HAL Project number: MC06020

Commercialisation of Precision Agriculture Technologies in the Macadamia Industry

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National Centre for
Engineering in Agriculture

NCEA

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Scope of the Report

This report presents large scale commercial testing and technology refinements of the technologies developed in the project MC03020. The primary purpose of this project was undertaking large scale testing of the technology and further refinement /development of the image detection algorithms and hardware.

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Media Summary

A prototype vision-based yield monitor has been developed for the macadamia industry. The system estimates yield for individual trees by detecting nuts and their harvested location. The technology was developed by the National Centre for Engineering in Agriculture, University of Southern Queensland for the purpose of reducing labour and costs in varietal assessment trials where yield for individual trees are required to be measured to indicate tree performance. The project was commissioned by Horticulture Australia Limited.

The prototype system consists of a pinwheel harvester which picks up fallen nuts on the ground. A camera mounted above the pinwheel views nuts accumulated in the pinwheel and automated analysis discriminates and counts nuts in the captured images. Geographic positioning equipment (i.e. GPS) is integrated with the vision system to enable nut counts to be attributed to particular trees.

The yield information can be used to determine the relative performance of trees and can be displayed on a Google Earth map for ease of evaluation. The prototype has potential to be developed into a commercial product that reduces the cost of data collection in varietal assessment trials conducted by research organisations such as CSIRO and the DPI.

Current practice for progeny trials in the macadamia industry require that macadamia nuts be hand collected and tagged for each tree. This is a labour intensive task that may involve the need to obtain casual staff. Mechanised harvesting is estimated to potentially enable cost reductions in progeny trials up to 59% for growers and the funding body Horticulture Australia Limited.

The prototype technology is a unique and labour-saving solution to macadamia yield assessment. The research project has successfully demonstrated the fusion of imaging and positioning technologies to provide a proof of concept for the yield assessment technique.

Recommendations for further work for the research comprise enhancing the system’s nut detection methods to account for trash and nut pooling and confirming performance through further field trials. This will allow development of the technology into a commercial product which could be used in varietal trials. .

Technical Summary

Varietal assessment trials in the macadamia industry require measurement of individual tree yields in a macadamia plantation. Currently macadamia nuts are hand collected and tagged for each tree which is a labour intensive task that may involve the need to obtain casual staff. Mechanised harvesting is estimated to potentially enable cost reductions in progeny trials up to 59% for growers, research bodies including CSIRO and the DPI and for the funding body Horticulture Australia Limited.

The National Centre for Engineering in Agriculture (NCEA) is developing technology for an automatic yield monitoring (AYM) system in the macadamia industry. This work follows on from an earlier project MC03020 which used a pinwheel harvester to pick up nuts from the ground and a camera mounted above the pinwheel to automatically identify and count nuts on the pinwheel. The pinwheel was custom-dyed blue to provide colour contrast with nuts for image processing purposes. Yield maps were generated by combining detected count with sensor inputs from a tree-detecting camera (Treecam), GPS receiver and radar odometer.

Work in the current project proceeded in three distinct phases, consisting of testing of the initial tractor-mounted prototype (Phase 1), enhanced colour detection on a prototype portable harvester (Phase 2) and proof of concept of nut detection with structured lighting (Phase 3). In Phase 1 of the project, the performance of the initial tractor-mounted AYM prototype was evaluated in commercial-scale field trials. The trial results indicated that the colour-based nut detection system was not sufficient for detecting husked (green and black) and dehusked (brown) nuts.

A prototype portable macadamia harvester was built to enable further development of the automated counting system at the NCEA in Phase 2 of the project. The portable harvester automatically performed nut pick up and counting operations on a portable unit featuring a pinwheel and embedded camera and processing system. An FPGA was used to execute initial colour processing steps that determined whether a pixel was part of the blue background or a nut. The portable harvester consistently demonstrated nut pick up rates greater than 90% for low and high densities of nuts on the ground. However, nut detection (i.e. counting) rates exhibited considerable variability which was determined to be due to a nut ‘pooling’ effect, in which nuts that were picked up in adjacent pins in the pinwheel were identified as a large piece of trash by the image processing algorithm.

A new nut detection approach based on structured lighting was developed in Phase 3 of the project with the primary goal of overcoming the pooled nuts problem. A focused line of light was projected onto the pinwheel such that a camera capturing images of the pinwheel could be used to distinguish the curved front surface of a nut from the blank space between pins and hence, ascertain the presence of a nut for counting. Nut detection results were very promising for the limited number of field trials conducted for this new approach.

This project has combined imaging and positioning technologies to provide a proof of concept for the automatic yield assessment technique. Improved algorithms and imaging techniques using structured lighting have been developed to better account for nut colour, trash and clusters of nuts on the pinwheel. A key recommendation for further work is to confirm and fine tune the new nut detection approach and trial the system on further field trials. The improved nut detection approach can then be integrated with the Prototype Yield Monitoring systems developed in project MC06020 and MC03020.

1 Introduction

1.1 Background

Varietal assessment trials in the macadamia industry require harvest yields in a macadamia plantation to be measured. As cultivars are generally planted in mixed rows, the count or weight of nuts from each metre along the ground is required. The standard measurement of harvest yield is the weight of the nuts collected after several runs of a macadamia harvester along rows of trees and the usual method of cultivar testing is the manual collection and counting of nuts by workers. This method is relatively accurate, but is becoming too costly due to rising employment costs and the general reduction in the number of skilled workers in the agricultural industry.

Mechanised harvesting is estimated to potentially enable cost reductions in macadamia progeny trials up to 59% (Hardner, 2005) which offers substantial savings to growers, research bodies including CSIRO and the DPI and to the project's funding body Horticulture Australia Limited (HAL). This project has been commissioned by HAL to evaluate mechanised yield assessment in macadamia plantations. The purpose of this project is to further improve a vision-based yield monitoring system that was developed in project MC03020. Outcomes of MC03020 are detailed in the next section followed by a description of the phases of the current project MC06020.

1.2 Review of MC03020 technology outputs

A macadamia yield monitoring system was developed that consisted of a pinwheel harvester mounted at the front of a tractor (Figure 1a). The pinwheel picked up nuts as the pinwheel moved over the ground (Figure 1b). A camera mounted above the pinwheel viewed nuts accumulated in the pinwheel and automated image processing discriminated and counted nuts in the captured images. The pinwheel was custom-dyed blue to provide colour contrast with nuts for image processing purposes. Geographic positioning equipment (i.e. GPS) was integrated with the vision system to enable nut counts to be attributed to particular trees. More detail is provided below about the nut detection camera and the creation of yield maps using Treecam, a GPS receiver and radar odometer.

1.2.1. Nut detection camera

The imaging device for counting nuts was a nut detection camera that was mounted above the pinwheel such that it could view nuts accumulated in the pinwheel. The nut detection camera was a newly developed technology by the NCEA (see specifications in Appendix A) which featured the capability for onboard image processing or data storage onto an SD card.

The principal design requirement for the nut detection software was real-time image processing and identification of nuts on the pinwheel. Image processing was based on colour and detected brown, black or green nuts collected in the blue pinwheel. The blue pinwheel enabled effective segmentation of the background based on colour such that non-background areas (e.g. nuts) could be identified. However, both nuts and trash (e.g. twigs and leaves) were picked up by the pinwheel and were identified as non-blue objects.

Size checking was required to ensure trash was not counted as nuts, since picked up nuts were typically physically smaller than trash. A size check of non-blue objects was implemented by dividing the image into grids and counting the number of grid cells the non-blue object spanned. By visual inspection of a set of evaluation images, nuts were effectively discriminated from trash using this size criterion. Automated nut detection and counting was further developed and tested in the current project MC06020.

(a) **(b)**

Figure 1. Macadamia harvesting apparatus for MC03020: (a) chassis supporting the pinwheel harvester mounted at the front of a tractor; and (b) detail of pinwheel. A GPS receiver is mounted on the post on the front right corner of the harvester chassis in image (a). The black metal fingers in the lower half of image (b) dislodge the nuts from the pinwheel and guide the nuts into a collection bucket as the pinwheel rotates.

1.2.2. Tree detection camera (Treecam)

A tree detection camera (named Treecam) was mounted at the side of the harvester chassis (Figure 2a) to detect trees in the field. Treecam faced the trees as the tractor moved alongside the trees and was the same type of camera as the nut detection camera. The captured images were stored on SD card and post-processed to determine parent trees.

(a) **(b)**

Figure 2. Yield mapping sensors mounted on harvester chassis: (a) Treecam; and (b) radar odometer.

1.2.3. GPS receiver

A DGPS 'CSI wireless CDA-2' receiver with accuracy 3 to 5 m was used to provide position information about trees to which nuts belonged. The receiver was placed at the front of the machine (Figure 1a). The GPS signal was logged when a tree was detected by Treecam.

1.2.4. Radar odometer

A radar odometer was used for measuring the groundspeed of the vehicle (Figure 2b). The 'JI Case Radar II' groundspeed sensor was mounted 35 degrees to the horizontal and was able to measure groundspeeds in the range of 0.33 to 66 mph (0.53 to 96.6 km/h). The typical groundspeed for harvesting macadamias is 5 to 10 km/h. The accuracy of the system was 1 to 3%.

Groundspeed information was required to determine the speed of the pinwheel. The speed of the pinwheel was used to calculate the average displacement of the nuts per frame in captured images which in turn was used to calculate the expected position of the nuts in following frames. This enabled nuts present in more than one frame to be flagged as already detected. Hence, nuts present in a sequence of frames were not counted more than once.

1.2.5. Post-processing of sensor inputs

In the post-processing step, data from Treecam, the GPS receiver and radar odometer were used to transform nut counts and detected tree positions into accurate yield maps (Figure 3). Yield information can be displayed on Google Earth.

A. Determine harvester location and heading (world co-ordinate system).

1. Either raw GPS records or predetermined GPS path points are passed through a b-spline type smoothing algorithm:
    i. In the case of raw GPS records the distance between control points is dynamically determined by the dhop signal quality field in $GPGGA.
    ii. In the case of predetermined paths the controls points are aligned with known locations.
2. Odometer readings are placed on interpolated positions on the b-spline curve.
3. Treecam records are examined simultaneously, and when a successful triangulation occurs determines closest tree by comparing position with a reference map.
4. Positioning error is calculated (difference between Treecam and map position), and initial GPS signal records in current run are back-adjusted to allow for the error.
5. Steps 1 to 4 are repeated until calculated Treecam position matches the reference map within 5 mm.
6. When a Treecam position is finalised as per Steps 1 to 5, the cumulative position error is applied to all future raw GPS records, and the algorithm then continues to work through the records in a progressive fashion until done.
7. At any point, heading is assumed to be aligned with line connecting the closest corrected odometer positions.

B. Determine position of nuts within harvester (local co-ordinate system).

1. The positions of separate components (cameras, GPS etc.) are recorded using a local co-ordinate system, measured in metres with the GPS antenna as the origin and direction of travel as the y-axis. This information along with component serial numbers etc. are stored in a harvester configuration file.
2. When a nut is detected, pixel (x, y) is converted to the local co-ordinate system and offsets are applied to allow for the relative positions of components.

C. Transform nut position to world co-ordinates, and assign to tree in reference map.

1. A transform is applied that combines nut position (local co-ordinate system), harvester position and heading (world co-ordinate system) to calculate nut position in world/GPS co-ordinates.
2. Nuts appearing in the same place but from different cameras/frames are filtered.
3. Nuts are then assigned to trees in a reference map. Method for this depends on the end user's requirements - for example it might be the closest tree, or the nut may have to lie within a polyline marking the canopy boundary.

Figure 3. Steps to convert GPS data, tree positions and nut counts into a yield map.

Accurate timing is the most important part of data fusion from multiple sensors. If unsynchronised data is accumulated, there is no method of rescheduling back into the original reference time sequence. Therefore, the microsecond timer in Microsoft Windows was used to timestamp all sensor data.

This concludes the review of technologies developed in project MC03020.

1.3 MC06020 project phases and milestones

At the completion of project MC03020, prototypes for vision-based macadamia nut counting and yield map generation had been developed. The purpose of follow-on project MC06020 was to further develop and test the vision-based nut counting system. Technology development in this project occurred in three distinct phases:

- Phase 1: Initial tractor-mounted prototype;
- Phase 2: Enhanced colour detection on a prototype portable harvester; and
- Phase 3: Proof of concept of nut detection with structured lighting.

Phase 1 was a continuation of the development and testing of the tractor-mounted nut counting system reported in Section 1.2. In Phase 2, a portable macadamia harvesting unit was constructed that enabled development and testing of the nut detection system at the NCEA. A FPGA-based embedded system and additional post-processing algorithms were also developed and evaluated in Phase 2. Phase 3 consisted of the development of a new vision-based system to count nuts. The three phases and the research milestones they addressed are described in the following sections.

1.3.1. Phase 1: Initial tractor-mounted prototype

The initial tractor-mounted prototype developed in MC03020 was required to be evaluated in commercial-scale field trials. Hence, Phase 1 of MC06020 addressed the following milestones from the project proposal:

- Conduct commercial scale reliability testing.
- Finalise precision agriculture technologies.

Key Performance Indicators (KPIs) for field testing of the prototype were established by the stakeholders (CSIRO, NSW Agriculture and Qld DPI) in November 2007 and are listed below:

- 75% harvester pick up (single round, i.e. the harvester picks up 75% of the nuts on the ground as it passes each tree one time only)
- 75% camera detect rate (i.e. at least 75% of nuts are correctly detected)
- maximum false positive rate (i.e. trash identified as nuts) of 2.5 nuts/m^2
- for 10 kg from 8 x 4 tree, 5 rounds

  +/- 500 g/tree for 1 tree x 1 replicate
  +/- 250 g/tree for 1 tree x 5 replicates
  +/- 100 g/tree for 5 trees x 5 replicates

1.3.2. Phase 2: Enhanced colour detection on a prototype portable harvester

Detection of different coloured nuts was identified as requiring further development in Phase 1. Hence, Phase 2 of the project was commissioned to address the following milestones in the project proposal:

- Develop initial colour classification technology for nut detection.
- Review and modify technology for robustness and reliability.
- Create a user interface.

- Field trialing and refinement of colour classification for nut detection.
- Manufacture or borrow a prototype harvester to undertake trials.
- Complete final accuracy testing with CSIRO.

The following specific course of action was determined in the meeting of stakeholders in November 2007:

- Develop and evaluate software algorithms to detect green, brown (dehusked) and black (husked) nuts.
- Develop an intuitive user interface and data handling operations for the software.
- Verify algorithm performance in preliminary field trials.
- Construct a portable harvester featuring a camera and odometer suitable for large-scale field trials of the nut detection system.
- Conduct large-scale trials (at a research farm in Bundaberg) of the nut detection system encapsulating a range of field conditions to enable a thorough evaluation of the accuracy of the nut counting hardware and software.

1.3.3. Phase 3: Proof of concept of nut detection with structured lighting

Field trials in Phase 2 of the project identified that high densities of nuts caused nut 'pooling', i.e. the image processing algorithm incorrectly identified groups of adjacent nuts on the pinwheel as a single object that was too large to be counted as a nut. Nut pooling was likely to occur under field conditions and was not satisfactorily overcome with the current platform. Hence, in August 2008 the following research objective was formulated:

- Develop a proof of concept PC-based vision system to assess nut numbers in a pooled situation.

2 Materials and methods

2.1 Phase 1 development

2.1.1. Nut identification cameras initial prototype

The camera system on the existing tractor-mounted pinwheel harvester was replaced with three identical embedded systems for nut detection, with each system monitoring one-third of the length of the pinwheel harvester. Each embedded system consisted of a microprocessor, camera and two halogen lights (Figure 4). The halogen lights were mounted on either side of the camera to reduce the effect of daylight fluctuations on captured images. The camera featured a VGA/QVGA CMOS image sensor which was able to record up to 60 fps (frames per second). Each camera was connected to its corresponding microprocessor via two serial RS232 ports. Further details of the embedded system hardware are included in Appendix A.

2.1.2. Nut detection software

The software program used to detect nuts on the embedded system in Phase 1 followed the process described in Section 1.2.2. The software used in Phase 1 (and enhanced in Phase 2) was written in the C programming language and implementation details are included in Appendix B.

Figure 4. Two (of three) embedded systems on the tractor-mounted harvester. Each system consisted of a microprocessor, camera and two halogen lights.

2.2 Phase 2 development

2.2.1. Prototype portable macadamia harvester

Trials with the initial tractor-mounted prototype established that further work was required on the software and hardware to increase the accuracy of detecting the different coloured nuts. Therefore, a small prototype portable macadamia harvester was built to enable further development of the automated counting system at the NCEA. A Bushrat unit (manufactured by Robmac Industries near Lismore) was determined to be suitable for the prototype portable macadamia harvester with some custom modifications. The Bushrat is a small unit with drive power provided by a Stihl two-stroke brush cutter motor and sprocket and chain drive. Throttle was positioned at the rear side of the Bushrat. The Bushrat moved forward when the throttle was increased and there was no reverse.

The Bushrat was modified into a portable macadamia harvester by the addition of a pinwheel which picked up nuts from the ground (Figure 5a). The pinwheel was dyed blue to provide colour contrast with the nuts for image processing. Metal fingers were fixed between the pins at the front of the pinwheel to remove the nuts from the pinwheel as the pinwheel rotated (Figure 5b). Buckets were positioned at the front of the pinwheel to collect the nuts as they were dislodged by the metal fingers.

A single embedded camera system (Section 2.1.1) was installed on the back frame of the portable harvester, with the camera facing towards the front of the harvester and focused on the blue pinwheel. A controlled lighting environment was implemented for the camera system by covering the portable harvester with black canvas which shielded the camera and pinwheel from sunlight (Figure 6). As in Phase 1, illumination was provided by two 50 W lamps mounted on either side of the camera at the rear of the harvester. A 12 V 7.2 Ah battery provided power for the electronic components and was mounted in one of the front nut collection buckets. A radar odometer (Section 1.2.4) was mounted on the portable harvester to enable measurement of the harvester’s groundspeed (Figure 6).

2.2.2. Embedded camera system for enhanced colour discrimination

The enhancement in Phase 2 was the addition of a colour detection system implemented on a Field Programmable Gate Array (FPGA). This addition considerably reduced the processing time of the microprocessor and allowed a more detailed inspection of each pixel’s colour attributes.

(a) **(b)**

Figure 5. Prototype portable macadamia harvester: (a) modified Bushrat chassis; and (b) detail of blue pinwheel, black metal fingers and nut collection buckets.

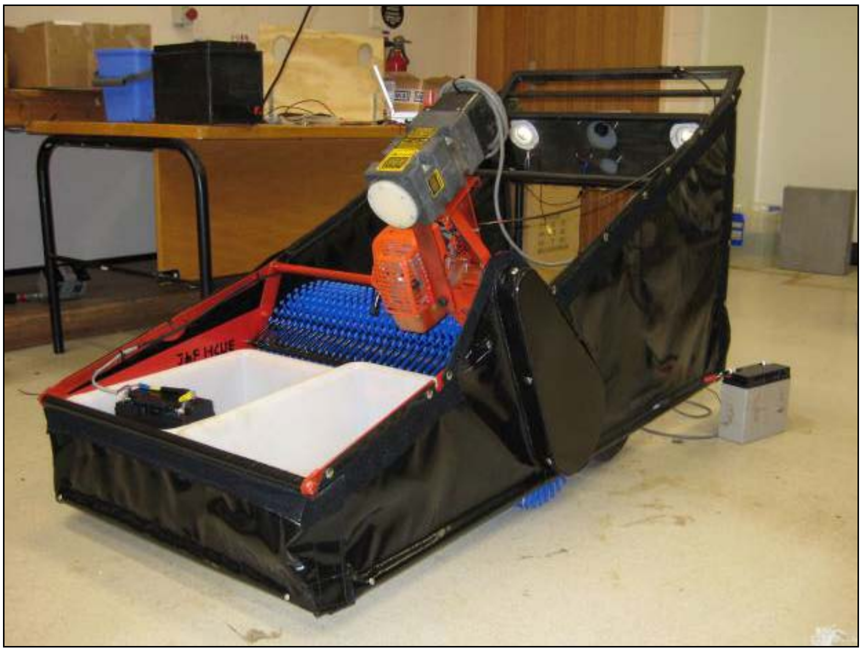


Figure 6. Assembled portable harvester (minus the canvas cover for the top of the harvester) with sides covered by black canvas. The radar odometer is mounted on top of the harvester's (orange-coloured) engine. The camera and two halogen lights are at the rear of the harvester.

The FPGA system converted the camera's VGA raw YCrCb output to raw RGB. The FPGA then executed a basic interpolation to resample the RGB values to QVGA resolution, which was found to be a satisfactory resolution for detecting nuts in the images. The red, green and blue components of each pixel were then compared to identify whether the pixel was likely to be a background pixel. If a pixel's blue channel intensity was greater than both its green and red channel intensities then the pixel was identified as blue background. Low light areas of the image did not produce accurate colour detection results and were automatically excluded from the analysis by applying a threshold to the pixel's luminance (Y) value. Algorithms were also developed to target the different colours expected of nuts (i.e. brown, green and black).

The output of the FPGA colour detection for each pixel was either a 'one' for nut colour detected or a 'zero' for blue background detected. The output was passed to the microprocessor for further shape analysis and was also displayed on a TV screen for visual inspection of the effectiveness of the colour detection. Typical results for colour-based nut detection are shown in Figure 7. By visual inspection of the video output, the system was effective at detecting colour nuts.

The microprocessor used the colour detection results to perform a size analysis as described in Section 1.2.2 to discriminate nut from trash. The microprocessor wrote nut detection results to an SD card.

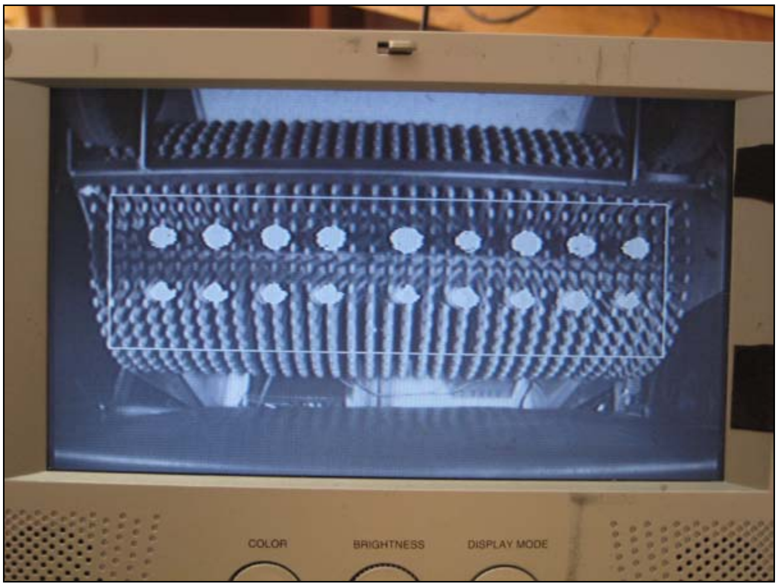


Figure 7. Typical nut detection results using FPGA colour analysis. The rectangle outline on the pinwheel is the region of interest that was analysed for nut detection. Detected nuts are overlaid with filled ellipses.

Optimum settings for the RGB values and the size of the region of interest in the image analysed by the FPGA were determined by field testing. The field tests consisted of using the harvester to pick up nuts that had been laid out on a grass field (Figure 8). By iteration through RGB values and recording corresponding nut detection accuracies (i.e. automatic versus manual nut count), the set of RGB values that resulted in the most accurate nut count was identified and these values were used as the optimal RGB values.

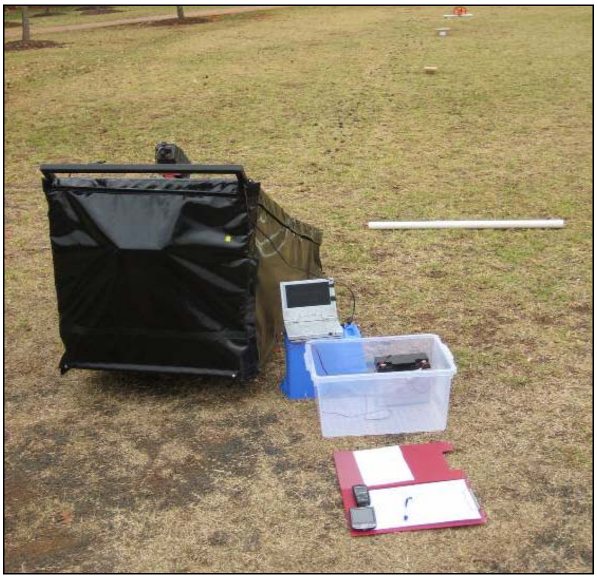


Figure 8. Field test setup to determine optimal RGB settings for FPGA.

An interface with the embedded system was developed for a personal digital assistant (PDA) to perform setup operations on the FPGA and microprocessor (Figure 9). The interface's functions included resizing the region of interest, RGB settings for the FPGA and data download from the SD card. Operating instructions for the PDA interface are included in Appendix C.

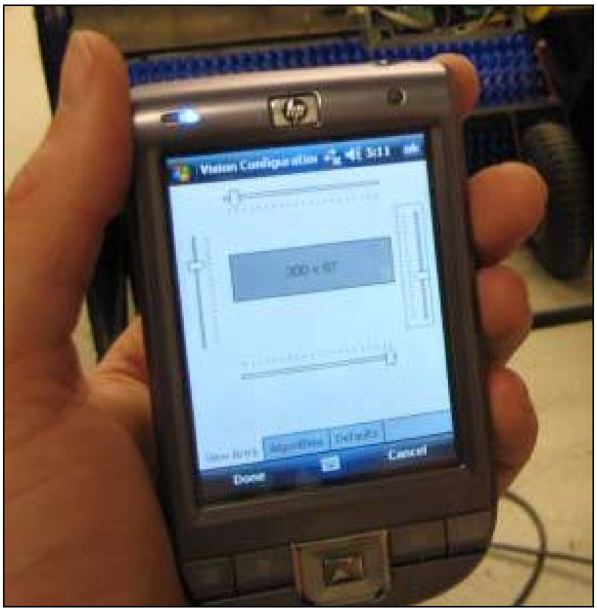
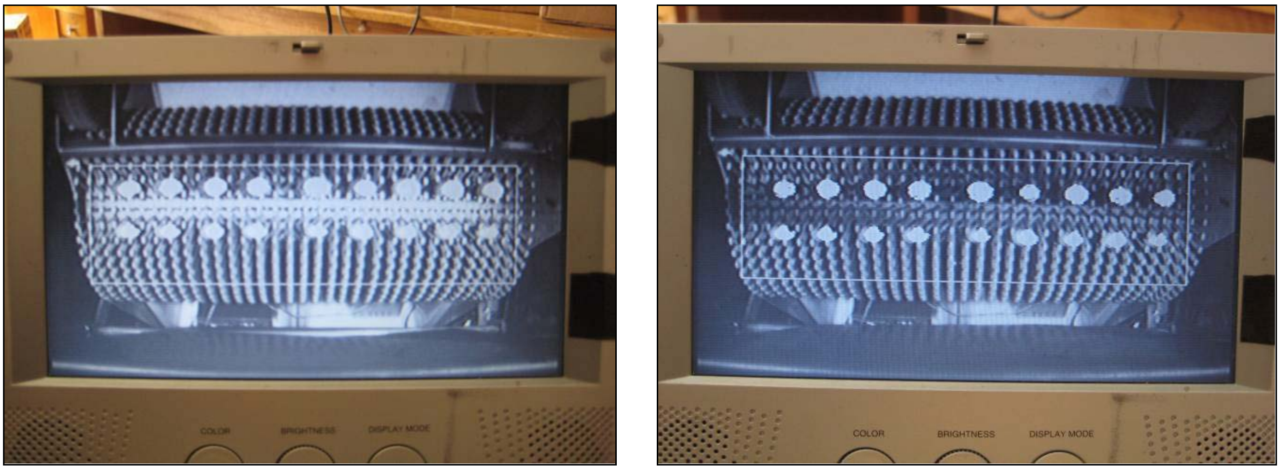


Figure 9. PDA interface to embedded nut counting system.

2.2.3. Diffusion of halogen lights

Visual inspection of the camera output on a TV screen revealed that the lamps were causing a reflection in the middle of the view area. The reflection caused inaccuracies in the detected nut counts. Therefore, fluorescent light tube diffusers were mounted in front of the lamps which spread the light more uniformly over the pinwheel (Figure 10). Nut counting accuracy was greatly improved by this modification.



(a) **(b)**

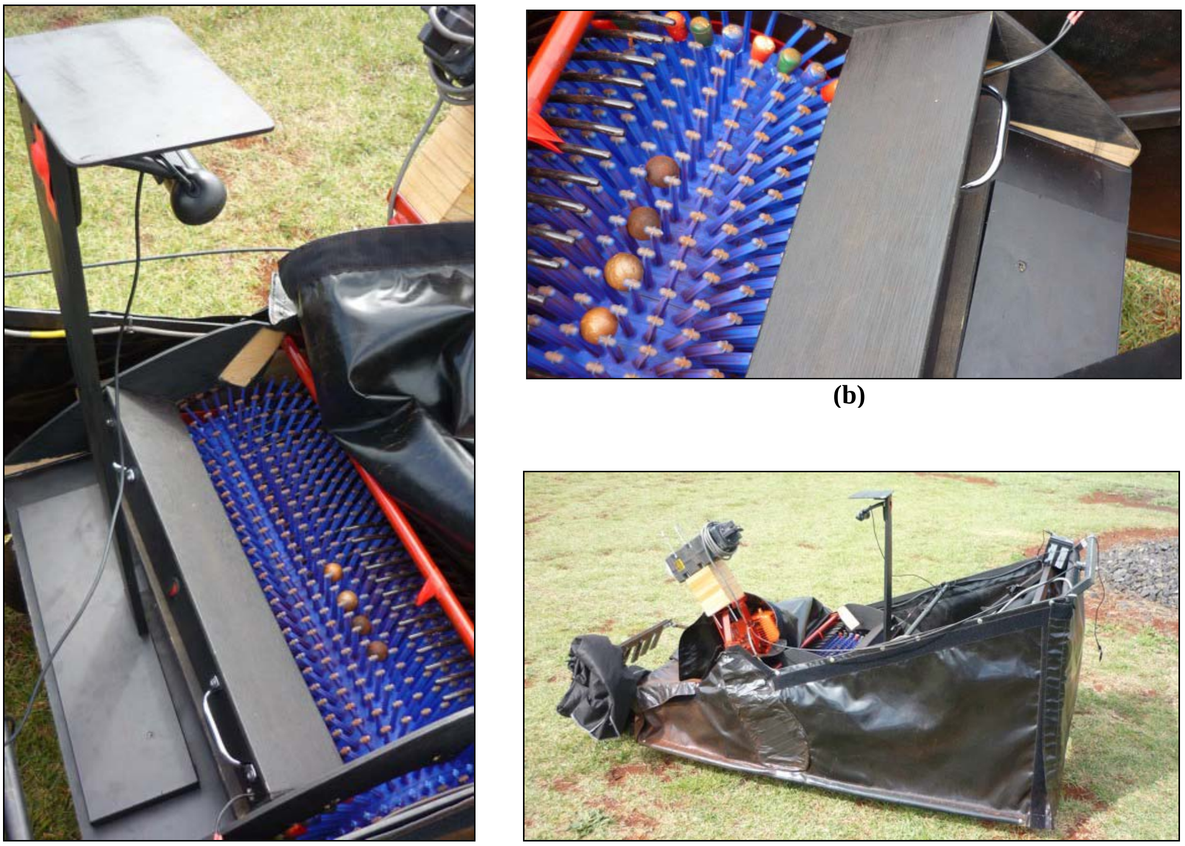
Figure 10. Video output screen demonstrating effect of diffusing the lamps: (a) before diffusion, with uneven illumination of the pinwheel; and (b) after diffusion, with uniform illumination of the pinwheel.

2.2.4. Slit post-processing algorithm

An alternative post-processing algorithm was developed to reduce computational requirements. The algorithm searched for coloured nuts within a region of interest spanning the width of the pinwheel but only a few pixels high (i.e. a 'slit' of the image). This process required a constant pinwheel rotation speed so the slit position relative to the pinwheel's rotation axis could be postulated on a per frame basis of a single video. However, the size of the slit could be calibrated for different pinwheel speeds by performing a setup procedure in which the algorithm was run multiple times on a sample video with the slit height being incrementally changed. The optimal slit size was determined when the error in nut detection on the evaluation video was minimised.

2.3 Phase 3 development

Colour- and shape-based image processing techniques evaluated in Phase 2 were not effective for counting nuts when nuts were touching in the pinwheel (e.g. when nuts were picked up in adjacent pins). Therefore, a new approach was developed with the primary goal of overcoming this 'pooled' nuts problem. The approach was based on structured lighting which is the projection of a light pattern, e.g. a focused line of light, onto an object. When the reflected light pattern is viewed at an angle, information about the shape of the surface in front of the light may be inferred.



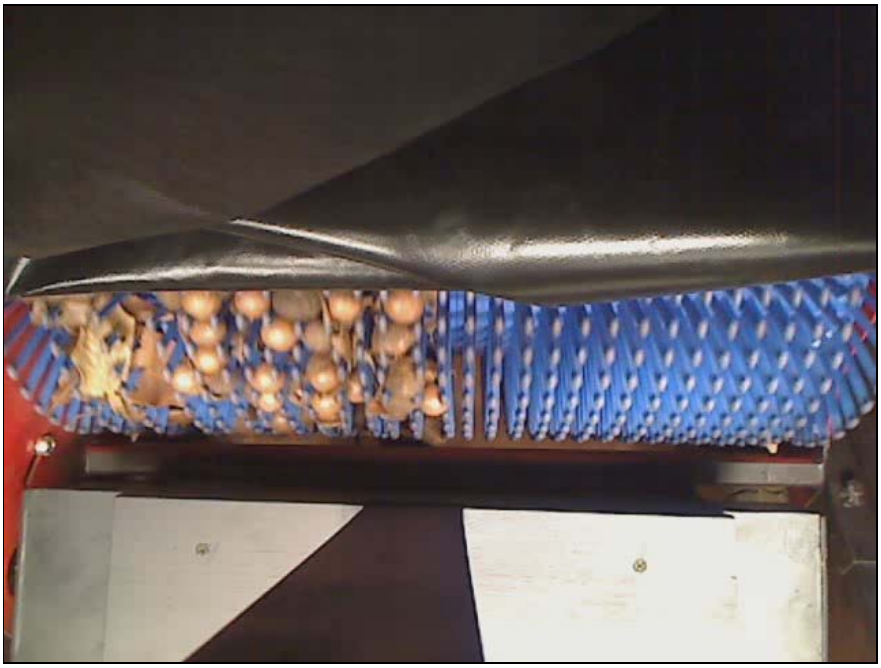
(b)

(a) **(c)**

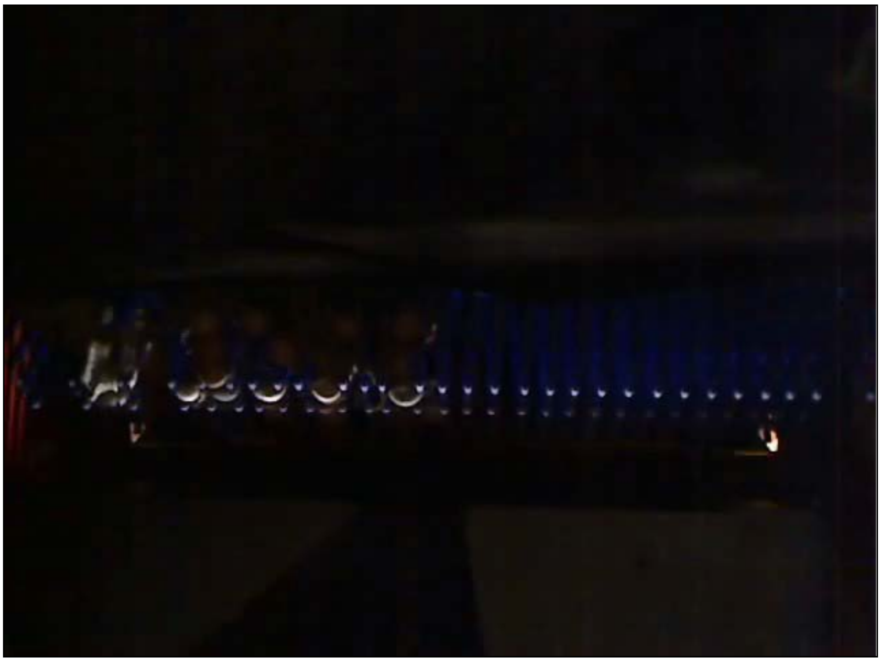
Figure 11. Apparatus on portable harvester for the structured lighting approach: (a) webcam mounted on a post, with structured lighting provided from the black box mounted above the pinwheel; (b) coloured chair tips on outer row of pins on pinwheel providing a reference for nut location on pinwheel; and (c) overall view of the portable harvester with the structured lighting apparatus (minus the canvas covering the top of the harvester).

In the present application, a focused line of light projected onto the pinwheel was used to distinguish the curved front surface of a nut from the blank space between pins and hence, ascertain the presence of a nut for counting. Apparatus used to implement the structured lighting system is shown in Figure 11. The line of light was produced by a LED strip light mounted in a slotted plywood box such that the LED strip's emitted light aligned with the slit in the front of the box. The plywood box was mounted next to the pinwheel.

The camera was a Logitech Quickcam Pro 9000 mounted 500 mm above the light source and connected to a laptop for image capture. The apparatus was enclosed in black canvas so that the image's principal light source was the LED strip light. Images of the pinwheel in this structured lighting environment featured the tips of pins represented as small circles, nuts as crescents and trash as irregular shapes (Figure 12). The reflected light pattern of adjacent nuts formed distinct shapes and hence, individual nuts on adjacent pins could be better identified. .



(a)



(b)

Figure 12. Comparison of camera view of pinwheel with natural and structured lighting: (a) natural lighting; and (b) structured lighting, in which the typical reflected light patterns of pins (small circles), nuts (crescents) and trash (irregular shapes, e.g. to the left of the image) are demonstrated.

The structured lighting image was predominantly a dark scene with areas of white light corresponding to reflections from pins, nuts or trash. The image processing steps were:

1. Threshold the image so that dark pixels become black and illuminated pixels become white.
2. For predefined regions of interest between pins, determine whether an object (i.e. a white shape) is present.
3. Check if the detected object is a crescent or otherwise. If the object is a crescent, increment the nut count.

A method of inferring pinwheel rotation was necessary to ensure the nuts detected by the line of light were in a different position (and hence, were different nuts) to nuts detected in the previous frame. The position of the projected beam of light relative to the pinwheel's rotation was indicated in captured images by coloured chair tips affixed to the outer row of pins on the pinwheel (Figure 11b). If the coloured chair tips in the present frame were the same as the colours detected in the previous frame, then the nuts in the pinwheel were likely to be the same nuts that were detected in the previous frame. This step could be enhanced in future work by using a microswitch, light sensitive switch or Reed switch mounted in a fixed position to trigger frame capture only when a pin on the pinwheel passes the switch as the pinwheel rotates.

Further developments could include the use of a laser line generator to project a focused beam of light onto the pinwheel which would provide a more focused line of light and less bulky apparatus. A higher-frame rate camera than the standard 30 fps offered by webcams may be necessary. For example, a line-scan camera which only scans the area of the pinwheel that is illuminated may be appropriate.

3 Results

3.1 Phase 1 results

Phase 1 progressed through reliability trials and several rounds of commercial scale accuracy testing. A statistical testing methodology was devised by Dr Ashley Plank (USQ) which produced a summary of the system accuracy results. The methodology was based on multiple replicates under known conditions. Details of the trial setup, data and results are included in Appendix D.

Three trials were undertaken at Hidden Valley Plantations, Beerwah. Two of the trials were conducted in April 2007 and the third in September 2007. The first two trials consisted of artificial (i.e. manually-arranged) plots harvested with only a single type of nut or trash whilst the third trial featured natural plots with differing levels of trash.

Data from the second trial (26 April 2007) provided the most meaningful information about system accuracy under varying conditions. These trials were organised to evaluate conditions that adversely affected nut detection accuracy. These conditions were the amount of trash and the amount of green nuts in husk, black nuts in husk and dehusked brown nuts picked up by the harvester. Data was accumulated from the three nut detection cameras, Treecam, the odometer and the GPS receiver. Manual nut counts were collected to enable comparison with the automatically-detected nut counts.

Results of automatically-detected nut counts versus manual nut counts are displayed in Figure 13. From this graph, the detection rates for green, brown and black nuts were 85.6%, 79.6% and 57.7%, respectively. In each case the correlation was greater than 0.93. By visual inspection, the false positive detection rate (i.e. the amount of trash identified as nuts) of the system was 0.95 nuts/m^2. The nut detection system was adequate for identifying green and brown nuts but not black nuts, with respect to the KPIs determined in Section 1.3.1. Further work was required to develop and test a more effective colour recognition system for all nut colours.

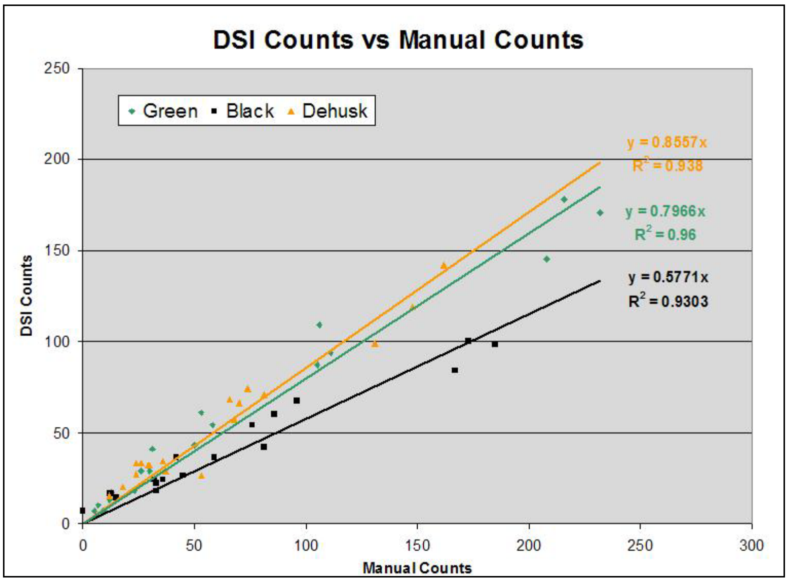


Figure 13. Automatic versus manual nut counts for green, brown and black nuts in the second trial (26 April 2007).

3.2 Phase 2 results

3.2.1. Nut distribution trials at DPI/CSIRO research farm in Bundaberg

A meeting between David Bell, Cameron McConchie, Steven Rees and Peter Werkman was held in June 2008 to determine the layout of the Phase 2 field trials. The purpose of the trials was to validate the accuracy of the new hardware and post-processing algorithms. The effect of the distribution density of nuts on the ground on nut detection rate was evaluated in the first set of trials. Nut pick up rate of the prototype portable harvester was also evaluated.

The trial site was a DPI/CSIRO research farm in Bundaberg where new varieties of macadamias are grown. The farm's conventional practice for collection of macadamia tree yield information (i.e. nut count and total nut weight for each tree) involves manual raking and counting of nuts. The site was prepared for mechanised yield assessment trials by blowing the leaves and nuts on the ground out from the tree line towards the centre of the rows with a leaf blower. The trial areas were relatively free of trash. Tests were conducted with the nuts closely spaced (i.e. high density of nuts, Figure 14a) and far apart (i.e. low density of nuts, Figure 14b).

Nut pick up rates of 100% were achieved with low density nut distributions (Table 1) but decreased to 81% for high density nut distributions (Table 2). In low density nut distributions, at least 93% of the manually counted nuts were detected by the automatic system (Table 1). However, automatic nut counts ranging between 30 and 118% of the corresponding manual nut counts were obtained for the high density nut distributions (Table 2).

By visual inspection of captured images, a contributing factor to the variance in the nut detection rate was 'pooling' of nuts. When nuts were located in adjacent pins in the pinwheel and appeared to be touching, the software was not able to distinguish individual nuts and hence, discounted the pooled nuts as a single, large piece of trash. Further trials to investigate nut pooling effects are reported in Section 3.2.3.

(a) (b)

Figure 14. Distribution density of nuts on the ground for field tests: (a) high density; and (b) low density.

Table 1. Nut pick up and detection rates for low nut distribution density.

Time	Nuts on ground	Nuts picked up	Nuts counted	% Picked up	% Counted
16.13	28	28	26	100%	93%
16.16	18	18	17	100%	94%

Table 2. Nut pick up and detection rates for high nut distribution density.

Time	Nuts on ground	Nuts picked up	Nuts counted	% Picked up	% Counted
9.43	66	63	52	95%	83%
9.47	73	59	31	81%	53%
9.54	30	30	26	100%	87%
9.58	89	86	42	97%	49%
11.05	37	37	11	100%	30%
11.14	17	17	20	100%	118%

3.2.2. Trash amount, groundspeed and nut distribution trials at NCEA test pad

Field trials were conducted to evaluate the effect of the amount of trash, harvester speed and nut distribution on the nut detection accuracy. The trials were conducted at a test pad at the NCEA which was an area of bare soil that simulated the conditions at the DPI/CSIRO research farm.

Large quantities of trash were artificially added to the NCEA test pad by scattering macadamia leaves collected from Hidden Valley Plantations on the test pad (Figure 15a). The nut distribution on the test pad was random and high density and fresh green nuts were used. In the high trash environment, the nut pick up accuracy of the pinwheel was between 90 and 95%. However, the amount of trash picked up was also high (Figure 15b) which caused the image processing algorithms to erroneously identify trash as nuts. Hence, nut detection rates ranged from 100 to 300% of the manually counted nut totals in the high trash environment.

Nut counting accuracy in the high trash environment was improved by reducing the maximum nut size in the image processing software settings. The software-defined maximum nut size at the start of the trials was 72 mm. However, the largest nut size observed in the field for this trial was 36 mm. Therefore, the software was potentially misidentifying leaves up to 72 mm in size as nuts.

(a) **(b)**

Figure 15. Trial area with high quantities of trash: (a) nuts and trash laid out on the ground; and (b) picked up nuts and trash deposited in nut collection buckets.

The next trials at the NCEA test pad were conducted to determine the optimal driving speed (i.e. groundspeed) of the portable harvester. The groundspeed tests occurred at the same location as in Figure 15a but without any trash on the test pad. Three different densities (10, 20 and 40 nuts/m^2) and speeds (2.0, 1.0 and 0.5 km/h) were evaluated resulting in nine density and speed combinations. Three replicates of the nine density and speed tests were conducted, resulting in a total of 27 tests. From these tests, the nut detection accuracy was highest at 2 km/h for all nut distribution densities. Double counts occurred at lower speeds (i.e. individual nuts were counted repeatedly as new nuts in sequential frames) and the image slit algorithm of Section 2.2.4 resulted in some misses at higher speeds (i.e. nuts moved too fast to occur within the image slit at the time instants of image capture).

The pick up efficiency for the three different densities at an average groundspeed of 2.0 km/h is shown in Figure 16. The nine different density and speed combinations all show a pick up efficiency of greater than 96%. The nut detection rate for the same nine situations is shown in Figure 17. From this graph, the best nut detection results occurred at the lowest nut distribution density. However, the high distribution density of nuts (40 nuts/m^2) also resulted in a high average nut detection rate of approximately 90%. By visual inspection of the captured images, the decrease in accuracy at the higher distribution density was a result of nut pooling.

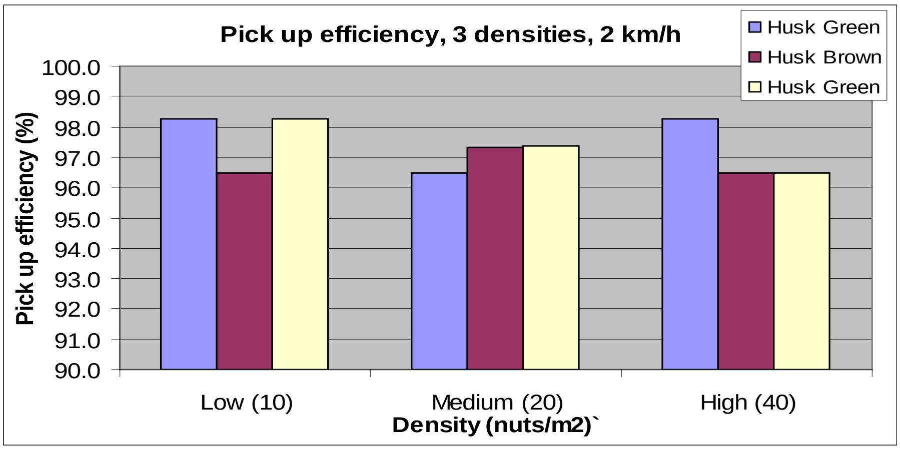


Figure 16. Pick up efficiency for three different densities at 2 km/h.

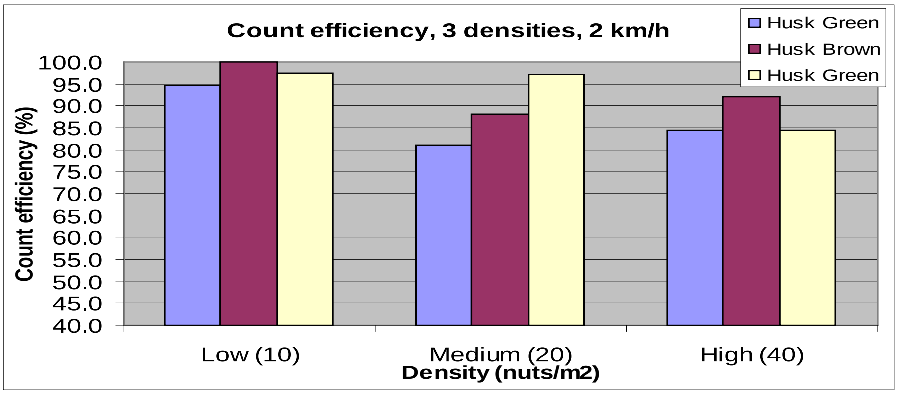


Figure 17. Count efficiency for three different densities at 2 km/h.

3.2.3. Nut pooling trials at NCEA test pad

Final tests of the portable harvester were conducted at the NCEA test pad to determine the density and distribution of nuts on the ground that most affected the occurrence of nut pooling. This was implemented in a series of four tests in which the nut density and distribution on the ground was arranged methodically before passing the portable harvester over the area. The four tests are described below and photographs of the trial site layout for each of the four tests are included in Figure 18.

- Test 1: Low density of nuts: 75 nuts equally distributed over an area of 10.0 m x 0.35 m.
- Test 2: High density of nuts: 85 nuts equally distributed over an area of 5.0 m x 0.35 m.
- Test 3: Repeat Tests 1 and 2 with random, instead of equal, distribution of nuts on the ground.
- Test 4: Repeat Test 3 with rubber fingers mounted on the front of the portable harvester to spread the nuts before being picked up (Figure 18d) in a potential mechanical solution to nut pooling in captured images.

Nut pick up and detection rates were counted and the nut detection rates were analysed with the software program BCMM_RTViewer.

The pick up and nut detection (i.e. count) rates were 98.9% and 95.1%, respectively, for the low density distribution of nuts in Test 1 (Table 3). Acceptable results were also obtained in Test 2 for an equally distributed, high density of nuts (Table 4), where the pick up rate and nut detection rates were 98.3% and 96.4%, respectively. The nut pick up rate was still high for a randomly distributed, high density of nuts in Test 3 (Table 5). However, in Test 3 the nut detection rate dropped to an average of 77.9%. By visual inspection of image processing results of Test 3 video, the low automatic nut count was a result of nut pooling.

Table 6 shows the result for Test 4 in which a randomly distributed, high density of nuts on the ground was physically manipulated by a fringe of rubber fingers mounted at the front of the portable harvester. The rubber fingers spread the nuts on the ground before the nuts were picked up. In comparison with Test 3 where no rubber fingers were used, the nut pick up rate dropped to 77.9% but the nut detection rate increased to 81.4%. However, the rubber fingers moved the nuts 10 to 40 cm from their original positions which may potentially introduce errors when establishing parent trees.

(a)

(b)

(c)

(d)

Figure 18. Nut density and distribution for Tests 1 to 4, represented in images (a) to (d), respectively: (a) low density, equally distributed; (b) high density, equally distributed; (c) high density, randomly distributed; and (d) high density, randomly distributed and rubber finger use.

Table 3. Results for Test 1: Low density, equally distributed nuts without use of the rubber fingers.

Time	Nuts	Nut density (nuts/m2)	Picked up	Pick up rate (%)	Counted 1 (Slit 5/70)	Counted 2 (Slit 10/50)	Count rate Calibration	Count rate Final
11.07	75	21	73	97%	69	71	95%	97%
13.29	75	21	74	99%	72	70	97%	95%
13.49	75	21	74	99%	73	68	99%	92%
13.56	75	21	75	100%	75	72	100%	96%
14.35	75	21	75	100%	74	72	99%	96%
Average			**74.2**	**98.9%**	**72.6**	**70.6**	**97.8%**	**95.1%**

Table 4. Results for Test 2: High density, equally distributed nuts without the use of the rubber fingers.

Time	Nuts	Nut density (nuts/m2)	Picked up	Pick up rate (%)	Counted 1 (Slit 5/70)	Counted 2 (Slit 10/50)	Count rate Calibration	Count rate Final
14.48	85	49	85	100%	84	81	99%	95%
14.55	85	49	84	99%	88	81	105%	96%
14.58	85	49	81	95%	79	73	98%	90%
15.02	85	49	84	99%	86	83	102%	99%
15.06	85	49	83	98%	84	80	101%	96%
17.16	85	49	84	99%	87	84	104%	100%
17.23	85	49	84	99%	85	82	101%	98%
Average			**83.6**	**98.3%**	**84.7**	**80.6**	**101.4%**	**96.4%**

Table 5. Results for Test 3: High density, randomly distributed nuts without use of the rubber fingers.

Time	Nuts	Nut density (nuts/m2)	Picked up	Pick up rate (%)	Counted 1 (Slit 5/70)	Counted 2 (Slit 10/50)	Count rate Calibration	Count rate Final
15.52	85	49	85	100%	78	71	92%	84%
15.55	85	49	84	99%	71	72	85%	86%
16.05	85	49	85	100%	59	57	69%	67%
16.10	85	49	83	98%	69	65	83%	78%
16.14	85	49	83	98%	63	62	76%	75%
Average			**84.0**	**98.8%**	**68.0**	**65.4**	**80.9%**	**77.9%**

Table 6. Results for Test 4: High density, randomly distributed nuts with use of the rubber fingers.

Time	Nuts	Nut density (nuts/m2)	Picked up	Pick up rate (%)	Counted 1 (Slit 5/70)	Counted 2 (Slit 10/50)	Count rate Calibration	Count rate Final
16.39	85	49	84	99%	67	66	80%	79%
16.45	85	49	85	100%	62	60	73%	71%
16.47	85	49	85	100%	66	67	78%	79%
16.56	85	49	81	95%	74	73	91%	90%
17.07	85	49	82	96%	77	73	94%	89%
Average			**83.4**	**98.1%**	**69.2**	**67.8**	**83.1%**	**81.4%**

3.3 Phase 3 results

Results for preliminary trials conducted with the structured lighting system are included in Table 7. The trials considered medium densities of nuts and included trash. The preliminary results demonstrated that the nut detection system performed within the nut detection KPIs when the harvester was operated at the recommended harvester groundspeed. The recommended harvester groundspeed corresponded to the speed at which the camera's frame rate (fixed at 30 fps) matched the time required for 1/48 of a pinwheel revolution, where there were 48 pins spaced equally on the pinwheel's circumference. The recommended groundspeed was calculated to be 2 km/h (the pinwheel diameter was 390 mm). As identified in the groundspeed evaluation of Section 3.2.2, lower speed caused over-counting of nuts whilst higher speed caused under-counting of nuts.

Table 7. Nut detection rates for structured lighting trials at different harvester groundspeeds.

Harvester groundspeed	Average count rate
Twice recommended harvester groundspeed (4 km/h)	56 %
Recommended harvester groundspeed (2 km/h)	93 %
Half recommended harvester groundspeed (0.5 km/h)	185 %

Image-based methods of inferring pinwheel speed (such as tracking coloured chair tips, Figure 11b) were not found to be a reliable method for identifying whether individual nuts had appeared in more than one frame. This was because some uncertainty was introduced when the boundary between chair tips was present in an image causing the colour of the chair tip to be inaccurately identified. In further work, frame capture could be triggered by pinwheel rotation as individual pins on the circumference of the pinwheel pass an external sensor, e.g. a Reed switch. It is anticipated this would lead to satisfactory nut detection performance at a range of harvester groundspeeds.

4 Discussion

This section lists the milestones of each phase and the corresponding research outcomes.

4.1 Research outcomes of Phase 1 milestones

- *Conduct commercial scale reliability testing.*

An intensive field program was undertaken to evaluate the automatic yield monitoring (AYM) technology. The field trials indicated that the current vision system was not capable of detecting all coloured nuts and hence, did not meet KPIs. Therefore, enhanced colour detection was recommended for Phase 2 of the research.

- *Finalise precision agriculture technologies.*

Sensors for generating yield maps (GPS, radar odometer and Treecam) have been successfully integrated with nut detection technology to enable yield mapping to an unprecedented spatial precision in the macadamia industry. The yield maps were interfaced with Google Earth for potential delivery of yield data to growers.

4.2 Research outcomes of Phase 2 milestones

- *Develop initial colour classification technology for nut detection.*

An FPGA-based embedded system was developed to enable more detailed colour processing while maintaining the real-time performance of the system. A post-processing step that analysed size of objects detected on the pinwheel was implemented on a microprocessor to discriminate nuts from other objects (e.g. trash) in the pinwheel. The nut detection technology was evaluated in field trials.

- *Review and modify technology for robustness and reliability.*

Considerable effort has been outlaid into refining the technology to enable its routine use. However, to date these efforts have not been successful in generating a system robust to the extensive range of conditions expected in the field. Therefore, enhancing system robustness has been identified as an area requiring further work.

- *Create a user interface.*

A PDA interface was developed which enabled users to conveniently and intuitively interact with the nut detection software. Functions available via this interface were image processing software settings and data download.

- *Field trialing and refinement of colour classification for nut detection.*

Field trials to evaluate the AYM's performance under varying nut distribution densities, harvester groundspeeds and trash amounts were conducted. The nut detection system did not perform to the required accuracy under all situations. This was found to be a result of the vision software being unable to differentiate individual nuts in a pooled nuts situation.

- *Manufacture or borrow a prototype harvester to undertake trials.*

A Bushrat unit was successfully modified into a prototype portable macadamia harvester which enabled field trials to be undertaken at the NCEA. The portable harvester achieved nut pick up rates greater than 75% which met the KPIs.

- *Complete final accuracy testing with CSIRO.*

Final testing with CSIRO and at the NCEA test pad established that nut pooling was an occurrence that prevented accurate nut detection and could not be overcome by the current vision system. Hence, further work is required to develop a system with satisfactory performance in a nut pooling situation.

4.3 Research outcomes of Phase 3 milestones

- *Develop a proof of concept PC-based vision system to assess nut numbers in a pooled situation.*

A proof of concept vision system using structured lighting was developed for counting nuts in a pooled situation. Preliminary tests were very positive. However, more development and refinement of the system is necessary before routine use or commercialisation is possible. There are several promising avenues for continued development of this nut detection technique.

5 Technology transfer

A field day has been identified as a major opportunity for technology transfer in this project. A field day at Hidden Valley Plantations, Beerwah, will be organised to demonstrate the final prototype system to interested researchers, growers, harvester contractors and manufacturers. It is anticipated that this will be a complete real-time live run of the system using manually scattered nuts stored from this harvest season. The yield map will be overlaid onto a geo-referenced aerial map of Hidden Valley Plantations to provide a live trial.

Contractor interest may potentially be encouraged at this field day to discover contractors willing to undertake the progeny harvesting. The requirements for a contractor to setup the system are as follows:

- purchase or build a harvester unit with front-mounted auger;
- purchase and fit pinwheels;
- mount vision system components (camera, lights and shading) to specification; and
- mount radar odometer and GPS systems to specification.

6 Recommendations

The following three actions are recommendations arising from this project.

- Investigate new methods of nut detection, such as the structured lighting approach described in Phase 3. Incorporate extra sensor technologies such as Reed switches to synchronise frame capture of devised vision system with pinwheel rotation.

- Evaluate the devised system under an extensive range of field conditions and develop the technology into a robust and accurate nut detection method.

- Pursue commercialisation of the technology for varietal trials.

7 Acknowledgements

The project team acknowledges the time, effort, materials and assistance contributed by David Bell and Hidden Valley Plantations.

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Appendix A: Nut detection camera specifications

Image sensor

- VGA/QVGA CMOS image sensor
- Minimum illumination 2.5lux
- Up to 60 frames per second analysis
- Lens: size optional, from:
    - **standard** 3.6mm (90º field of view);
    - **wide angle** 2.1mm (160º field of view); or
    - **telephoto** 16mm (21º field of view)

Processor

- 200 MHz processing power
- 2 Serial IO ports
- 1 Zigbee™ wireless channel
- Optional (colour or black/white) LCD display
- Secure Digital card (SD) mass storage device (currently up to 4 GB)
- Battery backed real-time clock

Image analysis

- Standard motion detection and recording
    - allows sensitivity and region masking specification
- Event driven image recording
- Image analysis techniques customised for your application

Physical

- Weatherproof
- Infrared sensitive (optional IR light add-on)
- Light-weight, small size for portable use
- Optional internal battery for autonomous deployment

Power requirements:

- 6-18 VDC Input
    - <100 mA monitoring/processing
    - <150 mA recording

Appendix B: Embedded software implementation

Software architecture

There are several operating systems that could be used on this hardware platform, including Windows CE ™, and versions of Linux. The downfall of any operating system, for these purposes, is the overhead processing. This project has not used an operating system, instead basing all tasks around the processing of each frame. As the CPU is not using DMA access to read the image frame into the memory buffer, no other processing can be scheduled simultaneously. There is a small amount of idle time available at the end of each line, and a substantial number of cycles at the end of each frame. During this time, the processor can schedule any off-vision processing required.

Bootloader

The bootloader runs first, initialising the hardware and preparing the system for the main application. Generally the bootloader is stored in some non-volatile memory area accessible to the system on start up. In this system, the first 12KB of the Dataflash is automatically downloaded into internal SRAM on reset.

The pseudo code is:

```
        Initialise stack pointers
        Setup GPIO pins as peripherals
        Swap clock speed to 180 MHz
Initialise External SRAM
        Initialise UARTs, TWI, SPI, Clock,
        Check for bootloader updates on SD card, serial port or other interface devices
        Copy Main program from Dataflash to external SRAM
        Set the Program Counter to Main Program initialise routine.
```

Generic embedded image processing.

The following pseudo code summarises the steps involved in bringing the system to functional state and reading, storing and processing images.

```
        Initialise Serial interfaces
        Initialise SD card interface
        Initialise Interrupt handlers
Main loop:
        Wait for Vsync (beginning of frame)
Row loop:
        Wait for Href (beginning of line)
        For 320 pixels:
                Wait for PClk (pixel valid signal)
                Copy 16 bit pixel values to internal SRAM area
        Copy Line data to external SRAM
        Goto Row loop until 240 lines read
```

Transform Frame. The same code may be used as any DirectShow filter.
Perform output stage – report or accumulate results, physical interface, write frame to mass storage device if required.
Check user interface – check for incoming commands from local or remote users.

Appendix C: Operating instructions for PDA interface

Start up the program	The program for counting the nuts can be started up by choosing the program “Maccas PDA” on the PDA
Blue tooth connection	Once the program is started up, press “connect” for establish the blue tooth connection.
Counting nuts	After pressing the “start” button, the nut counting is started. This is shown in the “general” sheet by the running status. In this sheet is also shown how much free space is left on the disk. In the “advanced” sheet, there is shown how much nut, radar and other messages are received. The gained data will be stored on the SD card of the Macadamia Harvester. Per run 2 files will be created. In a “.nut” file the information about the counted nuts is stored. In a “.rad” file the information about the measured speed from the radar odometer is stored.
View area settings	The view area can be changed by choosing “settings”, “vision” and “view area”. The upper border of the view area can be changed by dragging the left slider; the lower border can be changed by the right slider. In the same way the left and right border can be changed by the upper and lower slider. In the middle of the screen the horizontal distance and the vertical distance are displayed. The unit of these values are pixels displayed on the screen.
RGB settings	The RGB settings can be changed by choosing “settings”, “vision” and “algorithms”. Several vision algorithms are already programmed and can be chosen. By selecting one of the colour multipliers, already programmed RGB settings can be chosen. It is possible to change the settings of a chosen colour multiplier. It is also possible to change the dark level threshold. With this setting the minimum level of the pixel brightness can be changed.

Appendix D: Phase 1 field trial plans and results

D.1 Example experimental procedure

The trials set out in this appendix involve harvesting macadamia nuts of three types under various prescribed nut and trash density levels. The variables measured are the number of nuts distributed on the ground (NDIS), the number binned by the harvester (NBIN), the number detected by machine vision (NDET), the volume of trash binned by the harvester (TBIN) and the count of trash detected by machine vision (TDET).

The experiment divides into two parts. Part A comprises four treatments run in replicate blocks in which trash density only is varied at zero nut density. Part B comprises a 3 x 2 x 2 factorial run in replicate blocks. The three factors in Part B are nut density (med,hi), trash density (0,hi) and nut type (green husked, black husked, dehusked). Parts A and B are carried out on separate plots of suitable length to facilitate set-up and run efficiency.

Preparatory experimental procedure

1. Mark out two nearby experimental plots, each made up of a sequence of up to four continguous subplots. Each subplot comprises a 6m x 1.5m harvest zone and a 15m x 1.5m clearance zone. Each harvest zone is divided into 3 equal areas of 1.5m by 2m to aid uniform distribution of trash and nuts. The clearance zones facilitate stopping and starting of the harvester and clearing of the harvest head between harvest zones. The plots and nearby adjacent area should initially be free of trash and nuts and the ground surface typical in terms of texture, slope and degree of compaction of the harvest area under macadamia trees. Designate at random one plot as Plot A (to run Part A treatments) and the other as Plot B (to run Part B treatments). Record the number of subplots employed in each of plots A and B.
2. Define a typical high level of nut density (HIN) and a typical high level of trash density (HIT).
3. Make available a bin of green husked nuts only, a bin of black husked nuts only, a bin of de-husked nuts only and a bin of typical trash. Within these constraints, the nuts in each bin should vary in size, shape, shades of colour and texture as is typical.
4. Run the harvester over the two plots several times while free of nuts and trash, to ‘condition’ the plot.

Part A run procedure

5. For Part A treatments, select and record a sequence at random of the four treatments labeled TrA1 to TrA4 in Table A.1 (i.e. randomly withdraw tokens numbered 1 to 4 from a container).

Table D.1: Part A treatments.

Trash density			
25%HIT	50%HIT	75%HIT	100%HIT
TrA1	TrA2	TrA3	TrA4

   Apply these treatments in order to the harvest zones of successive subplots in Plot A. For example, if there are 4 subplots numbered from 1 to 4 and the random sequence of treatments is A3, A4, A2, A1 then apply a 75%HIT trash load to subplot 1, a 100%HIT trash load to subplot 3, a 50%HIT trash load to subplot 5 and a 100%HIT trash load to subplot 7. If there are fewer than 4 subplots, the available subplots are used and the missed treatments applied later.

6. Make two passes with the harvester over Plot A, recording NDET, TBIN, TDET for each pass for each subplot.

7. Clear the plot of trash. Repeat Steps 5 to 7 except that any treatments which have missed (in the case of there being fewer subplots than treatments) are applied in order to the subplots before beginning another replicate. Use the subplots successively so all the subplots in Plot A are used equally as far as possible over the course of the experiment. Each completed set of the four treatments represents a replicate block for Part A

Part B run procedure

8. For Part B treatments, select and record a sequence at random of the six treatments labeled TrB1 through TrB6 in Table A.2. Apply these treatments in order to the harvest zones of successive subplots in Plot B in the same manner as in Part A, using all available subplots and applying missed treatments later (like in Part A). In this step, no trash is placed on the subplots. NDIS is recorded for each subplot.

Table D.2: The twelve factorial treatment combinations for Part B.

	0%HIT		100%HIT	
	50%HIN	100%HIN	50%HIN	100%HIN
Husk (green)	TrB1	TrB2	TrB7	TrB8
Husk (black)	TrB3	TrB4	TrB9	TrB10
Dehusked	TrB5	TrB6	TrB11	TrB12

9. Make two passes with the harvester over Plot B, recording NDET and NBIN for each pass for each subplot.
10. Clear the plot of nuts.
11. Apply the missed treatments in order to the subplots and repeat Steps 9 and 10.
12. Select and record a sequence at random of the six treatments labeled TrB7 through TrB12 in Table 2. Apply these treatments in order to the harvest zones of successive subplots in Plot B starting with the next to be used subplot. Use all available subplots. Missed treatments are applied later. In this step, a high trash load is placed on the subplots. The nuts and trash should be spread and layered to simulate an actual tree-sourced distribution as far as possible either by premixing the nuts and trash and/or by staggering the distribution. NDIS is recorded for each subplot.
13. Make two passes with the harvester over Plot B, recording NDET, NBIN, TBIN and TDET for each pass for each subplot.
14. Clear the plot of trash and nuts and repeat steps 8 to 13 using the subplots equally as far as possible over the course of the experiment.
15. Generate as many replicate blocks for Parts A and B as time allows. The number of replicate blocks does not have to be the same in each part of the experiment. It is expected however that if both parts are run simultaneously efficiency gains are possible in that treatments can be implemented on one plot while harvesting occurs on the other.

D.2 Phase 1 Trial 1 (4 April 2007)

D.2.1. Trial 1 procedure

- The experimental plot was a 1.5 m x 6 m area of level land of typical harvest conditions which corresponds to a plot area of 9 m^2 (the width of the harvest mechanism is 1.8 m). The plot was marked out using surveyors paint and divided into 3 equal areas of 1.5m x 2 m to aid equal distribution of trash and nuts.
- The original design did not call for a Part A run with 0% trash. It was decided on site to perform and log this information just in case it was of use statistically. This data is included as TrA0 for both Series 1 and 2.
- The typical high level of nut density (HIN) was decided to be 50 nuts/m^2, giving a total of 450 nuts for 1 x HIN trials, 225 nuts for 0.5 x HIN trials and 0 nuts for 0 x HIN trials. A typical area of high trash was also marked out (as per above) and the trash collected into harvest bins of dimensions 680 mm x 380 mm x 350 mm. The trash was collected into 3 level bins and this was decided as the high level of trash density (HIT). Each bin is approximately 0.09 m^3 so that the total HIT was approximately 0.27 m^3.
- Dehusked nuts were collected. Both series were undertaken with dehusked nuts only.
- The trial plot and surrounding area was cleaned prior to running the harvester over the plot 3 times to condition the plot.
- For each trial, the 3 harvest bins were either empty, half full or full with trash as required. The appropriate level of nuts were divided by 3 and evenly dispersed into the 3 bins. The nuts were then mixed into the trash by hand in each bin. The contents of each bin was then laid into one of the 3 sub-areas and dispersed by hand to cover the full plot and simulate (as far as possible) a tree-sourced distribution.
- It was decided that a blow past not be performed as this would blow the majority of trash and nuts from the trial plot. It was also decided that 2 passes per treatment be performed as this is a normal harvest run. The trial was setup as required and the first pass performed. Nuts and data were collected from the harvester. A second pass was then performed with the remaining nuts and trash.
- Separate counts for binned nuts (NBIN) and data files were collected for each pass of every trial.

D.2.2. Trial 1 results

Table D.3. Part 1. Nut detection results on 4 April 2007.

Plot	Run	Sub-Plot	Green	Black	Brown	Husks	Trash (L)	total	Cam8	Cam12	Cam14	Total	Trash	Diam	NutArea	Colour	Est Trash
1	1	1	11	93	102	22	3.5	**228**	34	0	10	**44**	954	8	237	216	22
1	1	2	50	99	50	5	8	**204**	51	11	23	**85**	1522	9	292	202	79
1	1	3	40	84	77	11	6.5	**212**	27	9	21	**57**	1378	8	269	215	54
1	1	4	0	59	65	27	6	**151**	40	8	42	**90**	1575	8	281	209	77
1	2	1	1	32	59	8	2.5	**100**	30	1	20	**51**	1319	9	224	214	36
1	2	2	13	39	60	0	6	**112**	33	4	13	**50**	1539	9	299	200	47
1	2	3	6	57	62	5	6	**130**	63	7	26	**96**	1293	9	304	210	78
1	2	4	0	36	59	14	6.5	**109**	33	7	26	**66**	1561	9	277	207	60
1	3	1	1	15	53	9	2	**78**	32	0	21	**53**	1097	9	171	198	35
1	3	2	8	30	42	3	5	**83**	38	6	23	**67**	1488	8	225	191	63
1	3	3	8	33	60	5	4	**106**	29	4	25	**58**	1658	8	256	199	58
1	3	4	0	19	55	11	5	**85**	38	10	18	**66**	1347	9	233	207	50
1	4	1	1	10	28	5	2	**44**	19	3	13	**35**	1229	9	160	208	27
1	4	2	5	14	22	3	4.5	**44**	20	4	21	**45**	1302	9	236	198	41
1	4	3	2	27	37	4	5	**70**	25	2	30	**57**	1339	9	242	194	57
1	4	4	0	12	42	9	4.5	**63**	18	0	13	**31**	1468	9	267	216	27

Plot	Run	Sub-Plot	Green	Black	Brown	Husks	Trash (L)	Su m	Cam8	Cam12	Cam14	Total	Trash	Diam	NutArea	Colour	Est Trash
2	1	1	35	28	119	30	4	**212**	68	2	42	**112**	1433	9	318	217	88
2	1	2	56	43	135	43	2.5	**277**	69	5	8	**82**	1120	9	366	207	55
2	2	1	7	7	44	17	4	**75**	31	9	20	**60**	1355	9	204	210	43
2	2	2	6	6	46	10	2	**68**	27	3	8	**38**	1122	8	190	205	26
2	3	1	1	7	33	11	3	**52**	17	7	7	**31**	1215	8	213	205	23
2	3	2	1	2	14	5	2.5	**22**	10	3	7	**20**	1315	8	193	202	11

Table D.3. Part 2. Nut detection results on 4 April 2007.

Plot	Run	Sub-Plot	Green	Black	Brown	Husks	Trash (L)	sum	Cam8	Cam12	Cam14	Total	Trash	Diam	NutArea	Colour	Est Trash
3	1	1	2	17	41	9	2	**60**	38	3	8	**49**	893	8	216	201	32
3	1	2	7	16	34		2	**57**	34	0	6	**40**	837	9	211	198	27
3	1	3		21	21	8	6	**42**	32	3	20	**55**	1390	8	239	198	55
3	1	4	5	20	20	6	11	**45**	21	8	46	**75**	1838	8	269	201	74
3	2	1	2	5	40		2.5	**47**	37	2	14	**53**	926	8	161	201	29
3	2	2		3	23	1	1.5	**26**	28	2	1	**31**	392	8	134	199	7
3	2	3		8	12	6	6	**20**	19	7	13	**39**	1640	8	218	200	38
3	2	4	2	1	13	3	11	**16**	17	1	54	**72**	1836	8	249	207	72
3	3	1	4	5	25		1.5	**34**	33	1	8	**42**	700	8	130	202	15
3	3	2	2	4	14		1	**20**	16	0	12	**28**	1107	9	194	192	19
3	3	3	3	1	8	2	5	**12**	17	4	19	**40**	1639	9	246	196	38
3	3	4		7	10		6	**17**	17	5	13	**35**	1388	8	213	200	33

Table D.4. Automatic versus manual nut detection results for trash only trial (4 April 2007).

Series 1			Run	Trash volume	Total nuts	Auto count	False pos	FP/m^2	Delta trash
TrA0	Trash	100%	**1**	0	3	9	6	0.67	62
	Nuts	0	**2**	0	6	7.5	1.5	0.17	54
TrA1	Trash	25%	**1**	6	24	82.5	58.5	6.50	122
	Nuts	0	**2**	4.5	18	58.5	40.5	4.50	90
TrA2	Trash	50%	**1**	6	34	76.5	42.5	4.72	105
	Nuts	0	**2**	5	39	66	27	3.00	108
TrA3_1	Trash	75%	1	10	20	133.5	113.5	12.61	153
	Nuts	0	2	6	6	87	81	9.00	99
TrA3_2	Trash	75%	1	7	13	112.5	99.5	11.06	108
	Nuts	0	2	6	7	99	92	10.22	113
TrA4	Trash	100%	1	10	44	99	55	6.11	128
	Nuts	0	2	8	30	127.5	97.5	10.83	122
Series 2	Trash	0%	**1**	0	0	0	0	0.00	0
TrA0	Nuts	0	**2**	0	0	1.5	1.5	0.17	102
TrA1	Trash	25%	**1**	4.5	11	90	79	8.78	117
	Nuts	0	**2**	3	4	61.5	57.5	6.39	102
TrA2	Trash	50%	**1**	6	2	58.5	56.5	6.28	108
	Nuts	0	**2**	5	4	73.5	69.5	7.72	118
TrA3	Trash	75%	1	7	18.5	99	80.5	8.94	159
	Nuts	0	2	4	12	75	63	7.00	130
TrA4	Trash	100%	1	6	4	87	83	9.22	130
	Nuts	0	2	5	3	54	51	5.67	114

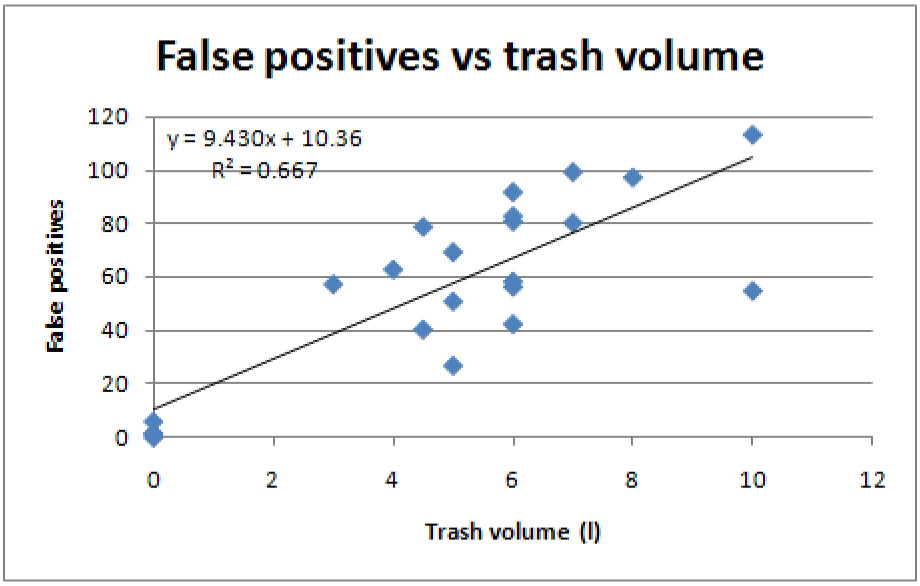
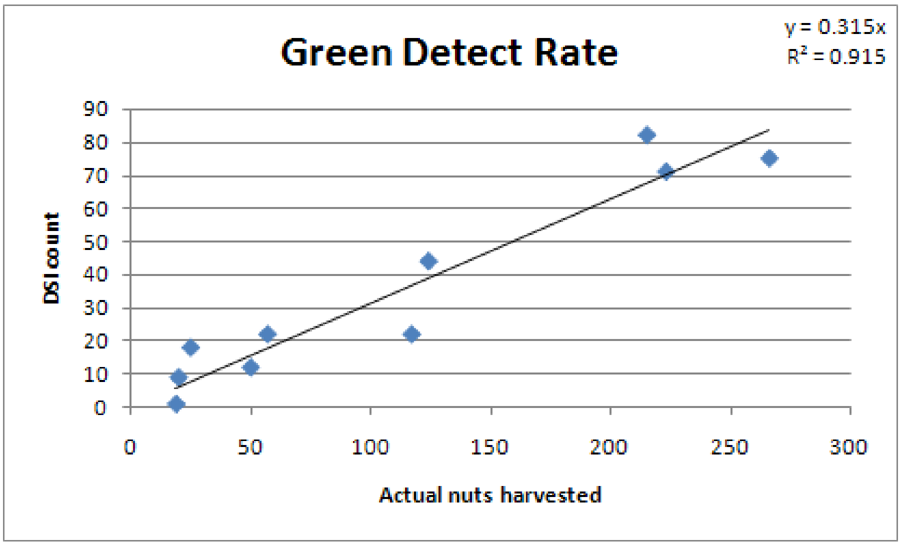


Figure D.1. Nut detection (false positive) results for trash only trial (4 April 2007).

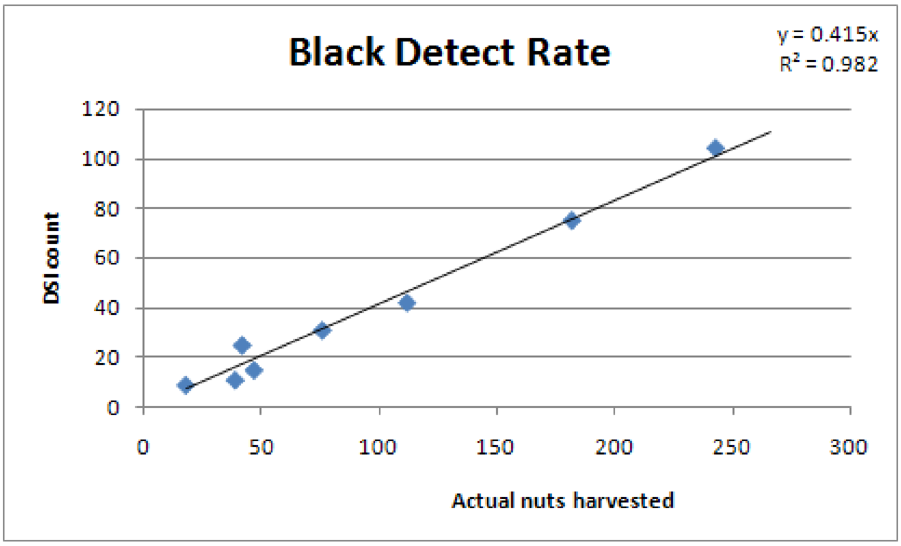
Table D.5. Automatic versus manual nut detection results for nut only trial (4 April 2007).

NUTS									Harvester Auto count			Detect Rate		
Series: 1			Run	Green	Black	Dehusk	Total	Efficiency	Green	Black	Dehusk	Green	Black	Dehusk
TrB1	Trash	0	1	117			117	52.00%	22			0.19		
Green	Nuts	225	2	18	1		19	17.59%	1			0.05		
TrB2_1	Trash	0	1	215			215	47.78%	82			0.38		
Green	Nuts	450	2	49		1	50	21.28%	12			0.24		
TrB2_3	Trash	0	1	221		2	223	49.56%	71			0.32		
Green	Nuts	450	2	57			57	25.11%	22			0.39		
TrB3	Trash	0	1		76		76	33.78%		31			0.41	
Black	Nuts	225	2		39		39	26.17%		11			0.28	
TrB4	Trash	0	1		175	7	182	40.44%		75			0.41	
Black	Nuts	450	2		45	2	47	17.54%		15			0.32	
TrB5	Trash	0	1			93	93	41.33%			63			0.68
Dehusk	Nuts	225	2			31	31	23.48%			16			0.52
TrB6	Trash	0	1			161	161	35.78%			113			0.70
Dehusk	Nuts	450	2			57	57	19.72%			32			0.56
Series: 2			Run	Green	Black	Dehusk	Total	Efficiency	Green	Black	Dehusk	Green	Black	Dehusk
TrB1	Trash	0	1	124			124	55.11%	44			0.35		
Green	Nuts	225	2	16	3	1	20	19.80%	9			0.45		
TrB2	Trash	0	1	266			266	59.11%	75			0.28		
Green	Nuts	450	2	25			25	13.59%	18			0.72		
TrB3	Trash	0	1		112		112	49.78%		42			0.38	
Black	Nuts	225	2		18		18	15.93%		9			0.50	
TrB4	Trash	0	1		243		243	54.00%		104			0.43	
Black	Nuts	450	2		35	7	42	20.29%		25			0.60	
TrB5	Trash	0	1			97	97	43.11%			82			0.85
Dehusk	Nuts	225	2			23.5	23.5	18.36%			17			0.72
TrB6	Trash	0	1			199	199	44.22%			162			0.81
Dehusk	Nuts	450	2		2	49.5	51.5	20.52%			30			0.58

After this trial, several software errors were detected and corrected to improve the accuracy. The error with most impact was the maximum size of nut allowed by the nut detection software. This incorrectly disregarded all large nuts, causing lower detect rates for green and black husked nuts.



(a)



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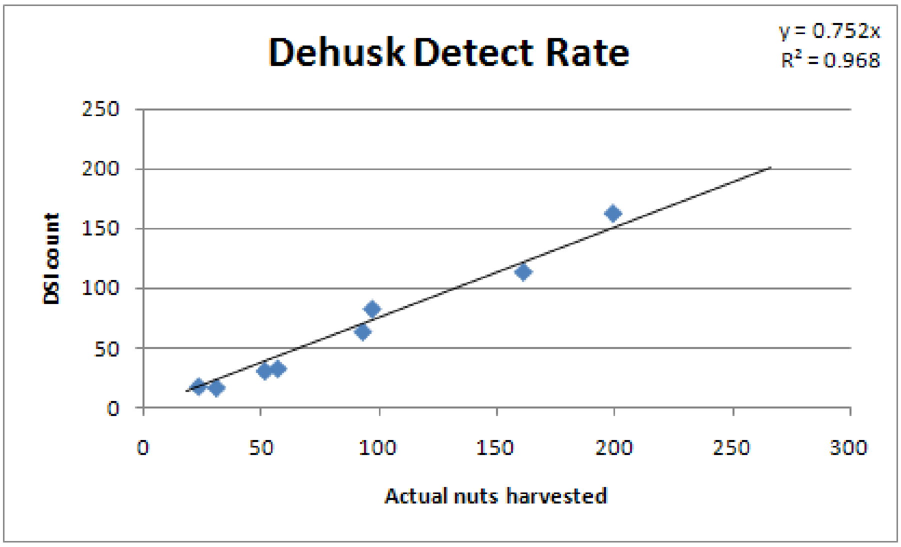


(c)

Figure D.2. Nut detection rates for different coloured nuts on 4 April 2007 trial: (a) 32% for green nuts; (b) 42% for black nuts; and (c) 75% for dehusked (brown) nuts.

D.3 Phase 1 Trial 2 (26 April 2007)

D.3.1. Trial 2 procedure

Simplified experimental procedures were determined for Trial 2 of Phase 1 and are set out below. The simplified structure offered a significant saving in time required for experimental setup while maintaining a layout that enabled sufficient statistical analyses to be conducted.

(A) Trash only trial

1 Set up one plot with TrA4 (100%)
2 Do eight runs, measuring harvested volume vs False Positive count
3 After eight runs, repeat on another plot. If not enough volume change, switch to TrA2 or TrA1 as appropriate for next batch of eight.
4 Do as many batches of eight as possible, with each run considered a replicate

(B) Nut only trials

1. Set up three plots, for each plot randomly select treatment TrB1-TrB6
2. Do three runs, measuring harvested nut count vs DSI count
3. Repeat as many batches of 3 plots x 3 runs as possible, each run is considered a replicate
4. Do six 3 x 3 repeats so all treatments are repeated on all plots.

D.3.2. Trial 2 results

Table D.6. Part 1. Automatic versus manual nut detection results for trash only trial (26 April 2007).

Series: 1			Run	Trash volume	Total nuts	Auto count	False pos	fp/m^2	Delta trash
TrA4		R/P: 1/1	1	7.5	3	105	102	11.33	540
	Trash	100%	2	6	6	83	77	8.56	424
	Nuts	None	3	6	6	90	84	9.33	452
			4	4	6	85	79	8.78	363
			5	4	5	87	82	9.11	387
			6	3	2	71	69	7.67	260
			7	3.5	3	60	57	6.33	233
			8	2	3	62	59	6.56	269
Series: 2			Run						
TrA4		R/P: 1/2	1	11	24	150	126	14.00	866
	Trash	100%	2	6	18	111	93	10.33	612
	Nuts	None	3	6	12	86	74	8.22	713
			4	6	10	84	74	8.22	460
			5	5	16	89	73	8.11	524
			6	4	13	77	64	7.11	448
			7	3	12	71	59	6.56	418
			8	3	9	69	60	6.67	448
Series: 3			Run						
TrA4		R/P: 1/3	1	7.5	34	146	112	12.44	534
	Trash	100%	2	6	39	126	87	9.67	499
	Nuts	None	3	5	23	92	69	7.67	369
			4	3.5	20	101	81	9.00	444
			5	3	19	79	60	6.67	277
			6	3	20	90	70	7.78	406
			7	2	11	87	76	8.44	331
			8	1.5	12	59	47	5.22	322

Table D.6. Part 2. Automatic versus manual nut detection results for trash only trial (26 April 2007).

Series: 1			Run	Trash volume	Total nuts	Auto count	False pos	fp/m²	Delta trash
TrA4		**R/P: 1/1**	1	6	20	90	70	7.78	444
	Trash	100%	2	3	6	74	68	7.56	214
	Nuts	None	3	1.5	15	53	38	4.22	167
			4	1.5	2	50	48	5.33	295
			5	1	1	39	38	4.22	290
			6	0.75	2	40	38	4.22	196
			7	0					
			8	0					
Series: 2			**Run**						
TrA4		**R/P: 1/2**	1	5	13	97	84	9.33	438
	Trash	100%	2	3.5	7	70	63	7.00	309
	Nuts	None	3	2	9	51	42	4.67	253
			4	2	8	43	35	3.89	296
			5	2	2	71	69	7.67	334
			6	1.5	0	53	53	5.89	226
			7	0					
			8	0					
Series: 3			**Run**						
TrA4		**R/P: 1/3**	1	5	44	123	79	8.78	361
	Trash	100%	2	3	30	106	76	8.44	369
	Nuts	None	3	2	13	55	42	4.67	290
			4	2	8	61	53	5.89	298
			5	1.5	4	36	32	3.56	200
			6	1.5	1	45	44	4.89	190
			7	0					
			8	0					

The measurement of trash is highly correlated with the false positives detected and also the volume of trash collected.

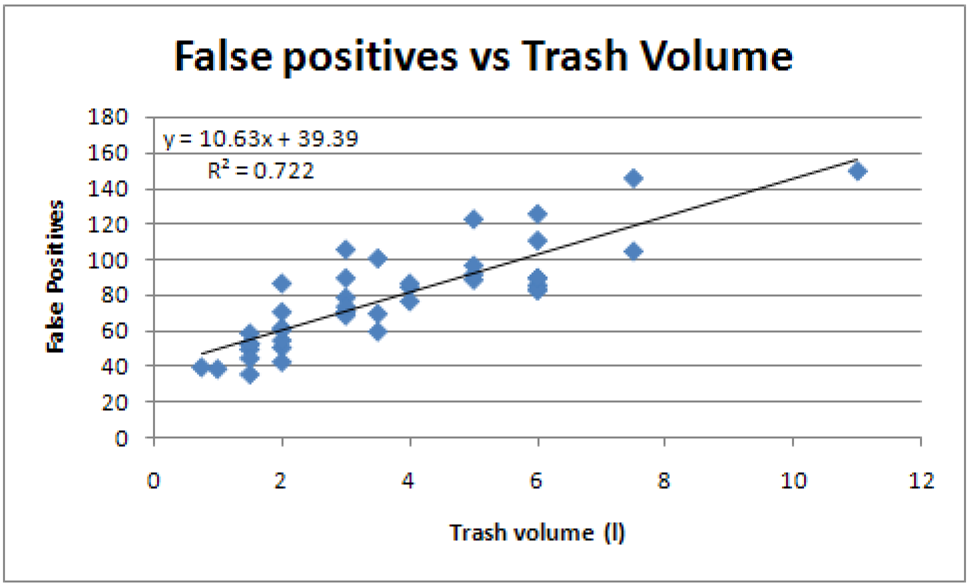


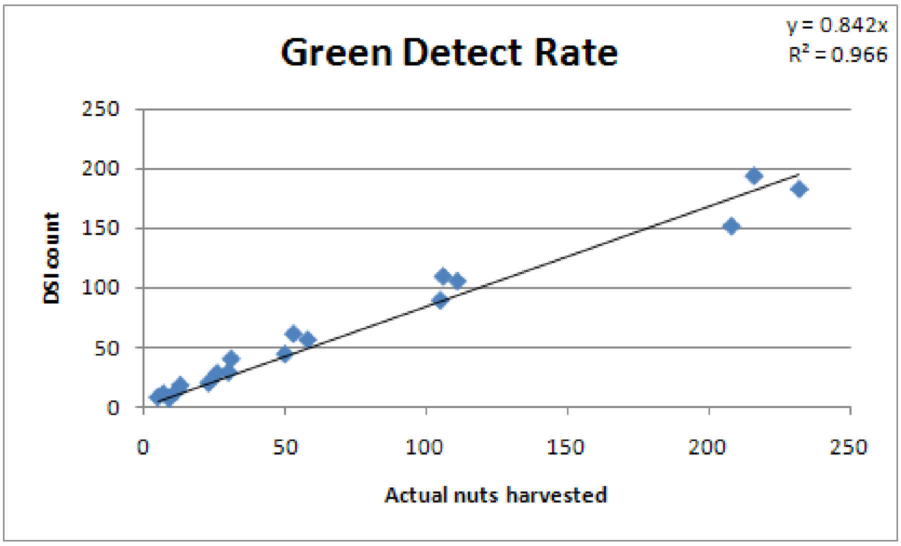
Figure D.3. Nut detection (false positive) results for trash only trial (26 April 2007).

Table D.7. Part 1. Automatic versus manual nut detection results for nut only trial (26 April 2007).

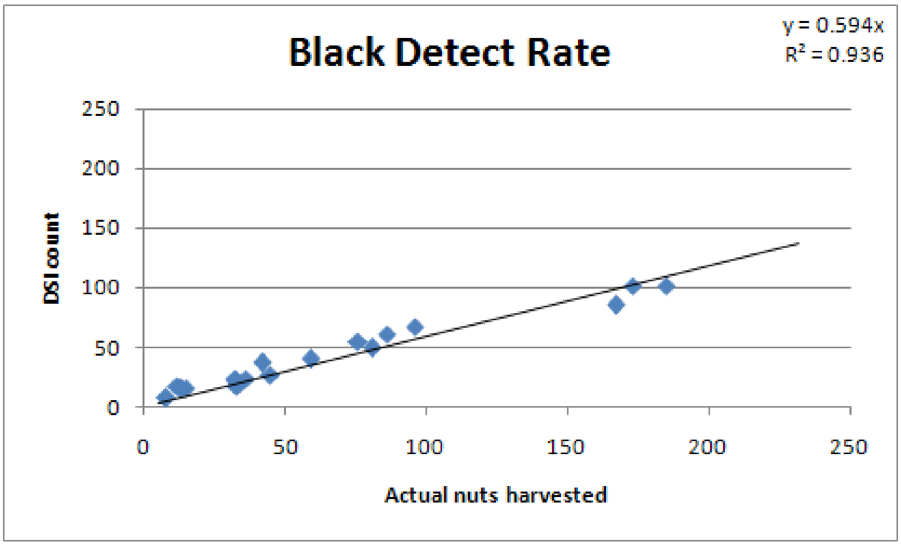
				NUTS					Harvester Auto count			Detect Rate		
Series: 1			Run	Green	Black	Dehusk	Total	Efficiency	Green	Black	Dehusk	Green	Black	Dehusk
TrB1		R/P: 1/1	1	104		2	106.00	70.67%	109			1.03		
	Trash	0%	2	30		1	31.00	70.45%	40			1.29		
Green	Nuts	150	3	3		2	5.00	38.46%	8			1.60		
TrB2		R/P: 2/1	1	216			216.00	72.00%	193			**0.89**		
	Trash	0%	2	53			53.00	63.10%	61			1.15		
Green	Nuts	300	3	12		1	13.00	41.94%	18			1.38		
TrB3		R/P: 3/2	1		96		96.00	64.00%		67			0.70	
	Trash	0%	2		37	5	42.00	77.78%		37			0.88	
Black	Nuts	150	3		12		12.00	100.00%		17			1.42	
TrB4		R/P: 4/2	1		173		173.00	57.67%		102			**0.59**	
	Trash	0%	2		73	3	76.00	59.84%		55			0.72	
Black	Nuts	300	3		14	1	15.00	29.41%		16			1.07	
TrB5		R/P: 5/3	1			66	66.00	44.00%			78			1.18
	Trash	0%	2			30	30.00	35.71%			33			1.10
Dehusk	Nuts	150	3			24	24.00	44.44%			28			1.17
TrB6		R/P: 6/3	1			131	131.00	43.67%			103			**0.79**
	Trash	0%	2			68	68.00	40.24%			58			0.85
Dehusk	Nuts	300	3			29	29.00	28.71%			33			1.14
Series: 2			Run	Green	Black	Dehusk								
TrB1		R/P: 1/3	1	111			111.00	74.00%	105			0.95		
	Trash	0%	2	25		1	26.00	66.67%	28			1.08		
Green	Nuts	150	3	5		2	7.00	53.85%	11			1.57		
TrB2		R/P: 2/3	1	208			208.00	69.33%	151			**0.73**		
	Trash	0%	2	58			58.00	63.04%	56			0.97		
Green	Nuts	300	3	23			23.00	67.65%	20			0.87		
TrB3		R/P: 3/1	1	1	80		81.00	54.00%		49			0.60	
	Trash	0%	2	1	29	3	33.00	47.83%		21			0.64	
Black	Nuts	150	3	1	11	1	13.00	36.11%		15			1.15	

Table D.7. Part 2. Automatic versus manual nut detection results for nut only trial (26 April 2007).

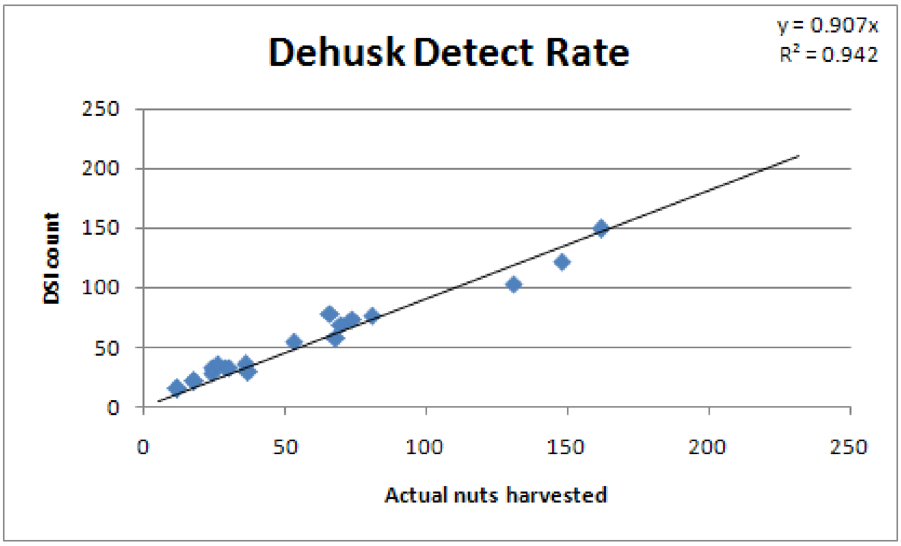
NUTS									Harvester Auto count			Detect Rate		
Series: 2			**Run**	**Green**	**Black**	**Dehusk**								
TrB4		**R/P: 4/1**	**1**		185		185.00	61.67%		102			**0.55**	
	Trash	0%	**2**		45		45.00	39.13%		27			0.60	
Black	Nuts	300	**3**		32		32.00	45.71%		24			0.75	
TrB5		**R/P: 5/2**	**1**			81	81.00	54.00%			77			0.95
	Trash	0%	**2**		1	35	36.00	52.17%			35			0.97
Dehusk	Nuts	150	**3**			12	12.00	36.36%			15			1.25
TrB6		**R/P: 6/2**	**1**			148	148.00	49.33%			122			**0.82**
	Trash	0%	**2**			70	70.00	46.05%			69			0.99
Dehusk	Nuts	300	**3**			37	37.00	45.12%			29			0.78
Series: 3			**Run**	**Green**	**Black**	**Dehusk**								
TrB1		**R/P: 1/2**	**1**	103		2	105.00	70.00%	89			0.85		
	Trash	0%	**2**	27		3	30.00	66.67%	29			0.97		
Green	Nuts	150	**3**	9			9.00	60.00%	7			0.78		
TrB2		**R/P: 2/2**	**1**	232			232.00	77.33%	182			**0.78**		
	Trash	0%	**2**	50			50.00	73.53%	44			0.88		
Green	Nuts	300	**3**	12			12.00	66.67%	14			1.17		
TrB3		**R/P: 3/3**	**1**		84	2	86.00	57.33%		61			0.71	
	Trash	0%	**2**		33	3	36.00	56.25%		24			0.67	
Black	Nuts	150	**3**		8		8.00	28.57%		7			0.88	
TrB4		**R/P: 4/3**	**1**		165	2	167.00	55.67%		85			**0.51**	
	Trash	0%	**2**		55	4	59.00	44.36%		40			0.68	
Black	Nuts	300	**3**		30	3	33.00	44.59%		17			0.52	
TrB5		**R/P: 5/1**	**1**		2	72	74.00	49.33%			73			0.99
	Trash	0%	**2**		1	23	24.00	31.58%			33			1.38
Dehusk	Nuts	150	**3**		1	17	18.00	34.62%			21			1.17
TrB6		**R/P: 6/1**	**1**			162	162.00	54.00%			149			**0.92**
	Trash	0%	**2**			53	53.00	38.41%			55			1.04
Dehusk	Nuts	300	**3**			26	26.00	30.59%			36			1.38



(a)

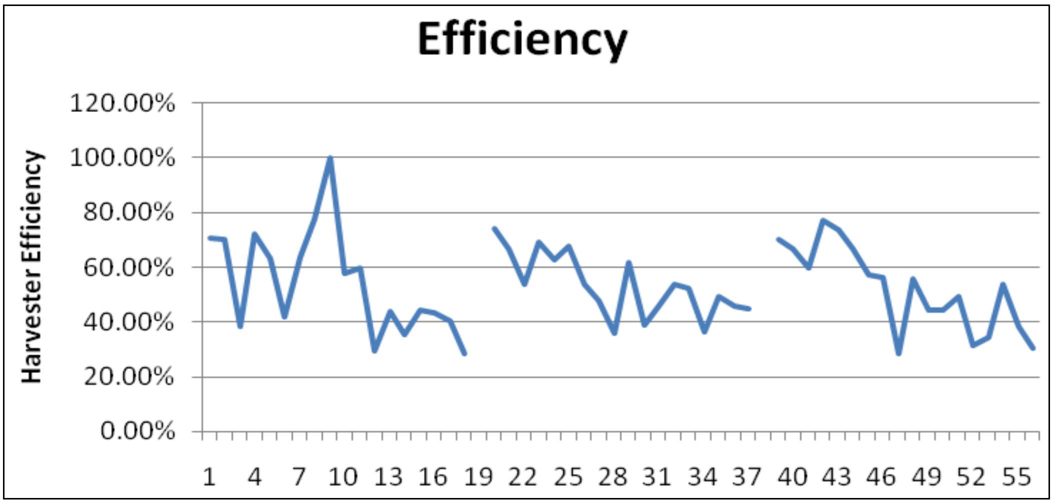


(b)

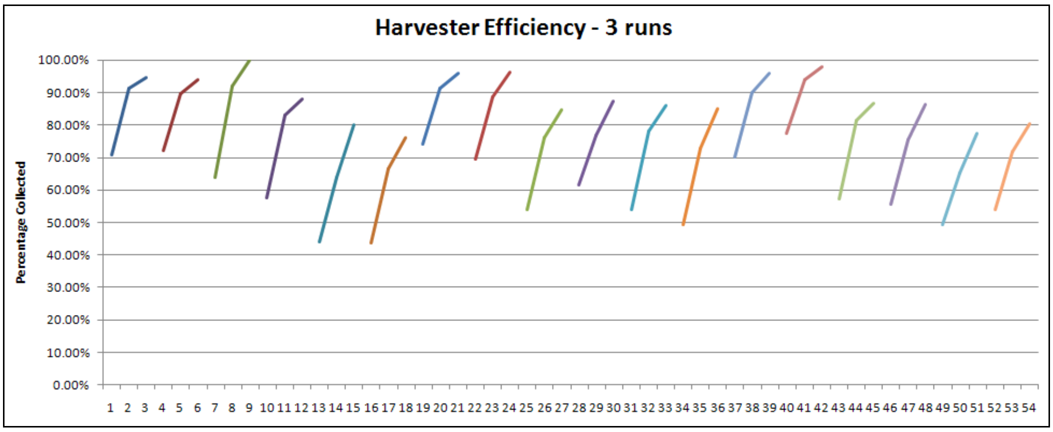


(c)

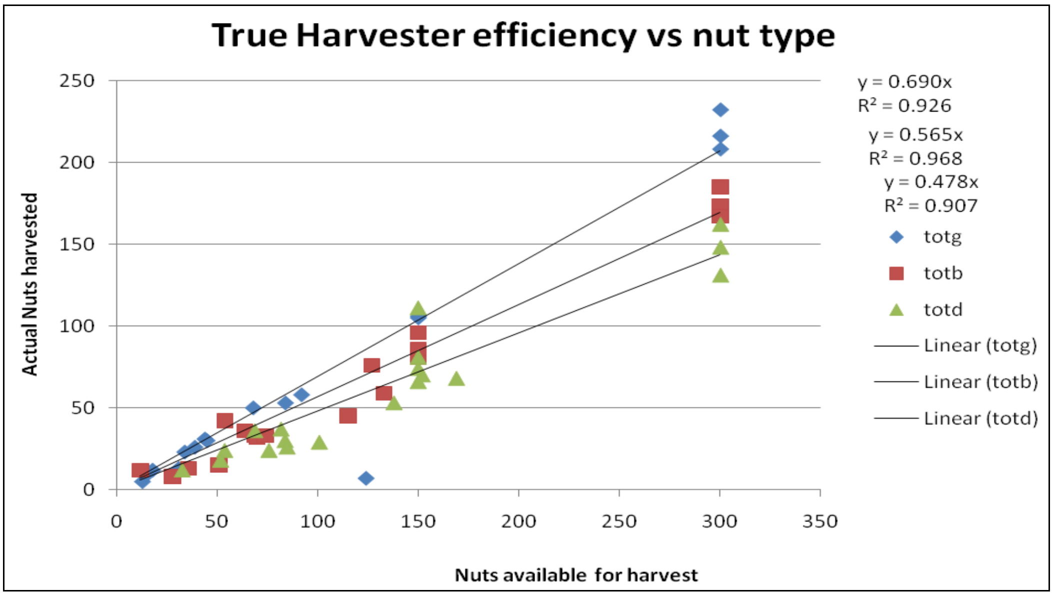
Figure D.4. Nut detection rates for different coloured nuts on 26 April 2007 trial: (a) 84% for green nuts; (b) 59% for black nuts; and (c) 91% for dehusked (brown) nuts.



(a)



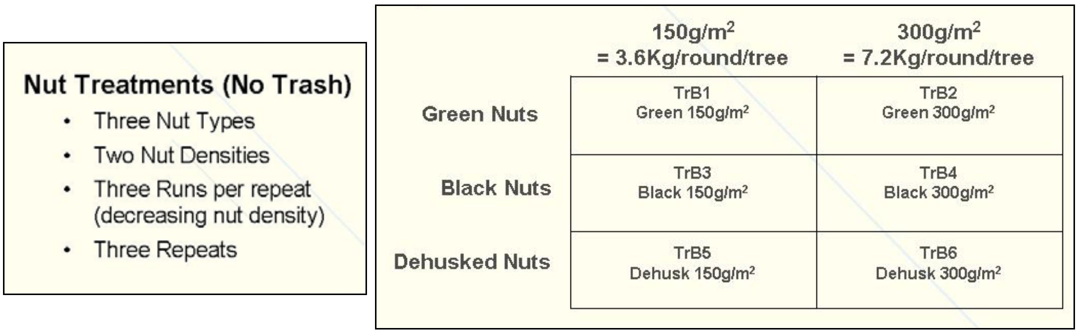
(b)



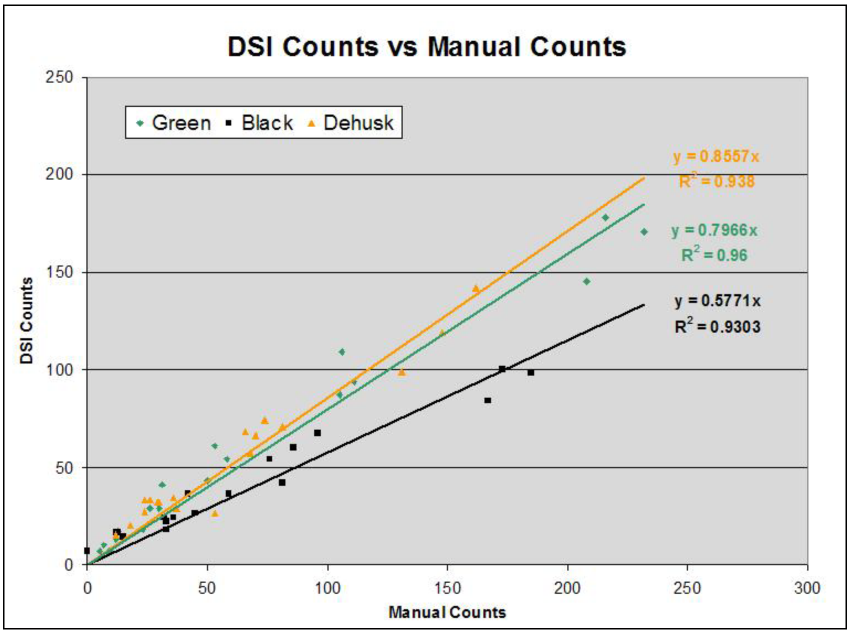
(c)

Figure D.5. Harvester efficiency (i.e. pick up rate) on 26 April 2007 trial: (a) for one run; (b) for three runs; and (c) versus nut type.

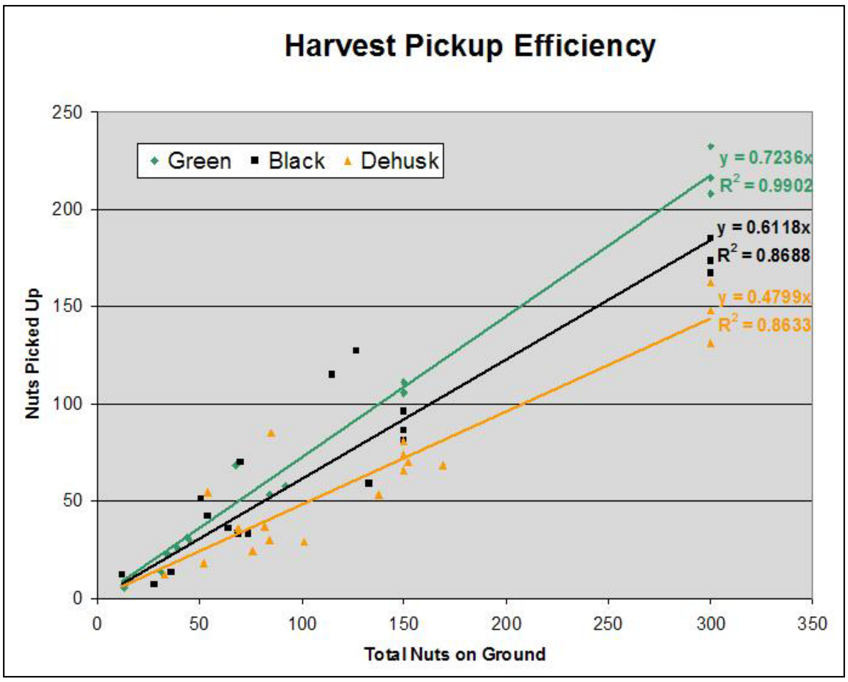
The efficiency of the harvester varies greatly between runs. It is expected that multiplying the harvester efficiency by detected nut count will give an accurate indication of tree yield.



(a)



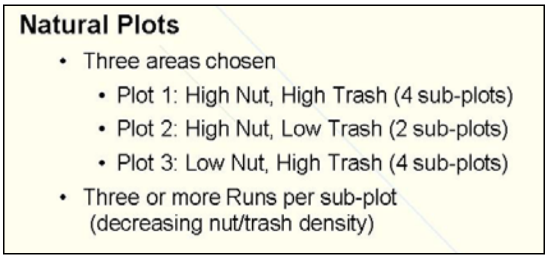
(b)



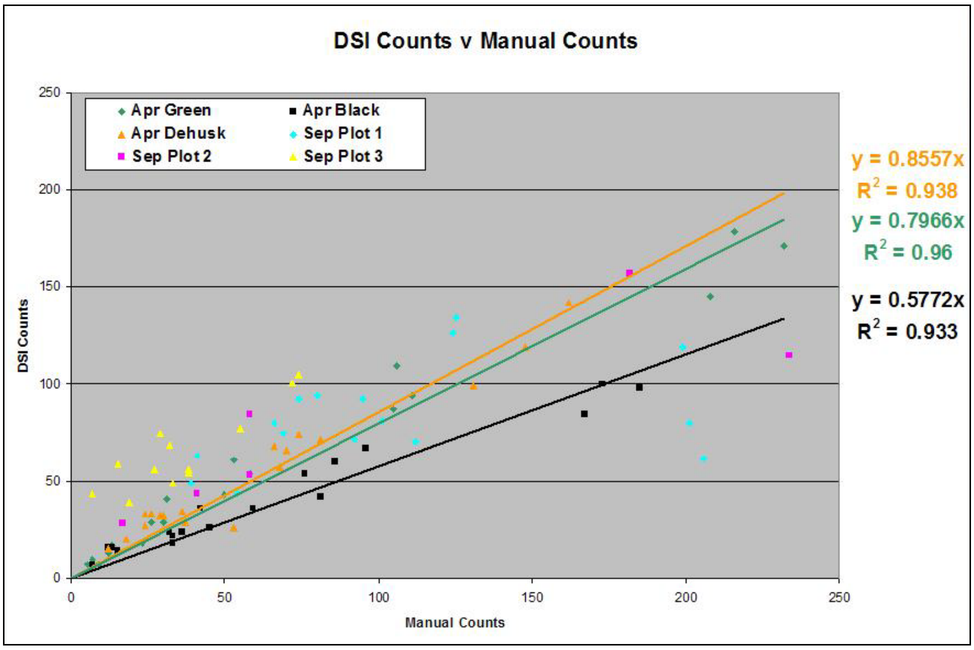
(c)

Figure D.6. Natural plot trials (26 April 2007): (a) trial layout; (b) nut detection rates; and (c) harvester pick up efficiency.

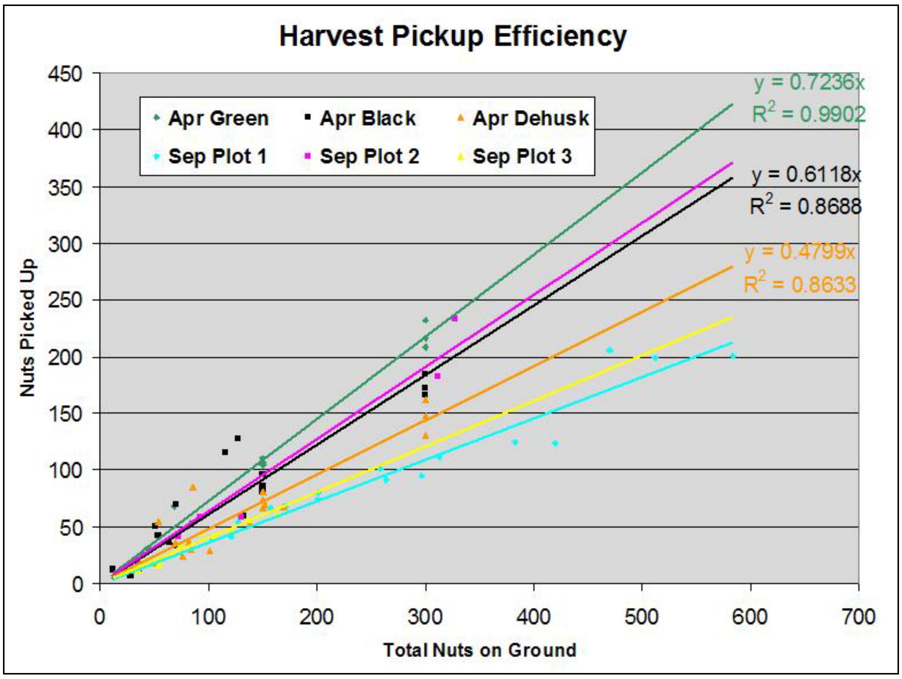
D.4 Phase 1 Trial 3 (September 2007) results



(a)



(b)



(c)

Figure D.7. Natural plot trials (26 April 2007 and September 2007): (a) trial layout; (b) nut detection rates; and (c) harvester pick up efficiency.