POTATO COUNCIL

Final Report

Evaluation of the impact of modified storage practices on sprout suppression

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1. Summary

Over three storage seasons CIPC application trials were carried out in commercial bulk stores. Trials assessed a modified system, based on North American practices, and were compared with conventional CIPC applications in Great Britain.

The modified treatment consisted of continuous recirculation of the CIPC fog, through the bulk pile, with fans operating at low speed. Air delivery to the pile was 'balanced' prior to application, to try to deliver similar amounts of CIPC into all laterals. This is necessary because reductions in fan speed, from the normal operating range for ventilation, would otherwise result in changes to the airflow dynamics of stores giving rise to uneven rates in different laterals. Fog was generated with equipment modified (by close coupling) to reduce the volume of air/fog introduced to the store by around 35%, compared with a standard application. A solvent-free formulation was selected, which further reduces the volume of air/fog introduced to the store during application. Reductions in the volume of fog applied reduce losses of chemical by limiting leakage as a result of displacement (i.e. volume in = volume out). Conventional treatments, for comparison, were carried out without recirculation of fog, with unmodified equipment and using a solvent-based CIPC formulation.

In all cases, the modified application procedure resulted in improvements. Improvements occurred as enhanced sprout control efficacy with reductions in mean maximum sprout length and sprout length variability, or an extension in storage duration. Improvements in sprout control efficacy were as a result of more even CIPC residue distributions and greater application efficacy. Application efficiency (mean residue value expressed as a proportion of the application rate) for first treatments were found to be 30%, an improvement compared with literature values of 10% (Noël *et al*, 2004). Second treatments resulted in application efficiencies of between *c.* 50-75%.

While sprout control efficacy was improved, the modified application procedure did not always result in reductions of CIPC input, and store design had an influence over this. In stores with a modest headspace (the volume of air contained in a store when it is loaded), applications were relatively efficient and input reductions were achieved. In stores with a large headspace, CIPC treatments did not result in significant residue levels and sprout control here was only achieved with relatively high, and therefore inefficient, CIPC use.

Modifications aimed at reducing fog volume at application are calculated to have reduced leakage of CIPC by *c.* 51%, resulting in higher application efficiency, compared with literature values, and less impact on the surrounding environment. Together, all modifications resulted in a significant extension in storage duration per gramme of CIPC input. However, the extent of improvement in storage duration also varied with store design, improving by 92% in the best case.

Redistribution of CIPC through the vapour phase, during storage over the weeks after application, was observed to move significant amounts of CIPC around the store and did, at times, help to balance residue levels within the pile.

The modified CIPC application procedure resulted in improved efficiency of CIPC application and more even residue distributions. As a result, sprout control efficacy was improved sufficiently to allow reductions in CIPC input in some stores. The modified application procedure represents an improvement in the use of CIPC and should be considered best practice in bulk potato storage.

2. Experimental section

Introduction

CIPC is used to provide sprout control allowing year round supply of potatoes in GB and, globally, is the most important sprout suppressant. In 2007, a European Maximum Residue Level (MRL) of 10 mg kg^{-1} of CIPC was implemented, on potatoes. To assist in meeting the MRL, improvements in the CIPC application process were sought.

The primary objectives of this project were to reduce the amount of CIPC applied in a season and to ensure crops stayed within the MRL, without compromising sprout control efficacy. Through doing this, the associated environmental impact of applying CIPC and the cost of storage could also both potentially be reduced.

Further restrictions on CIPC use have been imposed, in addition to those as a result of (EU 91/414) Annex 1 listing, to address concerns of PSD on residue limits. Changes are being implemented by the CIPC Stewardship Group (www.potato.org.uk/cipc) and include a limit of 36 g $tonne^{-1}$ for fresh potatoes, and 63.75 g $tonne^{-1}$ for potatoes for peeling or processing.

Experimental plan

CIPC application trials were carried out over the three years of the project in commercial bulk potato stores. Where possible, modified applications were carried out in parallel with conventional applications, but at some sites only the modified treatment was used.

In addition to the commercial scale trials, in years 1 and 2, small-scale experiments were carried out at Sutton Bridge Experimental Unit (SBEU). In the first year, these investigated the importance of recirculation air speed on CIPC deposition and, in the second year, redistribution of CIPC between potatoes.

In the final year, additional tests were carried out on a commercial scale to look at the scope for redistribution of CIPC within the bulk pile.

Commercial scale trials

CIPC application procedures in bulk stores in North America contrast markedly with those in Great Britain (Briddon & Jina, 2004), and differences are considered to be instrumental in their lower CIPC usage rates (J Forsythe, PIN/NIP Inc., personal communication). In North America applications are carried out with continuous, low airspeed re-circulation of store air/fog, through the bulk pile. Fan speed is reduced by fitting these with variable frequency drives (VFD), also known as inverters or variable speed drives. Recirculation of fog with fans operated at normal ventilation speeds is likely to result in excessive deposition of CIPC on fan blades/guards and can result in complete blockage of the fan (Figure 1).

In addition to re-circulation of fog, all foggers observed in North America had a close-coupled arrangement at the fog head and the solvent-free, solid CIPC ‘briquette’ was the formulation in general use. Close-coupling of the fog head (Figure 2) and the use of CIPC briquettes, both serve to reduce the volume of the applied fog and, as a consequence, reduce the amount of leakage from stores, by limiting displacement. Although a volume equivalent to that applied is lost from the store, during application, figures are difficult to obtain and the actual amount of CIPC lost will depend on how completely store air and fog are mixed. Park

(2004) estimated leakage to be within the range 13% to 33% in box stores.

In contrast, applications of CIPC in bulk stores in GB are typically carried out without recirculation (or just very brief use to 'clear the tunnel') and formulations are generally made up in a solvent, such as methanol or dichloromethane. Both open and close-coupled fog head arrangements are in use. Without recirculation, the CIPC applied effectively passes through the bulk pile once, and then collects in the store headspace.

FIGURE 1. COMPLETE BLOCKAGE OF A FAN WITH CIPC AFTER RECIRCULATION OF FOG AT FULL SPEED

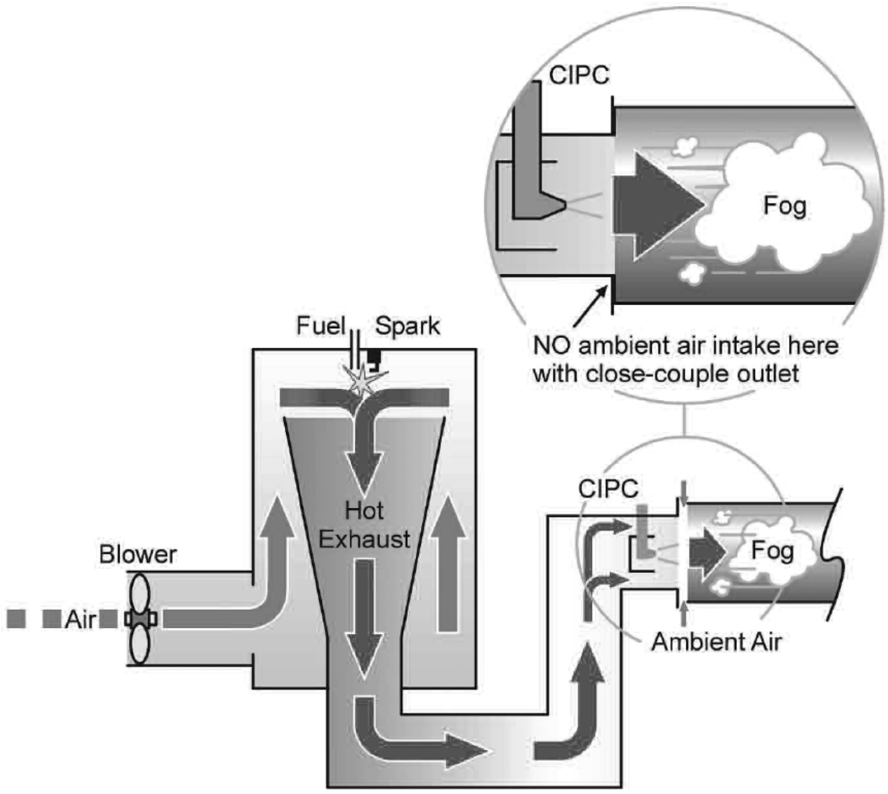


FIGURE 2. SCHEMATIC REPRESENTATION OF A FOGGER SHOWING OPEN AND CLOSE-COUPLED (INSET) ARRANGEMENTS FOR THE FOGGER OUTLET.

Principle

Recirculation of CIPC fog must take place with fans operating at reduced speed to limit the risk of fan blockage as a result of excessive CIPC deposition. In bulk stores fan output and the store's duct system are configured to be restrictive. In a well designed store this will result in build-up of static pressure which assists in obtaining a relatively even airflow into lateral ducts along the length of a main duct. When fan speed is reduced however, the static pressure distribution may be changed and airflow rates are likely to become unbalanced. Typically, airflow rates will be high in a few lateral ducts usually those nearest the return route to the fan. CIPC application without adjustment to compensate for this would result in an uneven distribution of the treatment with those lateral ducts receiving the most air also receiving an 'overdose' of CIPC.

Prior to application, the balance of the system during low-speed recirculation must be evaluated. This is assessed by measuring airspeed, from the main duct into lateral ducts, using an anemometer. Where airflow rates are particularly unbalanced, it may be necessary to reduce the outlet area of each lateral, perhaps to around 50% of its normal size. This will result in more even distribution of air, but is likely still to be unbalanced, with airflow rates in some laterals being greater than others. To balance the system completely, laterals with high airflow rates (usually close to the fan) will need *closing* further, and laterals with low airflow rates will need *opening* further. By increasing the outlet area of laterals with low airflow rates, and decreasing outlet area of laterals with high airflow rates, the system is balanced and equivalent volumes of air/CIPC are delivered to crop above all laterals. This should be checked prior to application. Once the system is balanced, CIPC is applied, and recirculated until the chemical has deposited.

McGowan undertook a second study tour in North America in 2007 to develop the research in this area. Observations of typical store design in NA indicated that generally stores were better sealed than in GB and had less headspace above the crop. The smaller headspace is intended to reduce the temperature stratification in store (Brook *et al,* 1995*;* Eltawil *et al,* 2006). Having a balanced airflow was considered critical in a store (J. Forsythe, PIN/NIP Inc., personal communication re: *Potato Storage Design Guide, BTU Corporation*), particularly to equalize temperatures and ensure even distribution of sprout inhibitors (Eltawil *et al,* 2006). Researchers in Denmark noted that temperature differences within a bulk pile lead to non-uniform condensation of CIPC throughout the pile (Christiansen & Lærke, *c.* 2002*).* Problems of excessive weight loss and lack of sprout control are often caused by an unbalanced airflow and recommendations are available for establishing the correct relationship between ventilation openings in bulk potato storage (Brook *et al,* 1995; Rastovski *et al,* 1987).

Redistribution of CIPC

Most users of CIPC recognise that storage of seed in buildings treated with the chemical is not suitable because CIPC particulates, as deposited by thermal fogging, can be readily volatilized and redistributed causing contamination of seed crop. The issue of CIPC redistributed in store after application was raised following examination of the first years CIPC deposit results (McGowan *et al,* 2006). The considerable scope for re-distribution, once it has been applied was demonstrated in a separate, small-scale experiment in year 2, as well as in other previous work (Park, 2006). CIPC is transported through the vapour phase and therefore distributes primarily in the direction of the airflow. This would help to distribute chemical around the store, particularly in a vertical plane through the height of the pile.

McGowan (*Study tour 2007, unpublished report*) reported that CIPC suppliers (1,4 Group, Idaho, USA) advise applicators and store managers to collect tuber samples three to four weeks post application, for quality control purposes. This period is left between CIPC application and residue assessment because changes in CIPC concentration are expected, and values after this period are considered more representative of the bulk of the crop.

Smaller scale experimental trials were conducted at Sutton Bridge Experimental Unit to address the question of CIPC distribution at a range of air recirculation speeds and CIPC redistribution during storage. This information will aid the understanding of what happens in a commercial store in the bulk of potatoes. The objective of the experimental trials was to determine the effect of airflow on distribution and the magnitude of redistribution of CIPC under defined ventilation conditions. In the third year of the project distribution and redistribution was assessed on a full commercial scale through the course of the storage season. A novel sampling system was developed to allow collection of samples from locations within the stack, thus improving the information available.

Materials and methods

Methods that were used in all three years of the study are described below. Details of specific methods used in one particular season are described in the section for that year.

Commercial modified application trials

Over three storage seasons, 2005/6, 2006/7 and 2007/8, modified thermal fog applications of CIPC were carried out at a number of commercial, bulk potato stores and, where possible, compared with conventional thermal fog applications. The number of stores increased, as the project progressed and, in the final year, 10,500 tonnes of crop of five cultivars (Hermes, Markies, Pentland Dell, Russet Burbank and Saturna) were treated. Treated stores covered a range of sizes and designs, with crop destined for both the chipping/French fry market and crisping.

Stores at two sites were used throughout the project and, at one of these, a store was treated conventionally for comparative purposes, in all three seasons. At other sites, the store managers decided to adopt the improvements seen in test stores and, therefore, no longer run a conventional control.

Conventional CIPC treatment

Conventional treatments consisted of application of 50% CIPC w/v in methanol *(MSS CIPC 50M* or *ProLong* formulations; United Phosphorus Ltd., Warrington, Cheshire, WA3 6AE) using a conventional, commercial, open-coupled *Unifog* machine (Stored Crop Conservation Ltd, Washingborough, Lincoln, LN4 1AF). Store ventilation systems were switched off prior to application and remained off until after the fog applied had settled.

Modified CIPC treatment

Modified treatments were made using 100% w/w solid CIPC briquette (*MSS Sprout-Nip* formulation; United Phosphorus Ltd., Warrington, Cheshire, WA3 6AE). Applications were made with a *Unifog* machine (SCC Ltd) with a close-coupled modification and the addition of a system which melted the briquette at the time of application. The stores' ventilation systems were run continuously, at a reduced fan speed, during application and this was maintained until ambient ventilation of the store when the fog had settled. Fan speed control was achieved by the installation of variable frequency drives (VFD).

The outlets from the main duct, into the lateral ducts, were adjusted prior to application (on the basis of air speed measurements) to compensate for the unbalanced airflow that occurs as a result of the reduced air volume displaced by fans operating at low speed. Leakage points in store were minimised where possible (e.g. around doorways) and all available internal doors and louvres were opened to provide the least possible restriction to recirculating air/fog.

Store managers were responsible for the timing and dose rate of CIPC applications, and in the case of re-applications, were not supplied with information about existing CIPC levels. In the event, all CIPC treatments were applied at a nominal rate of 14.25 g tonne^{-1}. The timing and duration of ambient ventilation for carbon dioxide/ethylene purging was also the responsibility of store managers and this generally took place earlier following the modified applications.

Headspace CIPC concentration.

Methanol solvent traps were used to determine airborne CIPC concentrations. Each trap contained approximately 200 ml of methanol (HPLC grade). Store air was drawn through the trap for 20 minutes at a known rate in the range 900-1400 ml min^{-1}. Traps were located on top of the bulk piles approximately 1.5 m from the gangway. Samples were collected at intervals up to approximately 8 hours after application.

Tuber CIPC deposit and residue assessment

Tuber CIPC residue values are determined on samples that have been washed, prior to CIPC being extracted and quantified. CIPC deposit values are obtained without washing and are used to indicate an 'initial distribution' of CIPC prior to being subjected to changes that occur in storage (volatilisation and redistribution).

Year 1: 2005-2006 storage season

Commercial scale trials

The modified method for application of CIPC was evaluated at two sites in commercial bulk stores of *cv.* Russet Burbank and compared with standard GB practices. Crop was held in all four stores for a nine-month period between October 2005 and June 2006. Stores 1, 2 and 3 were used in all three seasons of the project.

Two applications of CIPC were made using the modified system in store 2, compared with four, using the conventional method, in store 1.

In stores 3A and 3B, two treatments were made using both application methods.

Small scale trials – recirculation airspeed

A study was carried out to examine the effect of recirculation air flow rate on deposition and distribution of CIPC on potatoes.

Circa 0.5 tonnes of CIPC untreated tubers (cv. Hermes) were stored in each of four, 3m high piles using plastic pipes (600mm Ø). Each pipe was located in a separate 12-tonne capacity store which was held at 10°C until just prior to application. Where applicable, a fan was attached to the top of the pipes and adjusted to draw air through the tubers at specific airflow rates.

The airflow rates examined were:

No flow	
Low speed (5% capacity):	3 ft^3 min^{-1} t^{-1} (0.0015 m^3 s^{-1} t^{-1})
Medium speed (20% capacity):	12 ft^3 min^{-1} t^{-1} (0.006 m^3 s^{-1} t^{-1})
High speed (100% capacity):	60 ft^3 min^{-1} t^{-1} (0.03 m^3 s^{-1} t^{-1})

Stores were fogged with *MSS Sprout Nip* (United Phosphorus Ltd., Warrington, Cheshire, WA3 6AE) applied at a rate of 250g per store (equivalent to an application to a full store). Application was carried out with a burner temperature of c.475°C using a close-coupled Stored Crop Conservation *Unifog* machine.

When fogging was complete, and an initial headspace sample was taken, fans attached to pipes were enabled and applied fog was recirculated continuously for a period of eight hours.

Pipes were unloaded one day after application and tuber samples, for CIPC deposit analysis obtained. The sampling depths were 0 (surface), 5, 50, 100, 150, 200, 250, 295 and 300 cm (base).

Store headspace CIPC concentrations were measured periodically during the period of recirculation. Samples were taken, using a solvent trap method, immediately after fogging and at approximately 0.5, 2, 4 and 8 hours post- application.

CIPC deposits on fans were also recorded. The whole trial was repeated on a second occasion, for the purposes of replication.

Leakage - fogger testing

Foggers operated by CIPC contractors in Great Britain typically have an open-coupled design at the fog-head. By having a small gap between the fog-head and the pipe delivering chemical into store, additional ambient air is drawn in (by venturi effect), increasing the volume of gases introduced to store. Part of the modified application system used in this experimental work was a close-coupled configuration at the fog-head, to reduce the volume of fog applied.

Application of fog at a smaller volume flow will limit pressure differences between the store and its surrounding environment and so reduce the volume of gases (fog and store air mix) leaking from store during application, by displacement. In addition, not drawing in ambient air at the fog-head, may help to produce a fog of more consistent quality as ambient air temperature and humidity varies considerably.

A Stored Crop Conservation *Unifog* fogger, as used for the trial treatments, was tested to assess the difference in volume output of open and close-coupled configurations. An anemometer was used to measure air speed from the fog delivery pipe (aperture size 110mmØ) with the engine set at three speeds. Applications are carried out with the engine operating at c. 3300 rpm. Limitations of the measuring apparatus meant that readings had to be conducted with only the 'blower' operating throughout; there was no load from heating the air to the temperature normally used to perform CIPC treatments.

Year 2: 2006-2007 storage season

Commercial scale trials

Six stores (1, 2, 3A&B, 4A&B) were used in the second year with *cv.* Russet Burbank – as in year 1 – and *cv*. Saturna. Conventional treatments were made in stores 1 and 3B, while in stores 4A and B, two versions of the modified application system were used to assess if increasing recirculation air speed could be used to encourage more rapid deposition of CIPC on to the crop.

Stores 1 and 2 received only one application of CIPC. The conventionally treated crop was stored for *c*. 5½ months whereas the crop treated with the modified application was held for 7½ months with only 14 mg kg^{-1} of CIPC.

Stores 3A and B were each treated with three applications of CIPC and unloaded in January

2007 after only 4 ½ months of storage.
Stores 4A and B each received three applications of CIPC. However, at this site crop was kept in store long term (>7 months) and this level of use represents fewer applications than the average required for this duration (D Mackie, Spearhead Marketing, personal communication). Both the modified and the further modified (two stage airflow rates) resulted in relatively high application efficiencies and good levels of sprout control.

Small-scale trials – CIPC redistribution

Redistribution of CIPC was assessed by measurement of CIPC deposit levels on 'untreated' tubers ventilated with air after this had passed over CIPC treated tubers (figures 3, 4 & 5).

Four 1500mm lengths of twin walled plastic pipe (inside Ø 300mm) were loaded with 3 layers of untreated, washed tubers at the base, followed by approximately 7 layers of CIPC treated tubers. On top of the treated tubers the pipe was filled with untreated washed tubers up to 200mm below the edge of the pipe.

Each pipe contained approximately 60-70kg of crop. The untreated tubers were cv. Saturna, graded at Ø 65mm and the CIPC treated tubers were cv. Desiree, graded at Ø 45mm. The red colour of the treated crop allowed for easy identification of the treated layers. Crop was held at 10°C and ambient humidity.

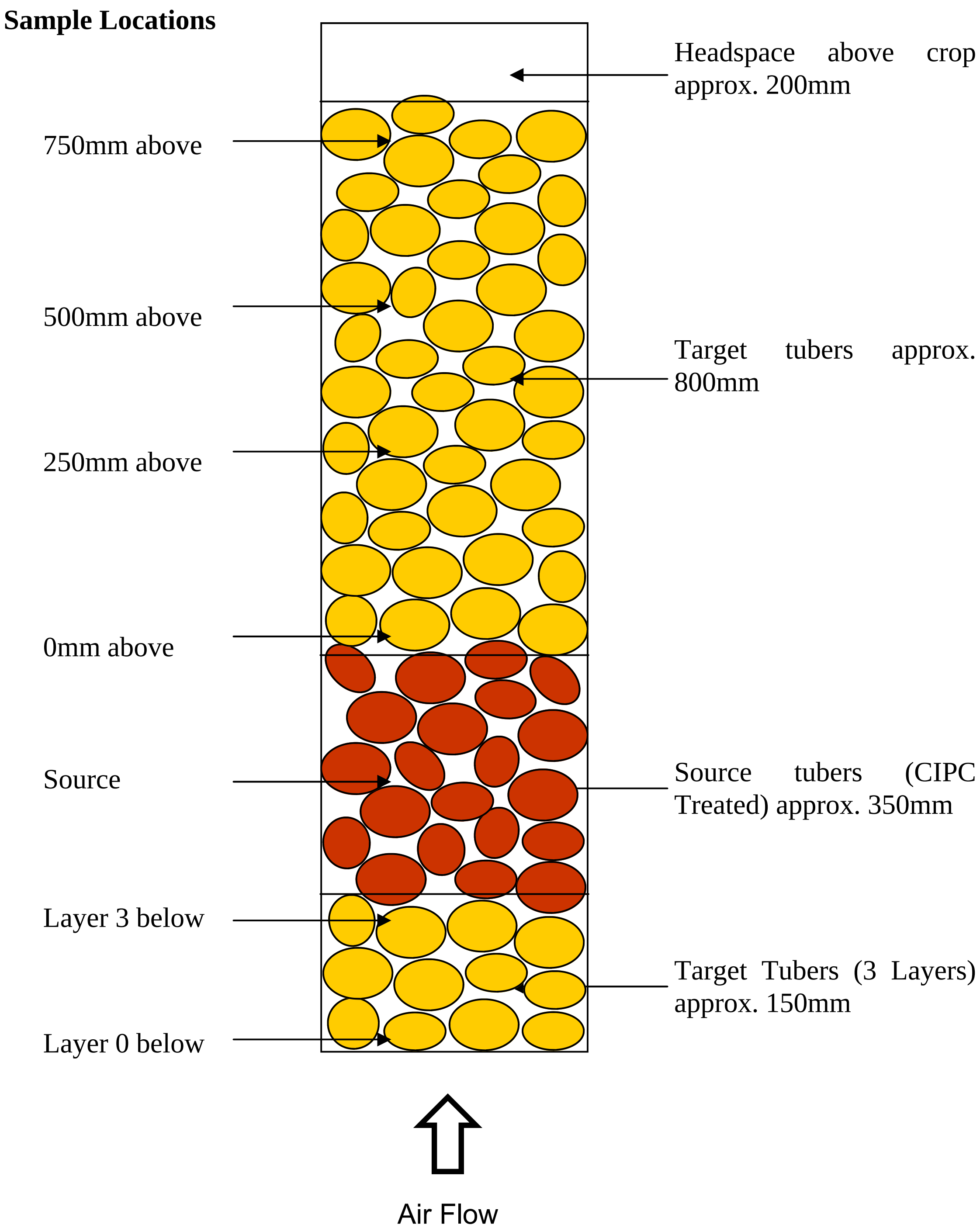


FIGURE 3. DIAGRAM OF PIPE SET UP IN REDISTRIBUTION TRIAL AND SAMPLE LOCATIONS

Fans, located at the top of each pipe, were used to draw air through the crop at a rate of c. 40 cfm $tonne^{-1}$ (c.0.02$m^3s^{-1}tonne^{-1}$, Table 1). Air was drawn from an uncontaminated store (air temperature 10°C, ambient humidity). A base layer of untreated crop was used to indicate if CIPC was being drawn into the pipe in the air steam.

	m^3/s/t	**cfm/t**
Pipe 1	0.022	**46.44**
Pipe 2	0.027	**56.23**
Pipe 3	0.022	**46.65**
Pipe 4	0.021	**44.50**

TABLE 1. AIR FLOW RATE AT THE START OF THE TRIAL.

FIGURES 4 & 5. ARRANGEMENT OF PIPES WITH FANS IN CIPC REDISTRIBUTION TRIAL.

Source tubers had CIPC applied using a Swingfog thermal fogger applying 0.5l of ProLong into a 12 tonne experimental store. The crop was laid out in a single well-spaced layer to ensure as even a deposit concentration on all tubers as possible. The rate of application was decided based on the outcome of previous CIPC applications under similar conditions (*McGowan et al, 2006, p23-29*).

On each occasion, one pipe was unloaded, with sampling taking place after 7, 14, 21 and 28 days of storage. Airflow rate was again measured at unloading.

CIPC deposit level was measured using three replicate tubers:
a) On 'source' crop at the start of the trial and after each pipe was unloaded.
b) On untreated tubers at heights of 0, 25, 50 and 75cm above the 'source' crop when each pipe was unloaded.
c) On untreated crop from level 1 (in contact with manifold base) and level 3 (in contact with 'source' tubers).

Leakage – weather and store considerations

Application of CIPC by conventional thermal foggers results in leakage from stores and therefore losses of CIPC. The modified application system used in commercial trials included changes that were designed to reduce the volume of applied fog and are expected to reduce losses from store and thus improve application efficiency. In order to better understand the potential for losses of CIPC, experimental work was carried out assessing 'leakiness' of stores.

Leakiness was assessed as a decline in carbon dioxide concentration [Vaisala GMP 222], after this was introduced from cylinder as outlined by *Zahradnik, 1969*. Method development work was conducted in an empty store, with carbon dioxide released immediately in front of the refrigeration intake. Fans were left running during carbon dioxide release. Store carbon dioxide concentration was monitored at a central point in the building, approximately 1 metre above ground level.

Initial testing was carried out under calm & windy weather conditions and with & without fans running continuously after carbon dioxide release (fans were operated during carbon dioxide introduction on all occasions to ensure thorough mixing with store air).

Year 3: 2007-2008 storage season

Commercial scale trials

Stores 1 and 2

Store 1 was treated with the modified application system and Store 2 was treated conventionally. Stores were of 1,500 tonne capacity with relatively small, separated headspaces (*c.* 1535-1780 m^3 depending on loading) and loaded with cv. *Russet Burbank* destined for long-term storage. A single modified treatment was applied (25 October 2007) using two of the four fans supplying each main duct, operated from a VFD at 30% (15 Hz) for recirculation. Once the laterals were adjusted for balance, the airflow range into laterals was 0.23-0.41m^3 s^{-1} with an air speed range of 1.07-2.57m s^{-1}. The distribution of air along the length of the store is presented in Appendix 1. The conventional store received two applications. Unloading of stores began in mid-June. The crop was stored for approximately 8½ months in the modified store and 9½ months in the conventional store. Stores were ventilated 4½ -5 hours after modified application and 10-12 hours after conventional treatment.

Store 3 (Bay A and B)

Only the modified treatment was applied in this store. Application was carried out to 2,100 tonnes of Pentland Dell in two bays divided by a central duct. The store is a converted hangar and is characterised by having a very large headspace (*c.* 6500 m^3). A single application was made on 15 November 2007. Fog was recirculated with fans operated at 22% (11 Hz) during fogging and increased to 30% (15 Hz) after the application was completed. The airflow into laterals was 0.09-0.29 m^3 s^{-1} calculated from air speeds measured within the range 1.22-3.05 m s^{-1}. Full details of the duct settings and air volumes are in Appendix 1. Fan speed was increased to 70% (35 Hz) about 3½ hours after application in an attempt to purge the store. Due to an electrical fault, the ambient louvres could not be operated. Unloading of Bay A started in January, after only 3 months of storage, and unloading of Bay B began in March (after 5 months' storage).

Stores 4 (Bay A and B) and 5 (Bay A and B)

All treatments were made using the modified application system. There were two stores each with a 1,500 tonne capacity on both sides of a central main duct. Each store had a moderate-sized headspace, intermediate in volume between that of stores 1, 2 and 3. One store was fitted with refrigeration. The refrigerated store (4) contained *cv.* Saturna (1325 tonnes in each bay) and had a headspace of *c.* 4300 m^3. Complete treatments were made on 4 October and 31 January. On 15 April, all of Bay A was treated for a third time, but only crop above laterals 1-9 in Bay B was treated again. The Saturna was stored until May when unloading began, a total storage duration of 8 months.

The ambient ventilated store (5) contained 2000 tonnes of *cv.* Hermes; Bay B was loaded with c. 1150 tonnes. However, Bay A was only part-filled with c. 850 tonnes of crop, giving a larger headspace (volume of air) of *c.* 5360 m^3. Sprouting was evident when the initial CIPC application was made on 7 November (especially in Bay A). A second treatment was applied on 3 January. The store was unloaded in March after a storage period of 5 months.

A two-stage air/fog recirculation regime was used in both stores, based on positive results from small-scale trials at SBEU and commercial trials in the second year. In both stores, the first applications had fans operating at just 10% (5 Hz) capacity during application and until one hour after fog was applied, after which time the fans were increased to 15% (7.5 Hz). At the second application, it was noted that fans were not operating sufficiently quickly and some fog was entering the store headspace directly from the fanhouse. Therefore, at the final application (made to the refrigerated store 4), it was decided to operate fans continuously at 15%, to ensure all of the applied fog was drawn into the main duct. Following all CIPC applications the stores were ventilated at *c.* 4½ hours post-application.

The range of air speeds measured in store 4 were 0.64-3.18m s^{-1} at 10% and 0.97-4.83m s^{-1} at 15% fan capacity. These equate to airflows into laterals ducts of 0.10-0.20m^3 s^{-1} across all applications when fans were running at 10% and between 0.15-0.46m^3 s^{-1} when fans were at 15%. In the store 5, air speed ranges were measured of 1.17-2.95m s^{-1} at 10% and 1.78-4.52m s^{-1} at 15% fan capacity. The calculated airflows were therefore 0.06-0.21m^3 s^{-1} across all applications with fans running at 10% and between 0.09-0.29m^3 s^{-1} with fans at 15. Some difficulty was experienced in achieving a uniform airflow due to the store being part-filled. Full details of air balance across the stores (including imperial units) are given in the Appendix.

Store 6 (Bay A and B)

This was a relatively small store containing c. 425 tonnes of cv.*Markies* in each of two bays either side of a central main duct, with a small communal headspace (1098m^3). Only the modified treatment was applied to this store. The first CIPC application was carried out on 30 November with second and third treatments on the 29 January and 18 March respectively. The times elapsed prior to ventilation following applications varied: these took place at 3½, 4½ and 7½ hours after applications 1, 2 and 3 respectively. The crop was stored until mid-June, a duration of 8 months. All applications were conducted with a single fan operating at 20% capacity (10 Hz) throughout treatment. Measured air speeds into laterals were in the following ranges: application 1, 1.98-2.92m s^{-1}(airflow 0.07-0.10m^3 s^{-1}), application 2, 2.03-2.95m s^{-1} (0.07-0.11m^3 s^{-1}) and application 3, 1.88-2.79m s^{-1} (0.07-0.10m^3 s^{-1}).

Headspace CIPC concentration

Headspace sampling of airborne CIPC concentration immediately following fog application was conducted in stores 4, 5 and 6. Methanol solvent traps were located in store, one set on top of the bulk pile approximately 1m from the main duct and above the penultimate lateral, a second set in the return path of the fog/air mix close to the fans. Air sampling pumps (SKC) were used to sample store air through the methanol (*c* .100ml, HPLC grade) at a known rate within the range 800-1300 ml min^{-1}. Samples were collected in duplicate at each location at intervals after application was completed. The approximate sample times were ½ hour, 1, 2 and 3 hours post-application.

Tuber CIPC residue concentration and sprouting

Netted tubers were placed in stores during loading in a 36 point, three-dimensional grid throughout the store. This ensured that samples taken at unloading represented the entire bulk, covering height, width and length and provided a comprehensive pattern of CIPC behaviour in each store. Netted samples were assessed for sprout growth and three tuber sub-samples were analysed individually for CIPC residue level.

Residue analysis was carried out by the hexane soxhlet extraction method of Khan (1999). The entire peel of each tuber was extracted as above and analysed by Gas Chromatography with Flame ionization detection (HP 5890A), using a General purpose DB-1, boiling point megabore column (HP). The mean of the three values is expressed with the associated 95% confidence interval.

CIPC distribution and redistribution assessment in commercial stores

Perforated drainage pipes (Ø 300mm, Figure 6) of lengths 2, 4 and 6m (including excess length to protrude from the stack surface) were located at three positions in Bay B of stores 4 and 5 (Figure 7), allowing samples to be inserted and recovered from depths of *c*. 1.00, 2.25 and 3.50m above the store floor. Pipes were located at store loading by laying them on the ‘face’ of the pile and holding them in position as the store was loaded. Pipes were kept in place by the weight of the surrounding potatoes and settled at an angle of repose of *c*. 37°, the same as the approximate natural angle of the crop (Eltawil *et al*, 2006). The lowest 1 m section of each pipe was perforated (32 no. Ø 32mm holes and 36 no. Ø 20mm holes. This was designed to allow free exchange of air/fog between sample material located in the pipes and the surrounding crop.

FIGURE 6. PERFORATION OF BASE OF SAMPLE PIPE TO ENCOURAGE UNIMPEDED MOVEMENT OF AIR AND CIPC THROUGH SAMPLES FOR ESTIMATION OF RE-DISTRIBUTION OF THE SPROUT SUPPRESSANT.

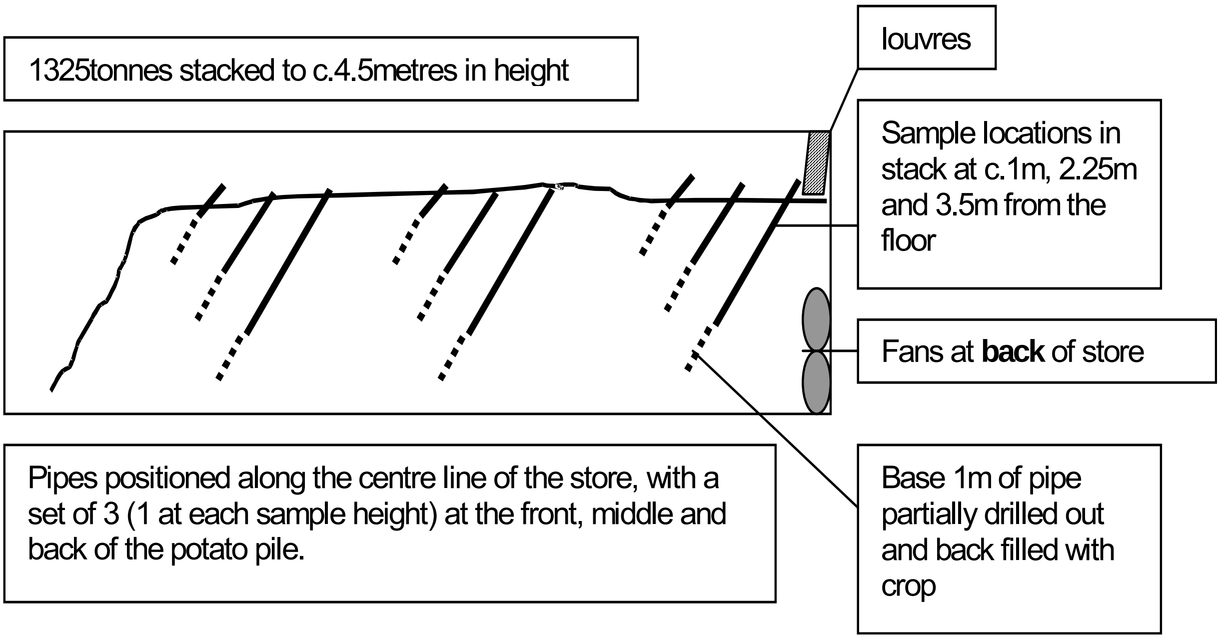


FIGURE 7. SCHEMATIC DIAGRAM OF THE DESIGN AND LAYOUT OF SAMPLE COLLECTION PIPES IN A BULK STORE

The pipes were located along the centre line of the store and, within each group, were offset such that the ends (the sample collection point) were not above any lower pipe and air/fog movement in these areas was not influenced by the presence of a pipe beneath. In this way, it is thought, a representative sample could be collected.

Samples (three tubers of *cv.* Desiree, red skin colour for easy identification) in nets were located in each sample pipe and were covered with an additional net containing *c.* 3 kg tubers. The end of the pipe protruding above the stack was also sealed to prevent short-circuiting of air.

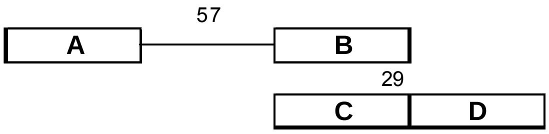
Samples were collected within 24 hours of applications (Figure 8). CIPC deposit analysis of these samples allowed CIPC application efficiency, at the different locations to be determined.

When these samples were removed, they were replaced with further untreated samples, which were removed just prior to subsequent applications. CIPC deposit analysis of these samples was used to indicate the magnitude of CIPC re-distribution at the different locations.

All samples assessed in the re-distribution trial were analysed for CIPC concentration without washing and therefore represent CIPC deposit values, which are greater than CIPC residue values. The unwashed tuber samples were analysed as previously described.

CIPC vapour concentration was measured at the base of the set of pipes in the middle section of Store 4. This was done on 20 February 2008, prior to and after purging of the store (for carbon dioxide control). Sampling was done in accordance with the method used by Park (2004) for collecting store air on an absorbent resin bed (Tenax), eluting the CIPC with 10ml of acetonitrile and analysis of the eluant by high pressure liquid chromatography (M. Smith, University of Glasgow, personal communication).

Store 5								
2007			**2008**					
Oct	**Nov**	**Dec**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**
	post app 1 7th, **A**			pre app 2 3rd, **B** post app 2 4th, **C**	unloading 3rd, **D**			
Time interval between sampling occasions (days)								



Store 4								
2007			**2008**					
Oct	**Nov**	**Dec**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**
post app 1 4th, **E**			pre app 2 31st, **F**	post app 2 1st, **G**		pre app 3 15th, **H**		unloading 4th, **I**
Time interval between sampling occasions (days)								

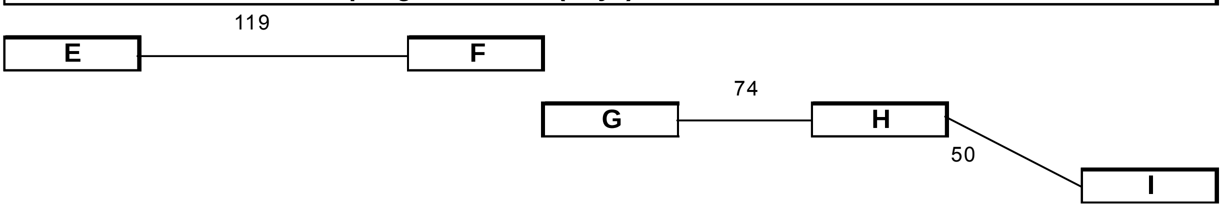


FIGURE 8. SAMPLE SCHEDULE FOR TUBER COLLECTION AROUND CIPC EVENTS, SAMPLING OCCASIONS A-D FROM STORE 5 AND E-I FROM STORE 4.

Results

Detailed results from years 1 and 2 of the study have been provided in interim project reports. As a result, summaries of the key results from these years are provided below. More detailed information is provided on results from year 3 of the study.

Year 1: 2005-2006 storage season

A summary of results for year 1 of the trial are shown in Table 2. All stores were unloaded after c. 9 months storage. At both sites the modified CIPC application system was superior, and resulted in more effective sprout control.

store	treatment	CIPC input (g tonne^{-1})	CIPC residue (mg kg^{-1})	standard deviation	max. sprout length (mm)	standard deviation
3A	modified	28.5	0.78	0.750	2.6	1.22
3B	conventional	28.5	0.70	0.698	3.2	1.17
1	modified	28.5	3.79	1.212	3.8	4.62
2	conventional	57.0	1.57	1.027	6.7	8.60

TABLE 2. SUMMARY OF COMMERCIAL TRIALS IN YEAR 1.

Mean residue levels at unloading were relatively low in stores 3A and 3B. This store had a large headspace and the results suggest an influence of store design on CIPC application efficiency. At the second site (stores 1 & 2, with a common design) the store using modified applications (store 1, 3.79 mg kg^{-1}) had higher residues values, even though it was treated with half the amount of CIPC. The greater CIPC usage rate in store 2, using the conventional application system, did not result in an improvement in sprout control efficacy. All residue levels were well within the MRL at a mean value of 3.8mg kg^{-1}.

The first year's commercial trials indicated that distribution of CIPC throughout the bulk of potatoes was improved using the modified application technique, with store managers reporting that "all four corners" of the store were effectively sprout controlled.

The relationship between sprout growth and CIPC residue levels of all samples at store unloading in year 1 is shown in Figures 9 and 10. Modified CIPC treatment resulted in 33% of samples with a mean maximum sprout length greater than 3mm, compared with a figure for conventional CIPC treatment of 63%.

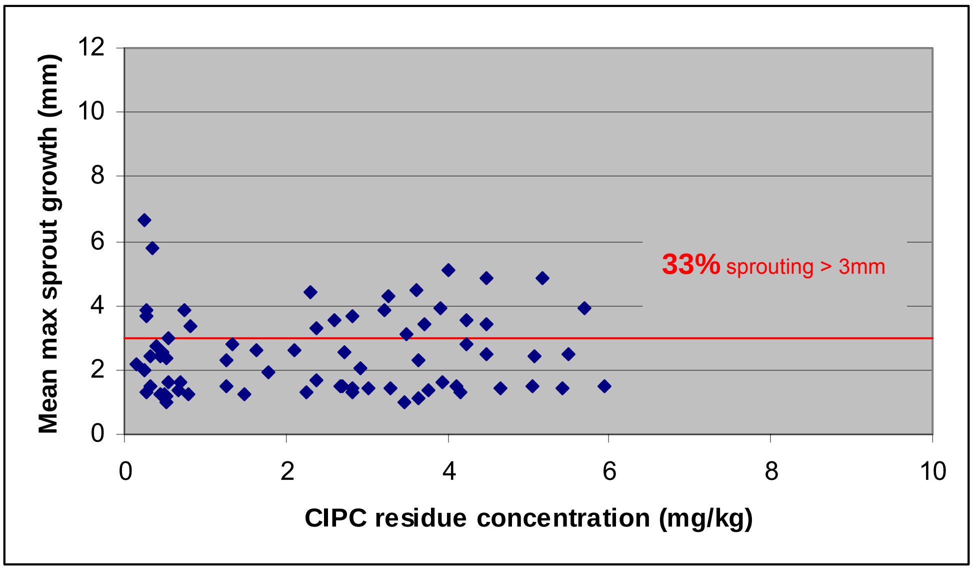


FIGURE 9. CORRELATION BETWEEN CIPC RESIDUE AND SPROUT GROWTH, ALL MODIFIED DATA YEAR 1

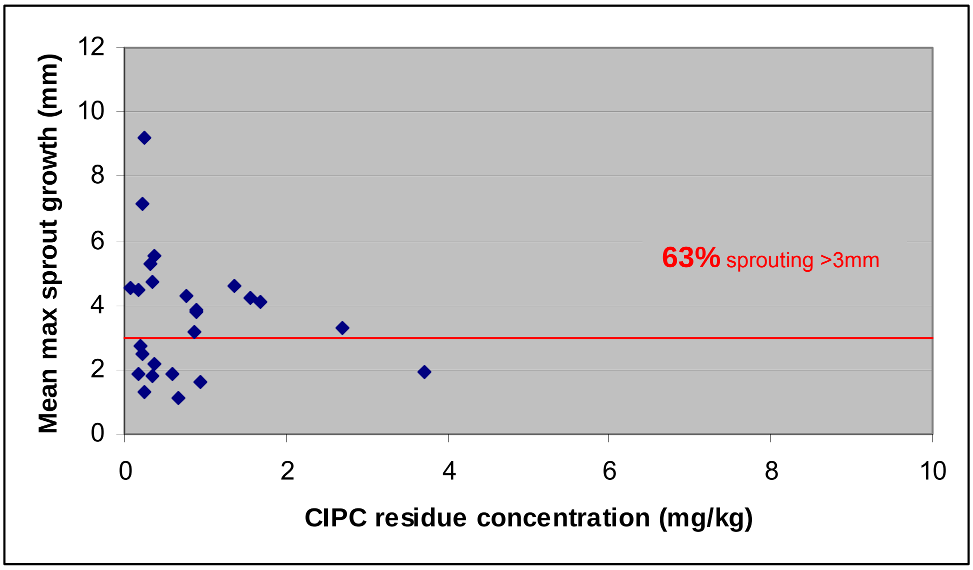


FIGURE 10. CORRELATION BETWEEN CIPC RESIDUE AND SPROUT GROWTH, ALL CONVENTIONAL DATA YEAR 1

Leakage - fogger testing

Testing of a fogger with the close-coupled modification showed a reduction in volume output of 35% (Figure 11). When extrapolated to a ‘commercial store scale’, such as stores 1 and 2, this would result in a reduction in store leakage (i.e. volume displaced by the fogger) from around 25% to about 15%. This could result in an extra 1.2kg of the CIPC applied remaining in store, and is equivalent to a 50.9% reduction in CIPC lost through leakage according to the model of Park (2004).

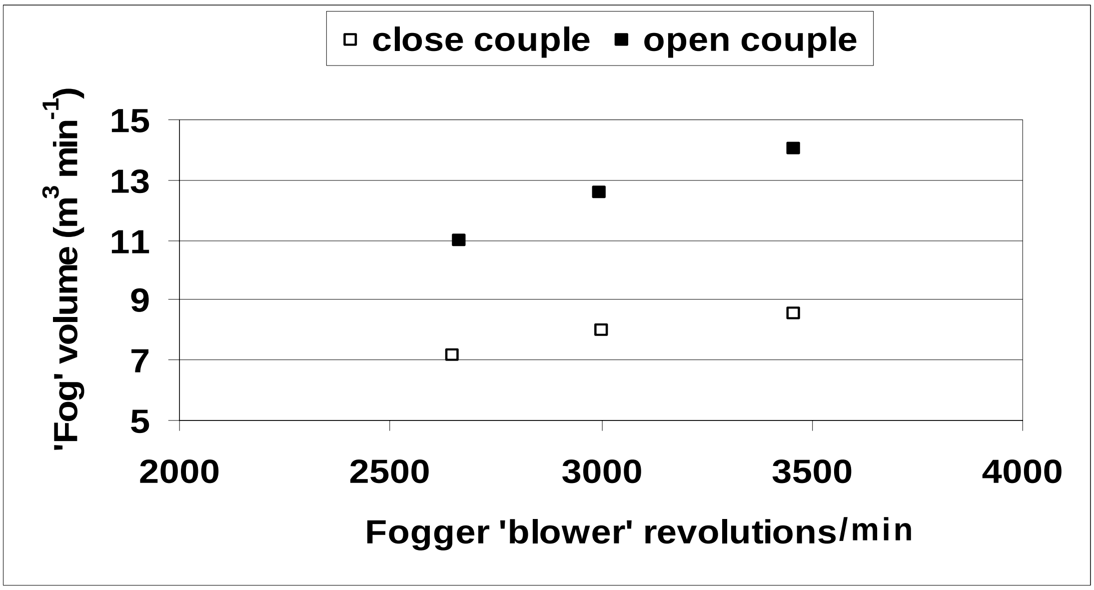


FIGURE 11. VOLUME FLOW RATE OF UNIFOG, WITH OPEN AND CLOSED COUPLING CONFIGURATION, AT DIFFERENT ENGINE SPEEDS.

Small scale trials – recirculation airspeed

Results for headspace CIPC concentration and CIPC deposit analysis are shown in Figures 12 & 13 and 14 & 15 respectively for the two occasions the trial was conducted. Headspace CIPC concentration was generally higher in the first trial. All treatments had a similar pattern of airborne CIPC concentration. The highest concentration generally occurred in samples taken one hour after application. In both trials, there was a tendency for the 'no recirculation' and '5% recirculation' treatments to result in relatively high concentrations of CIPC persisting in the headspace. This indicates that these treatments were relatively ineffective at encouraging deposition on tubers (and other surfaces), and correspond with the low application efficiency values obtained in these samples.

Without any recirculation treatment, overall CIPC deposit levels were low with a mean value of 7.6 mg kg^{-1}. In this treatment significant deposits of CIPC only occurred on tubers close to the surface, indicating the importance of sedimentation of fog. All recirculation treatments improved application efficiency with mean deposit values of 17.9, 18.8 and 30.6 mg kg^{-1} for 5%, 20% and 100% fan capacities respectively. In addition to increasing application efficiency, data indicate that greater airspeeds were associated with a more even deposition of CIPC on tubers.

Deposition on fans was measured as a change in weight following recirculation treatments. The deposits were not analysed but are assumed to be principally CIPC. Mean values were 0.7 g, 0.6 g and 20.5 g for the 5%, 20% and 100% recirculation rates respectively. These values correspond well with mean tuber deposit values for application efficiency (17.9 and 18.8 mg kg^{-1} for 5% and 20% rates and 30.6 mg kg^{-1} for 100% rate).

Together, data indicate that recirculation airflow rate has an impact on distribution of CIPC deposition. The small increase in airspeed, from 5% to 20% rates, had little impact on CIPC distribution or overall application efficiency. At 100% airflow rate, though, application efficiency was considerably increased and deposits were more evenly distributed. This treatment also resulted in more deposition on fans (equivalent to 8% of CIPC applied in the 100% recirculation treatment). Attachment to fans has usually been viewed as a loss of CIPC, because chemical is no longer available for deposition on the crop. However, these data suggest that deposition of CIPC on fans may be an indicator of efficiency of its application to the crop.

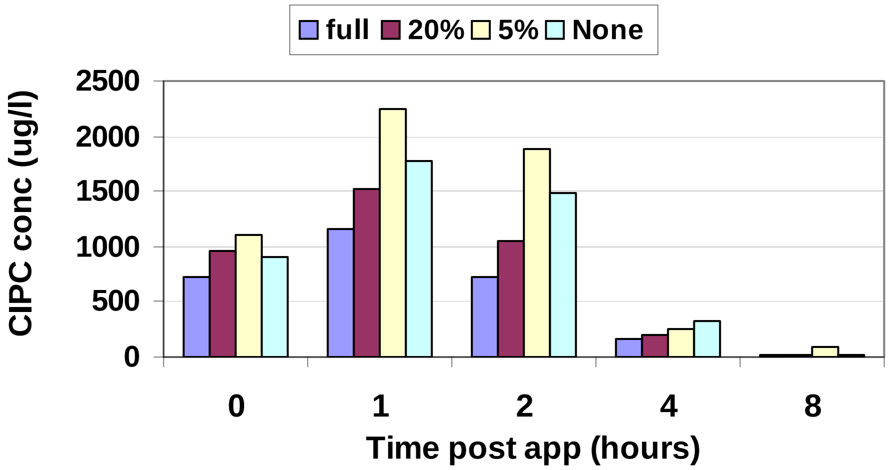


FIGURE 12 MEAN HEADSPACE CIPC CONCENTRATION (G LITRE) IN FIRST BULK EMULATION TRIAL

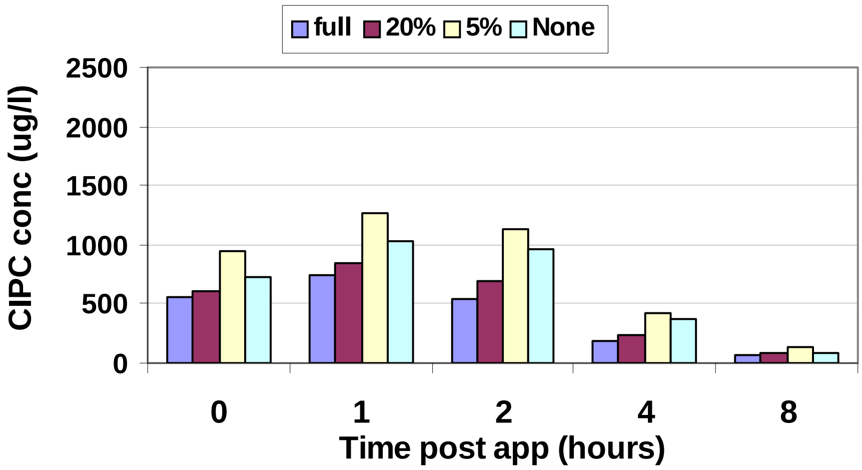


FIGURE 13 MEAN HEADSPACE CIPC CONCENTRATION(G LITRE) IN SECOND BULK EMULATION TRIAL

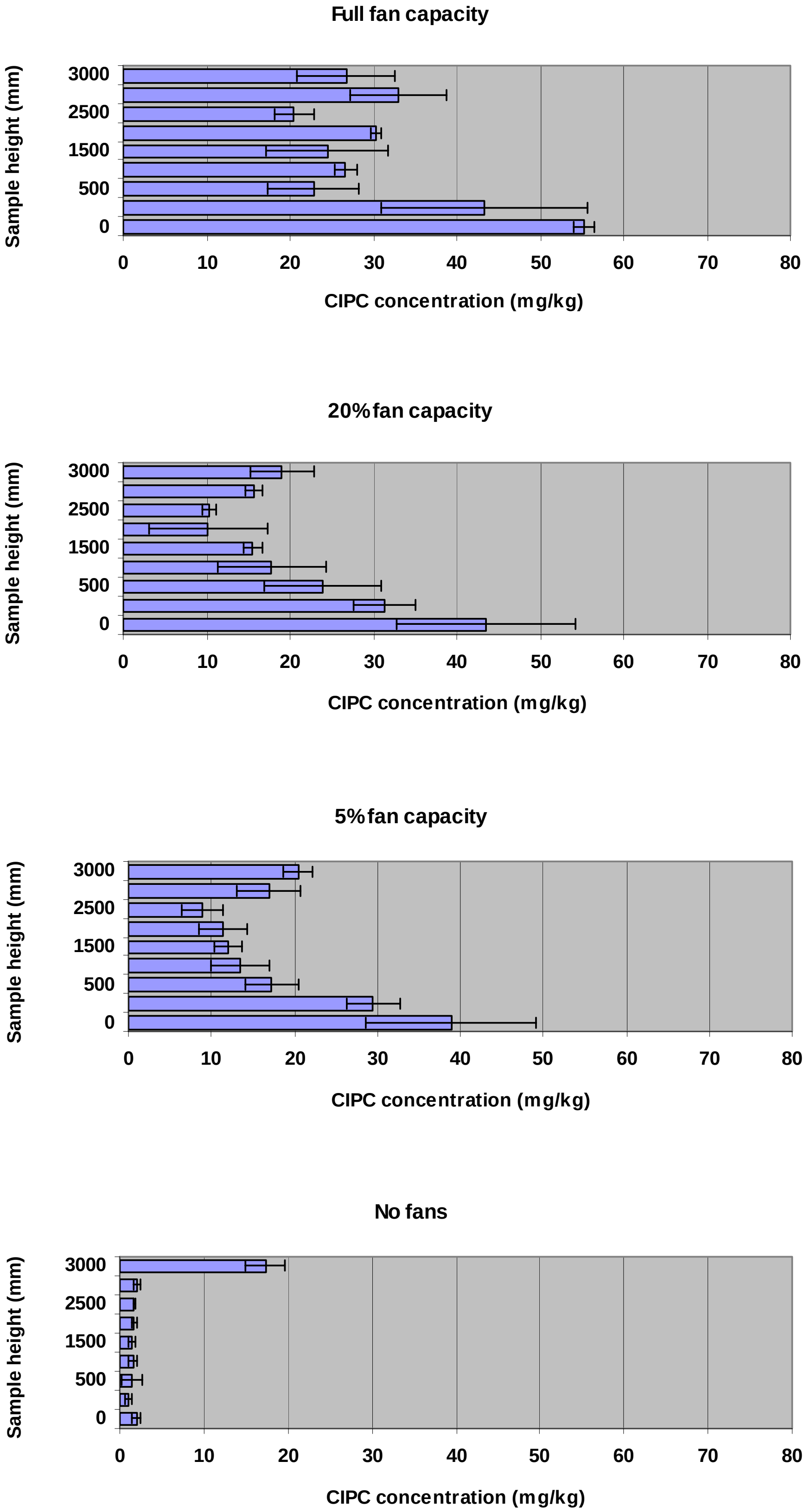


FIGURE 14 MEAN TUBER CIPC DEPOSIT CONCENTRATIONS IN FIRST BULK EMULATION TRIAL

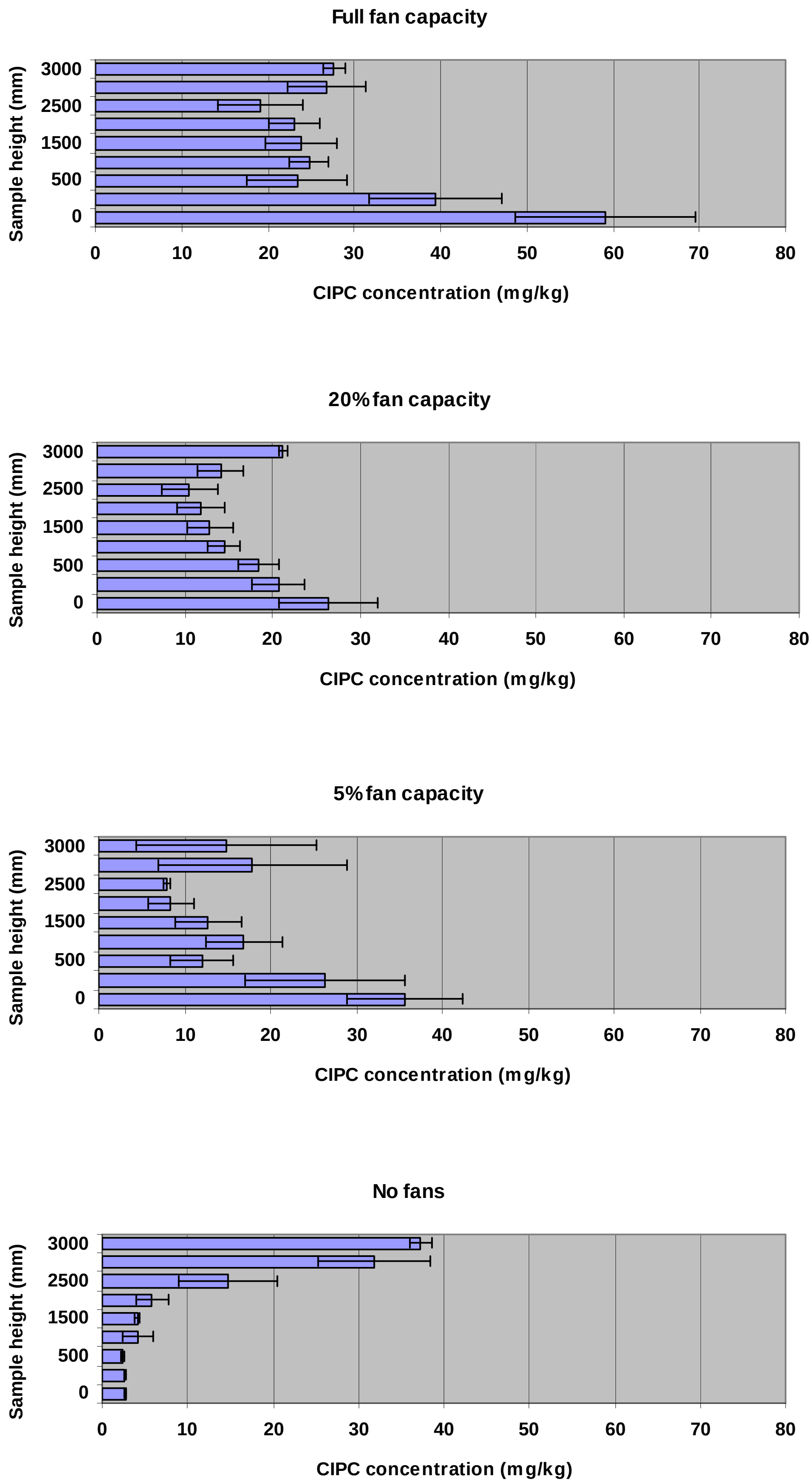


FIGURE 15 MEAN TUBER CIPC DEPOSIT CONCENTRATIONS IN SECOND BULK EMULATION TRIAL

Year 2: 2006-2007 storage season

Overall sprout control was more consistent following modified application of CIPC, compared with conventional applications. This was further improved by the two-stage recirculation regime. The strength of the modified system is in the consistency of CIPC deposition, and consequent sprout control, across the store (Table 3). CIPC deposit uniformity eliminates the sprout growth associated with areas with little CIPC deposition which would prompt re-treatment at an early stage.

store	treatment	CIPC input	CIPC residue (mg kg^{-1})	standard deviation	max. sprout length (mm)	standard deviation	storage duration (months)
3A	modified	42.75	0.64	0.597	2.1	0.86	4.5
3B	conventional	42.75	1.00	1.356	3.3	1.82	4.5
1	modified	14.25	0.73	2.000	1.7	0.45	7.5
2	conventional	14.25	1.81	1.410	1.4	0.79	5.5
4A	further modified	42.75	0.95	0.582	1.0	0.28	8
4B	modified	42.75	1.10	0.978	2.0	1.61	8

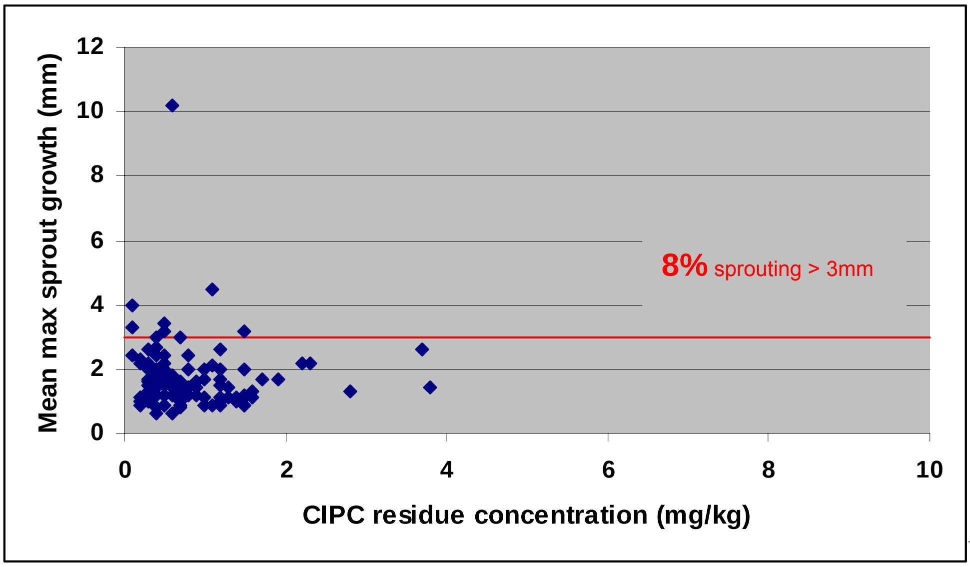
TABLE 3. SUMMARY OF COMMERCIAL TRIALS IN YEAR 2.

The effectiveness of CIPC application, as applied using the modified system, depended on the store. It is thought that stores with a smaller headspace, and thus a more efficient recirculation pathway for CIPC will benefit more.

In stores 1 and 2, with a modest sized headspace, a single application of CIPC resulted in CIPC residue levels that were broadly comparable with levels from stores 3A and 3B after three CIPC applications. Store 3 had a particularly large headspace.

Although application efficiency in store 3 was generally poor the modified CIPC application system remained superior with more effective and less variable sprout control efficacy. Conventional applications to this store resulted in relatively high CIPC residue values at the back of the store (crop associated with laterals furthest from point of fog introduction) and very low values at the front of the store. This is a common pattern observed when CIPC is applied conventionally in GB.

The relationship between sprout growth and CIPC residue levels for all stores in year 2 are shown in Figures 16 and 17. Modified application resulted in 8% of samples having a mean maximum sprout length in excess of 3 mm while, following conventional applications, 36% of samples had tubers with mean sprout length greater than 3 mm.



YEAR 2 DATA

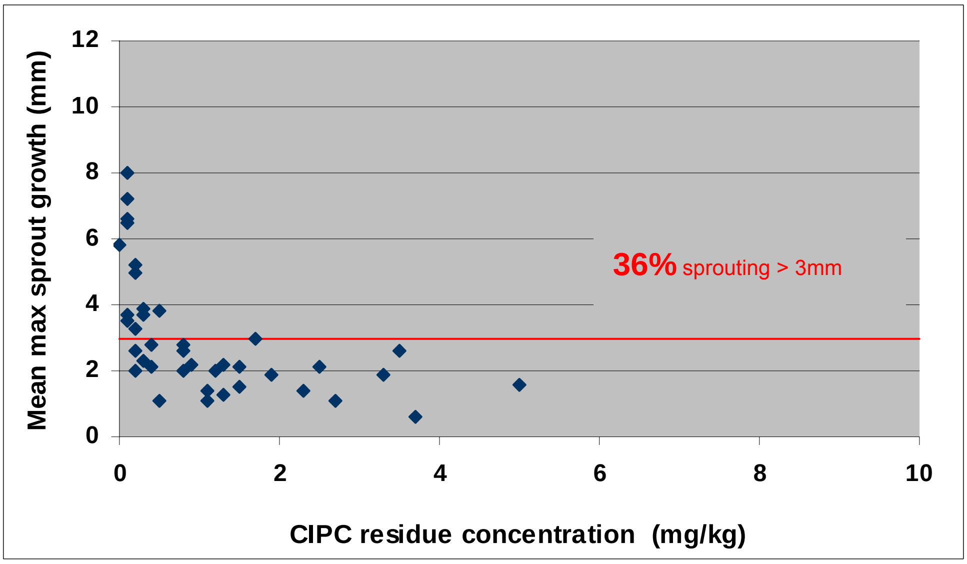


FIGURE 17 CORRELATION BETWEEN CIPC RESIDUE AND SPROUT GROWTH, ALL CONVENTIONAL YEAR 2 DATA

Small-scale trials – CIPC redistribution

The concentration of CIPC remaining on source tubers is shown in Figure 18. Results show there was no significant decline in CIPC throughout the duration of the trial and, therefore concentration of available CIPC was not a limiting factor to movement.

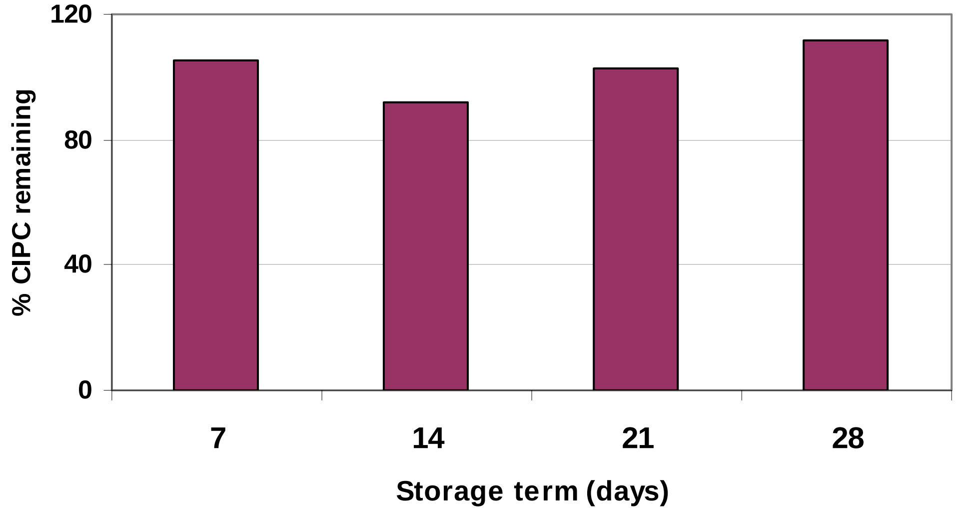


FIGURE 18. PROPORTION OF AVAILABLE CIPC REMAINING ON THE SOURCE CROP THROUGHOUT THE TRIAL

Redistribution of CIPC, from source tubers is shown in Figure 19. The movement of CIPC, from source tubers to untreated crop, was evident over the entire range of sample heights at commercially representative airflow rates. CIPC deposit levels on the potatoes accumulated steadily over the twenty-eight day period up to c.2.5mg kg^{-1} at 70cm distance from the source and c.7.5mg kg^{-1} directly above the source. The concentration of CIPC deposited on tubers (re-distributed) was inversely related to distance from the source.

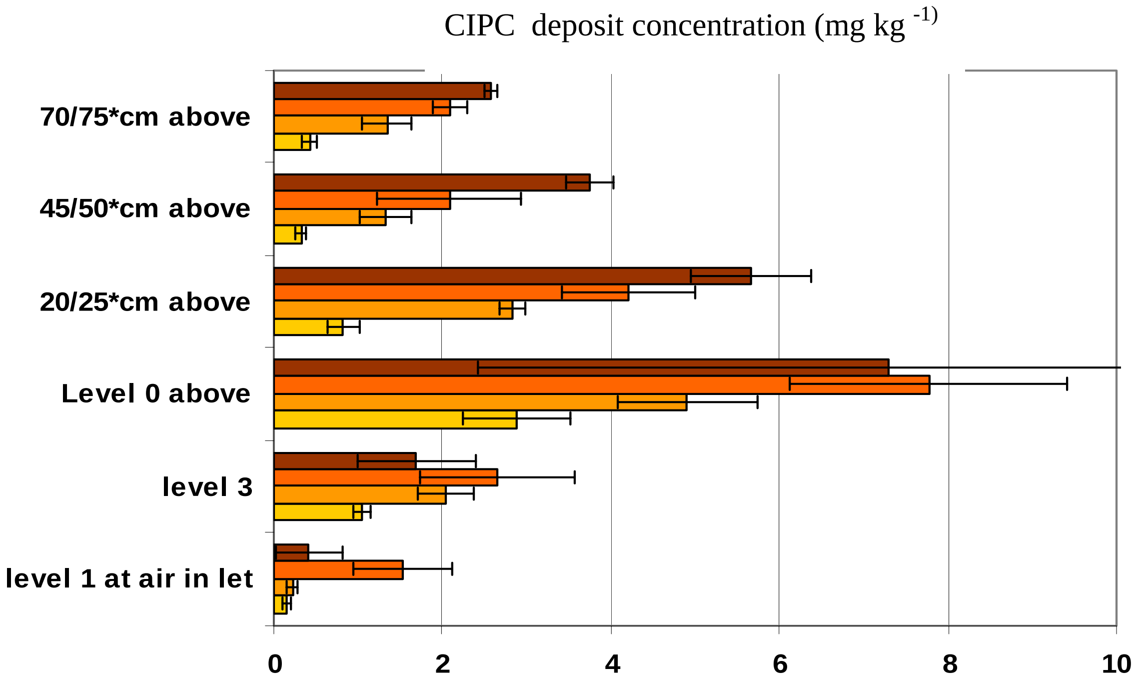


FIGURE 19 CONCENTRATION OF CIPC REDISTRIBUTED FROM THE 'SOURCE' CROP (* ONLY DAY 7 SAMPLES AT THIS HEIGHT, DUE TO 'SETTLING OF THE PILE'.

Although the results demonstrate the 'mobility' of CIPC, once it has been applied, distance of movement is a limiting factor. This serves to highlight the importance of the initial distribution of CIPC and how it will affect the potential for redistribution throughout a store. It confirms that airflow balance during application of CIPC is critical and a pre-requisite for achieving good initial distribution of the chemical.

The detection of CIPC on level 1 tubers (prior to source crop) suggests there was some contamination of the air supply. Deposit values on this material however, were always smaller than those on crop after air had passed over the source tubers. On day 21 a significantly higher CIPC level was detected on the tubers at level 1, the air inlet location. This may be due to contamination with particulate CIPC, dislodged during sampling.

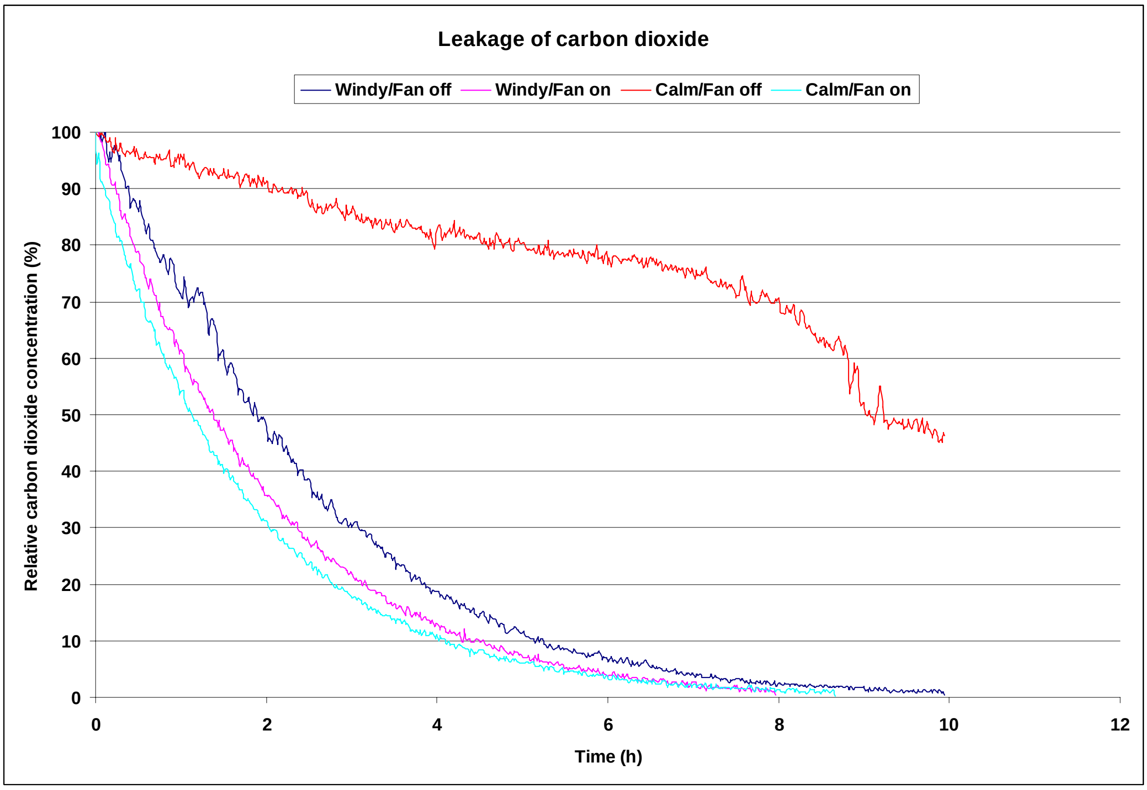
Samples from level 0, level 3 and level 1 were at risk of having particulate CIPC from the source material deposit onto them from above (level 1 and level 3) or be transferred by direct skin contact (level 0) between tubers. At levels 3 and 0 the gradual build up of CIPC observed suggests movement and deposition of CIPC through the vapour phase rather than in a particulate form. Particles would be more likely to cause a dramatic change in CIPC level, and with a large variability associated with the mean value.

Leakage – weather and store considerations

In order to better understand the potential for losses of CIPC, experimental work was carried out assessing 'leakiness' of stores. Initial testing was carried out under calm and windy weather conditions, and with and without fans running continuously (fans were operated during carbon dioxide introduction on all occasions to ensure thorough mixing with store air).

Results (Figure 20) indicate that windy weather conditions and the use of fans result in higher rates of leakage. Although leakage appears greatest in calm weather with fans on, there were significant differences in average wind speed when tests were carried out under 'calm' conditions. Ambient weather conditions are reported to have a significant effect on leakage of stores (Schaper *et al*, 1993).

Store ventilation systems may also exacerbate leakage. Where an air-mix facility is installed (ie fan with ambient and recirculation louvres in close proximity), the suction pressure from operation of the fan may encourage leakage by drawing ambient air through louvres, even when these are in the closed position. As modified CIPC treatments involve fan operation for recirculation, albeit at reduced speed, potential losses as a result of this are also of interest.



[1]600 tonne capacity (24m x 15m x 9m) box store with combined refrigeration & ambient air-mix system and overhead 'throw' delivery.
[2]Average wind speed at start of test period: Windy/Fan off 2,77 m s^{-1}, Windy/Fan on 2.79 m s^{-1}, Calm/Fan off 0.68 m s^{-1}, Calm/Fan on 1.46 m s^{-1}.

FIGURE 20. LEAKAGE OF CARBON DIOXIDE FROM STORE[1] WITH AND WITHOUT FAN OPERATION UNDER CALM AND WINDY WEATHER CONDITIONS[2]. CARBON DIOXIDE CONCENTRATION EXPRESSED AS A PROPORTION OF VALUE OBTAINED AFTER INITIAL INTRODUCTION AND CORRECTED FOR AMBIENT LEVELS.

Year 3: 2007-2008 storage season

Stores 1 and 2

Sprout control following the modified treatment was more effective with a mean maximum sprout length of 6.4 mm compared with 14.0mm for the conventional treatment (Figure 21). Sprout length was also less variable with the modified treatment with a standard deviation of 5.459, compared with 14.167 for the conventional treatment.

Stores 1 (Conventional) and 2 (modified); sprouting efficacy results

Mean maximum sprout length (mm)

Location *Top = c.40cm from surface Middle = c.2m from floor Bottom = c.40cm from floor*

Store 2 (Fans, DOOR, TUNNEL)

Location	Lat	c.1m from Tunnell	center under lights	c.1m from WALL
Top	Lat			
Middle				
Bottom				
Top	Lat	21.0	13.5	5.1
Middle		5.2	1.7	1.4
Bottom		1.5	3.7	2.8
Top	Lat	9.5		2.0
Middle		10.6	7.0	9.0.
Bottom		5.9	3.8	14.6
Top	Lat	7.4	13.3	
Middle		0.6	2.2	
Bottom				2.3

St 1 & 2 overall
mean **10.6**
st dev 11.614
95%C.I. *3.320*

Modified St 2
mean **6.4**
st dev 5.459
95%C.I. *2.281*

Store 1 (TUNNEL, Fans, DOOR)

Location	Lat	c.1m from Tunnell	center under lights	c.1m from WALL
Top	Lat 27	2.4		6.2
Middle	Lat 26	3.4		2.0
Bottom	Lat 25			
Top	Lat 18	17.3	15.1	
Middle	Lat 17	15.4	6.6	13.4
Bottom	Lat 16	0.8	6.8	4.7
Top	Lat 11		61.9	11.8
Middle	Lat 10	14.6	33.7	
Bottom	Lat 9	6.4	5.6	16.8
Top	Lat 4		9.3	
Middle	Lat 3	11.5	12.4	
Bottom	Lat 2	7.8	17.8	46.8

Conventional St 1
mean **14.0**
st dev 14.167
95%C.I. *5.553*

FIGURE 21. RESULTS OF SPROUT CONTROL EFFICACY IN STORES 1 AND 2.

Stores 1 (Conventional) and 2 (modified); CIPC residue results

mg of CIPC per kg on fresh weight basis

Location *Top = c.40cm from surface Middle = c.2m from floor Bottom = c.40cm from floor*

Fans DOOR

TUNNEL — STORE 2

Location	Lat	c.1m from Tunnell	center under lights	c.1m from WALL
Top	Lat			
Middle				
Bottom				
Top	Lat	0.62	0.81	0.73
Middle		1.15	0.86	1.31
Bottom		3.96	1.91	1.50
Top	Lat	0.48		0.40
Middle		1.24	1.04	0.90
Bottom		1.08	0.89	0.88
Top	Lat	1.02	1.01	
Middle		3.46	1.40	
Bottom				2.10

St 1 & 2 overall
mean **0.91**
st dev 0.810
95%C.I. *0.231*

Modified St 2
mean **1.31**
st dev 0.881
95%C.I. *0.368*

TUNNEL — STORE 1

Location	Lat	c.1m from Tunnell	center under lights	c.1m from WALL
Top	Lat 27	0.74		0.60
Middle	Lat 26	0.97		1.17
Bottom	Lat 25			
Top	Lat 18	0.26	0.20	
Middle	Lat 17	0.58	1.04	0.77
Bottom	Lat 16	0.83	1.56	2.19
Top	Lat 11		0.17	0.11
Middle	Lat 10	0.10	0.11	
Bottom	Lat 9	1.16	0.10	0.18
Top	Lat 4		0.33	
Middle	Lat 3	0.14	0.08	
Bottom	Lat 2	0.26	0.11	0.12

Conventional St 1
mean **0.56**
st dev 0.549
95%C.I. *0.215*

Fans DOOR

FIGURE 22. RESULTS OF CIPC RESIDUE ANALYSIS IN STORES 1 AND 2.

Reflecting differences in sprout control (Figure 22), the mean residual CIPC concentration was greater following the modified treatment (1.31 +/- 0.368mg kg^{-1} compared with 0.56 +/- 0.215mg kg^{-1} in the conventionally treated store). More of the CIPC applied could be accounted for, *c.* 9.4% at the end of the storage period, following the modified application procedure.

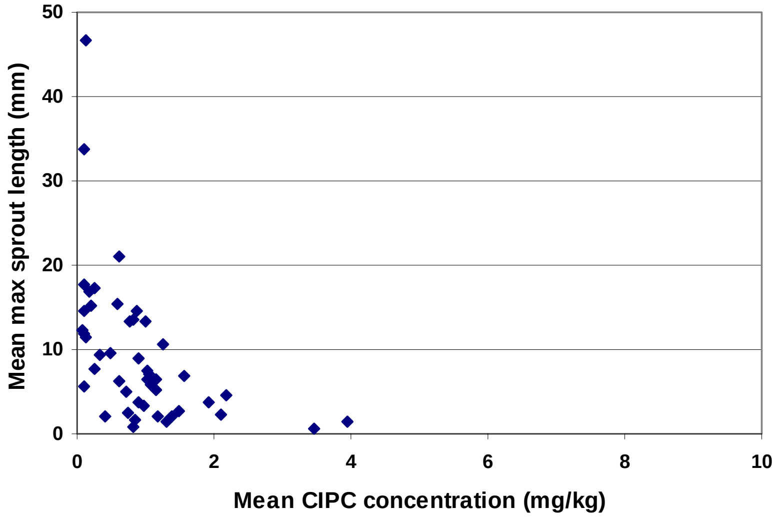


FIGURE 23 CORRELATION BETWEEN CIPC RESIDUE LEVELS AND SPROUT GROWTH, MODIFIED AND CONVENTIONAL DATA, STORES 1 AND 2

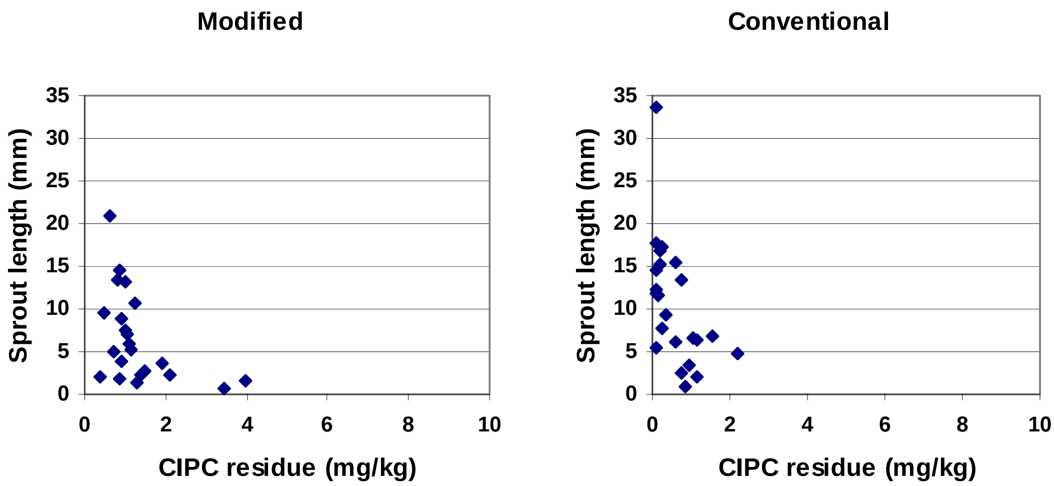


FIGURE 24. CORRELATION BETWEEN CIPC RESIDUE AND SPROUT GROWTH ACCORDING TO APPLICATION STYLE, STORES 1 AND 2

There was a similar overall pattern from both application methods (figures 23 & 24). Although a greater range of CIPC concentration was evident in the modified store, the lowest residue value was at least four times that of the lowest in the conventional treatment.. Less sprouting occurred in the modified store.

FIGURE 25. RESULTS OF SPROUT CONTROL EFFICACY IN STORE 3

Store 3B (modified); sprouting efficacy results

Mean maximum sprout length (mm)

Location

Top = c.40cm from surface
Middle = c.2m from floor
Bottom = c.40cm from floor

Location	STORE 3B: c.1m from WALL	STORE 3B: center under lights	STORE 3B: c.1m from TUNNEL		Fan / TUNNEL		STORE 3A: c.1m from TUNNEL	STORE 3A: center under lights	STORE 3A: c.1m from WALL
Top	0.4	0.6	0.2	Lat		Lat			
Middle	0.4	0.4	0.3						
Bottom	0.4	1.0	0.4						
Top	0.7	0.7	0.7	Lat	T	Lat			
Middle	0.8	1.0	0.9		U				
Bottom	1.0	1.0	0.9		N				
Top		0.8	0.7	Lat	N	Lat			
Middle	0.8	0.6	1.0		E				
Bottom	0.8		0.8		L				
Top	0.8	0.8	0.8	Lat		Lat			
Middle	0.8	0.8	0.7						
Bottom	0.7	0.9	1.0						

Mean **0.7**
stdev 0.220 *95%C.I. 0.074*

DOOR DOOR

FIGURE 26. RESULTS OF CIPC RESIDUE ANALYSIS IN STORE 3.

Store 3B (modified); CIPC residue results

mg of CIPC per kg on fresh weight basis

Location

Top = c.40cm from surface
Middle = c.2m from floor
Bottom = c.40cm from floor

STORE 3B

Location	c.1m from WALL	center under lights	c.1m from TUNNEL	
Top	0.59	0.51	0.51	Lat
Middle	0.55	0.49	0.59	
Bottom	0.77	0.59	0.73	
Top	0.41	0.77	0.52	Lat
Middle	0.64	0.69	0.54	
Bottom	0.64	0.67	0.85	
Top	0.47	0.19	0.57	Lat
Middle	0.68	0.49	0.72	
Bottom	0.68	0.57	0.93	
Top	0.36	0.30	0.43	Lat
Middle	0.13	0.36	0.47	
Bottom	0.41	0.86	0.88	

Mean **0.57**
stdev 0.184 *95%C.I. 0.060*

DOOR

Fan

TUNNEL

STORE3A

	c.1m from TUNNEL	center under lights	c.1m from WALL
Lat			
Lat			
Lat			
Lat			

DOOR

Sprouting in store 3 (Figure 25) was very well controlled with mean maximum sprout length generally ≤ 1mm. CIPC residue levels (Figure 26) were also low with a mean of 0.57 +/- 0.06 mg kg^{-1} and values not exceeding 0.9 mg kg^{-1}.

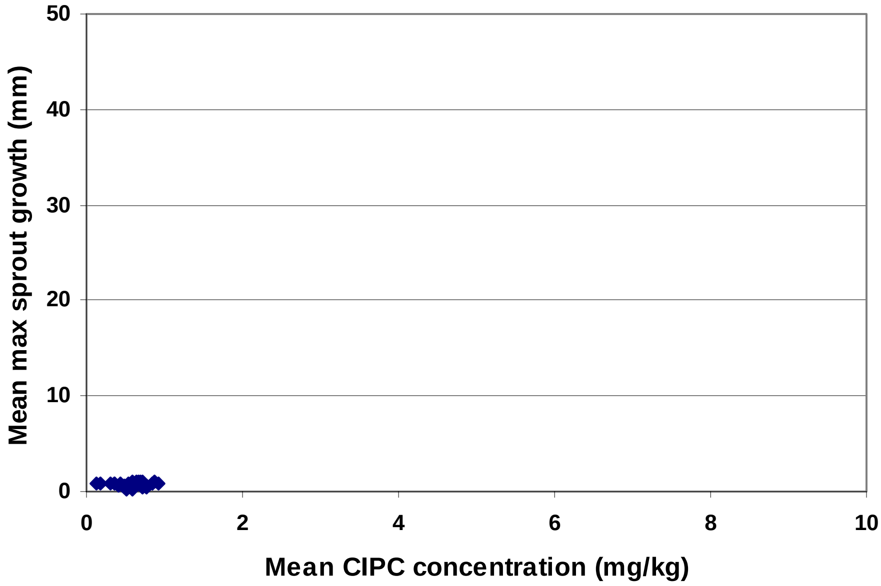


FIGURE 27. CORRELATION BETWEEN CIPC RESIDUE AND SPROUT GROWTH, MODIFIED STORE 3A

The pattern observed, when correlating sprout growth and residue data is similar to that of the second year's data for this store. There is very consistent sprout control (none of the 36 sample locations had tubers with sprouts in excess of 1 mm) at low levels of CIPC, less than 1 mg kg^{-1}. The benefit of uniformly distributed CIPC at this site is evident and contrasts sharply with the results of conventional applications carried out in previous seasons.

Stores 4A and 4B

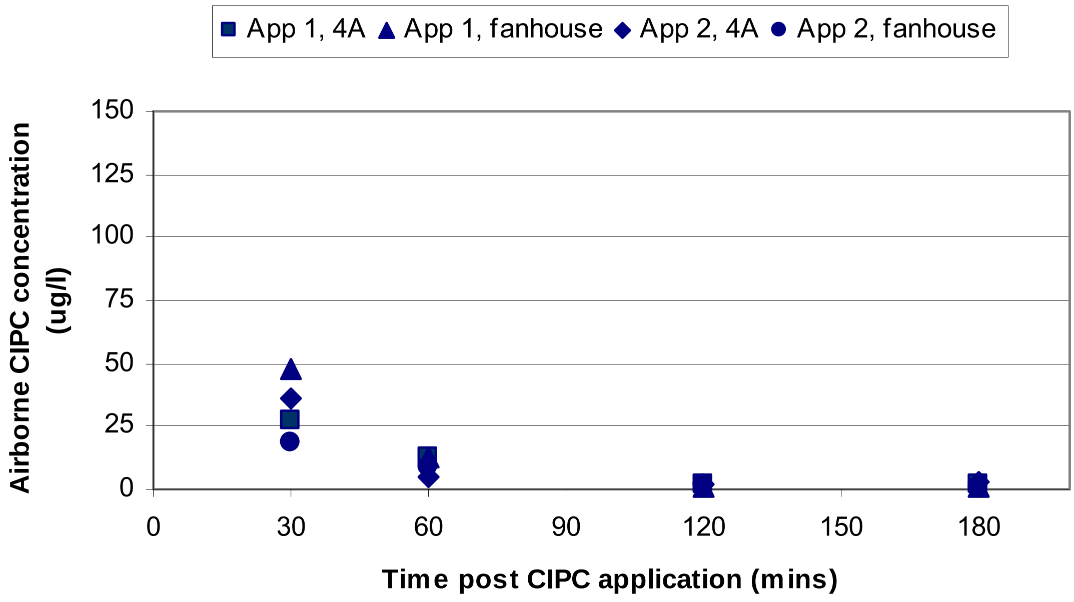


FIGURE 28. CIPC CONCENTRATION IN AIR FOLLOWING APPLICATION IN STORE 4.

Airborne CIPC concentrations in store 4 (Figure 28) are in line with the other store treated at this site and show a rapid decline, with almost complete deposition of the chemical within two hours of application.

FIGURE 29. RESULTS OF SPROUT CONTROL EFFICACY IN STORES 4A AND 4B.

Store 4A and 4B (both modified); sprouting efficacy results

Mean maximum sprout length (mm)

Location

Top = c.40cm from surface
Middle = c.2m from floor
Bottom = c.40cm from floor

Location	STORE 4A: c.1m from WALL	STORE 4A: center under lights	STORE 4A: c.1m from TUNNEL		Fan / TUNNEL		STORE 4B: c.1m from TUNNEL	STORE 4B: center under lights	STORE 4B: c.1m from WALL
Top	**1.8**	**5.8**	**19.3**	Lat		Lat	**6.9**	**4.2**	**2.4**
Middle	**7.2**	**8.6**	**12.5**				**2.4**	**2.9**	**4**
Bottom	**10.4**	**14.4**	**10.7**					**8.2**	**5.6**
Top	**13.4**	**3.2**	**27.2**	Lat	T	Lat	**18.6**	**3**	**5.9**
Middle	**9.2**	**3.4**	**12.1**		U		**15.6**	**8.2**	**8.7**
Bottom	**4.4**	**5.4**			N		**6.4**	**5**	**3**
Top	**4**	**4.3**	**9.4**	Lat	N	Lat	**14.8**	**9.6**	**7.6**
Middle	**7.3**	**6.5**	**13.9**		E		**6.8**	**8**	**4.8**
Bottom	**5.3**	**4.4**	**5.1**		L		**2.4**	**0**	**5.9**
Top	**2.6**	**8.7**	**38.6**	Lat		Lat	**13.1**	**5.8**	**12.4**
Middle	**6.1**	**7.3**	**29.7**				**20**	**5.6**	**7.8**
Bottom	**10.2**	**3**	**2.4**				**4.4**	**1.5**	**10.6**

	STORE 4A	STORE 4B
Mean	**9.7**	**7.2**
stdev	8.100	4.737
95%C.I.	*2.684*	*1.569*
	DOOR	DOOR

overall store values

Mean	**8.4**
SD	6.701
95% C.I.	*1.570*

FIGURE 30. RESULTS OF CIPC RESIDUE ANALYSIS IN STORES 4A AND 4B.

Store 4A and 4B (both modified); CIPC residue results

mg of CIPC per kg on fresh weight basis

Location

Top = c.40cm from surface
Middle = c.2m from floor
Bottom = c.40cm from floor

STORE 4A

Location	c.1m from WALL	center under lights	c.1m from TUNNEL	
Top	**0.61**	**0.46**	**0.25**	Lat
Middle	**0.81**	**1.25**	**0.50**	
Bottom	**0.73**	**0.63**	**0.72**	
Top	**0.31**	**0.89**	**0.25**	Lat
Middle	**0.62**	**1.03**	**0.68**	
Bottom	**0.95**	**0.64**		
Top	**0.53**	**0.59**	**0.33**	Lat
Middle	**1.06**	**0.61**	**0.35**	
Bottom	**1.38**	**1.19**	**1.55**	
Top	**0.99**	**0.59**	**0.45**	Lat
Middle	**0.37**	**0.65**	**0.40**	
Bottom	**1.46**	**1.77**	**0.80**	

Mean **0.75**
stdev 0.386 *95%C.I. 0.128*

Fan

TUNNEL

STORE 4B

Location		c.1m from TUNNEL	center under lights	c.1m from WALL
Top	Lat	**0.65**	**0.77**	**0.42**
Middle		**1.07**	**1.45**	**1.50**
Bottom			**1.11**	**1.12**
Top	Lat	**0.22**	**0.33**	**0.90**
Middle		**0.70**	**0.51**	**0.73**
Bottom		**1.22**	**1.18**	**0.75**
Top	Lat	**0.37**	**0.56**	**0.55**
Middle		**0.64**	**0.46**	**1.61**
Bottom		**1.54**		**0.75**
Top	Lat	**0.51**	**0.40**	**0.36**
Middle		**0.59**	**0.83**	**0.81**
Bottom		**0.77**	**1.31**	**0.79**

Mean **0.81**
stdev 0.379 *95%C.I. 0.127*

DOOR (Store 4A) **DOOR** (Store 4B)

overall store values

Mean	**0.78**
SD	0.380
95%C.I.	*0.090*

The mean maximum sprout length of samples at unloading was 8.4mm (SD 6.701) with slightly higher levels in Bay A (mean 9.65mm SD 8.10) than Bay B (mean 7.20mm SD 4.737). Sprout control in both bays was least effective in samples closest to the main duct, along the length of the store. In most cases, however, it was just middle and top located sample nets, in this area that had relatively poor sprout control, and control was effective in sample nets at the bottom of the stack. CIPC residue levels reflected sprouting levels with slightly higher values in Bay B (0.81 mg kg^{-1}, SD 0.379) compared with Bay A (mean 0.75mg kg^{-1}, SD 0.386). Overall residue levels were significantly lower in this store (mean 0.78 mg kg^{-1}) compared with store 5 (2.03 mg kg^{-1}). This difference is likely to be a reflection of the longer storage duration in store 4. Residue values were particularly low in samples from the top and middle of the stack, immediately adjacent to the main duct.

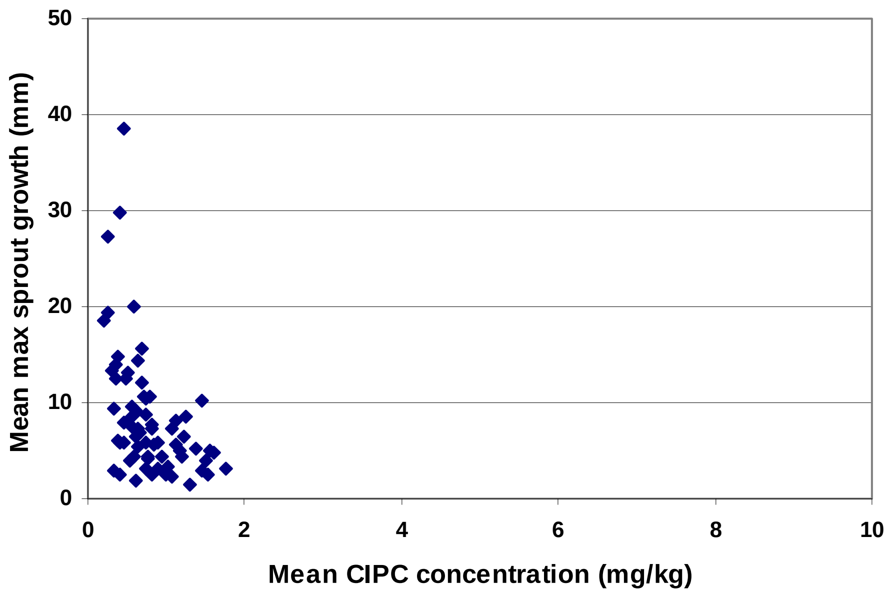


FIGURE 31 CORRELATION BETWEEN CIPC RESIDUE AND SPROUT GROWTH, MODIFIED STORES 4A AND 4B

At residues of 1 mg kg^{-1} of CIPC and below, there was a slight trend of increased growth with decreasing level of CIPC, but little growth in excess of 15mm. Sprout growth in the majority of the potatoes in store was reasonably well controlled with 1 mg kg^{-1} of CIPC.

Stores 5A and 5B

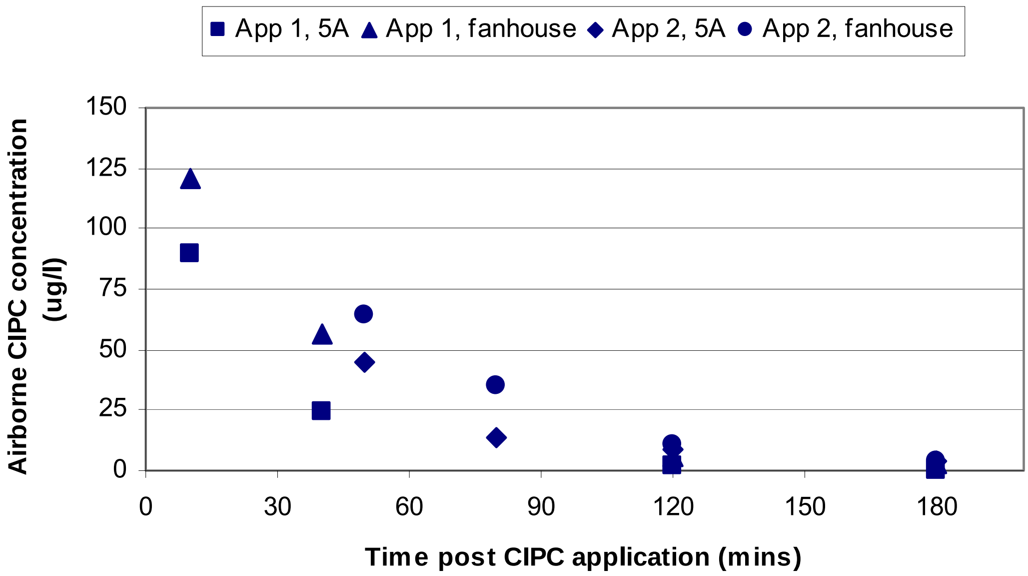


FIGURE 32. CIPC CONCENTRATION IN AIR FOLLOWING APPLICATIONS TO STORE 5.

The airborne CIPC concentration results showed a consistent effect with rapid clearing of a large proportion of the fog applied within 1½ - 2 hours post-application. A higher concentration of airborne CIPC was consistently present in samples obtained from the fan house.

FIGURE 33. RESULTS OF SPROUT CONTROL EFFICACY IN STORES 5A AND 5B.

Store 5A and 5B (both modified); sprouting efficacy results

Mean maximum sprout length (mm)

Location

Top = c.40cm from surface
Middle = c.2m from floor
Bottom = c.40cm from floor

Location	STORE 5A: c.1m from WALL	STORE 5A: center under lights	STORE 5A: c.1m from TUNNEL		Fan / TUNNEL		STORE 5B: c.1m from TUNNEL	STORE 5B: center under lights	STORE 5B: c.1m from WALL
Top	**12.4**	**5.6**	**6**	Lat		Lat	**31.2**	**6.9**	**12.2**
Middle	**9.9**	**5**	**5**				**16.1**	**6.4**	**21**
Bottom	**8.2**	**6.6**	**4.2**				**10**	**9**	**9.8**
Top	**3.8**	**4.1**	**2**	Lat	T	Lat	**13.8**	**4.7**	**8.4**
Middle	**11.6**	**3.3**	**3.6**		U		**7**	**9**	**8.7**
Bottom	**6.8**	**8.2**	**2.7**		N		**8.4**	**2.5**	**10.1**
Top	**10.5**	**4.2**	**9.7**	Lat	N	Lat	**8.3**	**9**	**5.7**
Middle	**6.2**	**7**	**8.2**		E		**8.2**	**6.5**	**10.4**
Bottom	**5.3**	**5.9**	**5**		L		**11.4**	**6.6**	**0**
Top	**10**	**7.2**	**18.4**	Lat		Lat	**11.4**	**4.6**	**7.3**
Middle	**15.4**	**11.8**	**12.2**				**13.1**	**8.9**	**8**
Bottom	**10.3**	**9.5**	**16**				**7.3**	**3.4**	**12.4**

overall store values
Mean **8.6**
SD 4.719
95% C.I. 1.090

Store 5A: Mean **7.8**; stdev 3.923; *95%C.I. 1.282*

Store 5B: Mean **9.4**; stdev 5.343; *95%C.I. 1.745*

DOOR (Store 5A) **DOOR** (Store 5B)

Store 5A and 5B (both modified); CIPC residue results

mg of CIPC per kg on fresh weight basis

Location

Top = c.40cm from surface
Middle = c.2m from floor
Bottom = c.40cm from floor

Fan / TUNNEL between stores

Location	STORE 5A: c.1m from WALL	STORE 5A: center under lights	STORE 5A: c.1m from TUNNEL			STORE 5B: c.1m from TUNNEL	STORE 5B: center under lights	STORE 5B: c.1m from WALL
Top	**0.57**	**3.13**	**1.85**	Lat	Lat	**1.08**	**2.55**	**1.05**
Middle	**1.90**	**2.92**	**0.96**			**1.08**	**4.17**	**1.05**
Bottom	**1.58**	**3.51**	**2.94**			**1.97**	**3.79**	**2.09**
Top	**1.45**	**1.66**	**3.07**	Lat	Lat	**0.78**	**1.80**	**1.12**
Middle	**1.62**	**2.78**	**3.97**			**2.17**	**3.91**	**1.80**
Bottom	**3.66**	**4.91**	**2.62**			**2.99**	**3.20**	**1.99**
Top	**0.36**	**2.96**	**0.45**	Lat	Lat	**0.70**	**1.55**	**0.91**
Middle	**1.89**	**4.59**	**1.91**			**2.49**	**2.15**	**1.55**
Bottom	**2.59**	**5.32**	**5.83**			**1.81**	**3.59**	
Top	**0.36**	**0.51**	**0.19**	Lat	Lat	**0.50**	**1.71**	**0.97**
Middle	**0.96**	**0.66**	**0.85**			**1.76**	**2.23**	**1.86**
Bottom	**0.33**	**0.47**	**0.74**			**2.86**	**1.97**	**0.63**

STORE 5A: Mean **2.11**; stdev 1.548; *95%C.I. 0.506* — DOOR

STORE 5B: Mean **1.94**; stdev 0.974; *95%C.I. 0.323* — DOOR

overall store values

Mean	**2.02**
SD	1.291
95%C.I.	*0.300*

Mean maximum sprout length overall was 8.6 mm (SD 4.72, Figure 33). Sprouting levels were slightly greater in Bay B (mean 9.4, SD 5.34) compared with Bay A (mean 7.8, SD 3.92). The lower sprouting levels in Bay A were reflected in greater CIPC residue levels (Figure 34) with a mean value of 2.11 mg kg^{-1} (SD 1.550). Mean residue values in Bay B were 1.94 mg kg^{-1} (SD 0.974). The distribution of sprouting was characterised by poor control at the front of the store (furthest from fans) in Bay A. Crop here also had particularly low residue values (<1.0 ppm). Poor sprout control in this area was due to the store not being completely filled, and the associated difficulties with balancing the store airflow when crop height above one or two laterals varies significantly from that above all the other laterals. Nevertheless, although sprout growth was evident at unloading, the crop was marketed successfully.

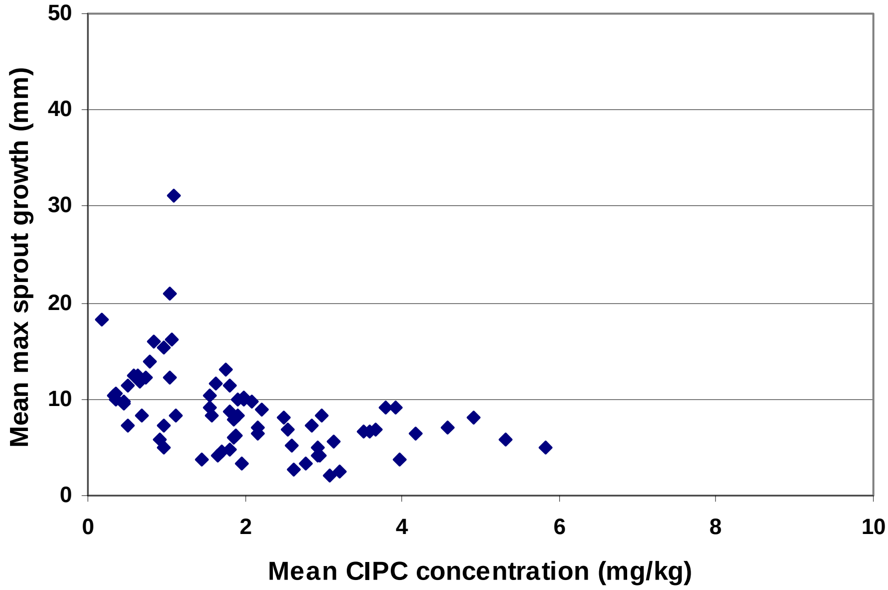


FIGURE 35. CORRELATION BETWEEN CIPC RESIDUE AND SPROUT GROWTH, MODIFIED STORE 5

There is a slight trend toward increased sprout growth below 1.8mg kg^{-1} in this store, although overall this tended to be in the areas mentioned previously.

Stores 6A and 6B

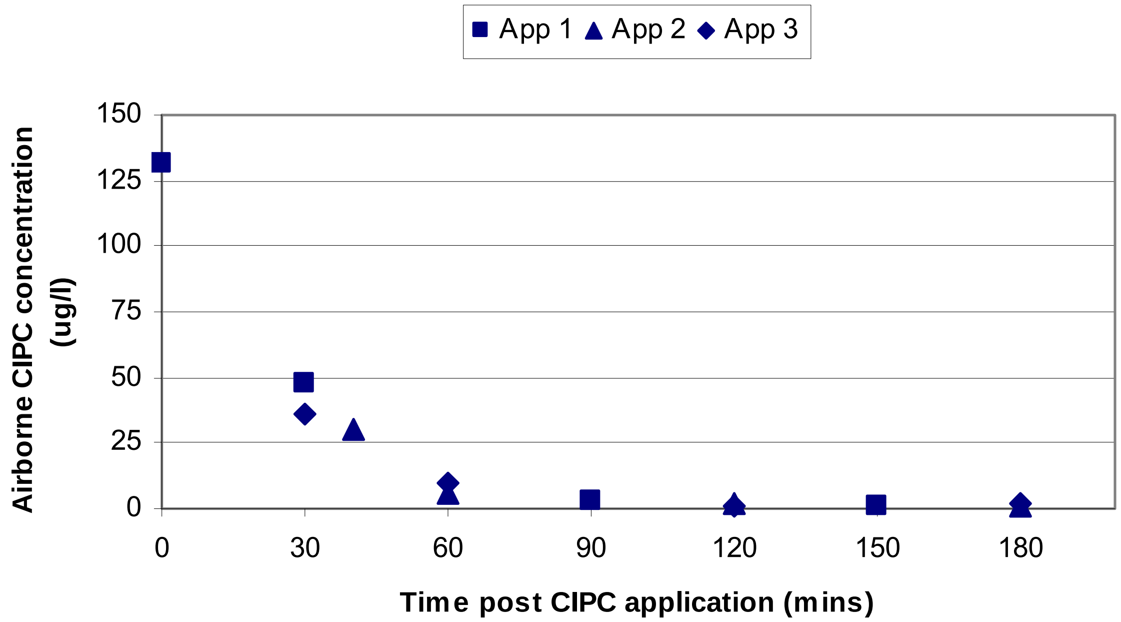


FIGURE 36. CIPC CONCENTRATION IN STORE AIR FOLLOWING APPLICATION IN STORE 6

Results are similar to those from the other stores and show a rapid decline in fog concentration with virtually complete clearing of fog within 1½ hours of application.

FIGURE 37. RESULTS OF SPROUT CONTROL EFFICACY IN STORES 6A AND 6B

Store 6A and 6B (both modified); sprouting efficacy results

Mean maximum sprout length (mm)

Location

Top = c.40cm from surface
Middle = c.2m from floor
Bottom = c.40cm from floor

Location	STORE 6A: c.1m from WALL	STORE 6A: center under lights	STORE 6A: c.1m from TUNNEL		TUNNEL		STORE 6B: c.1m from TUNNEL	STORE 6B: center under lights	STORE 6B: c.1m from WALL
Top	**1.5**	**0.9**	**1.5**	Lat	FANS	Lat	**1.0**	**2.0**	**1.4**
Middle	**1.2**	**1.7**	**1.0**				**1.0**	**1.4**	**0.9**
Bottom	**1.0**	**1.4**	**0.8**				**0.9**	**1.0**	**0.7**
Top	**1.0**	**0.9**	**1.2**	Lat		Lat	**1.3**	**0.9**	**2.1**
Middle	**1.0**	**1.0**	**1.0**				**2.2**	**1.0**	**1.0**
Bottom	**1.8**	**1.4**	**2.4**				**1.7**	**1.0**	**1.3**
Top	**0.9**	**1.0**	**1.0**	Lat		Lat	**1.3**	**1.0**	**1.1**
Middle	**1.0**	**1.0**	**1.3**				**1.6**	**1.2**	**1.0**
Bottom	**1.1**	**1.5**	**0.9**				**1.5**	**1.2**	**1.2**
Top	**1.0**	**1.0**	**1.0**	Lat		Lat	**1.2**	**1.4**	**1.0**
Middle	**1.0**	**0.9**	**2.6**				**1.0**	**1.0**	**0.9**
Bottom	**0.9**	**1.0**	**1.6**				**0.8**	**1.4**	**1.0**

Store 6A: Mean **1.2**; stdev 0.408; *95%C.I. 0.133*

Store 6B: Mean **1.2**; stdev 0.354; *95%C.I. 0.116*

DOOR | DOOR

overall store values

Mean	**1.2**
SD	0.380
95%C.I.	*0.088*

Figure 38. Results of CIPC residue analysis in stores 6A and 6B

Store 6A and 6B (both modified); CIPC residue results

mg of CIPC per kg on fresh weight basis

Location

Top = c.40cm from surface
Middle = c.2m from floor
Bottom = c.40cm from floor

Location	STORE 6A: c.1m from WALL	STORE 6A: center under lights	STORE 6A: c.1m from TUNNEL		TUNNEL		STORE 6B: c.1m from TUNNEL	STORE 6B: center under lights	STORE 6B: c.1m from WALL
Top	**0.90**	**4.40**	**2.90**	Lat		Lat	**0.80**	**2.10**	**1.40**
Middle	**3.20**	**5.60**	**3.90**				**2.70**	**2.80**	**4.80**
Bottom	**7.90**	**10.60**	**6.00**				**9.00**	**10.50**	**9.60**
Top	**5.80**	**5.10**	**1.70**	Lat	T	Lat	**1.50**	**3.40**	**2.80**
Middle	**7.70**	**5.10**	**2.80**		U		**1.80**	**3.30**	**4.60**
Bottom	**11.60**	**13.00**	**4.40**		N		**9.00**	**12.50**	**13.40**
Top	**3.60**	**7.60**	**5.30**	Lat	N	Lat	**1.60**	**4.10**	**3.10**
Middle	**12.00**	**10.40**	**4.30**		E		**3.20**	**4.70**	**5.00**
Bottom	**12.70**	**14.70**	**11.20**		L		**4.70**	**8.10**	**7.90**
Top	**4.30**	**5.20**	**5.60**	Lat		Lat	**1.80**	**1.80**	**2.10**
Middle	**8.50**	**7.50**	**3.10**				**4.30**	**5.90**	**4.30**
Bottom	**19.40**	**14.30**	**12.40**				**10.70**	**10.50**	**6.00**

Store 6A: Mean **7.35**, stdev 4.311, *95%C.I. 1.408* — **DOOR**

Store 6B: Mean **5.16**, stdev 3.477, *95%C.I. 1.136* — **DOOR**

overall store values

Mean	**6.26**
SD	4.042
95%C.I.	*0.934*

Sprout control at store 6 was very good with a mean maximum sprout length of 1.2 mm (SD 0.380) after long term storage.

CIPC residues in this store were particularly high with mean values of 7.35 mg kg^{-1} (SD 4.311) and 5.16 mg kg^{-1} (SD 3.477) for Bays A and B respectively. In both bays, particularly Bay A, there was a tendency for high values to occur in samples from the bottom of stack at sampling locations furthest from the fan. The poor distribution of CIPC residues in this store was not thought to be related to the application procedure but may be a result of store management. The store is a small, well-sealed building and, prior to CIPC applications, air from the store headspace was routinely recirculated through the crop. It is thought that this practice may have resulted in condensation on cooler tubers at the bottom of stack, leading to higher CIPC deposition and therefore residue levels. However, further work is needed to confirm this.

The overall mean residue levels (the value most in keeping with sampling procedures for MRL testing) were well below the MRL at 7.35 +/- 1.4 mg kg^{-1} in Bay A and 5.16 +/- 1.14mg kg^{-1} in Bay B.

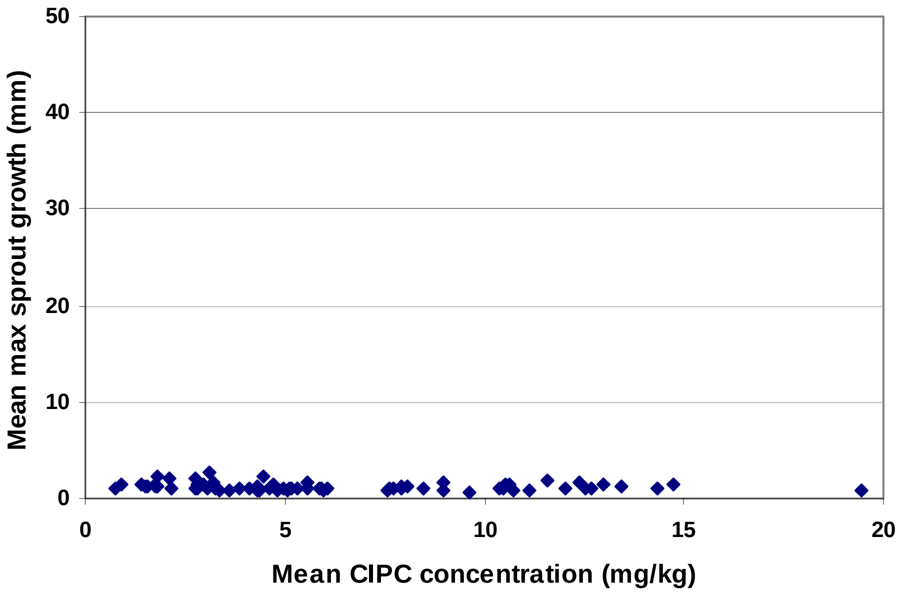


FIGURE 39. CORRELATION BETWEEN CIPC RESIDUE LEVEL AND SPROUT GROWTH, MODIFIED STORE 6A AND 6B

All concentrations of CIPC including those below 1 mg kg^{-1} maintained very good sprout control throughout the bulk of the crop.

CIPC distribution and redistribution assessment in commercial stores

Figure 40 shows the relative position and orientation of fans, recirculation louvres and samples. CIPC fog was applied into the fan house and drawn, by the fans, into the main duct.

Distribution and application efficiency results

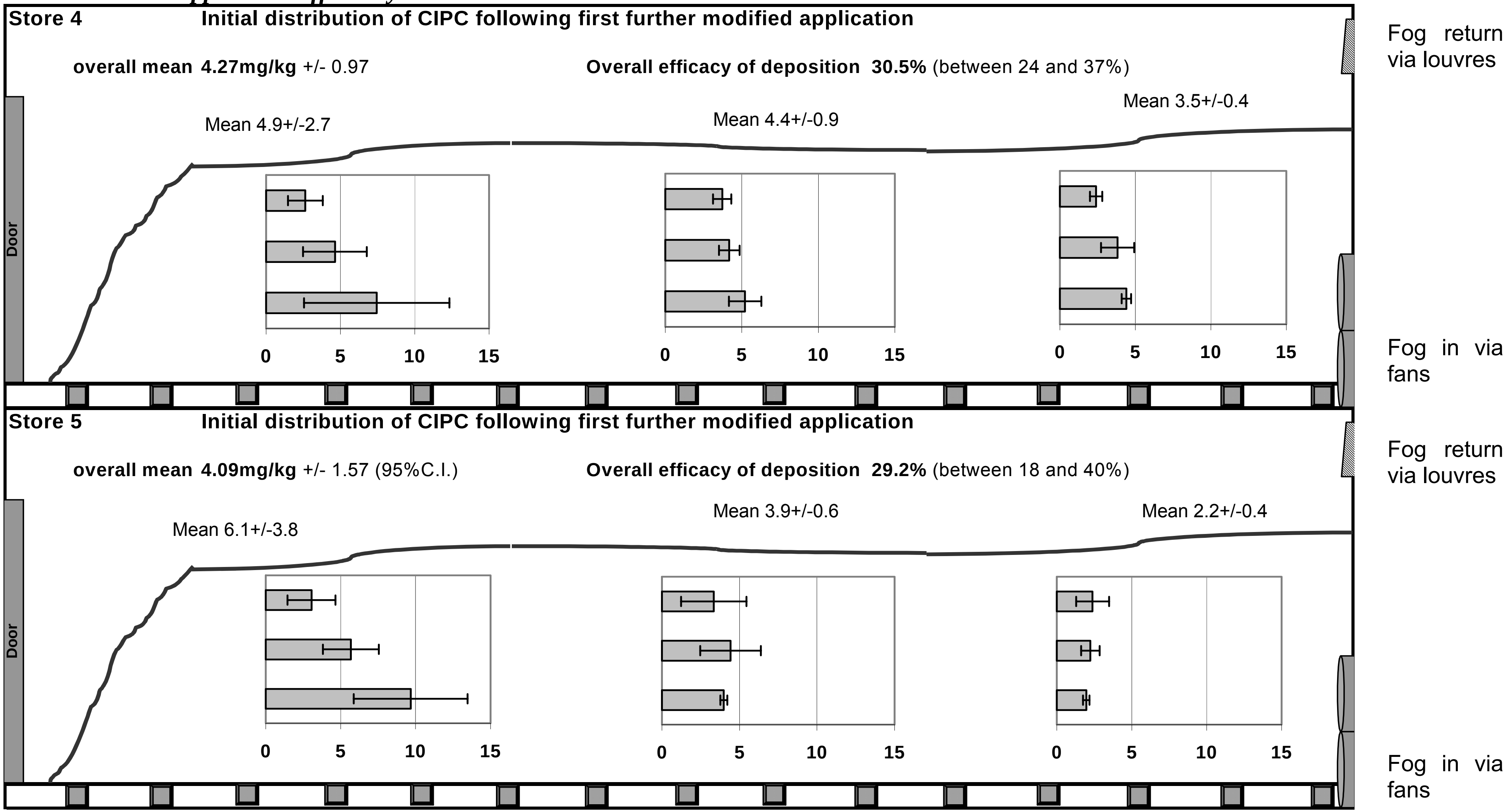


FIGURE 40. DISTRIBUTION OF CIPC DEPOSIT (MG KG^{-1}) IN BULK PILE FOLLOWING MODIFIED APPLICATIONS IN STORES 4 AND 5

Fans were operated at 10-15% of full speed (7.5-10 Hz). The overall efficiency of the first application was very similar in both stores with values of 30.5% and 29.2% respectively for stores 4 and 5, for tuber samples removed within 24 hours of application. Mean CIPC *deposit* values (as opposed to CIPC residue) were 4.27 and 4.09 mg kg^{-1} respectively.

Both stores had a similar pattern; CIPC deposit values at the two sampling positions nearest the fans were largely unaffected by bulk height. In both stores, however, at the sampling position furthest from the fan, the highest CIPC deposit values were recorded in samples from the base of the stack. In addition, there was a tendency for mean CIPC deposit levels for each group of three sample locations to increase, with distance from the fan. This effect was most apparent in store 5.

The CIPC deposit distributions, following the second application, are shown in Figures 40 and 41. Application efficiency was improved at the second application with values of 75.6% and 51.4% for stores 4 and 5 respectively.

Store 4

The CIPC deposit concentration following application 2 in store 4 was relatively high, with a mean value of 10.16 +/- 0.80 mg kg^{-1}. On this occasion deposit distribution was relatively even.

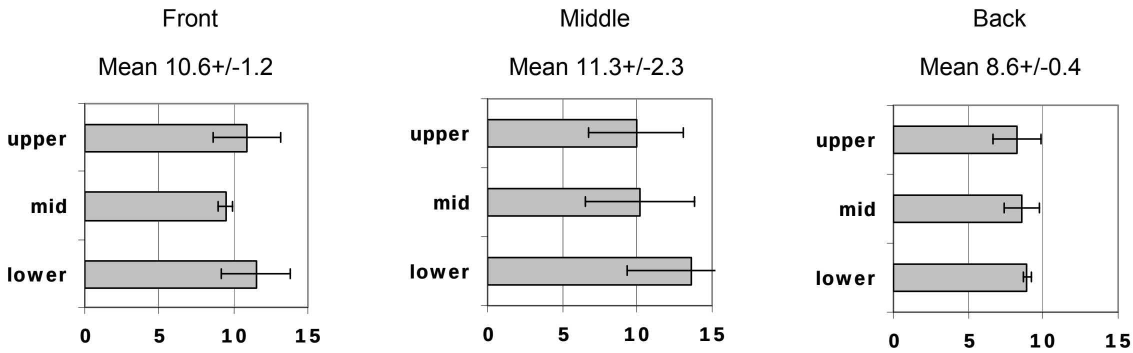


FIGURE 40. DISTRIBUTION OF CIPC (MG KG^{-1}) FOLLOWING 2ND APPLICATION INTO STORE 4

Store 5

The trend of mean deposit increasing with distance from the fans was also evident in samples obtained within 24 hours of application 2 to store 5.

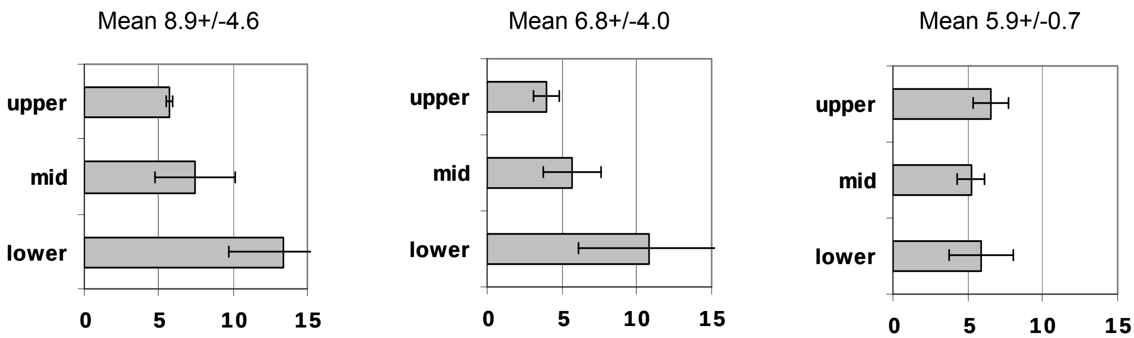


FIGURE 41 DISTRIBUTION OF CIPC (MG KG^{-1}) FOLLOWING 2ND APPLICATION INTO STORE 5

Redistribution results

Untreated samples were placed in store after an application and remained in place until just prior to the subsequent application to measure redistribution. CIPC deposits on these samples therefore provide information about the transport, or redistribution, of CIPC which is considered to take place largely via the vapour phase.

Store 4

Untreated samples (Figure 42) were held in store 4 for 119 days between applications 1 and 2. While mean levels (3.27 +/- 0.64 mg kg^{-1}) at the three sampling positions were similar to those in store 5 (3.40 +/- 0.26 mg kg^{-1}) deposits were generally highest in samples taken from the bottom of the bulk pile.

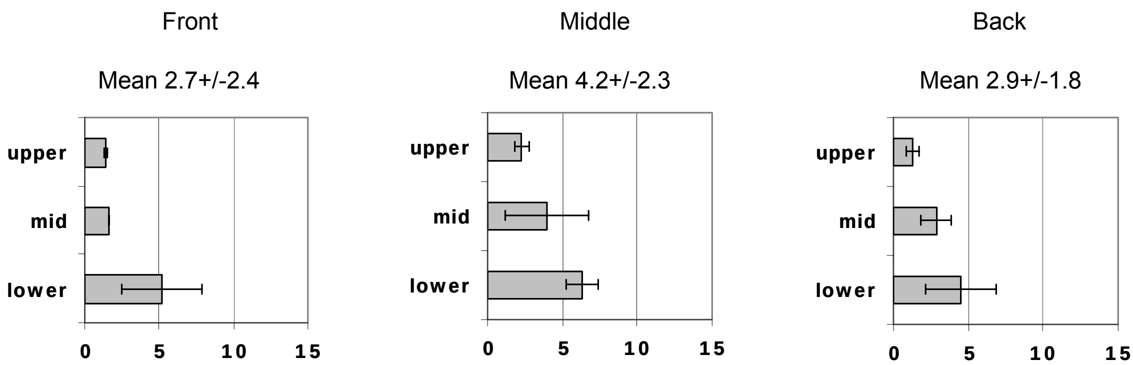


FIGURE 42. PRE APPLICATION 2, REDISTRIBUTION OF CIPC (MG KG^{-1}) AFTER 119 DAYS OF STORAGE, STORE 4

The period of storage between applications 2 and 3 (Figure 43), during which samples were subject to CIPC redistribution, was 74 days. The mean CIPC deposit value after this period was 1.55 mg kg^{-1}, which was considerably lower than the value obtained after application 1, when samples were held for 119 days. The distribution of CIPC deposits was similar to that measured after application 1, with the highest concentrations generally being found on samples at locations at the bottom of the stack.

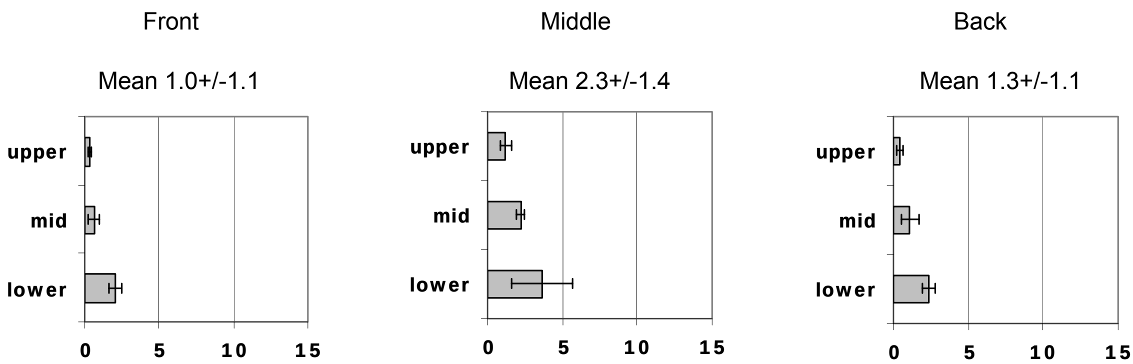


FIGURE 43. PRE-APPLICATION 3, REDISTRIBUTION OF CIPC (MG KG^{-1}) AFTER 74 DAYS IN STORE 4

Only the back section of the store (nearest the fans) received a third application of CIPC and was sampled at store unloading. Very little CIPC was redistributed to the back of the store over this time resulting in a mean CIPC deposit concentration of 0.30 +/- 0.13 mg kg^{-1}.

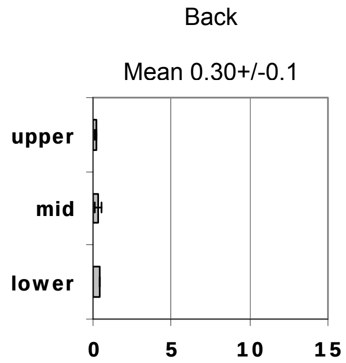


FIGURE 44. PRE-UNLOADING, REDISTRIBUTION OF CIPC (MG KG^{-1}) AFTER 50 DAYS, STORE 4

Store 5

Mean deposit levels of 3.40 +/- 0.26 mg kg^{-1} accumulated on these samples, during the 57 day storage period between applications 1 and 2 (Figure 45). Differences in concentration between the various sampling positions were very slight.

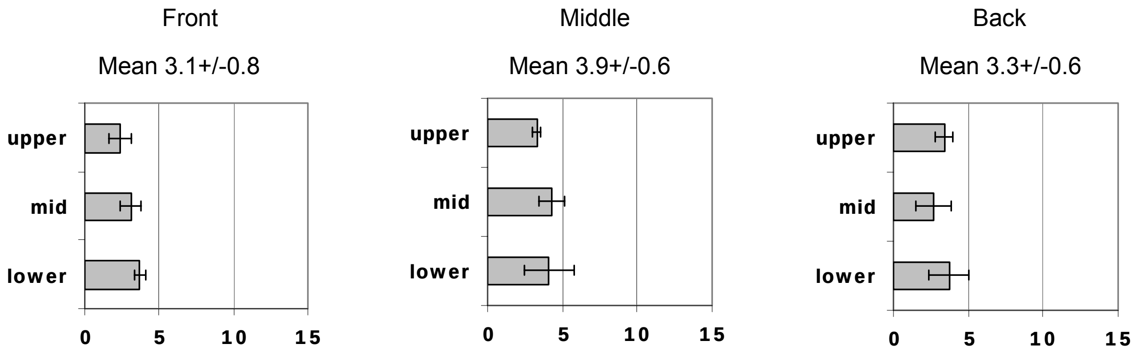


FIGURE 45. PRE-APPLICATION 2, REDISTRIBUTION OF CIPC (MG KG^{-1}) AFTER 57 DAYS, STORE 5

Although the period of storage during which redistribution took place following application 2 was much less (29 days) than that after application 1 (57 days), much higher deposit values of CIPC were recorded (mean 6.31 +/- 0.62mg kg^{-1}) and there was a marked effect of sample location (Figure 46). Deposit values in samples taken from nearest the fan were similar from all sampling heights. However, at the two sampling positions furthest from the fan, higher deposit values were measured on crop at the bottom of the stack.

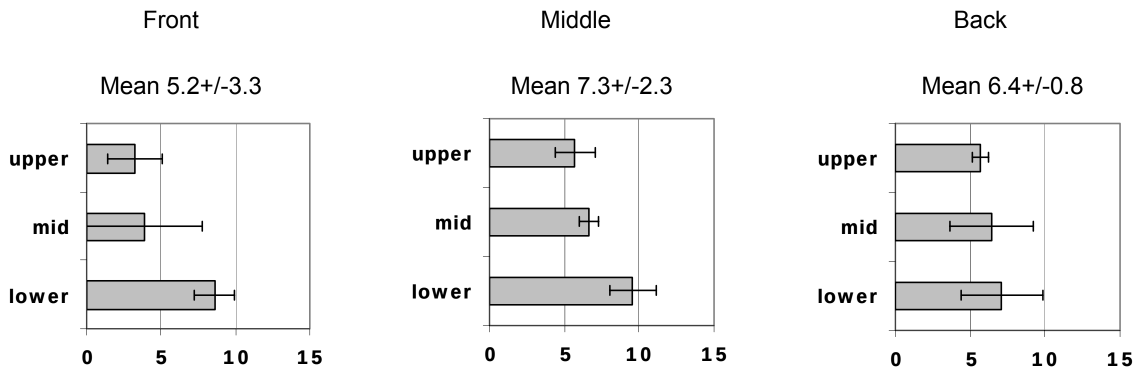


FIGURE 3. PRE-UNLOADING, REDISTRIBUTION OF CIPC (MG KG^{-1}) AFTER 29 DAYS, STORE 5.

CIPC vapour concentration

CIPC vapour was present in the air surrounding the potatoes within the middle of the stack under static store air conditions (i.e. no ventilation) and also in the residual turbulence following purging. Prior to purging, the CIPC vapour concentration in the store air, within the middle section of Store 4 at all heights, had a mean value of 5.79 +/- 0.75µg l^{-l}. After purging, the mean vapour concentration was measured at a higher mean of 8.05 µg l^{-1}, although with a greater range (SD 4.04 µg l^{-1}).

It is evident, therefore, that this vapour would have been subject to movement by the airflow around the store and subject to influence by storage conditions (i.e. temperature and humidity).

Discussion

Low-flow recirculation of reduced volume CIPC fog

Under conventional application conditions, CIPC fog is forced into a potato store and passes through the bulk only once, remaining in the headspace above crop until deposition occurs over time (normally up to approximately 8 hours). The modified system evaluated in this study utilises fans to recirculate the fog at a low rate increasing contact between CIPC and tubers and improving uptake on to crop. Typically CIPC is deposited fully after only approximately 4 hours.

In this work, the use of variable frequency drives enabled the fans to operate at a lower rate (generally between 10 and 30% of normal fan capacity) for CIPC applications. Airflow into laterals was measured and the lateral outlets from the main duct adjusted to optimise balance along the length of the duct, in order to provide an equal dosage of CIPC across the store. Fogger modifications were made to apply fog in less total volume (due to close coupling and the use of a solvent-free formulation) and, therefore, reduce any loss of chemical by limiting leakage resulting from store pressurisation.

Where direct comparisons were possible, the modified application system resulted in enhanced distribution of CIPC, improved efficacy and, in most cases, reduced chemical input (Table 4).

Store	Treatment	CIPC input (g t^{-1})	CIPC residue (mg kg^{-1})	Standard Deviation	Mean max sprout length (mm)	Standard Deviation
3A, year 1	Modified	28.50	0.70	0.70	3.5	4.4
3B, year 1	Conventional	28.50	0.78	0.75	6.7	8.6
3A, year 2	Modified	42.75	0.62	0.48	2.1	0.8
3B, year 2	Conventional	42.75	0.99	1.16	3.3	1.8
2, year 1	Modified	28.50	3.79	1.21	2.6	1.2
1, year 1	Conventional	57.00	1.57	1.03	3.2	1.1
2, year 3	Modified	14.25	1.31	1.31	6.4	5.4
1, year 3	Conventional	28.50	0.55	0.55	14.0	14.1

TABLE 4. COMPARISON OF INPUT, RESIDUE AND EFFICACY WITH STANDARD DEVIATIONS FOR STORES TREATED WITH CONVENTIONAL AND MODIFIED APPLICATIONS OF CIPC

It was notable that, as store managers' confidence in the system grew (through their own experience), the necessity to re-treat became less frequent. In addition, at all sites, there was a tendency for initial applications to be made earlier (more in line with GAP) as the project progressed.

Calculating the duration of storage gained from each gramme of CIPC applied per tonne and averaging this over the three years' data, allows comparison of treatments to be made over the entire duration of the project.

When all the project data are considered, there is a consistent improvement in the storage duration gained per unit dose of CIPC using the modified system, compared with the conventional approach. The extent of this improvement ranged from a 27% to 92% extension in duration of storage.

However, the extent of the benefit gained, is dependent on the design of the store and a major factor governing the success of the treatment is the relative volume of air in the building, compared with the crop and the ability of the building to contain that air, as discussed below:

Air volume

Figure 47 illustrates the effect of headspace volume on residual CIPC concentration, taking account of the amount of CIPC applied.

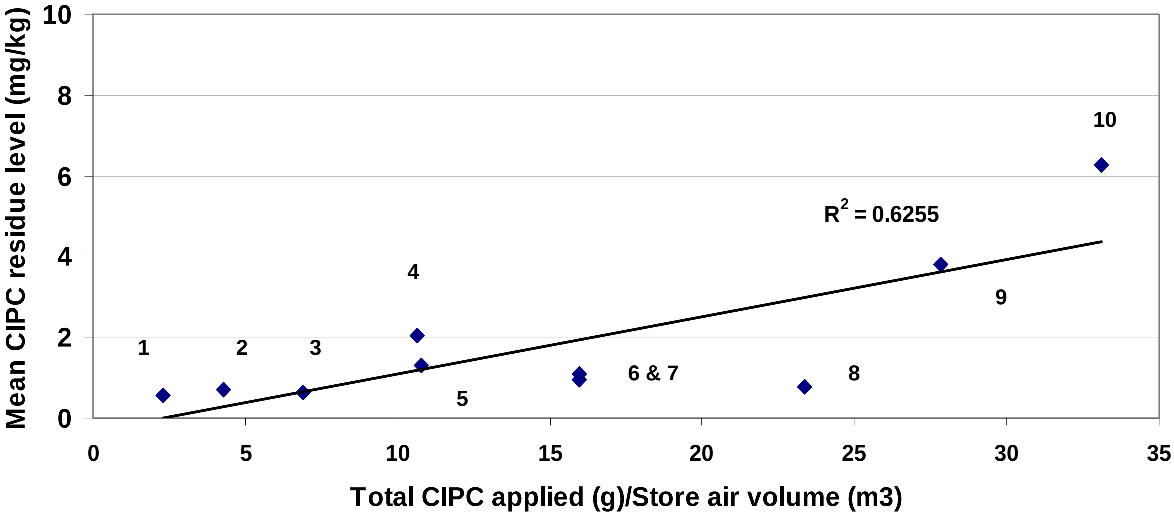


FIGURE 47. MEAN CIPC RESIDUE (MG/KG) RELATIVE TO CONCENTRATION OF CIPC APPLIED IN STORE HEADSPACE VOLUME (G/M^3), DATA FROM ALL MODIFIED STORES INCLUDING PARTIALLY FILLED AND PARTIALLY TREATED STORES (SEE TABLE 5).

Point	Store	Headspace volume (m^3)	No. of applications
1	3A	6503	1
2	3A	6668	2
3	3A and B	6503	3
4	5A and B*	5363	2
5	2	1782	1
6	4A	3878	3
7	4B	3878	3
8	4A and B	4290	2 full and 3rd partial
9	2	1535	2
10	6	1098	3

- One bay only partially filled

TABLE 5. STORE HEADSPACE VOLUME AND APPLICATION DETAILS FOR POINTS 1 –10 IN FIGURE 47.

These data suggest that CIPC residue level on the crop was directly influenced by store volume. Stores with the smaller headspace volumes retained more of the CIPC applied and therefore gained more benefit from treatment. Those stores with larger roof voids (or other air spaces) consistently had very low residual CIPC levels (<1 mg kg^{-1}).

Points 1, 2 and 3 show successively increased loadings of CIPC in store 3 (through further applications) but the residue level is not enhanced by the additional applications. In contrast, points 5 and 9 from store 2, with a smaller headspace, clearly show that there is an increased residue on the crop as a result of additional CIPC applications which indicates that there is more efficient use of CIPC in this store.

Points 4 and 8 represent storage situations that are best avoided. Point 4 is treatment of a partially filled store, where the additional air volume creates a greater dilution of CIPC for the tonnage treated. Point 8 is partial treatment of a completely filled store, by selectively closing some laterals. In this situation, although the amount of CIPC used is appropriate for the crop to be treated, the chemical is dispersed throughout the air volume of the store and this results in a lower application efficiency.

Partial treatment of stores and treatment of partially filled stores are both routinely practised in commercial stores, but users should be aware that they make inefficient use of CIPC. Wherever possible, CIPC application should take place with full stores. If the partial treatment scenarios are removed from Figure 47 (leaving only situations in which current best practice regarding store loading and treatment are followed), the influence of headspace volume becomes more apparent, with an R^2 value of 0.8295.

In summary, relatively small headspaces, such as those in stores 1 and 2, tend to make best use of the chemical applied, with applications resulting in significant residue concentrations. Larger headspaces, on the other hand, as in store 3, result in inefficient use of CIPC with even repeated applications not leading to substantial residue levels. These results suggest that significant cost savings and improved stewardship can be achieved through appropriate store selection and management.

The modified application treatment caused the airborne CIPC concentration in the store headspace to clear down to levels of *c.*15 µg l^{-1} or less within 90 minutes of fog application in all the stores tested in the third year. This process was faster in the stores that were fully loaded. Generally, CIPC was deposited within four hours of application using the modified system. This is a significantly shorter duration than that observed with conventional applications and may have benefits in terms of improved processing quality (Briddon *et al*, 2005), although this was not assessed.

Application efficiency improved significantly under the modified system when compared to typical values in the literature of *c.* 10% (Noël *et al,* 2004). Values of approximately 30% were achieved following the first application of the storage season. This was further improved with the second application, with efficiencies in the range 50-75%. The novel sampling system used in the third year provided more representative samples that could be taken as a reasonable reflection of the situation within the bulk.

Although application efficiencies were high, the overall mean residue concentrations from *all* stores treated with the modified system were below the MRL of 10 mg kg^{-1}.

The overall mean residue value for a store is considered most indicative of an MRL test due to the extensive sampling that should take place for this (Anon., 2002).

Residue levels were generally more uniform and predictable across any individual store following application using the modified system. The uniformity resulting from the modified application process will help to reduce instances where store managers are treating problem areas in stores that, conventionally, would receive little or no CIPC. Good sprout control was achieved with all inputs within the new limits (63.75 g $tonne^{-1}$ per season for processing crops – see www.potato.org.uk/cipc) with residue levels markedly below the MRL.

Leakage

Fogger output volumes were reduced by 35% through the use of the close-coupling modification. A further reduction in volume was achieved with the use of a solvent-free formulation. Reductions in the fog volume applied into store results in a decrease in the volume of store air displaced from *c.* 25% down to *c.* 15%. Extrapolation, using store 2 as an example and the model outlined by Park (2004), suggests that CIPC losses could be cut by 1.2 kg per application equivalent to a 50.9% reduction in losses of CIPC through leakage. This being the case the environmental impact of CIPC application is greatly reduced.

Redistribution

The pattern of higher deposits at the bottom of the pile following application was found previously by DeWeerd *et al* (2003). It is the general working principle of most applications of CIPC in North America, that the chemical is distributed evenly along the length of the store during application. Subsequently, air recirculation through the crop during storage brings about re-distribution, raising residue levels higher in the stack by volatilising the chemical from the bottom of the stack.

Redistribution is responsible for significant movements of the CIPC dose applied. This mobilisation via vapour that occurs during normal storage can assist in balancing out deposit levels on potatoes. The starting distribution, interim conditions (temperature, humidity, air movement) and duration over which it occurs will all affect the resulting pattern. However, it is logical that the more uniform distribution achieved with the modified application technique enables the process to be more effective than would be possible with less uniformly distributed CIPC particles.

Hazards

Results of small-scale trials and some work on a commercial scale indicate that deposition of CIPC on potatoes increases with increasing airflow and recirculation rate. There is, however, a risk that if fan speeds are increased to achieve this excessive attachment of CIPC to fans and fan guards will result. The use of fans which can displace high volumes of air at relatively slow rotational speeds is therefore beneficial. Also, to minimise the risk of blockages, fan guards should be replaced if these are corroded or of a very fine mesh. Fan guards should also be cleaned regularly to limit corrosion.

The use of flammable solvents in a store presents a risk of fire and/or explosion. The use of solid CIPC in this trial was primarily to reduce leakage, but an additional benefit is the removal of solvent from the process, both in application and transportation.

Explosion risk can be accentuated by a build up of dust. Risks should be minimised by regular (annual) cleaning to prevent dust accumulation.

Care should be taken to avoid conditions that may interfere with CIPC deposition on potatoes. Store management practices which result in condensation on the crop should be avoided as part of best practice but, if condensation does occur, high levels of CIPC deposition can result on the affected potatoes.

As ever, it is important with the modified system to get CIPC onto potatoes before they break dormancy. CIPC is most effective when it is applied before the onset of sprouting; further research into timing of the initial application is on-going (PCL project R297).

The modified system is an improvement on existing practices. Due care and attention must be taken to maintain high standards in store care, crop storage and setting up for CIPC application. Without these fundamentals it is unlikely that any benefit will be gained from the system.

Cost-benefit analysis

It is important for any new technique, developed from experimentation, to demonstrate a commercial benefit if it is to be considered for adoption by industry.

In carrying out a cost-benefit analysis, it has been assumed that storage is in a 1000 tonne bulk store suitable for retro-fitting of a variable frequency drive (VFD):

Typically, for a 1000 tonne store, the cost of CIPC treatment three times per season would ordinarily be about £1/tonne/application which equates to a cost of £3000 per year.

For the modified treatment system, there are additional costs. Primarily, setting up a store to use the modified system will be governed by the installation of a VFD which could be included at an indicative cost of £2900 and installation at £800. If this equipment is written off over 10 years this equates to a cost of £370 per year.

Additionally, an anemometer is required to assess and balance airflow. At a cost of £300 over 10 years, this equates to a further £30 per year (less if the instrument is used on more than one store).

Labour to carry out the balancing can be costed at ½ man day per store, say, £100 per store per season.

Use of solid CIPC briquettes, as tested in this work, would add a further 5p/tonne/application or £50 per application. For one application, this gives a total additional cost of £550 per store per year; for two, £600 and for three treatments, £650.

However, if use of the modified system results in a saving of one application per season, there is a net financial benefit of £1000-£600 = £400 per year.

Further savings would be additive at the full cost of treatment (£1000) less the incremental cost of briquettes (£50), i.e £950 per application.

This means that a saving of one application per season would more than cover any additional costs, so there is clearly a potential benefit to the adoption of the modified technique where a saving in CIPC use can be attained. This has been clearly demonstrated in all of the stores evaluated – except the one with an extremely large roof void.

Additional benefits can also accrue. More uniform application of CIPC has the potential to reduce losses due to higher moisture loss in sprouted crop or labour costs incurred when blending crops to address inconsistent quality. A 0.1% gain on weight loss is worth £100 per 1000 tonne store at £100/t. Fitting a VFD to a fan can also reduce energy costs significantly and may reduce maximum demands for electrical start-up [www.potato.org.uk/energy].

Just as importantly, with the more uniform deposition, and improved sprout control per gramme of CIPC applied using the modified system there is less risk of exceeding the Maximum Residue Level.

Conclusions

The modified application process developed and evaluated in this trial is a superior method for applying CIPC. The adoption of the process will result in improvements in sprout control efficacy as a result of an improvement in the evenness of CIPC residues.

In most stores, the procedure will result in a significant reduction in CIPC input requirements, but this will be influenced by store design. In stores with a large headspace, the benefits of the system will be diluted and, in this work, significant residue levels of CIPC on tubers were difficult to achieve. As a result, relatively high rates of chemical use were required to obtain satisfactory sprout control. In this situation, a marked reduction in CIPC inputs, compared with conventional practice, cannot be expected.

The effect of store air volume, relative to that occupied by the crop, on application efficiency also highlights a potential problem. Data indicate that residue values increase as the air/headspace volume decreases. Although clearly of value in the design of new stores and selection of stores for installing equipment for modified applications, the treatment of partially filled stores (dose rates for which are governed by the tonnage stored) makes inefficient use of CIPC and should therefore be discouraged. Partial treatment of a fully loaded store should also be avoided as this too results in inefficient use of CIPC.

Results of the trials show that effective sprout control, in a range of bulk storage scenarios, can be achieved cost-effectively using the modified system. Additionally, these results can be achieved well within the new stewardship limits for use of CIPC[1]. The technique has potential for widespread adoption throughout bulk potato storage in Great Britain to achieve improved efficiency of CIPC use and consistency of sprout control — at zero net cost to the industry.

CIPC application to bulk stores is already acknowledged as being more effective, compared with most box stores, due to the positive delivery of air (and therefore CIPC). The modifications discussed represent current best practice for CIPC use. Trials are on-going to translate these findings to box stores.

[1] CIPC usage limit: Maximum dose 36 g tonne^{-1} per season, unless crops are for peeling/processing where the limit is 63.75 g tonne^{-1} per season.

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The authors would also like to thank the managers of the commercial stores for their assistance in carrying out this work.

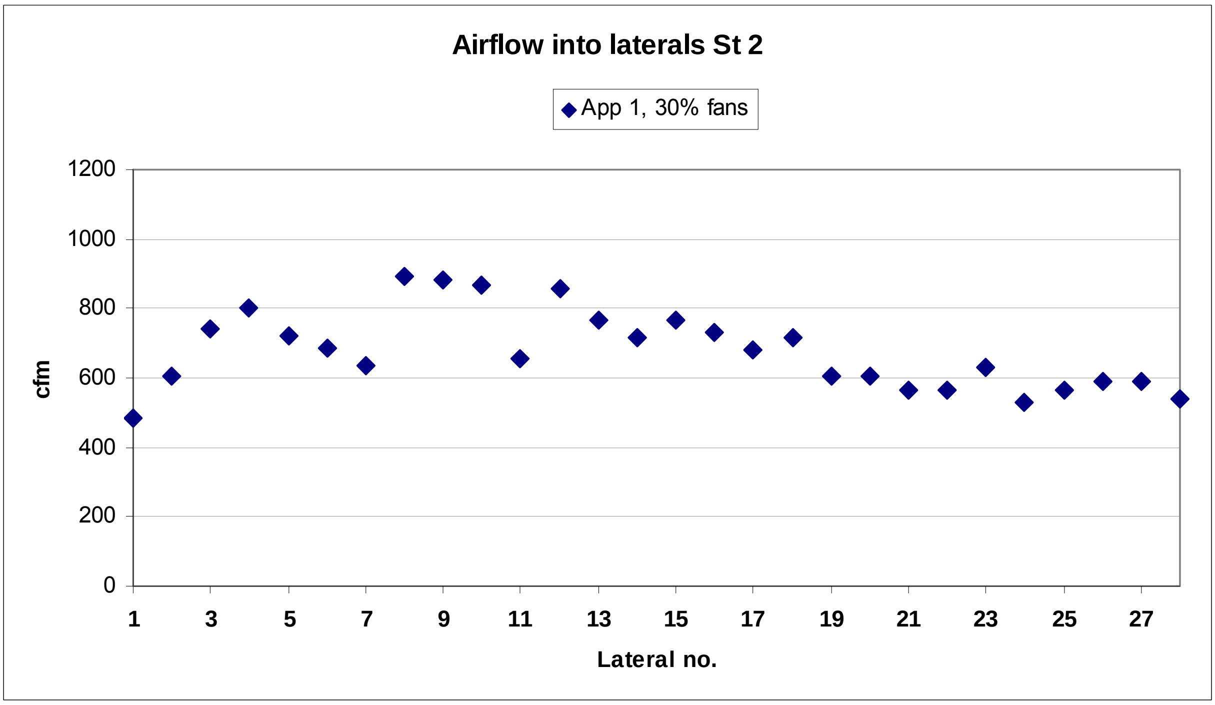
Appendix

Store 2

Air speeds into laterals (ft/min)
Application 1

Lateral number	Store 2 2 fans at 30%
1	305
2	380
3	465
4	505
5	455
6	430
7	400
8	355
9	350
10	345
11	260
12	340
13	305
14	285
15	305
16	290
17	270
18	285
19	240
20	240
21	225
22	225
23	250
24	210
25	225
26	235
27	235
28	215
mean	308
standard deviation	83
plus 1 st dev	392
minus 1 st dev	225

Range in metric units 1.07-2.57m s^{-1}

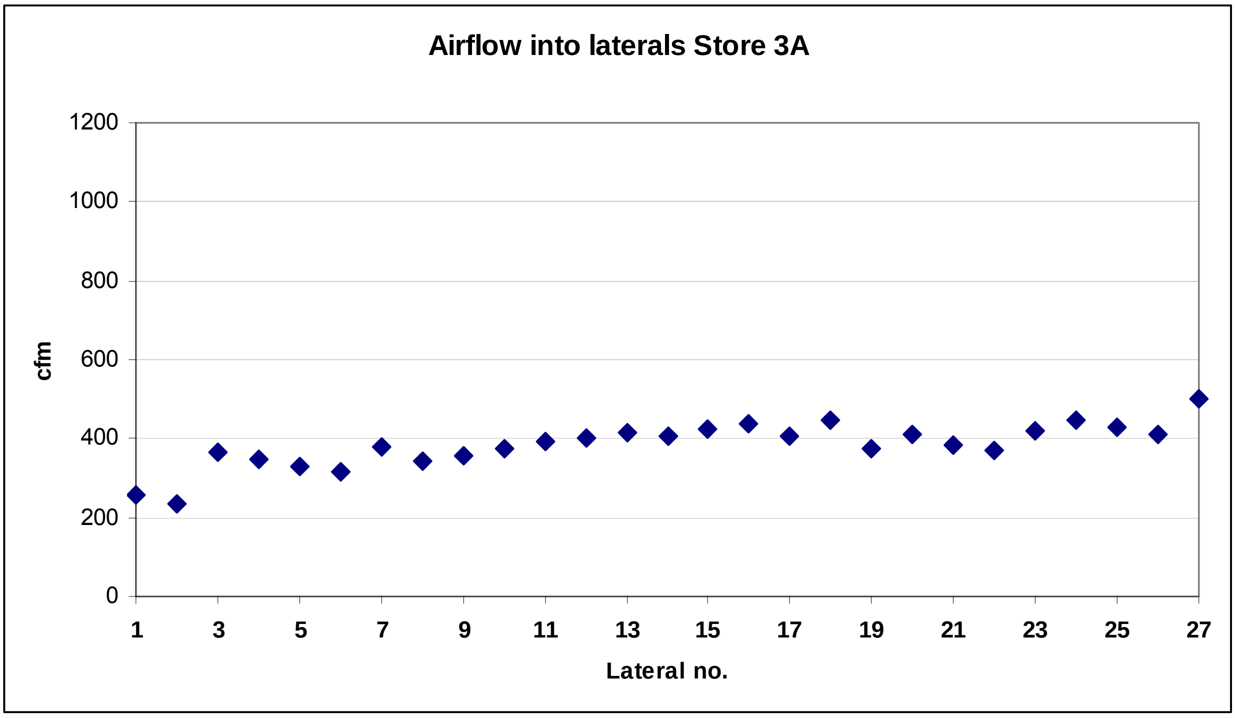

Airflow into laterals St 2
App 1, 30% fans
1200
1000
800
600
400
200
0
cfm
1
3
5
7
9
11
13
15
17
19
21
23
25
27
Lateral no.

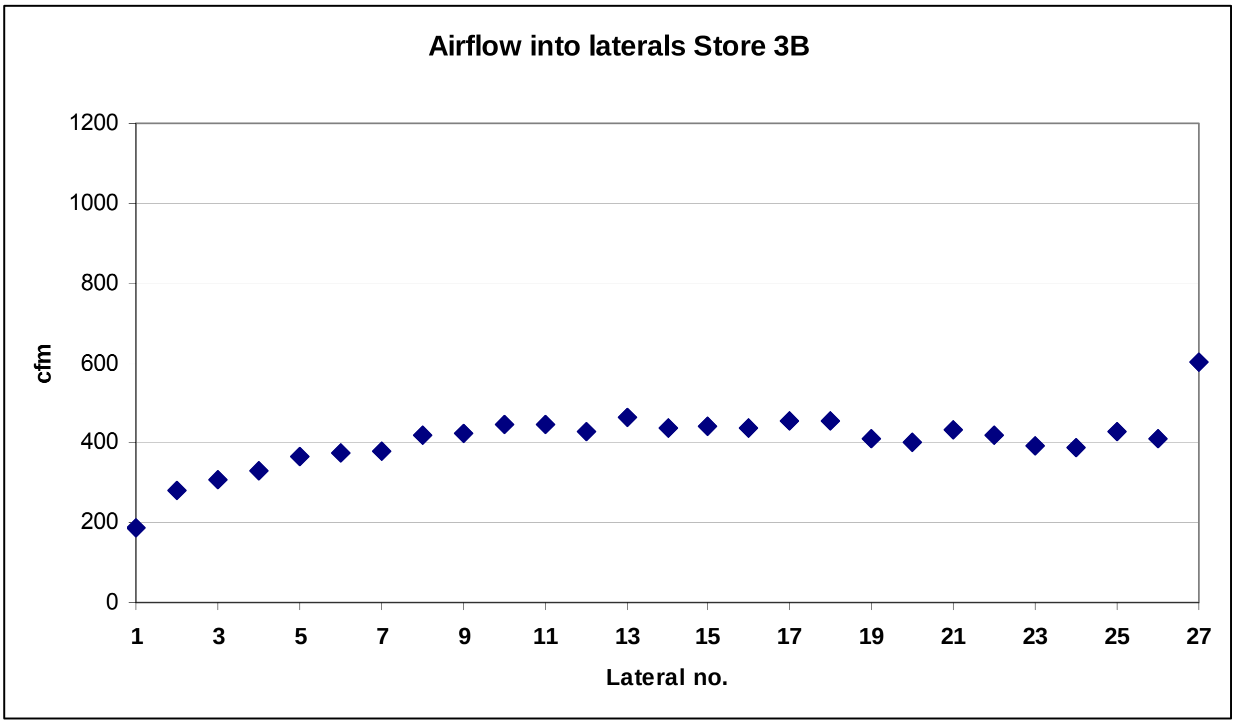
Stores 3A and B

Air speeds into laterals (ft/min)
Application 1

Lateral number	Store 1 fans at 22%	Store 2 fans at 22%
1	480	350
2	410	490
3	600	500
4	530	510
5	480	530
6	440	520
7	500	500
8	430	530
9	430	510
10	430	510
11	430	490
12	420	450
13	420	470
14	400	430
15	400	420
16	400	400
17	360	400
18	380	390
19	310	340
20	330	320
21	300	340
22	290	320
23	310	290
24	320	285
25	300	300
26	280	280
27	240	290
mean	393	414
standard deviation	85	90
plus 1 st dev	478	503
minus 1 st dev	309	324

Range in metric units 1.22-3.05m s^{-1}


Airflow into laterals Store 3A
cfm
1200
1000
800
600
400
200
0
1
3
5
7
9
11
13
15
17
19
21
23
25
27
Lateral no.


Airflow into laterals Store 3B
cfm
1200
1000
800
600
400
200
0
1
3
5
7
9
11
13
15
17
19
21
23
25
27
Lateral no.

Stores 4A and B

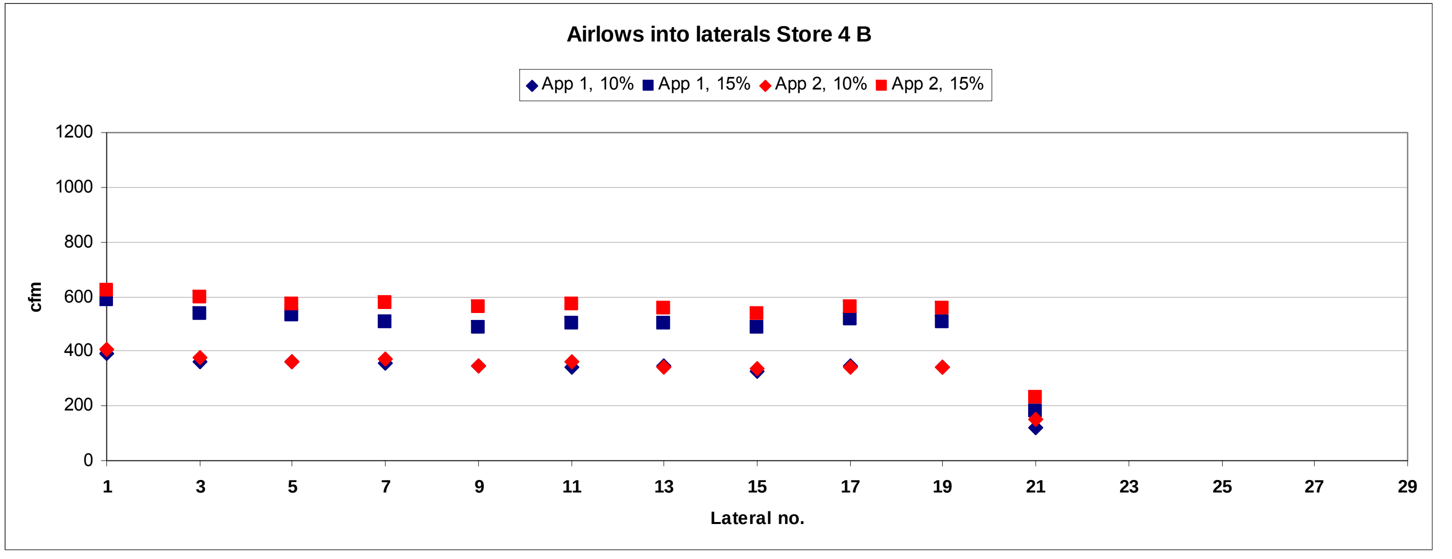
Air speeds into laterals ft/min

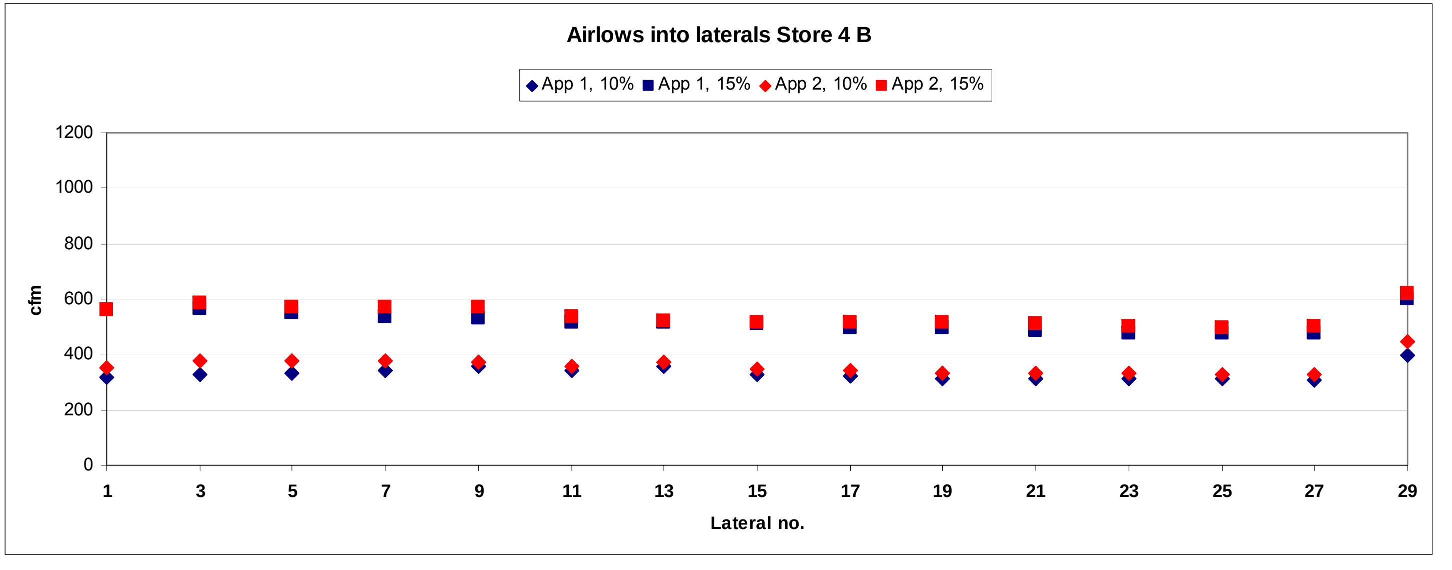
	Application 1		Application 2	
Lateral number	Store 4A 10%	Store 4A 15%	Store 4A 10%	Store 4A 15%
1	560	840	580	890
3	520	770	540	860
5	520	760	520	820
7	510	730	530	830
9	500	700	500	810
11	490	720	520	820
13	500	720	490	800
15	470	700	480	770
17	500	740	490	810
19	490	730	490	800
21	320	490	400	620
23	no crop	no crop	no crop	no crop
25	no crop	no crop	no crop	no crop
27	no crop	no crop	no crop	no crop
29	no crop	no crop	no crop	no crop
mean	489	718	504	803
standard deviation	61	85	45	68
plus 1 st dev	550	803	549	871
minus 1 st dev	429	633	459	734

Air speeds into laterals ft/min

	Application 1		Application 2	
Lateral number	Store 4B 10%	Store 4B 15%	Store 4B 10%	Store 4B 15%
1	490	860	540	860
3	470	810	540	840
5	480	790	540	820
7	490	770	540	820
9	510	760	530	820
11	490	740	510	770
13	510	740	530	750
15	470	730	500	740
17	460	710	490	740
19	450	710	480	740
21	450	700	480	730
23	450	680	480	720
25	450	680	470	710
27	440	680	470	720
29	230	350	260	360
mean	456	714	491	743
standard deviation	66	113	70	117
plus 1 st dev	522	827	560	859
minus 1 st dev	390	601	421	626

Range in metric units 0.64-3.18m s^{-1} at 10% and 0.97-4.83m s^{-1} at 15%


Airlows into laterals Store 4 B
App 1, 10%
App 1, 15%
App 2, 10%
App 2, 15%
1200
1000
800
600
400
200
0
cfm
1
3
5
7
9
11
13
15
17
19
21
23
25
27
29
Lateral no.


Airlows into laterals Store 4 B
App 1, 10%
App 1, 15%
App 2, 10%
App 2, 15%
1200
1000
800
600
400
200
0
cfm
1
3
5
7
9
11
13
15
17
19
21
23
25
27
29
Lateral no.

Store 5 A and B

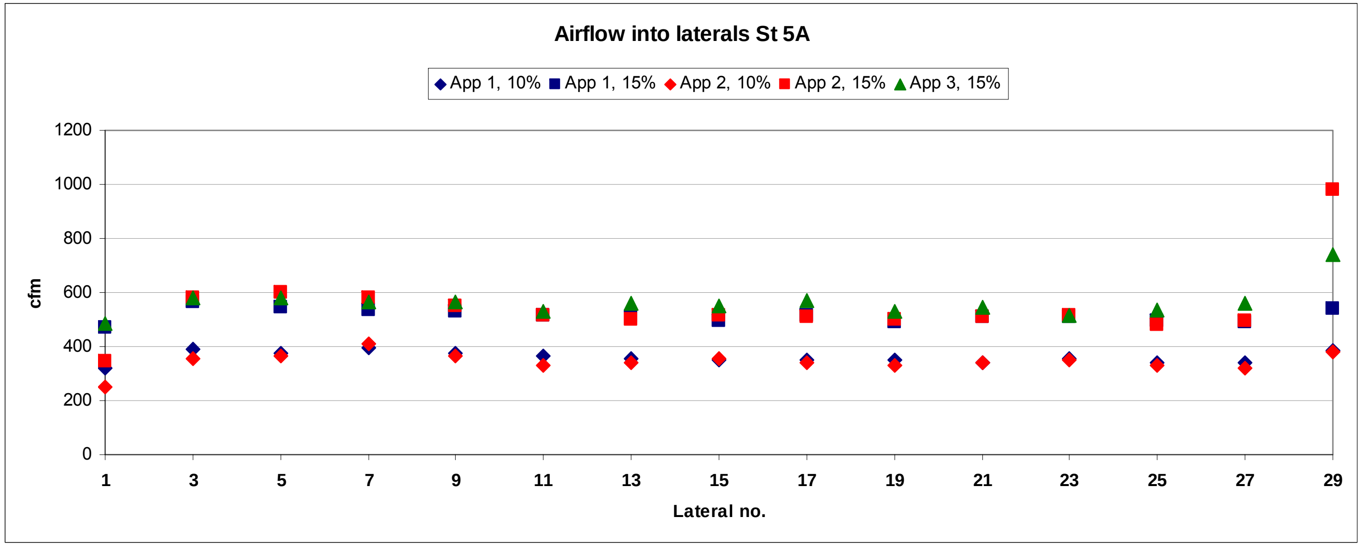
Air speeds into laterals ft/min

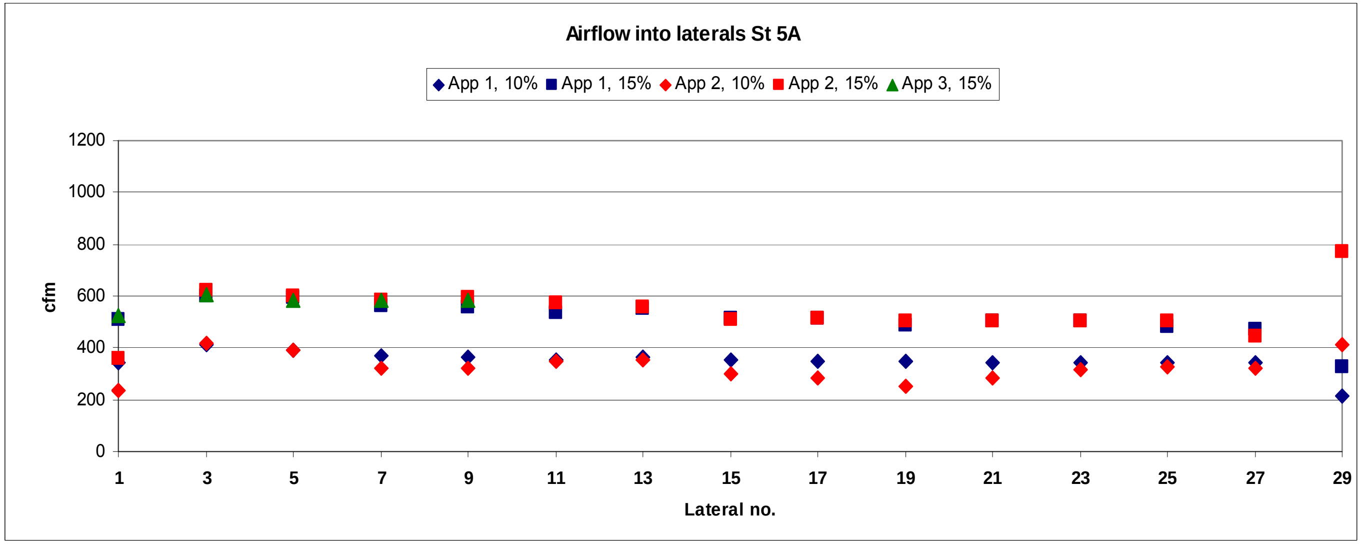
	Application 1		Application 2		Application 3	
Lateral number	Store 5A 10%	Store 5A 15%	Store 5A 10%	Store 5A 15%	Store 5A 10%	Store 5A 15%
1	625	920	490	670		950
3	560	810	510	830		830
5	540	780	520	860		830
7	570	770	590	830		810
9	540	760	520	790		810
11	520	740	470	740		760
13	510	730	490	720		800
15	500	710	510	740		790
17	500	740	490	730		820
19	500	700	470	720		760
21	490	730	490	730		780
23	510	730	500	740		740
25	490	710	470	690		770
27	490	700	460	710		800
29	225	315	220	570		430
mean	505	723	480	738		779
standard deviation	86	126	78	71		108
plus 1 st dev	591	849	558	809		887
minus 1 st dev	419	597	402	667		671

Air speeds into laterals ft/min

	Application 1		Application 2		Application 3	
Lateral number	Store 5B 10%	Store 5B 15%	Store 5B 10%	Store 5B 15%	Store 5B 10%	Store 5B 15%
1	610	910	420	640		940
3	590	860	600	890		870
5	560	850	560	860		840
7	530	810	460	840		840
9	520	800	460	850		840
11	510	770	500	820		
13	520	790	510	800		
15	510	740	430	730		
17	500	740	410	740		
19	500	700	360	720		
21	490	720	410	720		
23	490	720	450	720		
25	490	690	470	720		
27	490	680	460	640		
29	125	190	240	450		
mean	496	731	449	743		866
standard deviation	109	164	84	112		43
plus 1 st dev	605	895	533	854		909
minus 1 st dev	387	567	366	631		823

Range in metric units 1.17-2.95m s^{-1} at 10% and 1.78-4.52m s^{-1} at 15%


Airflow into laterals St 5A
App 1, 10%
App 1, 15%
App 2, 10%
App 2, 15%
App 3, 15%
cfm
0
200
400
600
800
1000
1200
1
3
5
7
9
11
13
15
17
19
21
23
25
27
29
Lateral no.

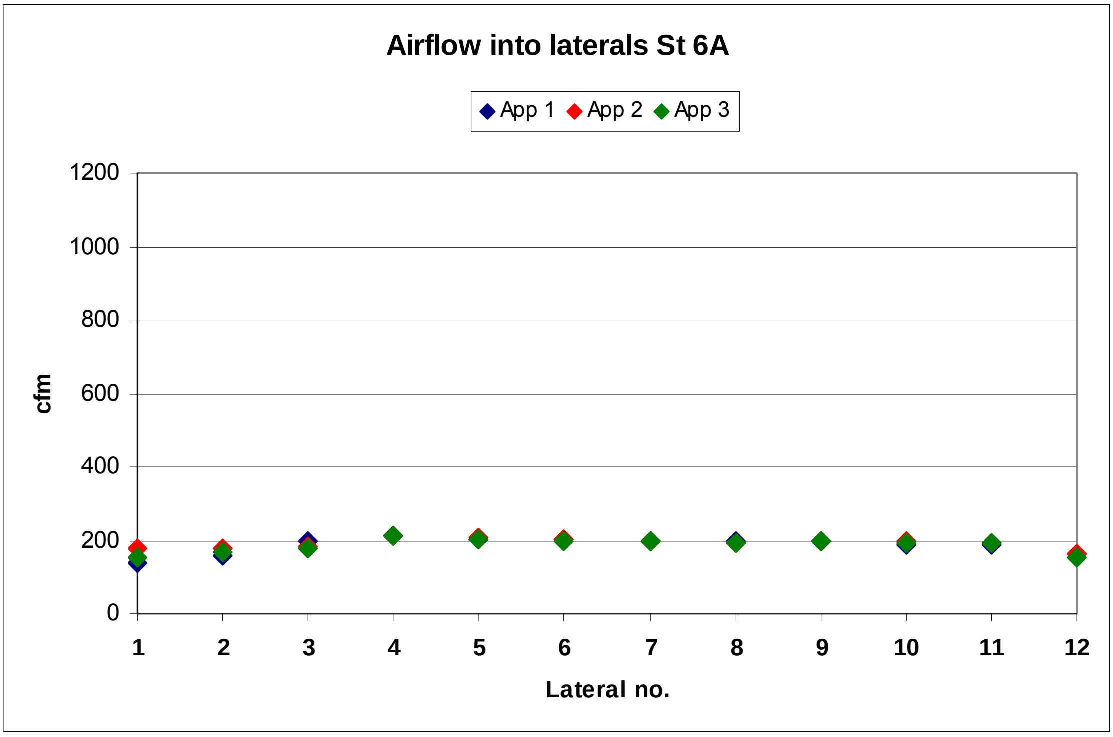

Airflow into laterals St 5A
App 1, 10%
App 1, 15%
App 2, 10%
App 2, 15%
App 3, 15%
cfm
0
200
400
600
800
1000
1200
1
3
5
7
9
11
13
15
17
19
21
23
25
27
29
Lateral no.

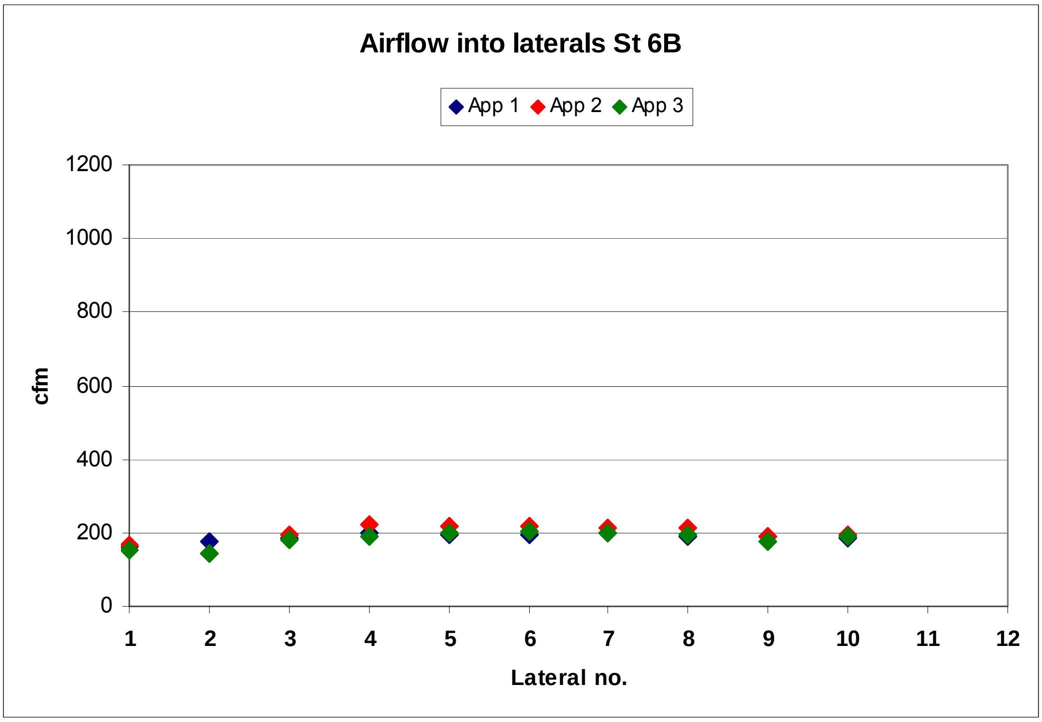
Stores 6 A and B

Air speeds into laterals ft/min

Lateral number	Application 1 Store 6A 20%	Application 1 Store 6B 20%	Application 2 Store 6A 20%	Application 2 Store 6B 20%	Application 3 Store 6A 20%	Application 3 Store 6B 20%
1	450	530	580	540	500	500
2	515	575	580	470	550	460
3	500	470	470	500	460	460
4	450	420	450	470	450	400
5	430	410	440	460	430	420
6	430	410	430	460	420	430
7	410	420	420	450	420	420
8	410	400	400	450	400	410
9	410	400	410	400	410	370
10	390	390	410	405	400	400
11	390		400	n/a	400	n/a
12	410		410	n/a	390	n/a
mean	433	443	450	461	436	427
standard deviation	40	63	64	41	48	37
plus 1 st dev	473	505	514	501	484	464
minus 1 st dev	393	380	386	420	388	390

Range in metric units 1.88-2.95m s^{-1}




Airflow into laterals St 6B
App 1
App 2
App 3
1200
1000
800
600
400
200
0
cfm
1
2
3
4
5
6
7
8
9
10
11
12
Lateral no.

3. Project deliverables

1. A method of CIPC application has been developed and assessed which can result in improved sprout control with a reduction in CIPC usage rates in bulk stores. In addition to the final report, a guidance document (**Improving the use of CIPC in bulk stores**) has been produced on how to carry out such applications and is available to growers, store managers and CIPC application contractors.

2. Fogger modification and formulation selection have been highlighted as having an influence on the success of CIPC treatments. This information is applicable to all types of storage, not only bulk stores.

3. Store volume has an influence on CIPC application success. This is of value for constructors of stores and managers with a range of store sizes. The selection of stores, particularly for long-term storage, should take account of store volume to help ensure satisfactory sprout control with the limited dosages of CIPC now available. This information is also relevant to all store types.

4. Information on the financial implications of adopting modified practices has been provided based on case studies of commercial bulk stores.

5. Development of a novel sampling system that improved knowledge base on CIPC distribution and redistribution within bulk stores.

Information from this project will be useful for:

1. The CIPC Stewardship Group. To assist in making better use of reduced CIPC inputs, allowing growers to comply with the statutory limits and providing information on how to reduce CIPC residues in final products.

2. Continuing to improve efficiencies in CIPC usage by store managers in line with the general principles of pesticide stewardship.

3. A reduction in environmental contamination with CIPC by limiting excessive or unnecessary leakage.

4. Results of the research will be used to develop PCL advice to growers, and production protocols.