FINAL REPORT

Development of CIPC best practice recommendations for low-temperature box stores to minimise risk of exceeding the Maximum Residue Level

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S463 **December 2016**

Summary

CIPC was applied once as a hot-fog, at 50% (7g tonne^{-1}) and 100% (14g tonne^{-1}) rates, to replicate boxes at 10°C, 7°C or 3.5°C early in storage (during temperature pull-down) or after a period of storage at 3.5°C.

Store temperature at the time of application, did not have an important effect on tuber CIPC deposit concentration, with application rate having the main effect.

In year 1, data was obtained which indicated a greater propensity for CIPC applied at warmer store temperature to generate CIPC vapour during subsequent storage, but this was only evident at the lower CIPC application rate, and then only for a short period in storage. The effect was not apparent in data from 2014-15. CIPC vapour concentration was primarily determined by store temperature at the time of sampling, as opposed to temperature at the time of CIPC application, and was largely unaffected by CIPC application rate.

Although not always statistically significant, where differences occurred, sprout control was most effective from early applications of CIPC (at 10°C). Untreated tubers, located in treated boxes after application, adsorbed significantly more CIPC during temperature pull-down (c.0.014mg kg^{-1} day^{-1} from 10°C to 3.5°C) compared with treatments at 3.5°C (c.0.0035mg kg^{-1} day^{-1}) and contributing 0.2-0.3mg kg^{-1} to CIPC residue level.

In low temperature stores (<5°C), efficacy of CIPC is improved by early application, during store temperature pull-down, while stores are still relatively warm.

Contents

1. Introduction

Chlorpropham (CIPC) is of critical importance to the GB potato industry as a sprout suppressant. It remains the most common post-harvest treatment, accounting for more than 80% of chemical applications to UK stored potatoes (FERA 2008, 2010, 2012 and 2014). CIPC is an established active substance which was successfully reviewed by the EU (91/414 ECC) and a statutory Maximum Residue Level (MRL) of 10 mg kg^{-1} was introduced in 2007. Subsequently, risks of exceedance of the MRL were identified from routine regulatory tests and use of the chemical was referred to the then Advisory Committee on Pesticides (now the Expert Committee on Pesticides [ECP]).

Referral resulted in the formation of the UK's Potato Industry CIPC Stewardship Group in 2008, as a condition of continued CIPC authorisations. As part of its commitment to CIPC stewardship, AHDB funded research aimed at improving the distribution of CIPC residues in commercial box stores. During this work, reported by Briddon *et al*. (2013), high residue values were still being detected in some low-temperature stores and it was therefore decided to carry out further, more intensive trials on a semi-commercial scale in stores at Sutton Bridge Crop Storage Research.

During the period of 'CIPC stewardship', statutory testing by the Pesticide Residues in Food Committee revealed eight further exceedances of the MRL. All but one of these occurred in box stored potatoes and five were in low-temperature stores.

Low-temperature box stores were recognised as presenting particular difficulties for CIPC use. The following characteristics were considered to contribute to an increased risk of MRL exceedance.

- The majority of UK box stores employ the 'overhead throw' type ventilation system, with no design mechanism for delivering treatments to the target.
- CIPC treatments were generally applied in the absence of active recirculation (Burfoot *et al*. 1996). Such treatments were reported to result in variable CIPC residue distributions with higher CIPC concentrations on crops in top boxes and

relatively low concentrations in lower boxes (Briddon *et al*. 2013, Burfoot *et al*. 1996).

- Lower residue concentrations in bottom boxes could be associated with poor efficacy prompting, in the absence of knowledge about residue levels, further chemical applications and thus potential overdosing of top boxes.
- Storage conditions were also considered to be implicit in increasing the risk of an MRL exceedance. The use of a low storage temperature (< *c*. 5°C, to maintain the appearance of fresh-pack crops) means the volume of suitable cold ambient air available for cooling purposes is limited and so temperature is often maintained in such stores largely, or even entirely, with refrigeration.

  At these low temperatures, the CIPC saturation vapour concentration, is reduced compared with warmer stores. At a storage temperature of 3°C, the CIPC saturation vapour pressure (SVP) in air is approximately 30% (0.03 μg/L) of that at 10°C (0.1 μg/L) (Park, 2004). Together, the limited use of ambient ventilation and the reduced SVP are thought to be important in limiting loss of CIPC from the store. Additionally, residue decline through volatilisation is less, thus maintaining relatively high residue values over extended storage periods.
- CIPC product labels allowed crops to be marketed two (2) days after applications had taken place, so minimising any opportunity for residue decline should a crop be unloaded early from stores holding multiple stocks.

Together, all of these factors were considered to pose a particular risk for exceedances of the MRL for CIPC. The Potato Industry CIPC Stewardship Group therefore decided to limit CIPC use in low temperature stores (those with a holding temperature ≤5°C) to a single application (at up to the maximum individual dose), made early in storage.

In a pilot study, carried out at SBCSR, a semi-commercial scale trial was conducted (SBCSR & Glasgow University, 2013) which suggested sprout control in low temperature stores could be improved by making applications earlier, while crops are warmer, during the period of pull-down to holding temperature. The aim of this work reported here was to determine if the effects of this pilot trial could be repeated, and, if so, how useful this may be as a means of improving sprout control in crops stored at low temperature.

2. Material and methods

2.1 Season 2012-13

One hundred kilogram capacity wooden boxes were made up as shown in Fig. 1. Each box included a centrally located netted sample, cv Maris Piper, for efficacy assessment, and a randomised grid of washed tubers (cv Melody) for CIPC analyses, located two tuber layers below the surface. Boxes were fitted with a 'sample port' terminating amongst tubers in the centre of the box. This was used to assess CIPC vapour concentration in air from within boxes, amongst sample tubers, after adsorption on *Tenax* tubes.

All boxes were initially held in a CIPC untreated store, the temperature of which was reduced at a rate of 0.5°C per day. When store temperature achieved 10°C, 7°C and 3.5°C, three replicate boxes were transferred to each of two treatment stores, at the same temperature, and CIPC applied at 14 g tonne^{-1} (100%) or 7 g tonne^{-1} (50%) rates *(ProLong, UPL, Warrington, Cheshire [50% w/v CIPC in methanol]).* Additional boxes were treated at 3.5°C after a period of storage, on 22 January 2013 (3.5°C late).

CIPC applications were made with a Swingfog SN-50 *(Swingtec GmbH, Isny, Germany)* fitted with a 1mm nozzle. Stores were left off and kept sealed for 24 hours after applications.

Following applications (24 hours), boxes were transferred to a separate, empty store allowing sampling to be carried out in isolation from boxes treated previously. Tubers were sampled for analysis of initial CIPC deposit concentration and, at this time, four washed, untreated tubers were located in the corners of each box, two tuber layers below the surface. Untreated tubers were analysed to allow the redistribution of CIPC (by the vapour phase) to be quantified. After sampling was completed, the temperature of the store was reduced to 3.5°C, also at a rate of 0.5°C per day. Humidity control was enabled (95 ±5% Relative Humidity) when the final holding temperature was achieved.

Applications of CIPC were carried out on 6 December, 2012 (10°C), 12 December, 2012 (7°C) and 19 December, 2012 (3.5°C). Stores were unloaded, CIPC residue samples taken and sprout control efficacy assessments carried out on 20 June, 2013. Three replicate boxes were used for each treatment combination.

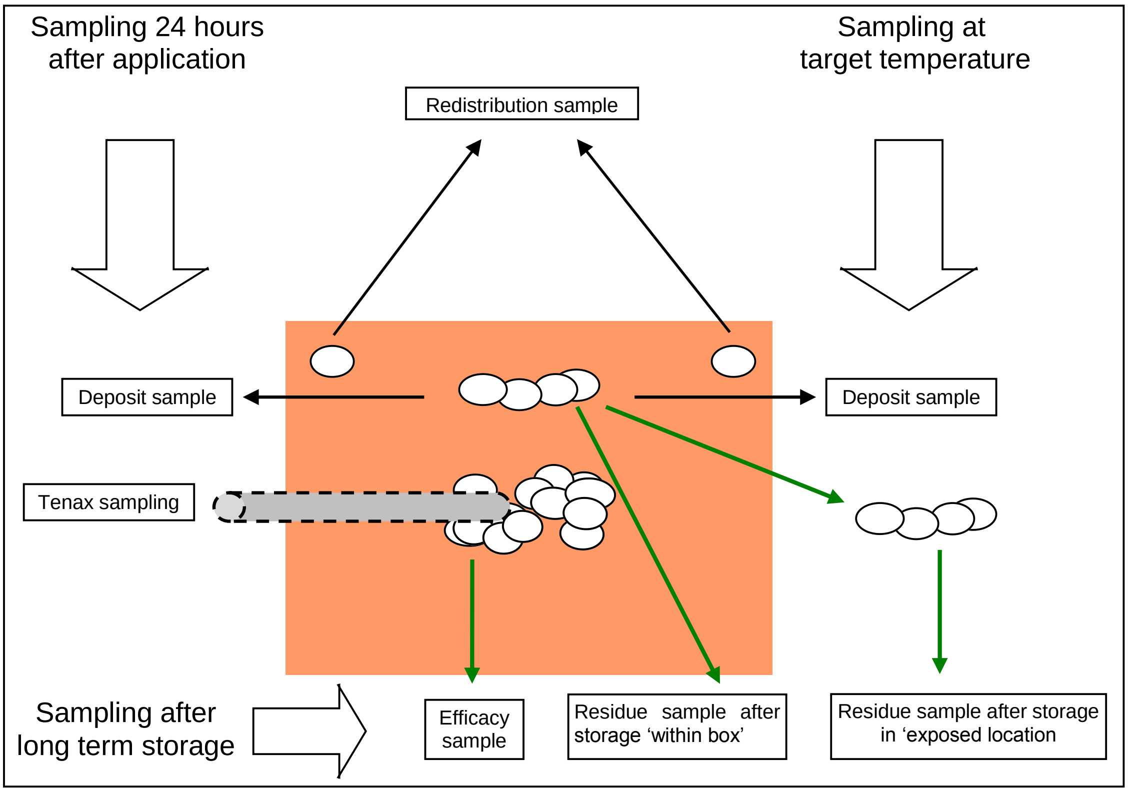

Fig. 1. Diagram of sample boxes, showing position of samples and timing.

2.2 Season 2013-14

Experimental work in year 2 was similar to that in 2012-13, but with the following modifications:

- Cultivar Maris Piper was used for all samples (CIPC deposit, CIPC residue and sprout control efficacy).
- Post-treatment CIPC deposit and residue samples consisted of a single tuber, rather than a 3-tuber composite sample.
- CIPC re-distribution tuber samples consisted of a single tuber, rather than 4-tuber composite samples.

- In addition, untreated re-distribution sample tubers were located in such a way that they were only in direct physical contact with other untreated tubers, for results to more accurately represent just CIPC re-distributing via the vapour phase.
- Efficacy of sprout control was assessed after a period of shelf-life emulation (20ºC and 95% RH), in addition to assessment directly from store.

Applications of CIPC were carried out on 19 November, 2013 (10°C), 25 November, 2013 (7°C) and 2 December, 2013 (3.5°C). Final treatment (3.5°C late) took place, after a period of storage, on 20 January 2014.

Stores were unloaded and CIPC residue samples taken on 27 June, 2014. Sprout control efficacy assessments were carried out on 1 July 2014. Efficacy assessments were repeated after a period of storage to emulate shelf-life (two weeks at 20ºC and 95% RH [4 July to 18 July 2014]).

2.3 Season 2014-15

Experimental work in year 3 was the same as in year 2. Applications of CIPC were carried out on 22 October, 2014 (10°C), 28 October, 2014 (7°C) and 4 November, 2014 (3.5°C). Final treatment (3.5°C late) took place, after a period of storage, on 6 January 2015.

Stores were unloaded, CIPC residue samples taken and sprout control efficacy assessments completed on 6 May, 2015. Efficacy assessments were repeated during storage at 20ºC and 95% RH for 14 days and 30 days to emulate shelf-life conditions.

2.4 Sampling at different humidity levels

In 2015 additional sampling was conducted to try and gain a better understanding of the role of humidity on CIPC saturation vapour pressure and adsorption to tubers, and to determine if this may have contributed to the unusual results in the 2013-14 season. Work was carried out in the same stores that initial treatments had taken place in, using the same 8 tonnes of previously treated bulk-up crop. No further treatments with CIPC were made and the stores were held at 3.5ºC, 7ºC or 10ºC, with samples taken over a 24 hour period at each and with the store fabric and treated bulk-up potatoes being the only source of CIPC vapour. Differences in humidity were achieved by the use of humidification in one store (High RH) and by placing containers of salt in the other store (Low RH).

Three replicate Tenax tubes were sampled and three washed, untreated tubers were placed in a length of 10cm diameter tube fitted with a fan generating a known airflow. The tubers were subjected to the airflow for 24 hours, with the Tenax sampling started approximately 8 hours after the tubers were positioned. Sampling was carried out on 18 June (3.5°C), 23 June (7°C) and 30 June (10°C).

3. Results

3.1 Initial CIPC deposit levels

2012-13

The results of initial CIPC deposit concentration (24 hours after application) and that when the target store temperature was achieved is shown in Table 1a. The 50% rate of CIPC resulted in a mean CIPC deposit concentration of 1.4 mg kg^{-1} and the 100% rate, 3.0 mg kg^{-1}. Concentrations were unchanged in samples obtained when target temperature was achieved, with mean values of 1.3 mg kg^{-1} and 3.3 mg kg^{-1} for 50% and 100% rates respectively. Storage temperature at the time of CIPC application did not have an overriding effect on deposit levels at 24 hours or when target temperature was achieved and differences were not generally significant.

Table 1a. CIPC deposit levels (mg kg^{-1}) 24 hours after application and when target store temperature was achieved, 2012-13.

application rate (g tonne^{-1})	application temp/timing	24 hours	SD	target temperature	SD
14	10°C	4.4 [3.7][1]	1.37	4.3	0.47
	7°C	1.8	0.23	3.1	0.88
	3.5°C	2.7	0.14	2.5	0.33
	3.5°C 'late'	3.0	0.56	3.1	0.31
	mean	**3.0**	1.18	**3.3**	0.83
7	10°C	1.5	0.19	1.9	0.19
	7°C	1.0	0.21	1.0	0.17
	3.5°C	1.2	0.18	0.9	0.09
	3.5°C 'late'	1.7	0.33	1.5	0.23
	mean	**1.4**	0.36	**1.3**	0.45

[1]One replicate sample had a high concentration (6.0 g/t), the remaining two replicates had values of 3.6 and 3.7 g/t. An 'outlier' was not apparent in this box when target temperature was achieved.

2013-14

Initial CIPC deposits are shown in Table 1b. Values were approximately one half of the concentration that occurred in 2012-13, at 0.8 and 1.3 mg kg^{-1} respectively for 50% and 100% rates. Concentrations were similar in samples when the target holding temperature was achieved with values of 0.7 mg kg^{-1} and 1.4 mg kg^{-1} respectively for 50% and 100% CIPC application rates. In the 24 hour samples, there was a tendency for deposit levels to increase as the store temperature at application decreased (with some significant differences in deposit level p=<0.05) but this effect was not evident in deposits on samples taken once the target storage temperature was achieved. This effect was also not evident in data for 2012-13.

Table 1b. CIPC deposit levels (mg kg^{-1}) 24 hours after application and when target store temperature was achieved, 2013-14.

application rate (g tonne^{-1})	application temp/timing	24 hours	SD	target temperature	SD
14	10°C	0.9	0.18	1.1	0.34
	7°C	1.0	0.22	1.3	0.52
	3.5°C	1.3	0.19	1.6	0.68
	3.5°C 'late'	2.0	0.39	1.4	0.14
	mean	**1.3**	0.49	**1.4**	0.43
7	10°C	0.6	0.09	0.7	0.04
	7°C	0.7	0.09	0.6	0.19
	3.5°C	0.8	0.09	0.8	0.05
	3.5°C 'late'	0.9	0.10	0.7	0.10
	mean	**0.8**	0.14	**0.7**	0.12

2014-15

Initial CIPC deposit concentrations for samples from 2014-15 are shown in Table 1c. Values were similar to those observed in 2012-13, at 1.2 and 2.4 mg kg^{-1} for 50% and 100% rates respectively. Concentrations were unchanged in samples taken when target temperature was reached, with mean values of 1.1 and 2.5 mg kg^{-1} for 50% and 100% rates respectively. Although there were significant differences in CIPC deposit concentration, these are thought to be due to applications being carried out at different times, rather than any overriding effect of store or crop temperature at application, with different degrees of application efficiency exhibited over the three seasons.

Table 1c. CIPC deposit levels (mg kg^{-1}) 24 hours after application and when target store temperature was achieved, 2014-15.

application rate (g $tonne^{-1}$)	application temp/timing	24 hours	SD	target temperature	SD
14	10°C	3.4	0.48	3.1	0.50
	7°C	2.5	0.84	3.1	0.40
	3.5°C	1.8	0.11	2.1	0.19
	3.5°C 'late'	1.9	0.80	1.6	0.23
	mean	**2.4**	0.70	**2.5**	0.76
7	10°C	1.4	0.34	1.1	0.08
	7°C	1.5	0.11	1.6	0.25
	3.5°C	1.0	0.26	0.9	0.10
	3.5°C 'late'	0.7	0.17	0.9	0.21
	mean	**1.2**	0.37	**1.1**	0.31

3.2 CIPC vapour

2012-13

The CIPC vapour concentration associated with treatments are shown in Table 2a. During the initial stages of storage, when temperature was relatively warm, CIPC vapour concentration was relatively high, with values close to 0.2 µg L^{-1}. Vapour concentration was significantly lower, typically in the range 0.01-0.04 µg L^{-1}, during the holding phase, with a storage temperature of around 3.5°C.

CIPC dose rates of 7g $tonne^{-1}$ and 14 g $tonne^{-1}$ had no significant effect on CIPC vapour concentration early in storage, or at assessment in March or June.

Table 2a. CIPC vapour concentration (µg L^{-1}), 2012-13.

treatment	24 hrs	SD	pull-down	SD	target temp	SD	March	SD	June	SD
14g tonne^{-1}										
10°C	0.22	0.04	0.18	0.08	0.13	0.05	0.03	0.01	0.04	0.01
7°C	0.15	0.01			0.10	0.01	0.02	0.01	0.04	0.01
3.5°C	0.14	0.02					0.03	0.00	0.04	0.01
3.5°C 'late'	0.08	0.03					0.02	0.00	0.05	0.02
mean	**0.15**	0.06	**0.18**	0.08	**0.12**	0.04	**0.02**	0.01	**0.04**	0.01
7g tonne^{-1}										
10°C	0.20	0.02	0.19	0.03	0.11	0.00	0.01	0.00	0.04	0.00
7°C	0.14	0.03			0.08	0.00	0.01	0.00	0.03	0.01
3.5°C	0.14	0.00					0.01	0.00	0.04	0.00
3.5°C 'late'	0.08	0.03					0.02	0.01	0.03	0.01
mean	**0.14**	0.05	**0.19**	0.03	**0.10**	0.01	**0.01**	0.01	**0.03**	0.01

With crop at *c.* 7°C (Fig. 2), application at 10°C resulted in a greater concentration of CIPC vapour compared with application at 7°C at the 7g tonne^{-1} rate (p=0.0009). This effect was also apparent at 3.5°C, with the warmer application temperature resulting in a higher concentration of CIPC vapour. At the 14 g tonne^{-1} rate, application temperature did not result in significant differences in vapour concentration.

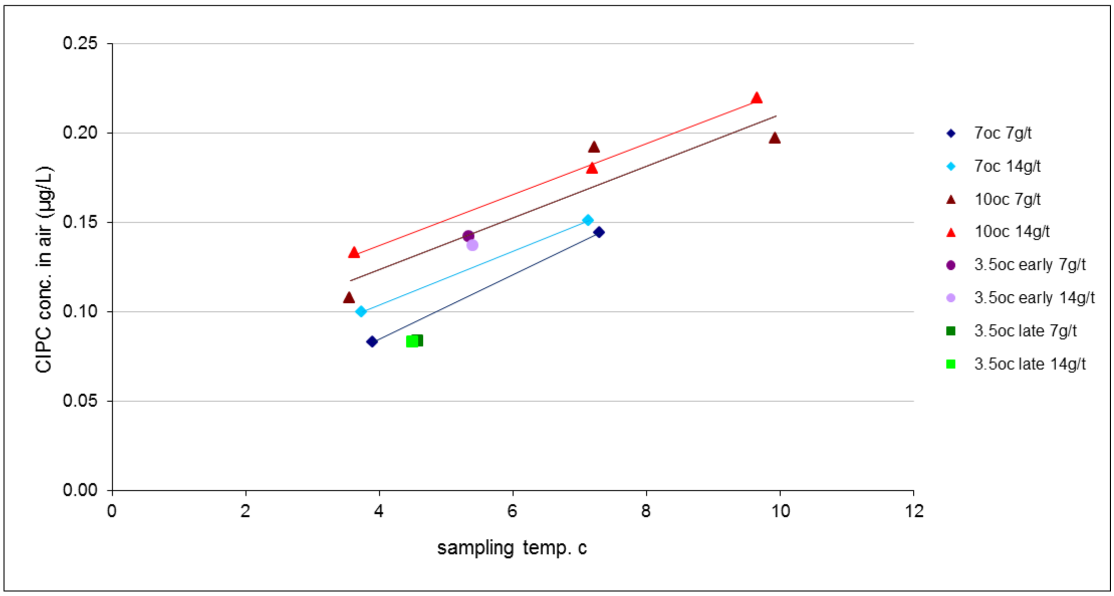

Fig. 2. Mean CIPC vapour concentration (µg l^{-1}) after applications and during temperature pull-down.

2013-14

The CIPC vapour concentrations measured for treatments in 2013-14 are shown in Table 2b in the Appendix. Concentration values were generally very high and beyond the scale anticipated from previous work (L. Park, PhD Thesis, University of Glasgow, 2004). The reason for these high values measured is not known but values for standard deviation suggest the source of variation was systematic rather than random. However, checking of experimental procedures used at SUERC (the analyst) and SBCSR did not reveal any particular problems. Nevertheless, the data were considered unreliable.

New air sampling pumps and an electronic rotameter were purchased prior to the start of 2014-15 trial work.

2014-15

The CIPC vapour concentrations measured following each of the treatments are shown in Table 2c. Values were within the range reported elsewhere and similar to those observed in 2012-13. As in the 2012-13 season, there was no significant effect of dose rate on CIPC vapour concentration. Although differences were observed as a result of application temperature, these showed different trends from the results in 2012-13, with the greatest difference occurring between the 3.5°C and 3.5°C 'late' treatments.

Table 2c. CIPC vapour concentration (µg L^{-1}), 2014-15.

CIPC rate/ temp/timing at treatment	24 hrs	SD	pull-down	SD	target temp	SD	March	SD
14g $tonne^{-1}$								
10°C	0.19	0.03	0.13	0.00	0.10	0.03	0.05	0.01
7°C	0.08	0.02			0.12	0.02	0.05	0.01
3.5°C	0.19	0.04			0.12	0.00	0.05	0.01
3.5°C 'late'	0.07	0.01			0.06	0.00	0.06	0.03
mean	**0.13**	0.06			**0.10**	0.03	**0.05**	0.01
7g $tonne^{-1}$								
10°C	0.14	0.02	0.11	0.00	0.10	0.02	0.04	0.01
7°C	0.12	0.03			0.11	0.00	0.05	0.00
3.5°C	0.19	0.01			0.11	0.01	0.04	0.01
3.5°C 'late'	0.09	0.01			0.06	0.00	0.04	0.02
mean	**0.13**	0.04			**0.10**	0.03	**0.04**	0.01

3.3 CIPC redistribution

2012-13

The CIPC concentrations measured in untreated sample tubers, located within treated boxes *after* applications had been made, are shown in Table 3a. The CIPC concentration of these samples was used as a measure of CIPC 'mobility', or potential for re-distribution. CIPC on these samples was considered principally to have been delivered via the vapour phase.

Table 3a. CIPC deposit concentration (mg kg^{-1}) on untreated tubers, 2012-13.

treatment	10-3.5°C (12 days)	SD	7-3.5°C (7 days)	SD	post app. 3.5°C	SD	3.5°C (*c* 6 months)	SD
14g $tonne^{-1}$								
10°C	1.13	0.025					2.20	0.252
7°C			0.51	0.143			2.45	0.333
3.5°C							1.61	0.233
3.5°C 'late'					0.23	0.042	1.39	0.053
						mean	**1.92**	0.493
7g $tonne^{-1}$								
10°C	0.46	0.032					1.05	0.144
7°C			0.28	0.126			1.10	0.063
3.5°C							0.93	0.098
3.5°C 'late'					0.11	0.039	1.01	0.040
						mean	**1.02**	0.103

Although there was an effect of storage temperature, with CIPC adsorbed to a greater concentration (per day) in warmer treatments, it was application rate that had the greatest effect during the pull-down phase. During this time, adsorption of CIPC on untreated tubers after application at 7g $tonne^{-1}$ was approximately half that following applications at 14g $tonne^{-1}$. During storage at 3.5°C, there were no differences in CIPC adsorption as a result of application temperature at the 7g $tonne^{-1}$ rate. However, at the higher 14 g $tonne^{-1}$ rate, application at 10°C or 7°C resulted in more CIPC adsorbing to untreated tubers.

2013-14

Levels of CIPC adsorbed to untreated tubers in 2013-14 were considerably lower than those in 2012-13. This reduction was anticipated because untreated tubers were only placed in contact with other untreated tubers whereas, in year 1, untreated tubers had been placed directly adjacent to treated potatoes (i.e. without any 'buffer'). In addition, in 2013-14, efficiency of application was generally lower with CIPC deposit levels approximately 50% of those measured in the previous year. Results from 2013-14 indicate that application rate did not have an important effect on CIPC re-distribution.

Table 3b. CIPC deposit concentration (mg kg^{-1}) on untreated tubers, 2013-14.

treatment	10-3.5°C (12 days)	SD	7-3.5°C (7 days)	SD	post app. 3.5°C	SD	3.5°C (*c* 6 months)	SD
14g $tonne^{-1}$								
10°C	0.17	0.099					0.76	0.302
7°C			0.12	0.126			0.74	0.295
3.5°C							0.75	0.154
3.5°C 'late'							0.66	0.254
						mean	**0.73**	0.224
7g $tonne^{-1}$								
10°C	0.19	0.054					0.61	0.325
7°C			0.06	0.049			0.52	0.150
3.5°C							0.66	0.165
3.5°C 'late'							0.45	0.160
						mean	**0.56**	0.200

2014-15

The concentration of CIPC adsorbed to untreated tubers in 2014-15 was broadly similar to that measured in 2013-14. Application at 10°C, at the 14g $tonne^{-1}$ rate, resulted in significantly greater CIPC adsorption than for the other treatments. This effect of temperature was not apparent at the lower dose rate (7g $tonne^{-1}$).

Table 3c. CIPC deposit concentration (mg kg^{-1}) on untreated tubers, 2014-15.

treatment	10-3.5°C (20 days)	SD	7-3.5°C (15 days)	SD	post app. 3.5°C	SD	3.5°C (*c* 6 months)	SD
14g $tonne^{-1}$								
10°C	0.32	0.062					0.94	0.057
7°C			0.46	0.146			0.59	0.044
3.5°C							0.71	0.091
3.5°C 'late'							0.67	0.065
						mean	**0.73**	0.150
7g $tonne^{-1}$								
10°C	0.22	0.053					0.58	0.048
7°C			0.26	0.072			0.60	0.119
3.5°C							0.65	0.198
3.5°C 'late'							0.45	0.038
						mean	**0.57**	0.087

3.4 CIPC residue

2012-13

CIPC residue concentrations after storage are shown in Table 4a. Samples were either left '*in situ'* within boxes for the duration of the experiment (6-7 months) or 'exposed' to the store air. For the latter, 'exposed' samples were removed from boxes, when the target store temperature had been achieved, and suspended in the store headspace, so as to be exposed to a larger volume of recirculating air.

The residue concentration of *in situ* samples, which were washed prior to treatments to remove any soil, was very similar to initial deposit values. CIPC application rate was the main determinant of residue level, with no effect of application temperature evident. Storage of samples in the 'exposed' location resulted in lower residue concentrations. The difference in residue concentration, between *in situ* and exposed samples, was greatest in samples treated at the 100% application rate. At this rate, 'exposed' residues were approximately one half of '*in situ'* samples, whilst, at the 7 g tonne^{-1} rate, exposure to air only resulted in a residue reduction of approximately 20%.

Table 4a. CIPC residue levels (mg kg^{-1}) after storage in *in-situ* and under *exposed* conditions, 2012-13.

application rate (g/t)	application temp/timing	*in situ*	SD	*exposed*	SD
14	10°C	4.3[1]	1.07	2.1	0.13
	7°C	3.1	0.47	1.4	0.03
	3.5°C	2.5	0.07	1.2	0.04
	3.5°C 'late'	2.9	0.40	1.3	0.18
	mean	**3.2**	0.89	**1.5**	0.38
7	10°C	1.9	0.19	1.4	0.11
	7°C	1.2	0.11	1.1	0.18
	3.5°C	1.0	0.12	1.1	0.49
	3.5°C 'late'	1.6	0.56	0.9	0.08
	mean	**1.4**	0.45	**1.1**	0.32

[1]Higher variability was observed in this treatment in terms of CIPC deposit 24 hours after application.

2013-14

Data for CIPC residue levels after storage were broadly similar to deposit levels at 24 hours after application. This also occurred in year 1. However, there was little evidence of residue decline in samples in either the 'exposed' or '*in situ'* storage locations.

Table 4b. CIPC residue levels (mg kg^{-1}) after storage *in-situ* and under *exposed* conditions, 2013-14.

application rate (g/t)	application temp/timing	*in situ*	SD	*exposed*	SD
14	10°C	1.1	0.05	1.3	0.03
	7°C	1.4	0.36	1.2	0.34
	3.5°C	1.6	0.33	1.0	0.04
	3.5°C 'late'	2.5	1.09	1.0	0.33
	mean	**1.7**	0.74	**1.1**	0.24
7	10°C	0.7	0.05	1.1	0.11
	7°C	0.8	0.11	1.2	0.21
	3.5°C	0.6	0.11	0.9	0.59
	3.5°C 'late'	0.8	0.24	0.7	0.10
	mean	**0.7**	0.15	**1.0**	0.34

2014-15

The range of data for CIPC residue levels was similar to those in 2013-14. CIPC application rate was the main determinant of residue level, with no effect of application temperature evident. Storage of samples in the exposed location resulted in reduced residue concentrations. 'Exposed' residue sample values were approximately 50% *of in situ* samples at both the 100% and 50% CIPC application rates.

Table 4c. CIPC residue levels (mg kg^{-1}) after storage *in-situ* and under *exposed* conditions, 2014-15.

application rate (g/t)	application temp/timing	*in situ*	SD	*exposed*	SD
14	10°C	2.3	0.53	1.1	0.22
	7°C	1.5	0.36	1.0	0.17
	3.5°C	1.9	0.42	0.8	0.04
	3.5°C 'late'	1.8	0.53	0.7	0.21
	mean	**1.9**	0.33	**0.9**	0.20
7	10°C	1.1	0.32	0.7	0.12
	7°C	1.2	0.11	0.7	0.05
	3.5°C	0.8	0.15	0.7	0.13
	3.5°C 'late'	0.8	0.18	0.5	0.11
	mean	**1.0**	0.18	**0.6**	0.04

3.5 Sprout control efficacy

2012-13

At both the 7 g tonne^{-1} and 14 g tonne^{-1} application rates (Table 5a), sprout control was most effective in the earliest treatments, applied at 10°C, and no significant effect of CIPC dose rate was apparent. Treatments applied later (7°C and 3.5°C early or late) were less effective, and the higher dose rate was more successful (p=0.0354) at controlling sprouting. These effects were also apparent in results for the other assessments of sprouting.

Table 5a. Mean maximum sprout length (mm) and sites of sprouting at store unloading, 2012-13.

application rate (g/tonne)	application temp/timing	sprout length (mm)	SD	sites of sprouting	SD	unsprouted (%)	SD
14	10°C	1.7	2.11	2.5	2.02	23	7.8
	7°C	3.2	3.59	3.8	2.32	8	0.2
	3.5°C	3.5	4.31	3.6	2.26	12	10.6
	3.5°C 'late'	3.1	3.30	3.5	2.13	14	11.2
	mean	**2.9**	3.48	**3.3**	2.24	14	6.4
7	10°C	2.0	2.15	2.9	2.20	24	13.9
	7°C	4.3	4.51	4.1	2.00	11	6.1
	3.5°C	4.2	5.02	4.0	2.45	14	6.4
	3.5°C 'late'	4.5	4.56	4.1	2.17	10	2.5
	mean	**3.7**	4.30	**3.8**	2.26	15	6.6

2013-14

Efficacy assessment results for 2013-14 season are shown in Table 5b. Although CIPC deposit levels were lower in 2013-14, overall sprout control efficacy was better compared with 2012-13. Storage duration was approximately 3 weeks longer in 2013-14, with initial application taking place approximately 2 weeks earlier, and unloading approximately one week later. Differences in sprout length and sites of sprouting at store unloading were very slight, and not significant, but treatment at 10°C at the 7g tonne^{-1} rate resulted in significantly fewer sprouted tubers (p=0.0330). In 2013-14 sprouting was also assessed after an additional period of 'shelf-life' (2 weeks at 20°C, Table 5c).

Table 5b. Mean maximum sprout length (mm) and sites of sprouting at store unloading, 2013-14.

application rate (g/tonne)	application temp/timing	sprout length (mm)	SD	sites of sprouting	SD	unsprouted (%)	SD
14	10°C	1.0	0.91	1.2	1.01	31	20.5
	7°C	1.0	1.20	0.9	0.91	36	12.0
	3.5°C	1.3	1.42	1.3	1.21	29	6.1
	3.5°C 'late'	1.1	1.10	0.9	0.77	31	9.2
	mean	**1.1**	1.17	**1.1**	1.00	32	3.0
7	10°C	0.7	0.79	0.7	0.93	49	6.1
	7°C	1.2	1.17	1.0	0.88	32	6.9
	3.5°C	1.1	1.36	0.9	0.86	40	4.0
	3.5°C 'late'	1.2	1.50	1.0	1.07	37	6.1
	mean	**1.1**	1.24	**0.9**	0.94	40	7.3

The additional period of shelf-life testing resulted in a small increase in sprout length in crops treated at 14g $tonne^{-1}$, and a relatively large increase at the lower CIPC application rate. There was a notable increase in variability of sprout length of some treatments after the period of shelf-life. Although sprouting levels were lowest in samples treated at 3.5°C 'late', differences were not statistically significant.

Table 5c. Mean maximum sprout length (mm) and sites of sprouting after shelf-life storage, 2013-14.

application rate (g/tonne)	application temp/timing	length	SD	sites	SD
14	10°C	1.8	1.69	2.1	1.01
	7°C	3.6	4.27	2.5	1.41
	3.5°C	1.9	2.35	2.0	1.22
	3.5°C 'late'	1.3	1.01	2.3	1.58
	mean	**2.1**	2.76	**2.2**	1.33
7	10°C	10.8	6.33	4.7	1.90
	7°C	15.4	4.73	5.6	1.47
	3.5°C	7.5	13.68	3.5	1.66
	3.5°C 'late'	5.0	5.54	3.4	2.05
	mean	**9.7**	9.20	**4.3**	2.00

2014-15

Results of efficacy assessments at store unloading for 2014-15 are shown in Table 5d. Efficacy of sprout control was generally very good in all treatments, and there were no statistically significant differences.

Sprouting was also assessed after an additional period of 'shelf-life' (4 weeks at 20°C, Table 5e). Although sites of sprouting increased after the period of shelf life, sprout length changes were small and there remained no significant differences in sprouting levels from treatments.

Table 5d. Mean maximum sprout length (mm) and sites of sprouting at store unloading, 2014-15.

application rate (g/tonne)	application temp/timing	sprout length (mm)	SD	sites of sprouting	SD	unsprouted (%)	SD
14	10°C	1.3	0.86	2.0	1.39	13	4.6
	7°C	1.8	1.76	2.4	1.47	8	4.0
	3.5°C	1.7	1.28	2.2	1.82	12	6.9
	3.5°C 'late'	1.8	1.43	2.9	1.89	8	6.9
	mean	**1.6**	1.38	**2.4**	1.68	10	2.7
7	10°C	1.2	0.69	2.1	1.69	12	10.6
	7°C	1.4	1.07	1.9	1.39	11	6.1
	3.5°C	1.2	1.00	1.5	1.33	24	8.0
	3.5°C 'late'	1.3	0.71	1.9	1.21	8	4.0
	mean	**1.3**	0.88	**1.9**	1.42	14	7.1

Table 5e. Mean maximum sprout length (mm) and sites of sprouting after four weeks of shelf-life storage, 2014-15.

application rate (g/tonne)	application temp/timing	sprout length (mm)	SD	sites of sprouting	SD
14	10°C	1.9	3.21	6.7	1.92
	7°C	2.7	3.28	6.2	1.49
	3.5°C	2.0	1.76	6.4	1.35
	3.5°C 'late'	3.0	4.34	6.2	1.29
	mean	**2.4**	3.30	**6.4**	1.54
7	10°C	1.8	1.97	6.6	1.34
	7°C	2.1	2.14	7.0	1.46
	3.5°C	2.0	2.29	6.8	1.37
	3.5°C 'late'	1.7	2.02	6.6	1.49
	mean	**1.9**	2.10	**6.8**	1.42

3.6 The effect of humidity

The use of salt or humidification in separate stores resulted in a *c.*10% difference in relative humidity at each of the storage temperatures.

No significant changes in CIPC vapour concentration occurred as a result of the differences in relative humidity (Table 6a). Values at 7°C and 10°C were similar to those measured by Park (2004), but at 3.5°C, values were higher. There was no difference in vapour concentration at 3.5°C and 7°C.

Although there was no effect of humidity on CIPC vapour concentration, mean CIPC residue levels of potato tubers were 65% greater, after ventilation for 24 hours, in the lower humidity store (Table 6b). Differences in CIPC residue concentration were significant at the 10°C (p=0.01) and 3.5°C (p=0.003) store temperatures, but not significant at 7°C (p=0.079).

Table 6a. Mean CIPC vapour concentrations(μg L^{-1}).

temperature	humidity (RH)	CIPC (μg L^{-1})	SD
10°C	98.7%	0.13	0.040
	88.3%	0.13	0.039
7°C	98.7%	0.07	0.006
	86.9%	0.09	0.014
3.5°C	97.6%	0.07	0.015
	84.9%	0.08	0.024

Table 6b. Mean CIPC residue levels.

temperature	humidity (RH)	CIPC (μg g^{-1})	SD
10°C	98.7%	0.28	0.055
	88.3%	0.43	0.026
7°C	98.7%	0.22	0.039
	86.9%	0.36	0.093
3.5°C	97.6%	0.11	0.006
	84.9%	0.22	0.029

4. Discussion

Storage of potatoes at low temperature (3.5°C) results in little sprouting pressure, and applications of CIPC at 7 g tonne^{-1} and 14 g tonne^{-1} rates generally maintained sprout growth of cv Maris Piper at low levels (<4.5 mm) at store unloading. Overall average sprout length, for all treatments, were 3.3 mm (SD 1.04), 1.1 mm (SD 0.18) and 1.5 mm (SD 0.26) in 2012-13, 2013-14 and 2014-15 respectively. In season 2014-15, there were no significant effects of applications (CIPC dose rate or temperature at the time of application) on sprout growth. In 2012-13 and 2013-14 however, there were significant differences in sprout development. At both CIPC rates in 2012-13, application at 10°C resulted in most effective sprout control. Delaying application until later in the store temperature pull-down programme resulted in poorer sprout control at unloading, which could be ameliorated to an extent by the higher (14 g tonne^{-1}) CIPC application rate. In 2013-14 sprout control was generally more effective and there were few differences, but at the 50% CIPC application rate (7 g tonne^{-1}), application at 10°C resulted in the largest proportion of unsprouted tubers at store unloading. Sprouting was maintained at its lowest level in season 2013-14, when overall CIPC deposit levels were lowest, suggesting dose rates were sufficient for sprout control efficacy.

In previous work (Briddon *et al*. 2013) vapour concentration was greater, at a storage temperature of 3.5°C, when the CIPC had been applied at a store temperature of 10°C compared with 7°C or 3.5°C, and this was thought to perhaps be a method of improving efficacy, with reduced inputs, in low temperature stores. Although there was evidence of a higher application temperature giving rise to greater vapour release in 2012-13 (Fig 2), this was not duplicated in 2014-15 (Table 2c). In addition, in 2012-13, the effect was not long lived, with no differences in CIPC vapour concentration as a result of application temperature from samplings later in the season (sampling in March and June in Table 2a). A greater propensity to generate CIPC vapour from applications carried out at warmer temperatures would also be anticipated to result in greater adsorption of CIPC to untreated tubers, located after treatments had taken place. Data do not support this.

Data indicate that while application at 10°C cannot be anticipated to give rise to a greater rate of CIPC vapour release at a storage temperature of 3.5°C, compared with application at 7°C or 3.5°C, there are still advantages to early application, while crop is still relatively warm. The saturation vapour concentration of CIPC is reported to be low, but is strongly influenced by temperature. Approximately linear over the range of temperatures that may typically be found in potato stores, the saturation vapour concentration of circa 0.03 µg L^{-1} at 3°C is approximately 15% of that of air at 15°C (Park, 2004). This results in even short periods at relatively warm temperature having a disproportionate effect on CIPC re-distribution, as measured by adsorption of CIPC on untreated tubers. Using data from Tables 3b and 3c, untreated tubers adsorbed CIPC at a mean rate of 0.014 mg kg^{-1} day^{-1} during the pull-down period from 10°C to 3.5°C. This compares with a mean rate of 0.0035 mg kg^{-1} day^{-1} from applications carried out at 3.5°C. Overall, application at 10°C resulted in at least 20-30% greater CIPC adsorbtion on untreated tubers compared with treatment at 3.5°C. Although it is not possible in this experiment to link re-distribution directly to efficacy of sprout control, the recorded values for the pull-down period from 10°C to 3.5°C (0.17-0.19 mg kg^{-1} in 2013-14 and 0.22-0.32 mg kg^{-1} in 2014-15) are reported to be sufficient for effective sprout control (Briddon et al. 2013).

In the 2012-13 and 2014-15 storage seasons, CIPC residues at store unloading were influenced by the position of samples in store, with samples left in boxes (*in situ*) having concentrations approximately twice those of exposed samples, which were suspended in the store headspace, and thus exposed to a much larger volume of recirculating air. This indicates that residue decline through volatilisation is limited in situations where airflow rates are small, as indicated in Briddon et al (2009) and smaller than those suggested by Kleinkopf (2004), around 1ppm for stores with processing potatoes. In such situations (e.g. non-positively ventilated stores) therefore, effective distribution is more critical as there is reduced scope for re-distribution, so any poor initial distribution of CIPC is likely to be preserved.

Control of sprout growth by CIPC in potatoes held at low temperature (3-4°C) has been reported to be problematic, with symptoms of treatment appearing only gradually (D. Hudson, Storage Forum, SBCSR February 2013 & Briddon *et al*. 2013). CIPC dose rates may also be considered relatively high, in comparison with storage at processing potato temperatures, given the extension in dormancy and low sprout growth rates at storage temperatures below 5°C. Data obtained in other work (Briddon *et al*. 2013, Briddon *et al*. 2014), indicate that high tuber CIPC residue values persist for long periods under pre-pack storage conditions and this may be associated with an increased risk of exceeding the MRL for CIPC. The gradual appearance of symptoms of sprout control and longevity of CIPC residues are both consistent with the low saturation vapour concentration that exists in low-temperature potato stores.

5. Conclusions

In two out of three seasons, the application of CIPC early in storage, while stores were still relatively warm, resulted in improved sprout control during storage at 3.5°C, when compared with later applications made after stores had been cooled to the holding temperature. In a third season, there were no differences in sprouting levels.

Warmer stores (i.e. those at >3.5°C) had a higher CIPC vapour concentration and this resulted in a significantly greater proportion of CIPC adsorbing to untreated tubers, placed in boxes, after applications. This was indicative of a higher propensity for CIPC to re-distribute at higher temperatures. Efficacy of sprout control in low temperature stores (<5°C) is maximised by carrying out applications early, while crop is still warm.

6. References

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Appendix

1. CIPC vapour concentrations in samples in 2013-14

Table 2b. CIPC vapour concentration (μg L^{-1}), 2013-14.

CIPC rate/ temp/timing at treatment	24 hrs	SD	pull-down	SD	target temp	SD	March	SD	June	SD
14g tonne^{-1}										
10°C	0.86	0.17	3.95	4.85	11.64	3.16	0.51	0.32	0.06	0.06
7°C	0.75	0.00			11.55	3.27	0.28	0.29	0.03	0.00
3.5°C	8.53	1.18			13.12	1.52	1.13	0.99	0.54	0.80
3.5°C 'late'	0.31	0.03					0.99	1.01	0.86	1.36
mean	**2.78**	3.74	**3.95**	4.85	**12.10**	2.52	**0.73**	0.73	**0.37**	0.77
7g tonne^{-1}										
10°C	0.67	0.10	1.20	0.28	11.03	2.42	0.17	0.15	0.02	0.01
7°C	0.90	0.08			10.36	2.81	0.81	0.71	0.79	1.34
3.5°C	7.93	1.52			22.10	7.91	0.66	0.63	0.49	0.75
3.5°C 'late'	0.33	0.07					0.89	0.86	0.52	0.76
mean	**2.60**	3.50	**1.20**	0.28	**14.50**	7.19	**0.63**	0.62	**0.45**	0.79