A Yield Mapping System For Sugar Cane Chopper Harvesters

A dissertation by

GRAEME J COX

in fulfilment of the requirements of degree of Doctor of Philosophy

Submitted: December, 2002
Abstract

Yield maps provide essential information for the spatial analysis and evaluation of crop production management at a within field level. Technology has been developed to conduct yield mapping in various crops including grain, potatoes and forage, but as yet no technology exists for yield mapping sugar cane. The chopper harvester is the most common form of mechanical harvester for sugar cane. Therefore, the goal of this research is to develop a yield mapping system for the chopper type sugar cane harvester.

After a review, it is proposed that a suitable accuracy goal for the sugar cane mass flow sensor would be ‘less than 5% cumulative measurement error, 95% of the time (2 standard deviations), measured over a 100m$^2$ harvest area’.

Existing mass flow sensors for other crops are reviewed. Based on this review four potential techniques are proposed to measure the mass flow rate of sugar cane. These were defined as the chopper power, elevator power and feed roller separation and weigh pad. These were tested simultaneously by placing various sensors on a single harvester and comparing the sensor outputs with the mass flow rate as measured by a weigh truck. In this trial, all techniques offered potential but none produced results close to the accuracy goal. A weighing technique, known as the ‘weigh pad’, offered the most potential for improvement and potential to accurately measure the mass flow rate with a single calibration under all conditions. The weigh pad technique suffered from very small load cell sensitivity to flow rate, drift in baseline readings and susceptibility to mechanical noise/acceleration dynamics.

An opportunity arose to install a complete yield mapping system on a harvester within a commercial operation. This opportunity was accepted to assess the potential for applying yield maps to the agronomic management of sugar cane. Because the weigh pad sensor required further development at this stage, chopper and elevator power were used as a measure of mass flow rate. A full yield mapping system was developed. Yield mapping, directed soil sampling and variable rate gypsum application was conducted on a case study field. Economic analysis shows a clear economic benefit when compared with standard management.

Analysis is conducted on the weigh pad sensor examining its susceptibility to mechanical noise/acceleration dynamics. Theory is developed to mathematically model the effects of acceleration dynamics on the accuracy of weigh pad sensor. Laboratory bench testing
supported the mathematical model. From the theoretical and experimental analysis a number of conclusions are drawn:

- The weigh pad should be made as light as possible to minimise the error due to dynamic conditions.
- Electronic analogue filters should be used to reduce the noise due to external acceleration.
- The weigh pad should be as rigid as possible to maximise its natural frequency.

A new weigh pad sensor was designed based on these conclusions. Field trials indicated the effects of external accelerations dynamics were significantly reduced. Baseline drift was then found as the next major factor limiting accuracy. The baseline drift was principally caused by the secondary extractor fan of the harvester inducing a negative pressure on the weigh pad. A rubber curtain placed between the weigh pad and the secondary extractor fan reduced the negative force on the weigh pad due to the secondary extractor fan by 74% (from 17 N to 4.4 N). Therefore it is recommended the curtain be used to minimise the impact of the secondary extractor fan on the baseline drift of the weigh pad.

A yield mapping system has been developed for the sugar cane chopper harvester incorporating the weigh pad sensor, a ground speed sensor, a DGPS receiver, a yield display/monitor and data logger. Three identical systems have been constructed and installed on three harvesters for the 1998 cane harvest season. The results show sugar cane could be yield mapped using standard yield mapping principles.

The level of accuracy being achieved by the yield mapping system is less than 16% error, with 95% confidence, over a measurement area of approximately 1400 m$^2$. Although the accuracy achieved is not to the desired research goal, yield maps were produced with satisfactory detail to make agronomic management decisions. The reliability of the sugar cane yield mapping system under field condition in a commercial operation was satisfactory. However, two techniques are proposed (“auto-zeroing” and “batch weighing” techniques) to improve the accuracy and reliability of the weigh pad readings during wet or adverse harvesting conditions.

After note: At the time of writing the NCEA along with Case Austoft (CNH) were continuing to conduct research and development on the system and are intending to make the yield mapping system available as a standard item on new harvesters and a retrofit unit on existing harvesters in the near future (C. Barret, per. comm. 2001). The proposed “auto-zeroing” and “batch weighing” techniques are being tested.
Acknowledgments

Dedicated to Flora Cox (Mum).

Thanks for doing the best you could.

I would firstly like to show appreciation to my supervisors, Assoc Prof Harry Harris, Dr Randolph Pax and Dr Nigel Hancock. Their continual support and advice throughout the project gave me what was required to keep the job going.

I gratefully acknowledge the support and contribution made by:

- Australian Sugar Research and Development Corporation (SRDC) for a postgraduate scholarship.
- Les Perkins, Don Pollock and other Pivot Agriculture staff in their financial support of this research,
- Dave Cox and for providing a trial site and the purchase field equipment,
- Robert Dick for ongoing advice and support and proof reading of thesis,
- Neil Havermale from Red Hen systems for providing GPS and data logging hardware,
- Alan Green and Burdekin Agriculture College for providing a trial site and harvester,
- Mal Baker and other Case Austoft staff for assistance and providing harvesters for trials,
- Bundaberg Sugar staff from Fairymead Sugar Mill who providing a trials site,
- Pat Brosnan and other Davco Farming staff for their assistance,
- Incitec staff who assisted with the soil analysis,
- BSES for a weigh truck.

I must thank my friends for their help and good times.

Special thanks go to my wife, Helen, who has been a great support and motivator.
Certification Of Dissertation

I certify that the ideas, experimental work, results, analyses, software and conclusions reported in this report are entirely my own effort, except where due acknowledgment has been given. I also certify that the work is original and has not been previously submitted for assessment in any other course.

Signature of Candidate

Student Number

ENDORSEMENT:

Supervisors:

Name

Position

Signature

Date
Table of Contents

Abstract ........................................................................................................................................ i
Acknowledgments ....................................................................................................................... iii
Certification Of Dissertation ........................................................................................................ iv
Table of Contents ....................................................................................................................... v
List of Figures ........................................................................................................................ xiv
List of Tables ............................................................................................................................... xv

Chapter 1 - Introduction ........................................................................................................... 1
  1.1 Objectives ........................................................................................................................ 2
  1.2 Publications From This Research ................................................................................. 3
  1.3 Definition of Terms ......................................................................................................... 4
  1.4 The Dissertation .............................................................................................................. 4
  1.5 Background ...................................................................................................................... 5
    1.5.1 Sugar Cane ........................................................................................................ 5
    1.5.2 Sugar Cane Harvesting ....................................................................................... 6
    1.5.3 Precision Agriculture (PA) ............................................................................... 8
    1.5.4 Global Positioning System (GPS) ..................................................................... 10

Chapter 2 - The Potential of Precision Agriculture for the Australian Sugar Industry 12
  2.1 Environmental Benefits ................................................................................................. 12
  2.2 Economic Benefits ........................................................................................................ 14
    2.2.1 Input Savings ..................................................................................................... 14
    2.2.2 Productivity Gains ............................................................................................ 17
  2.3 Conclusion .................................................................................................................... 18

Chapter 3 Yield Mapping Review ....................................................................................... 19
  3.1 Introduction .................................................................................................................... 19
  3.2 The Need ......................................................................................................................... 19
  3.3 Yield Mapping Theory ................................................................................................... 20
  3.4 Yield Mapping Technology ............................................................................................ 21
  3.5 Previous Developments ................................................................................................. 23
  3.6 Existing Mass Flow Rate Measurement ........................................................................ 24
    3.6.1 Grain Sensors ..................................................................................................... 25
    3.6.2 Sugar beet and Potatoes Sensors ....................................................................... 26
3.6.3 Forage Sensors ................................................................. 26
3.6.4 Nature of Measurement Errors ........................................ 27
3.7 Literature Review Update .................................................... 36
3.7.1 Sugar Cane Yield Monitor Developments ......................... 36
3.7.2 Some Yield Monitor Developments In Other Crops ............ 37
3.8 Conclusion ............................................................................ 38

Chapter 4 - Mass Flow Rate Sensing of Sugar Cane .................. 40
4.1 Sensor Requirements .......................................................... 40
4.1.1 Functional Requirements .................................................. 40
4.1.2 Performance Requirements .............................................. 41
4.2 Potential Sensing Techniques .............................................. 43
4.2.1 Chopper Power Measurement .......................................... 44
4.2.2 Elevator Power Measurement ......................................... 47
4.2.3 Volume Measurement – Feed Roller Separation .................. 51
4.2.4 Mass Measurement – Weigh Pad ...................................... 54
4.3 Position of Mass Flow Measurement .................................... 57
4.4 Conclusion ............................................................................ 57

Chapter 5 - Preliminary Field Trials of Potential Sensors ............ 59
5.1 Introduction ........................................................................... 59
5.2 Materials .............................................................................. 59
5.2.1 Harvester and Weigh Truck ............................................... 59
5.2.2 Sensor Designs ............................................................... 60
5.2.3 Data Acquisition System .................................................. 63
5.3 Method .................................................................................. 64
5.3.1 Site ................................................................................... 64
5.3.2 Testing Procedure ............................................................ 64
5.3.3 Field/Crop Conditions ...................................................... 66
5.3.4 Data Processing ............................................................... 66
5.4 Results .................................................................................. 67
5.4.1 Chopper Power ............................................................... 68
5.4.2 Elevator Power ............................................................... 70
5.4.3 Feed Roller Separation .................................................... 71
5.4.4 Weigh Pad ...................................................................... 73
5.5 Discussion ............................................................................. 76
5.5.1 Chopper Power ............................................................... 78
5.5.2 Elevator Power ............................................................... 80
5.5.3 Feed Roller Separation .................................................... 82
<table>
<thead>
<tr>
<th>Chapter 6</th>
<th>Development of Preliminary Sugar Cane Yield Maps And Their Agronomic Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.1</td>
<td>Introduction</td>
</tr>
<tr>
<td>6.2</td>
<td>Yield mapping</td>
</tr>
<tr>
<td>6.2.1</td>
<td>Results</td>
</tr>
<tr>
<td>6.2.2</td>
<td>Discussion</td>
</tr>
<tr>
<td>6.3</td>
<td>Directed Soil sampling</td>
</tr>
<tr>
<td>6.4</td>
<td>Variable Rate Application</td>
</tr>
<tr>
<td>6.4.1</td>
<td>Economics</td>
</tr>
<tr>
<td>6.5</td>
<td>Conclusions</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Chapter 7</th>
<th>Dynamic Response of the Weigh Pad Sensor</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.1</td>
<td>Introduction</td>
</tr>
<tr>
<td>7.2</td>
<td>Nature Of The Problem</td>
</tr>
<tr>
<td>7.3</td>
<td>Theory</td>
</tr>
<tr>
<td>7.3.1</td>
<td>Acceleration-Error relationship</td>
</tr>
<tr>
<td>7.3.2</td>
<td>Acceleration Characteristics</td>
</tr>
<tr>
<td>7.3.3</td>
<td>Acceleration-Time relationship</td>
</tr>
<tr>
<td>7.3.4</td>
<td>Mathematical Model</td>
</tr>
<tr>
<td>7.4</td>
<td>Bench Testing</td>
</tr>
<tr>
<td>7.4.1</td>
<td>Materials and Method</td>
</tr>
<tr>
<td>7.4.2</td>
<td>Results</td>
</tr>
<tr>
<td>7.4.3</td>
<td>Discussion</td>
</tr>
<tr>
<td>7.4.4</td>
<td>Conclusions</td>
</tr>
<tr>
<td>7.5</td>
<td>Real Time Correction Using Acceleration Measurements</td>
</tr>
<tr>
<td>7.6</td>
<td>Field Trials</td>
</tr>
<tr>
<td>7.6.1</td>
<td>Introduction</td>
</tr>
<tr>
<td>7.6.2</td>
<td>Materials and Method</td>
</tr>
<tr>
<td>7.6.3</td>
<td>Results</td>
</tr>
<tr>
<td>7.6.4</td>
<td>Discussion</td>
</tr>
<tr>
<td>7.7</td>
<td>Conclusion</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Chapter 8</th>
<th>Effect of the Secondary Extractor Fan on the Weigh Pad</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.1</td>
<td>Introduction</td>
</tr>
<tr>
<td>8.2</td>
<td>Potential Solutions</td>
</tr>
<tr>
<td>8.3</td>
<td>Materials and Method</td>
</tr>
<tr>
<td>8.4</td>
<td>Results</td>
</tr>
</tbody>
</table>
8.5 Discussion ...................................................................................................................155
8.6 Conclusion ..................................................................................................................157

Chapter 9 - Weigh Pad Sensor Final Design .................................................................158
9.1 Introduction .................................................................................................................158
9.2 Design Considerations ............................................................................................158
  9.2.1 Light Weight ........................................................................................................158
  9.2.2 Strength ...............................................................................................................159
  9.2.3 Reliability ............................................................................................................159
  9.2.4 Foreign Matter Build-up ....................................................................................160
9.3 Sensor Design .............................................................................................................162
9.4 Sensor Installation ......................................................................................................165
9.5 Conclusion ..................................................................................................................169

Chapter 10 - Prototype Yield Mapping System ............................................................171
10.1 Introduction .............................................................................................................171
10.2 Materials and Method ...............................................................................................172
  10.2.1 Accuracy Trial ...................................................................................................174
10.3 Results ......................................................................................................................174
10.4 Discussion ................................................................................................................178
  10.4.1 System Accuracy ..............................................................................................178
  10.4.2 Weigh Pad Sensor Operation .........................................................................178
  10.4.3 Yield Mapping System ..................................................................................182
10.5 Conclusion ................................................................................................................185

Chapter 11 – Conclusion ..............................................................................................186
11.1 Review .....................................................................................................................186
11.2 Conclusions .............................................................................................................191
11.3 Recommendations for Further Research ...............................................................191

References ...................................................................................................................... xvi
Appendices ....................................................................................................................... xxiii
Appendix A: Feed Roller Separation Sensor Design and Calibration .........................xxv
Appendix B: Field Trials Sensor Signal Conditioning ................................................... xxix
Appendix C: Vibration Testing Frame .......................................................................... xxxiii
Appendix D: 1997 Weigh Pad Design ............................................................................xxxv
Appendix E: 1997 Fixed Weigh Pad Design .................................................................... xlv
Appendix F: Yield Monitor Data File Format ................................................................... xlix
Appendix G: Soil Analysis Results .................................................................................. lli
List of Figures

Figure 1-1. Sugar cane yield map derived from the outcomes of this research. .......................2
Figure 1-2. A 12 month old sugar cane crop ready for harvest, which yielded 120t/ha. ..........6
Figure 1-3. A sugar cane crop being harvested 'green', with a ‘Haul-out' truck along side. ....7
Figure 1-4. A side view of the chopper sugar cane harvester. (picture courtesy of S.Kroes)...8
Figure 1-5. The concept of Precision Agriculture as seen by AGCO (Agco, 1998)...............10
Figure 2-1. Effect of Nitrogen application rate on sugar cane yield and nitrogen leaching. 
(Adapted from Verburg et al., 1996) ..............................................................................13
Figure 2-2. Model to determine the potential financial savings of site specific application of 
inputs versus blanket application, on a hypothetical field. .............................................16
Figure 3-1. Yield Mapping Hardware.....................................................................................21
Figure 3-2. Process for yield map production.........................................................................22
Figure 3-3. Linear calibration characteristics. ........................................................................28
Figure 3-4. Probability distribution of yield monitor errors. ..................................................29
Figure 3-5. Relationship between yield monitor error and sample size.................................30
Figure 3-6. Result of trials by Doerge (1997) showing the nature of yield monitor error.....31
Figure 3-7. Result of trials by Wilcox (1998) showing the nature of yield monitor error.....32
Figure 3-8. Yield monitor error modeled with a bias of 0% and standard deviation of 5% at 
1ha..................................................................................................................................33
Figure 4-1. The location of the four mass flow sensing techniques throughout the sugar cane 
harvester (picture courtesy of S. Kroes)..........................................................................44
Figure 4-2. Chopper system of the sugar cane harvester. .......................................................45
Figure 4-3. Elevator of the chopper sugar cane harvester.......................................................47
Figure 4-4. Simple model of the force, necessary to raise sugar cane billets up a harvester 
elevator............................................................................................................................48
Figure 4-5. Theoretical elevator power requirement for varying coefficients of friction and 
elevator angles. ...............................................................................................................50
Figure 4-6. Volume measurement using the Feed roller operation.........................................52
Figure 4-7. Conceptual design of elevator weigh pad.............................................................55
Figure 4-8. Theoretical error of weigh pad for varying operating slopes. ..............................56
Figure 5-1. Feed roller separation sensor arrangement...........................................................62
Figure 5-2. Elevator weigh pad arrangement........................................................................63
Figure 5-3. Block diagram of the instrumentation on the cane harvester..............................64
Figure 5-4. Field layout for the sensor trials..........................................................................65
Figure 5-5. Typical data from the beginning of a run for the ground speed and oil flow rate measurements..................................................................................................................68
Figure 5-6. Typical data from the beginning of a run for the chopper power measurements..68
Figure 5-7. Frequency spectrum of the chopper pressure signal during normal cane flow conditions..............................................................................................................................69
Figure 5-8. Calibration results of the chopper power measurements (Note nonzero y axis).69
Figure 5-9. Typical data from the beginning of a run for the elevator power measurements.70
Figure 5-10. Frequency spectrum of the elevator pressure signal during normal cane flow conditions..........................................................................................................................70
Figure 5-11. Calibration results of the elevator power measurements.................................71
Figure 5-12. Typical data from the beginning of a run for the Feed Roller Separation measurements........................................................................................................................71
Figure 5-13. Frequency spectrum of the Feed roller Separation signal during normal cane flow conditions........................................................................................................................72
Figure 5-14. Calibration results of the feed roller separation measurements.......................72
Figure 5-15. Typical data from the beginning of a run for the weigh pad measurements.....73
Figure 5-16. Zoomed view of the data in Figure 5-15 showing the peaks in the load cell measurements as cane travels over the weigh pad..............................................................73
Figure 5-17. Frequency spectrum of the weigh pad signal during normal cane flow conditions..............................................................................................................................74
Figure 5-18. Frequency spectrum of the weigh pad signal during free running conditions...74
Figure 5-19. Frequency spectrum of the weigh pad accelerometer signal during normal cane flow conditions............................................................................................................75
Figure 5-20. Calibration results of the weigh pad measurements.........................................75
Figure 6-1. Correlation of daily calibration results (10% error bars).....................................91
Figure 6-2. Yield Map produced using the Chopper measurement........................................92
Figure 6-3. Yield Map produced using the Elevator measurement........................................93
Figure 6-4. Aerial photo of the yield mapped field.................................................................94
Figure 6-5. Yield map of field under study with soil sample positions marked.....................97
Figure 6-6. Linear correlation of crop yield with magnesium (Mg), sodium (Na) and a combination of magnesium and sodium (0.5Mg + Na). ..................................................101
Figure 6-7. Recommendation equation for gypsum application............................................103
Figure 6-8. Histogram of crop yield for the field under study................................................106
Figure 6-9. A cost comparison of various of application scenarios over 5 years for the field under study..................................................................................................................107
Figure 7-1. Raw weigh pad signal under zero cane flow conditions (free running) along with the filtered equivalent..................................................................................................110
Figure 7-2. Weigh pad signal displaying the noise superimposed on the mass flow rate signal........................................................................................................................................111
Figure 7-3. Free body diagram of weigh pad system........................................................................................................................................112
Figure 7-4. Acceleration measurements taken on the Elevator of a sugar cane harvester...115
Figure 7-5. Frequency Spectrum of the acceleration data..........................................................115
Figure 7-6. Histogram of acceleration data showing a mean of 0.3 g and a standard deviation of 2.0 g. ........................................................................................................................................115
Figure 7-7. Gaussian distribution of the total population of accelerations due to vibrations.116
Figure 7-8. Relationship between acceleration distribution and sample size. .........................117
Figure 7-9. Apparatus for vibration bench testing of the weigh pad. .........................................119
Figure 7-10. Weigh pad design examined in bench tests.........................................................120
Figure 7-11. Typical accelerometer measurements on the weigh pad during testing. ..........121
Figure 7-12. FFT frequency spectrum of the accelerometer measurements. ........................121
Figure 7-13. Typical load cell measurements on the weigh pad during testing.....................122
Figure 7-14. FFT frequency spectrum of the load cell measurements.................................122
Figure 7-15. Results of bench test for lowest acceleration setting.........................................123
Figure 7-16. Experimental relationship between average time, the mass applied and percent error in measurement for lowest acceleration setting. .....................................123
Figure 7-17. Modelled relationship between average time, the mass applied and percent error in measurement for lowest acceleration setting. .....................................124
Figure 7-18. Modelled relationship between measurement error, weigh pad mass and average time. .............................................................................................................................125
Figure 7-19. Accelerometer and load cell signals along with the corrected mass reading (off scale) ........................................................................................................................................130
Figure 7-20. Signals shown in Figure 6.19 with y scale adjusted to fit corrected mass reading......................................................................................................................................131
Figure 7-21. Block diagram of the instrumentation installation on the cane harvester.............132
Figure 7-22. The weigh pad installed in the harvester (viewed from underneath the elevator.)133
Figure 7-23. Average mass flow rate versus average weigh pad reading in kilograms per second. ........................................................................................................................................134
Figure 7-24. Cumulative mass comparison for weigh pad in green cane .............................136
Figure 7-25. Cumulative mass comparison for weigh pad in burnt cane...............................136
Figure 7-26. Effect of the secondary extractor fan on the weigh pad. .....................................139
Figure 7-27. Foreign matter build-up around hinged weigh pad ............................................140
Figure 8-1. Position of the secondary extractor fan on the harvester........................................144
Figure 8-2. Position of the secondary extractor fan, weigh pad and shroud .........................145
Figure 8-3. Weigh pad load cell measurement for no cane flow ..............................................146
Figure 8-4. Frequency spectrum of the load cell measurement for no cane flow.................146
Figure 8-5. Weigh pad load cell measurement for flow rate around 25kg/s.......................146
Figure 8-6. Frequency spectrum for Weigh pad load cell measurement for flow rate around 25kg/s........................................................................................................147
Figure 8-7. Use of a curtain to reduce the impact of the extractor fan on the weigh pad....148
Figure 8-8. Use of a vents to reduce the impact of the extractor fan on the weigh pad......149
Figure 8-9. Typical installation of the short curtain.........................................................150
Figure 8-10. Typical Short curtain design. .................................................................150
Figure 8-11. Typical installation of the long curtain.......................................................151
Figure 8-12. Relationship between harvester engine speed and secondary extractor fan speed.152
Figure 8-13. Relationship of secondary extractor fan speed to air speed and suction pressure.152
Figure 8-14. Air speed profile from the floor of the elevator to the shroud......................153
Figure 8-15. Pressure gradient measured along the elevator. ........................................153
Figure 8-16. Effect of short curtain on pressure measured along the elevator for different curtain positions.................................................................154
Figure 8-17. Effect of long curtain on pressure measured along the elevator for different curtain positions.................................................................155
Figure 9-1. Weigh pad located to minimise effect of foreign matter build-up on sensor accuracy. .................................................................161
Figure 9-2. Overhang required to prevent mud/foreign matter build up around the edge of the weigh pad.................................................................162
Figure 9-3. Underside view of weigh pad installed in an Austoft harvester......................168
Figure 9-4. Topside view of weigh pad installed in a Cameco harvester.........................168
Figure 9-5. Close-up view of the load cell mount assembly installed on a Cameco harvester.169
Figure 10-1. Yield mapping system components............................................................172
Figure 10-2. The Microtrak Grain-Trak display/interface......................................................173
Figure 10-3. Comparison of yield monitor measurements with haul out bin weights.......175
Figure 10-4. Typical yield map produced by prototype yield mapping systems. (Courtesy of D.Pollock, Pivot Agriculture, 2001) .................................................................177
Figure 10-5. Leaf matter wedged between the weigh plate edge and the elevator floor......179
Figure 10-6. Clearance between the weigh plate and an elevator flight, viewed from behind the flight in the direction of elevator travel.........................................................180
Figure 10-7. Build up of extraneous matter (mainly mud) on the base of an elevator flight just prior to travelling over the weigh plate. (Viewed from above and in front of the flight)............................................................................181
Figure 10-8. Build up of extraneous matter (mud and leaf matter) on the base of an elevator flight. (Viewed from above the flight)..................................................................181
Figure 10-9. Piece of sugar cane billet wedged under an elevator flight just prior to travelling over the weigh plate. (Viewed from in front of the flight)............................................182
List of Tables

Table 5-1. Summary of Results.................................................................76
Table 6-1. Sample of data collected by the yield mapping system..............88
Table 6-2. Correlation results between yield, magnesium and sodium. ....101
Table 6-3. Cost associated with application of precision agriculture to the field under study.105
Table 7-1. Summary of calibration results from weigh truck trials. ..........135
Table 7-2. Summary of accuracy statistics from weigh truck trials. ..........137
Table 10-1. Accuracy of the yield monitor over each bin......................176
Table 10-2. Accuracy of the yield monitor over the whole day..............176