Weed Resistance Risk Management in Glyphosate-Resistant Cotton

Jeff Werth

(BAppSc, The University of Queensland)

A thesis submitted for the degree of Doctor of Philosophy

The School of Food, Agriculture and Wine

The University of Adelaide

Australia

2006

TABLE OF CONTENTS

ABSTRACT XII

CHAPTER 1 1

INTRODUCTION 1

CHAPTER 2 4

LITERATURE REVIEW 4

2.1 INTRODUCTION 5

2.2 HERBICIDE RESISTANCE 8

2.2.1 Resistance defined 8
2.2.2 Evolution of herbicide resistance 9
2.2.2.1 Genetic Variation 9
2.2.2.2 Selection Pressure 10
2.2.3 Glyphosate resistance 11
2.2.4 Current situation in Australia 13
2.2.5 Using IWM to delay resistance 15

2.3 HERBICIDE-RESISTANT CROPS 16

2.3.1 Herbicide-resistant crop use 16
2.3.1.1 The Australian scene 17
2.3.2 IWM impacts of herbicide-resistant crops 17
2.3.2.1 Benefits of Herbicide-Resistant Crops 18
2.3.2.2 Concerns of Herbicide-Resistant Crops 18
2.3.2.3 Weed populations and population dynamics 19
2.3.2.4 Changes in IWM practices 21

2.4 GLYPHOSATE-RESISTANT COTTON 22

2.4.1 Glyphosate mode of action 22
2.4.1.1 Translocation through the plant 22
2.4.1.2 Action at the target site 23
2.4.2 Glyphosate resistance 24
2.4.2.1 Mechanisms of resistance 24
2.4.2.2 Development of Roundup Ready® cotton 24
2.4.3 Glyphosate-resistant cotton and the cotton industry 25
2.4.3.1 Effect on IWM practices 25
2.4.3.2 Limitations and New Technology 27

2.5 INTEGRATED WEED MANAGEMENT 28

2.5.1 What is Integrated Weed Management 28
2.5.2 Reasons for adopting IWM 28
2.5.2.1 Reducing herbicide use 29

2.5.2.2 Delaying herbicide resistance 29
2.5.2.3 Weed species shift 30
2.5.3 Integrated Weed Management practices 30
2.5.3.1 Tillage 31
2.5.3.2 Crop rotation 33
2.5.3.3 Crop competition 34
2.5.3.4 Biological control 35
2.5.3.5 Herbicides 35
2.5.3.6 Herbicide-resistant crops 36

2.6 THE AUSTRALIAN COTTON INDUSTRY 37

2.6.1 Weed management in cotton 37
2.6.1.1 Current practices and herbicide use 37
2.6.1.2 Integrated Weed Management in cotton 39
2.6.2 Weed management economics in cotton 41
2.6.3 Roundup Ready® cotton 43

2.7 POPULATION DYNAMICS OF GRASS WEEDS OF COTTON 44

2.7.1 *Echinochloa crus-galli* (Barnyardgrass) 44
2.7.1.1 Growth 44
2.7.1.2 Reproduction 45
2.7.1.3 Dormancy and germination 46
2.7.1.4 Crop competition 48
2.7.1.5 Response to weed management practices 49
2.7.2 *Urochloa panicoides* (Liverseed grass) 50
2.7.2.1 Growth and reproduction 50
2.7.2.2 Germination 50
2.7.2.3 Response to weed management practices 51

2.8 RESISTANCE MODELING 52

2.8.1 Modeling herbicide resistance 52

2.9 CONCLUSIONS 56

CHAPTER 3 58

GROWER SURVEY – WEED MANAGEMENT PRACTICES IN GLYPHOSATE-RESISTANT AND CONVENTIONAL COTTON FIELDS IN AUSTRALIA 58

3.1 INTRODUCTION 59

3.2 MATERIALS AND METHODS 60

3.2.1 Experimental procedure 60
3.2.2 Statistical analysis 62

3.3 RESULTS 62

3.3.1 Crop rotations 62
3.3.2 Flexibility and cost effectiveness of glyphosate-resistant cotton 63
3.3.3 Weed species and prevalence 64
3.3.4 Weed management 67

3.3.5 Herbicide mode of action ____ 68
3.3.6 Herbicide use ____ 69
3.3.7 Possible changes to weed management with enhanced glyphosate-resistant technology ____ 71

3.4 DISCUSSION ____ 72

CHAPTER 4 ____ 76

POPULATION DYNAMICS OF BARNYARDGRASS AND LIVERSEED GRASS UNDER A RANGE OF WEED MANAGEMENT REGIMES IN A GLYPHOSATE-RESISTANT COTTON SYSTEM. ____ 76

4.1 INTRODUCTION ____ 77

4.2 MATERIALS AND METHODS ____ 78

4.2.1 Experimental site ____ 78
4.2.2 Experimental design ____ 78
4.2.3 Experimental procedure ____ 79
4.2.3.1 Weed populations ____ 80
4.2.3.2 Seed bank measurements ____ 81
4.2.4 Statistical analysis ____ 82

4.3 RESULTS ____ 82

4.3.1 Seed bank measurements ____ 82
4.3.2 Weed emergence ____ 84
4.3.3 Overall weed numbers ____ 87

4.4 DISCUSSION ____ 90

CHAPTER 5 ____ 93

ABOVE-GROUND BIOMASS AND SEED PRODUCTION OF BARNYARDGRASS AND LIVERSEED GRASS IN COMPETITION WITH COTTON. ____ 93

5.1 INTRODUCTION ____ 94

5.2 MATERIALS AND METHODS ____ 95

5.2.1 Experimental sites ____ 95
5.2.2 Experimental Design ____ 97
5.2.3 Experimental procedure ____ 98
5.2.4 Statistical analysis ____ 100

5.3 RESULTS ____ 100

5.3.1 Vegetative growth ____ 100
5.3.1.1 Barnyardgrass ____ 100
5.3.1.2 Liverseed grass ____ 101
5.3.2 Seed production ____ 103
5.3.2.1 Barnyardgrass ____ 103

5.3.2.2 Liverseed grass 105
5.3.3 Reproductive effort 107

5.4 DISCUSSION **108**

CHAPTER 6 **111**

DOSE-MORTALITY RESPONSE OF BARNYARDGRASS AND LIVERSEED GRASS TO GLYPHOSATE **111**

6.1 INTRODUCTION **112**

6.2 MATERIALS AND METHODS **113**

6.2.1 Experimental Sites 113
6.2.2 Experimental Design 113
6.2.3 Statistical Analysis 114

6.3 RESULTS **114**

6.3.1 Barnyardgrass response 115
6.3.2 Liverseed grass response 116

6.4 DISCUSSION **117**

6.4.1 Herbicide resistance implications 118

CHAPTER 7 **120**

PREDICTING THE RATE OF GLYPOSATE RESISTANCE EVOLUTION IN GRASS WEEDS IN GLYPHOSATE-RESISANT COTTON **120**

7.1 INTRODUCTION **121**

7.2 MATERIALS AND METHODS **122**

7.2.1 The Model 122
7.2.2 Initial frequency of glyphosate resistance alleles 123
7.2.3 Genetic aspects 123
7.2.4 Germination characteristics 125
7.2.5 Weed control impacts 126
7.2.6 Seed production 128
7.2.7 Seedbank characteristics 129

7.3 RESULTS **129**

8.3.1 Weed management influences on glyphosate resistance 129
7.3.2 Initial frequency of glyphosate resistance alleles 132
7.3.3 Fitness penalties and resistance evolution 133

7.4 DISCUSSION **134**

CHAPTER 8 ____ 137

GENERAL DISCUSSION ____ 137

8.1 INTRODUCTION ____ 138

8.2 CURRENT PRACTICES AND HERBICIDE USE IN GLYPHOSATE-RESISTANT AND CONVENTIONAL COTTON FIELDS ____ 138

8.3 RESPONSE OF BARNYARDGRASS AND LIVERSEED GRASS TO A RANGE OF MANAGEMENT PRACTICES IN A GLYPHOSATE-RESISTANT COTTON SYSTEM ____ 140

8.4 GROWTH AND SEED PRODUCTION OF BARNYARDGRASS AND LIVERSEED GRASS IN COMPETITION WITH COTTON ____ 141

8.5 THE EFFECT OF GLYPHOSATE DOSE ON SURVIVORSHIP OF BARNYARDGRASS AND LIVERSEED GRASS ____ 142

8.7 MODELLING THE EVOLUTION OF GLYPHOSATE RESISTANCE IN TWO GRASS WEEDS ____ 143

8.8 CONCLUSIONS ____ 144

APPENDICES ____ 147

BIBLIOGRAPHY ____ 172

TABLE OF TABLES

TABLE 2.1. HERBICIDE-RESISTANT WEED SPECIES IN AUSTRALIA BY MODE OF ACTION GROUP (HEAP 2006; PRESTON AND REIGER 2000). 14
TABLE 2.2. INCIDENCE OF CONFIRMED GLYPHOSATE-RESISTANT RIGID RYEGRASS POPULATIONS IN AUSTRALIA (PRESTON PERS. COMM.). 15
TABLE 2.3. HERBICIDES CLASSIFIED ACCORDING TO MODE OF ACTION THAT ARE COMMON TO COTTON ROTATIONS (ROBERTS 1998*B*) 38
TABLE 2.4. COST OF WEED MANAGEMENT OPERATIONS IN COTTON (NSW AG 2002) 42
TABLE 3.1. AREA OF COTTON GROWN, PERCENTAGE OF GLYPHOSATE-RESISTANT COTTON PLANTED AND AVERAGE NUMBER OF YEARS GLYPHOSATE-RESISTANT COTTON HAS BEEN GROWN, FOR THE SURVEYED GROWERS IN EACH OF THE REGIONS. 61
TABLE 3.2. CROP ROTATIONS USED IN CONJUNCTION WITH CONVENTIONAL AND GLYPHOSATE-RESISTANT COTTON ACROSS ALL REGIONS SURVEYED. 63
TABLE 3.3. GROWER PERCEPTIONS OF THE FLEXIBILITY AND COST EFFECTIVENESS OF GLYPHOSATE-RESISTANT COTTON IN MARCH 2003. 64
TABLE 3.4. THE 10 MOST COMMON WEEDS IN CONVENTIONAL AND GLYPHOSATE-RESISTANT COTTON FIELDS AS REPORTED BY GROWERS. 65
TABLE 3.5. WEEDS THAT INFLUENCED THE GROWER'S DECISION TO GROW GLYPHOSATE-RESISTANT COTTON, AND PERCEPTION OF WEED PREVALENCE AND CONTROL IN GLYPHOSATE-RESISTANT AND CONVENTIONAL COTTON FIELDS. 66
TABLE 3.6. PERCENTAGE OF GROWERS ADOPTING VARIOUS WEED MANAGEMENT PRACTICES IN GLYPHOSATE-RESISTANT AND CONVENTIONAL COTTON FIELDS. 68
TABLE 3.7. HERBICIDE MODES OF ACTION USED IN CONVENTIONAL AND GLYPHOSATE-RESISTANT COTTON FIELDS. 69
TABLE 3.8. GLYPHOSATE USE IN THE COTTON CROPS AND IN THE FULL ROTATION ACROSS REGIONS. 70
TABLE 3.9. USE OF HERBICIDES OTHER THAN GLYPHOSATE IN GLYPHOSATE-RESISTANT AND CONVENTIONAL COTTON FIELDS. 71
TABLE 3.10. GROWER PERCEPTIONS ON POSSIBLE CHANGES IN WEED MANAGEMENT PRACTICES WITH THE INTRODUCTION OF ENHANCED GLYPHOSATE-RESISTANT COTTON. 72
TABLE 4.1. HERBICIDES, HERBICIDE RATES AND TIMINGS USED IN EACH TREATMENT IN SYSTEMS EXPERIMENT IN THE 2003-04 SEASON. TREATMENTS APPLIED IN SUCCESSIVE SEASONS ARE LOCATED IN APPENDIX 4.1 80
TABLE 4.2 DENSITY OF BARNYARDGRASS PLANTS THROUGHOUT THE DURATION OF THE GLYPHOSATE-RESISTANT SYSTEMS EXPERIMENT. 88
TABLE 4.3 DENSITY OF LIVERSEED GRASS PLANTS THROUGHOUT THE DURATION OF THE GLYPHOSATE-RESISTANT SYSTEMS EXPERIMENT. 89

TABLE 7.1. BARNYARD GRASS GERMINATION PROBABILITIES APPLIED TO INDIVIDUAL COHORTS WITHIN THE MODEL (BASED ON SYSTEMS EXPERIMENT DATA IN CHAPTER 4)........................ 126
TABLE 7.2. LIVERSEED GRASS GERMINATION PROBABILITIES APPLIED TO INDIVIDUAL COHORTS WITHIN THE MODEL (BASED ON SYSTEMS EXPERIMENT DATA IN CHAPTER 4)........................ 126

TABLE OF FIGURES

FIGURE 2.1. NUMBER OF GERMINABLE SEEDS AT FOUR SOIL DEPTHS IN NO-TILLAGE (NT), CHISEL PLOW (CP), AND MOLDBOARD PLOW (MP) (CARDINA ET AL. 2002) 32

FIGURE 2.2. THE ANNUAL DORMANCY CYCLE IN THE PERCENTAGE OF SEEDS GERMINATING AFTER VARIOUS PERIODS OF BURIAL IN SOIL. SEEDS WERE BURIED IN 1993 (□) OR 1994 (■) AND GERMINATED AT 25^{O}C WITH LIGHT (HONEK ET AL. 1998). 47

FIGURE 4.1 SOIL SEED BANK DENSITIES FOR BARNYARDGRASS AND LIVERSEED GRASS UNDER THE VARIOUS WEED MANAGEMENT TREATMENTS IN THE FIELD. BARS INDICATE STANDARD ERROR OF THE MEAN. 83

FIGURE 4.2 TOTAL GERMINATIONS OF LIVERSEED GRASS AND BARNYARD GRASS IN THE FIELD FROM THE INITIAL IRRIGATION OF THE FIELD IN PREPARATION FOR COTTON PLANTING (NOTE THE VARIATION IN SCALE ALONG THE Y AXIS): (●) RR ONLY, (▼) RR + IWM, (■) RR + RES, (♦) RR + GRASS AND (▲) IWM ONLY. 86

FIGURE 5.1. BARNYARDGRASS ABOVE-GROUND BIOMASS PER PLANT. IN THE 2004-05 GRAPH THE FIRST PLANTING IS DENOTED BY ●, AND THE SECOND PLANTING BY ○. REGRESSION PARAMETERS ARE LISTED IN APPENDIX 5.4. BARS INDICATE STANDARD ERROR OF THE MEAN. 101

FIGURE 5.2. LIVERSEED GRASS ABOVE-GROUND BIOMASS PER PLANT. IN THE 2004-05 GRAPH THE FIRST PLANTING IS DENOTED BY ●, AND THE SECOND PLANTING BY ○. REGRESSION PARAMETERS ARE LISTED IN APPENDIX 5.4. BARS INDICATE STANDARD ERROR OF THE MEAN. 102

FIGURE 5.3. BARNYARDGRASS SEED PRODUCTION. IN THE 2004-05 GRAPH THE FIRST PLANTING IS DENOTED BY ●, AND THE SECOND PLANTING BY ○. REGRESSION PARAMETERS ARE LISTED IN APPENDIX 5.4. BARS INDICATE STANDARD ERROR OF THE MEAN. 104

FIGURE 5.4. LIVERSEED GRASS SEED PRODUCTION. IN THE 2004-05 GRAPH THE FIRST PLANTING IS DENOTED BY●, AND THE SECOND PLANTING BY ○. REGRESSION PARAMETERS ARE LISTED IN APPENDIX 5.4. BARS INDICATE STANDARD ERROR OF THE MEAN. 106

FIGURE 5.5. SEED PRODUCTION PER PLANT EXPRESSED IN RELATION TO ABOVE GROUND BIOMASS PER PLANT. REGRESSION PARAMETERS ARE LISTED IN APPENDIX 5.4. 107

FIGURE 6.1 DOSE MORTALITY-RESPONSE OF BARNYARDGRASS TO INCREASING RATES OF GLYPHOSATE IN 2003, 2004 AND 2005. REGRESSION PARAMETERS ARE LISTED IN APPENDIX 6.3. BARS INDICATE STANDARD ERROR OF THE MEAN. 115

FIGURE 6.2 DOSE MORTALITY-RESPONSE OF LIVERSEED GRASS TO INCREASING RATES OF GLYPHOSATE IN 2003, 2004 AND 2005. REGRESSION PARAMETERS ARE LISTED IN APPENDIX 6.3. BARS INDICATE STANDARD ERROR OF THE MEAN. 116

FIGURE 7.1. CUMULATIVE PROBABILITY DISTRIBUTIONS FOR PREDICTED RATES OF GLYPHOSATE RESISTANCE EVOLUTION FOR BARNYARD GRASS AND LIVERSEED GRASS UNDER THE 5 WEED MANAGEMENT REGIMES INVESTIGATED. INITIAL FREQUENCY OF RESISTANT ALLELES SET AT $1X10^{-8}$. NOTE THAT ALL CURVES ARE REPRESENTED; HOWEVER, RESISTANCE EVOLVED ONLY IN THE RR ONLY TREATMENT. 130

FIGURE 7.2. CUMULATIVE PROBABILITY DISTRIBUTIONS FOR PREDICTED RATES OF GLYPHOSATE RESISTANCE EVOLUTION FOR BARNYARD GRASS AND LIVERSEED GRASS UNDER THE 5 WEED MANAGEMENT REGIMES. INITIAL FREQUENCY OF RESISTANT ALLELES SET AT $1X10^{-6}$. 131

FIGURE 7.3. CUMULATIVE PROBABILITY DISTRIBUTIONS FOR PREDICTED RATES OF GLYPHOSATE RESISTANCE EVOLUTION FOR BARNYARD GRASS AND LIVERSEED GRASS FOR THE RR ONLY TREATMENT FOR A RANGE OF INITIAL RESISTANCE FREQUENCIES. 132

FIGURE 7.4. CUMULATIVE PROBABILITY DISTRIBUTIONS FOR PREDICTED RATES OF GLYPHOSATE RESISTANCE EVOLUTION FOR BARNYARD GRASS AND LIVERSEED GRASS FOR THE RR ONLY TREATMENT FOR A RANGE OF FITNESS PENALTIES. INITIAL FREQUENCY OF RESISTANT ALLELES IS $1X10^{-8}$. 133

TABLE OF PLATES

PLATE 4.2 IRRIGATION OF FIELD IN SYSTEMS EXPERIMENT. 81
PLATE 5.1. POLYCAGES WHERE THE EXPERIMENT EXAMINING THE GROWTH AND SEED PRODUCTION OF BARNYARDGRASS AND LIVERSEED GRASS WAS CONDUCTED IN 2003-04. .. 96
PLATE 5.2. FIELD WHERE THE EXPERIMENT EXAMINING THE GROWTH AND SEED PRODUCTION OF BARNYARDGRASS AND LIVERSEED GRASS WAS CONDUCTED IN 2004-05 (BARNYARDGRASS PLANTS ARE THE TALLER PLANTS IN THE MIDDLE OF THE PICTURE, WITH LIVERSEED GRASS PLANTS TO THE RIGHT). 96
PLATE 7.1 MICROSCOPE VIEW OF BARNYARDGRASS FLORETS ILLUSTRATING THE DEGREE TO WHICH STAMEN AND STIGMA ARE EXPOSED. 124
PLATE 7.2 MICROSCOPE VIEW OF LIVERSEED GRASS FLORETS ILLUSTRATING THE DEGREE TO WHICH STAMEN AND STIGMA ARE EXPOSED. 125

ABSTRACT

The introduction of glyphosate resistance into Australian cotton systems will have an effect on conventional weed management practices, the weed species present and the risk of glyphosate resistance evolving in weed species. Therefore, it is important that the effects of these management practices, particularly a potential reduction in Integrated Weed Management (IWM) practices, be examined to determine their impact on weed population dynamics and resistance selection.

The study began in 2003 with a survey of 40 growers in four major cotton growing regions in Australia to gain an understanding of how adoption of glyphosate resistance had influenced the weed spectrum, weed management practices and herbicide use after three years of glyphosate-resistant cotton being available. The 10 most common weeds reported on cotton fields were the same in glyphosate-resistant and conventional fields. In this survey, herbicide use patterns were altered by the adoption of glyphosate-resistant cotton with up to six times more glyphosate being applied and with 21% fewer growers applying pre-emergence herbicides in glyphosate-resistant cotton fields. Other weed control practices, such as the use of post-emergence herbicides, inter-row cultivation and hand hoeing, were only reduced marginally.

A systems experiment was conducted to determine differences in the population dynamics of *Echinochloa crus-galli* (barnyardgrass) and *Urochloa panicoides* (liverseed grass) under a range of weed management regimes in a glyphosate-resistant cotton system. These treatments ranged from a full IWM system to a system based soley on the use of glyphosate. The experiment investigated the effect of the treatments on the soil seed bank, weed germination patterns and weed numbers in the field. All applied treatments resulted in commercially acceptable control of the two grass weeds. However, the treatments containing soil-applied residual herbicides proved to be more effective over the period of the experiment. The treatment with a reduced residual herbicide program supplemented with glyphosate had a level of control similar to the full IWM treatments with less input, providing a more economical option. The effectiveness of these treatments in the long-term was examined in a simulation model to determine the likelihood of glyphosate resistance evolving using barnyardgrass and liverseed grass as model weeds.

Seed production and above-ground biomass of barnyardgrass and liverseed grass in competition with cotton were measured. In all experiments, seed production and biomass plant^{-1} decreased as weed density increased while seed production and biomass m^{-1} tended to increase. Seed production m^{-1} reached 40,000 and 60,000 for barnyardgrass and liverseed grass, respectively. In 2004-05, weeds were also planted 6 weeks and 12 weeks after the cotton was planted. Biomass and seed production of the two weeds planted 6 weeks after cotton were significantly reduced with seed production declining to 12,000 and 2,500 seeds m^{-1} row for barnyardgrass and liverseed grass, respectively. Weeds planted 12 weeks after cotton planting failed to emerge. This experiment highlighted the importance of early season weed control and effective management of weeds that are able to produce high seed numbers.

A glyphosate dose-mortality experiment was conducted in the field to determine levels of control of barnyardgrass and liverseed grass. Glyphosate provided effective control of both species with over 85% control when the rate applied was greater than 690 g ae ha^{-1}. Dose-mortality curves for both species were obtained for use in the glyphosate resistance model.

Data from the experimental work were combined to develop a glyphosate resistance model. Outputs from this model suggest that if glyphosate were used as the only form of weed control, resistance in weeds is likely to eventuate after 12 to 17 years, depending on the characteristics of the weed species, initial resistance gene frequencies and any associated fitness penalties. If glyphosate was used in conjunction with one other weed control method, resistance was delayed but not prevented. The simulations suggested that when a combination of weed control options was employed in addition to glyphosate, resistance would not evolve over the 30-year period of the simulation. These simulations underline the importance of an integrated strategy in weed management to prevent glyphosate resistance evolving from the use of glyphosate-resistant cotton. Current management conditions of growing glyphosate-resistant (Roundup Ready®) cotton should therefore prevent glyphosate resistance evolution.

Declaration of Originality

This work contains no material which has been accepted for the award of any other degree or diploma in any university or other tertiary institution and, to the best of my knowledge and belief contains no material previously published or written by any other person, except where due reference has been made in the text.

I give consent to this copy of my thesis, when deposited in the University Library, being made available in all forms of media, now or hereafter known.

Jeff Werth

Acknowledgments

There are a number of people whose time and effort have assisted me with the completion of this thesis. I would like to thank Ian Taylor for his guidance and direction for me to take a change of career and undertake this study, and for his role as a mentor and supervisor.

I am grateful to have had supervisors who were available and willing to provide support and guidance. Thanks to Chris Preston for his role as principle supervisor. Although he is very busy, he was always quick to respond on matters that needed attention. I also thank him for his assistance with university matters that were difficult for me as a remote student. I also thank Grant Roberts for his role as a supervisor and mentor on a regular basis and for his availability and willingness to provide input and direction. Thank you also to Jeanine Baker with her help on the modelling parts of the thesis and for being so quick to get chapters back to me.

I also wish to thank a number of people at the Australian Cotton Research Institute (ACRI) for their assistance. Thank you to Lewis Wilson for undertaking the role of replacement supervisor when Grant relocated. I also wish to thank Graham Charles whose insights into weed issues in the cotton industry have been appreciated.

Thank you also to those who helped me with some of the day-to-day operations. Thank you to Graham Skelton for his assistance in soil coring and hand-picking and ginning cotton, and Grant Mycin for his help soil coring. Thank you also to Clare Felton-Taylor and Darren Hodgsen for their assistance with a number of tedious tasks. A big thank you also to the farm staff at ACRI for the operations they carried out and the use of equipment.

I also thank the CRC's for Australian Weed Management, and the Cotton Catchment Communities CRC for their funding support.

Last, but not least, I thank my beautiful wife Dyahn for her unconditional support and her willingness to relocate to Narrabri and leave friends, family, house and job in order for me to undertake this study. Her love and support has given me the confidence to complete this thesis.