when applied pre-emergence), whilst Shotput had little effect on *S. nigrum* but was toxic to the unspecified *Solanum* spp. We can therefore draw a preliminary conclusion that Centium is reasonably safe to both trap crop species as long as care is taken with the rate chosen in relation to the soil type on which it is applied. On the other hand, it is clear that Shotput is not safe to the unspecified *Solanum* spp at the rates tested, either pre or post emergence. Also, Praxim appears to be phytotoxic to both species, but especially to *S. nigrum*, so it would not be worth continuing with this product in any future experiments. The fact that Shotput was only partly phytotoxic to *S. nigrum* in both 2014 and 2015 indicates that it might be useful for pre-emergence weed control in this species.

It would be interesting to investigate what the effect of tank mixes of Centium and Shotput at varying rates would have on black nightshade, because this would broaden the spectrum of weed control. Tank mixing might be necessary in a commercial situation to help establish black nightshade as it emerges and cover the ground less well than the unspecified *Solanum* spp, and so the need for effective residual herbicides is greater. The situation with post-emergence herbicides is less clear cut. Titus may have a potential role with both trap crop species, subject to it not stunting trap crop growth. Shotput may also have a role post-emergence with black nightshade (only). Field experience in potatoes with this product indicates that it is very effective at killing late germinating fat hen at even lower rates than those tested here and so there would be a demand for its use. In some potato cultivars, there are label recommendations to mix Titus with Shotput post-emergence of the crop, and that would certainly be a combination worth evaluating on black nightshade.

Further work is also needed to refine the potential role of Agroxone. In these experiments, distortion of the foliage of the trap crop could be seen. This is hardly surprising, given that the active ingredient (MCPA) is a hormone herbicide. However, if Agroxone does not significantly delay canopy development, such distortion should not matter. As long as the roots continue to grow the trap crop will still stimulate PCN hatch.

From previous field experience it was abundantly clear that poor weed control resulted in poor establishment and poor trap crop plant size This in turn resulted in poor trap crop performance and an explosive weed burden in the field. Acceptable weed control is therefore a vital part of trap crop development.

If herbicide programmes cannot be developed for use in the field, it may be that a combination of overall herbicide treatment and cultivation between the rows may be attractive. In these circumstances the spacing of plants along the row would be relatively narrow, so that rapid crop canopy development would inhibit late germinating weeds. At the same time, the row width would be relatively wide so that cultivation could occur between the rows. This method of weeding was used in the past in sugar beet and other row crops and is experiencing renewed interest now as technology using cameras linked to computers allows automatic steering of the weeding units. This maximises weed control and minimises crop damage, while at the same time allowing the tractor on which the equipment is mounted to be driven at a commercially acceptable speed.

A combination of herbicides and cultivation may indeed prove to be the best option in the field from the point of view of controlling plants growing from true potato seed (TPS). These are clearly undesirable because they will allow reproduction of PCN. In this experiment it was noticed that one of the weed species emerging from the field collected soil was TPS. This was not unexpected as unsterilised soil was used which had been collected from fields in which potatoes had been regularly grown over many rotations. The extent of TPS contamination would vary with the variety of potato grown in recent rotations. In the case of this experiment, Maris Piper was the most recently grown variety in all three soil types, and since this is known to produce many berries, the emergence of TPS along with the trap crop should not come as any surprise. Maris Piper still accounts for around 15% of the GB potato area, and at one stage was around

30% of the planted area, so TPS from this variety can be expected to emerge in potato fields for many years to come. Other varieties produce few if any berries. These would include Agria (chip shops), Hermes (crisping) and Harmony (pre-pack) and so TPS emergence after the production of these crops would be expected to be significantly less.

Over three years this project has further demonstrated the potential of trap crops as a method of controlling PCN. In particular black nightshade and the unspecified *Solanum* spp show most promise and are possible alternatives to sticky nightshade which is currently the only species available commercially. Black nightshade appears to have the edge in terms of reducing PCN levels but the unspecified *Solanum* spp is much easier to establish. Ultimately it is possible that the choice of most effective trap crops will be a compromise between efficacy of PCN control and ease of establishment. Soil type and sowing date are important factors to take into account when establishing trap crops and it is possible in future that specific trap crops will be used in different situations/rotations. Herbicide screens have given an indication of those products that are trap crop safe and these will be vitally important in developing an agronomy package that maximises trap crop establishment. Further understanding of the potential of trap crops to act as a host to PCN or other potato diseases is also required to allay any fears that a trap crop may prove detrimental in a potato rotation. Work in this project has concentrated on pot experimentation but future work will be required in the field to investigate how this influences trap crop performance.

6. Conclusions

6.1. Summary of main conclusions.

- Black nightshade and the unspecified *Solanum* spp showed good potential as trap crops over the three years of the project and gave best control of PCN. Black nightshade reduced PCN egg numbers by between 76% and 45% and the unspecified *Solanum* spp by between 65% and 45%.

- Levels of PCN control in excess 90% were recorded for black nightshade in a peaty loam, silt loam and loamy sand.

- The optimum period for sowing trap crops appears to be in the period from late April to mid-July, when temperatures are high. Later sowings (August and September) are prone to failure. In practical terms, it may be possible to drill trap crops immediately after winter barley if the ground is cleared quickly, but better results are more likely in the late spring as a whole season crop.

- The longer the growing season for the trap crop the greater the reduction in the PCN population. This was reflected in root dry weight with the earliest sowings producing the highest root dry weight

- Sticky nightshade was less effective as a candidate trap crop species than black nightshade or the unspecified *Solanum* spp in the pot trials of this project. Sticky nightshade reduced PCN egg numbers by 34% over Years 1 and 2 whereas the comparable figure for black nightshade was 60%.

- Thorn-apple and woody nightshade were difficult to establish and also had significantly less impact on PCN than black nightshade, the unspecified *Solanum* spp and sticky nightshade and should be omitted from any future trap crop work.

- It was not possible to demonstrate differences in PCN control based on either one or six plants per pot. The effect of the higher plant population was to reduce dry weight per plant as a result of plant to plant competition. Field work is required to determine the optimum established plant population for maximum PCN reduction.

- Getting candidate trap crop species to reliably germinate is a problem requiring investigation; a solution must be found if they are to successfully establish under field conditions. Black nightshade was the worst in this regard, showing variations in germination which could not be explained. The unspecified *Solanum* spp showed the highest and most consistent level of germination.

- The impact of soil type on the efficacy of trap crops was variable. There was limited evidence to suggest that different species may perform best in particular soil types.

- There was some evidence to suggest that PCN cyst numbers increased in the presence of trap crops in year three although egg numbers were still reduced. This suggests that any new cysts contained few eggs.

- In practical terms, although black nightshade was most effective at reducing PCN levels it may be that other species are better candidate trap crops as their establishment is more reliable and their canopies are more vigorous and give better weed suppression.

- None of the herbicides tested were entirely crop-safe.

- Soil type had a significant effect on the phytotoxicity of the herbicides tested. Both black nightshade and the unspecified *Solanum* spp were killed to a greater extent when grown in the loamy sand and sandy loam soils than in the silt loam.

- Black nightshade was relatively tolerant of clomazone and metribuzin applied pre-emergence, and metribuzin, rimsulfuron, MCPA applied post-emergence.

- The unspecified *Solanum* spp had a similar spectrum of herbicide tolerance to that of black nightshade, with the exception of metribuzin, to which it was intolerant.

- The herbicides pendimethalin (Stomp Aqua), prosulfocarb (Defy) and metribuzin + flufenacet (Artist), all applied in Year 2, and metobromuron (Praxim) in Year 3, were particularly phytotoxic to black nightshade. The same herbicides were a little less phytotoxic to the unspecified *Solanum* spp, but not sufficiently so to conclude that any of them would be safe when used in the field.

- In the herbicide screening work in Year 2, which included sticky nightshade, the emergence was so poor that it is not possible to draw firm conclusions as regards herbicide tolerance.

- Further screening work is required to refine possible herbicide programmes.

6.2. Future research.

Any future research should aim to build on that in the current project to develop further the practice of using trap crops as a sustainable method of controlling PCN. All work in the current project has been done in pots and future studies should seek to evaluate trap cropping in the field. The following topics are potential areas of interest the best candidate species, trap crop agronomy, risks associated with developing trap crops and developing methodology to evaluate other potential trap crop species.

7. REFERENCES

Clayton, R., Storey, M., Parker, B., Ballingall, M. and Davies, K. (2008). Impact of reduced pesticide availability on control of potato cyst nematodes and weeds in potato crops. Potato Council

Doncaster, C. C. (1957). Growth, invasion and root diffusate production in tomato and black nightshade inoculated with potato-root eelworm. Nematologica, **11**, 7-15.

Fenwick, D. W. (1940). Methods for the recovery and counting of cysts of *Heterodera schachtii* from soil. Journal of Helminthology **18**: 155-172

Fidler, J. H. L. (1963). Some new equipment for routine assessment of levels of soil infestation by potato root eelworm, *Heterodera rostochiensis* Woll. Annals of Applied Biology **51**: 269-275.

Fryer, J. D. & Makepeace, R. J. (1978). *Weed control handbook. Volume 2. Recommendations including plant growth regulators* (No. Ed. 8). Blackwell Scientific Publications.

Roberts, H. A. & Lockett, P. M. (1978). Seed dormancy and field emergence in *Solanum nigrum* L. Weed Research, 18(4), 231-241.

Russel, B. P., Todd, A. R. & Waring, W. S. (1949). The potato eelworm hatching factor. 4. *Solanum nigrum* as a source of the potato eelworm hatching factor. Biochemistry Journal **45**, 528-530.

Scholte, K. (2000). Growth and development screening of plants with potential non-tuber bearing Solanaceae for use as trap crops for resistance to and induction of juvenile hatch of potato cyst nematodes and their effects on the numbers of juveniles in cysts. Annals of Applied Biology, **136**, 239-246.

Scholte, K. & Vos, J. (2000). Effect of potential trap crops and planting date on soil infestation with potato cyst nematodes and root knot nematodes. Annals of Applied Biology **137** 31-42.**,** 153-164.

Timmermans, B. G. H. (2005). Solanum sisymbriifolium(Lam.): A trap crop for potato cyst nematodes. PhD Thesis, Wageningen University, the C.T. de Wit Graduate School for Production Ecology and Resource Conservation (PE&RC), Wageningen, The Netherlands.

Timmermans, B. G. H., Vos, J., Van Nieuwburg, J., Stomph, T. J., Van der Putten, P. E. L. & Molendijk, P. G. (2007). Field performance of BGH (2005). *Solanum sisymbriifolium*, (Lam.): A trap crop for potato cyst nematodes. I. Dry matter accumulation in relation to sowing time, location, season and plant density. Annals of applied biology, 150(1), 89-97 PhD Thesis, Wageningen University, The Netherlands.

Timmermans, B. G. H., Vos, J., van Nieuwburg, J., Stomph, T. J. & van der Putten, P. E. L. (2007). Germination rates of *Solanum sisymbriifolium*: temperature response models, effects of temperature fluctuations and soil water potential. Seed Science Research **17**, 221-231 or pursues a related point.

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