Strategic applications of nitrogen fertiliser to increase the yield and nitrogen use efficiency of wheat

A thesis submitted for the degree of Masters Of Agricultural Science

School of Agriculture, Food and Wine

The University of Adelaide

Peter Hooper

January 2010

TABLE OF CONTENTS

ABSTRACT ..... **v**

DECLARATION ..... **vii**

ACKNOWLEDGMENTS ..... **viii**

LIST OF FIGURES ..... **ix**

LIST OF TABLES ..... **xvii**

LIST OF ABBREVIATIONS ..... **xix**

1. General introduction **1**

2. Review of literature **6**

2.1 Introduction 6
2.2 Nitrogen use in southern Australia 7
2.2.1 The role of nitrogen fertiliser 7
2.2.2 Nitrogen fertiliser use in southern Australia 8
2.2.3 Grain yields in southern Australia 10
2.3 Nitrogen use efficiency 12
2.3.1 Definition of nitrogen use efficiency 12
2.3.2 Current NUE values 13
2.3.3 The physiological limit to NUE 14
2.4 Factors limiting NUE 19
2.4.1 High pre-anthesis water use 20
2.4.2 Storing water soluble carbohydrates 22
2.5 Methods for improving NUE 23
2.5.1 Increasing nitrogen uptake 24
2.5.2 Balancing pre-anthesis and post anthesis water-use 26
2.5.3 Reducing soil evaporation 28
2.5.4 Extending leaf area duration 30
2.5.5 Delayed applications of nitrogen fertiliser 30
2.5.5.1 Delayed nitrogen applications and NUE 31
2.5.5.2 Benefits of delayed nitrogen applications 32
2.6 Summary 36

3. General materials and method **37**

3.1 Introduction 37
3.2 Site descriptions 37
3.2.1 Soils 37
3.2.2 Climate 39
3.3 Agronomy 41
3.4 Sampling and measurement 42
3.5 Nitrogen use efficiency 44
3.6 Data analysis 44

3.7 Experimental treatments 45
3.8 Nitrogen application timing in relation to crop growth stage and rainfall 45

4. Grain yield, grain quality and NUE 50
4.1 Introduction 50
4.2 Method 51
4.3 Results 52
4.3.1 Grain yield 52
4.3.2 Grain protein 57
4.3.3 Total grain nitrogen 59
4.3.4 Screenings 62
4.3.5 Harvest index 63
4.3.6 Nitrogen harvest index 64
4.3.7 Agronomic efficiency 64
4.3.8 Apparent recovery 67
4.3.9 Physiological Efficiency 69
4.4 Discussion 71
4.5 Conclusion 77

5. Canopy development 78
5.1 Introduction 78
5.2 Method 79
5.3 Results 79
5.3.1 Dry matter 79
5.3.2 Total plant nitrogen 84
5.3.3 Total crop nitrogen uptake 89
5.3.4 Green Area Index 93
5.3.5 Light interception 101
5.4 Discussion 105
5.5 Conclusion 112

6. Yield formation and components 114
6.1 Introduction 114
6.2 Method 115
6.3 Results 115
6.3.1 Shoot number at stem elongation (GS30) 115
6.3.2 Head number and tiller mortality 119
6.3.3 Grain number 123
6.3.4 Individual grain weight 128
6.3.5 Grains per spike 132
6.3.6 Spikelets per head 135
6.3.7 Grains per spikelet 136
6.4 Discussion 138
6.5 Conclusion 144

7. Review of current nitrogen management research 145
7.1 Introduction 145
7.2 Nitrogen rate 146
7.3 Time of application 147

7.4 Plant density.....149

8. General discussion 153

9. REFERENCES 160

APPENDICES.....167

Appendix A: Grain yield, grain quality and NUE table of significance 167
Appendix B: Canopy development: Dry matter, Shoot N% and Total shoot N table of significance 168
Appendix C: Canopy development: Green area index and light interception table of significance 169
Appendix D: Yield formation and components table of significance.....170
Appendix E: the Zadoks cereal growth scale (Zadoks et al. 1974).....171

ABSTRACT

In southern Australia a large proportion of crop nitrogen requirements are usually applied early in the season, either just before or at sowing, or during the first 6-8 weeks after sowing. However, the time of greatest demand for nitrogen by wheat crops is during the stem-elongation phase when the crop is growing fastest, while early demand for nitrogen is small

The study utilised two field sites in South Australia (Hart and Mintaro) over two seasons (2003-04) to examine the effect of delayed applications of nitrogen fertiliser on nitrogen use efficiency (NUE) to dryland wheat. Treatments were applied to manipulate the crop canopy and to measure the balance between canopy size and structure and crop nitrogen uptake.

In both seasons and sites significant ($P<0.05$) grain yield increases were obtained by later nitrogen application times. Grain protein also increases with rate of applied nitrogen and delayed time of application, with the 1st node (GS31) treatment generally producing the highest values. Applying higher rates of nitrogen fertiliser reduced NUE, while later applications were able to increase NUE. Canopy manipulation was able to increase crop nitrogen uptake, coinciding with improved grain yield formation. Generally, the data suggest that the nitrogen taken up later in the season is used very efficiently by the crop.

The experiments outlined in this thesis showed that there is potential to improve NUE in dryland wheat grown in southern Australia, using tactical applications of nitrogen fertiliser.

DECLARATION

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 to Peter Hooper and, to the best of my knowledge and belief, contains no material previously published or written by another 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 for loan and photocopying, subject to the provisions of the Copyright Act 1968.

I also give permission for the digital version of my thesis to be made available on the web, via the University's digital research repository, the Library catalogue, the Australasian Digital Theses Program (ADTP) and also through web search engines, unless permission has been granted by the University to restrict access for a period of time.

Peter J Hooper

ACKNOWLEDGMENTS

I would like to especially thank my supervisors; David Coventry and Glenn McDonald (University of Adelaide) and Allan Mayfield (Allan Mayfield Consulting) for initiating the study and providing continued contribution and support. An input of technical expertise, experimental guidance, academic advice, editorial direction and comments are some of the numerous roles they performed, all of which were greatly appreciated.

I am grateful for the assistance I received from many researchers, technicians, agronomists and farmers from within Australia and overseas, the names of whom are too numerous to mention.

A special thanks goes to my parents and friends for their continual support and encouragement.

I also wish to thank the South Australian Grains Industry Trust for their financial support and the Hart Fieldsite Group for the provision of land and support. The use of data from Pivot fertiliser and various grower groups is also acknowledged.

LIST OF FIGURES

Figure 2.1. Seasonal pattern of nitrogen demand for wheat crops of high and low nitrogen status (Angus 2001). 7

Figure 2.2. Total nitrogen consumption (kt) in Australia. Source (ABARE 2009). 10

Figure 2.3. Five year moving average grain yield (t/ha) for Australia between 1969/70 and 2007/08. (ABARE 2009). 11

Figure 2.4. Trend in grain yield (t/ha) for the South East (●), Mid-North and Yorke Peninsula (■), Eyre Peninsula (▲) and state average (□) for South Australia (ABARE 2009). 11

Figure 2.5. Decreasing soil evaporation with higher ground cover at flowering (Angus and van Herwaarden 2001).....29

Figure 3.1. Nitrogen application timing shown as arrows in relation to rainfall events at Hart in 2003.....48

Figure 3.2. Nitrogen application timing shown as arrows in relation to rainfall events at Hart in 2004.....48

Figure 3.3. Nitrogen application timing shown as arrows in relation to rainfall events at Mintaro in 2003. 49

Figure 3.4. Nitrogen application timing shown as arrows in relation to rainfall events at Mintaro in 2004. 49

Figure 4.1. The grain yield response to nitrogen at Mintaro in a) 2003 and b) 2004. Values are the averages for Frame and H45 as the Variety x N treatment interaction was not significant. Symbols represent sowing (●); mid-tillering (■); 1st node (▲); T1+T2+T3 (+); T2+T3 (○); T2+T5 (□); T3+T4 (◊); T3+T5 (Δ). (LSDs [0.05] for nitrogen rate x timing are 0.14 for 2003 and 0.32 for 2004 at Mintaro). 53

Figure 4.2. The grain yield response to nitrogen at Hart for a) Frame and b) H45 in 2003. Symbols represent sowing (●); mid-tillering (■); 1st node (▲); T1+T2+T3 (+); T2+T3 (○); T2+T5 (□); T3+T4 (◊); T3+T5 (Δ). (LSD [0.05] for nitrogen rate x timing x variety is 0.38 in 2003 at Hart). 54

Figure 4.3. The grain yield response to nitrogen at Hart in 2004. Values are the averages for Frame and H45 as the Variety x N treatment interaction was not significant. Symbols represent sowing (●); mid-tillering (■); 1st node (▲); T1+T2+T3 (+); T2+T3 (○); T2+T5 (□); T3+T4 (◊); T3+T5 (Δ). (There were no significant differences (P<0.05) at Hart in 2004). 56

Figure 4.4. The relationship between grain protein and nitrogen rate for both Frame and H45 at Mintaro and Hart in 2003 and 2004. Symbols represent sowing (●); mid-tillering (■); 1st node (▲); T1+T2+T3 (+); T2+T3 (○); T2+T5 (□); T3+T4 (◊); T3+T5 (Δ). (LSDs [0.05] for nitrogen rate x timing are ns and 1.07 for Hart and Mintaro in 2003, and 0.74 and 0.91 for Hart and Mintaro for 2004). 58

Figure 4.5. The relationship between total grain nitrogen and nitrogen rate with application timing for both Frame and H45 at Mintaro in 2003 and 2004. Symbols represent sowing (●); mid-tillering (■); 1st node (▲); T1+T2+T3 (+); T2+T3 (○); T2+T5 (□); T3+T4 (◊); T3+T5 (Δ). (LSDs [0.05] for nitrogen rate x timing were 1.07 in 2003, and 0.91 for 2004). 61

Figure 4.6. The relationship between total grain nitrogen and nitrogen rate for both cultivars and all application timings at Mintaro in 2003 and 2004, and Hart 2003. Symbols represent Mintaro 2003 (●); Mintaro 2004 (■); Hart 2003 (▲). (LSDs [0.05] for nitrogen rate is 6.34 for Mintaro and ns for Hart in 2003, and 6.93 for Mintaro in 2004.) The dashed line represents 50% apparent recovery of applied fertiliser in the grain. 61

Figure 4.7. The relationship between physiological efficiency and grain protein at Mintaro for 100 kg N/ha in 2003 (●); 200 kg N/ha in 2003 (○); 100 kg N/ha in 2004 (■) or 200 kg N/ha in 2004 (△). 70

Figure 5.1 Dry matter production for nitrogen rate with days after sowing (DAS), between mid-tillering (GS22) and anthesis (GS65) (including maturity at Mintaro), averaged for the varieties Frame and H45 at a) Hart and b) Mintaro in 2003 and 2004. (LSDs [0.05] for nitrogen rate at Hart are 5.50, ns, and 51.7 in 2003, and ns in 2004. For Mintaro 5.50, 4.90, 81.5 and 51.5 in 2003, and 2.59, ns, 57.1 and 108.0 in 2004).....81

Figure 5.2. Dry matter production with nitrogen rate for Frame and H45 at Mintaro in 2003 and 2004 measured at a) mid-tillering (GS22) b)1st node (GS31). Symbols represent sowing (●), mid-tillering (■) and T1+T2+T3 (▲) in 2003, and sowing (○), mid-tillering (□) and T1+T2+T3 (Δ) in 2004. (LSDs [0.05] for nitrogen rate x timing in 2003 are 6.4 and 9.8 for GS22 and GS31 respectively, and for 2004 3.0 and 25.6 for GS22 and GS31 respectively). 82

Figure 5.3. Dry matter production with nitrogen rate and application timing for Frame and H45 at Mintaro in 2003 and 2004 measured at a) anthesis 2003 b) anthesis 2004 c) maturity 2003 d) maturity 2004. Symbols represent sowing (●); mid-tillering (■); 1st node (▲); T1+T2+T3 (+); T2 + T3 (○); T3 + T5 (Δ). (LSDs [0.05] for nitrogen rate x timing in 2003 are 107.8 and 68.2 for anthesis and maturity respectively, and for 2004 77.3 and 144.9 for anthesis and maturity respectively).....83

Figure 5.4. The relationship between dry matter production measured at anthesis and time of nitrogen application for 100 kg N/ha (●) and 200 kg N/ha (+) at Mintaro in 2003 and 2004. The treatments are the single applications of nitrogen at mid tillering (T2) and 1st node (T3). (LSDs [0.05] for nitrogen rate x timing are as per Figure 5.3).....84

Figure 5.5. Shoot nitrogen concentration for nitrogen rate and days after sowing, across all varieties and application timings. Symbols represent Hart 0 kg N/ha (●); Hart 40 kg N/ha (■); Hart 80 kg N/ha (▲); Mintaro 0 kg N/ha (○); Mintaro 100 kg N/ha (□); Mintaro 200 kg N/ha (Δ). 85

Figure 5.6. The effect of fertiliser rate on the shoot nitrogen content (%) at different growth stages at Mintaro in 2004. The data are the averages across all varieties and applications timings. Symbols represent mid-tillering (GS22) (●); 1st node (GS31) (■); 1st awn emergence (GS49) (▲); anthesis (GS65) (○); maturity (□). (LSDs [0.05] for nitrogen rate are 0.12, 0.27, 0.13, 0.17 and 0.08 for GS22, GS31, GS49, anthesis and maturity respectively).....87

Figure 5.7. The effect of nitrogen fertiliser rate on shoot nitrogen content (%) at 1st node (GS31) averaged across both varieties at Hart in 2003. Symbols represent sowing (●); sowing + mid-tillering + 1st node split (▲); mid-tillering (GS22)(■). (LSDs [0.05] for nitrogen rate x timing is 0.31)....88

Figure 5.8. The effect of nitrogen fertiliser rate and time of application on the shoot nitrogen content (%) at awn emergence (GS49), averaged across both varieties at Mintaro in 2004. Symbols represent sowing (●); sowing + mid-tillering + 1st node split (+); 1st node (GS31)(▲); T2 + T3 (○). (LSDs [0.05] for nitrogen rate x timing is 0.16 for Mintaro in 2004)....88

Figure 5.9. The effect of nitrogen rate and time of application on shoot nitrogen content (%) at anthesis (GS65), averaged across all varieties at a) Hart in 2003 and b) Mintaro in 2004. Symbols represent sowing (●); sowing + mid-tillering + 1st node split (+); mid-tillering (GS22)(■); 1st node (GS31)(▲); T1+T2 (◊); T2 + T3 (○); T3 + T5 (Δ). (LSDs [0.05] for nitrogen rate x timing are 0.16 for Hart in 2003, and 0.23 for Mintaro in 2004).....89

Figure 5.10. Total plant nitrogen content between mid-tillering (GS22) and anthesis (GS65) averaged for all varieties, timings and nitrogen rates at Mintaro 2003 (●); Hart 2003 (○); Mintaro 2004 (■); Hart 2004 (□). 91

Figure 5.11. The effect of fertiliser nitrogen rate on total plant nitrogen content averaged for all timings and varieties at a) Mintaro and b) Hart in 2003 and 2004 measured at different growth stages. For 2003 symbols represent mid-tillering (GS22) (■); 1st node (GS31)(▲); anthesis (●), and for 2004 mid-tillering (□); 1st node (Δ); anthesis (○). (LSDs [0.05] for nitrogen rate x timing at Hart are ns, ns, and 14.9 for GS22, GS31 and anthesis respectively, in 2003, and 8.35 for anthesis in 2004. At Mintaro the LSDs are 3.1, 3.6 and 25.2 at GS22, GS31 and anthesis respectively for 2003 and 1.6, 8.3 and 10.9 at GS22, GS31 and anthesis respectively for 2004).....91

Figure 5.12. Total plant nitrogen (kg/ha) and nitrogen applied (kg N/ha) for application timing at 1st node (GS31), averaged for both Frame and H45 at Mintaro in a) 2003 and b) 2004. Symbols represent sowing (●); mid-tillering (■); T1+T2+T3 (+). (LSDs [0.05] for nitrogen rate x timing are 10.8 for 2003, and 4.5 for 2004). 92

Figure 5.13. Total plant nitrogen (kg/ha) and nitrogen applied (kg N/ha) for application timing at anthesis, averaged for both Frame and H45 at Mintaro in a) 2003 and b) 2004. Symbols represent sowing (●); mid-tillering (GS22)(■); T1+T2+T3 (+);1st node (GS31)(▲); T1 + T2 (□); T2 + T3 (○); T3 + T5 (Δ). (LSDs [0.05] for nitrogen rate x timing are ns for 2003, and 14.7 for 2004). 93

Figure 5.14. Change in GAI with days after sowing until anthesis (GS65) for both Frame and H45 at a) Mintaro and b) Hart for 2003 and 2004. Symbols represent Frame 2003 (●); H45 2003 (■); Frame 2004 (○); H45 2004 (□).The solid black line is GAI=3.5, which is approx 90% light interception. 94

Figure 5.15. GAI and nitrogen applied (kg N/ha) at Hart, measured at a) 1st node (GS31) or b) 1st awn emergence (GS49) for Frame and H45 in 2003. Symbols represent sowing (●); mid-tillering (■); 1st node (GS31)(▲); T2 + T3 (○); T1+T2+T3 (+); T2 + T5 (□). Solid line represents Frame and dashed line H45. (LSDs [0.05] for nitrogen rate x timing are ns for GS31, and 0.92 for GS49). 95

Figure 5.16. GAI and nitrogen applied (kg N/ha) at Mintaro, measured at a) 1st node (GS31) or b) 1st awn emergence (GS49) in 2003 or tip of flag (GS37) in 2004, for Frame and H45. Symbols represent sowing (●); mid-tillering (■); 1st node (GS31)(▲); T2 + T3 (○); T1+T2+T3 (+); T2 + T5 (□). Solid line represents 2003 and dashed line 2004. (LSDs [0.05] for nitrogen rate x timing are 0.19 and 0.41 for GS31 in 2003 and 2004, and ns and 0.34 for GS49 and GS37 in 2003 and 2004). 97

Figure 5.17. GAI and nitrogen applied (kg N/ha) at Mintaro, measured at anthesis, for Frame and H45. Symbols represent sowing (●); mid-tillering (■); 1st node (GS31)(▲); T2 + T3 (○); T1+T2+T3 (+); T2 + T5 (□); T3 + T5 (△). Solid line represents 2003 and dashed line 2004. (LSDs [0.05] for nitrogen rate x timing are 0.28 for 2003 and 0.19 for 2004). 98

Figure 5.18. The relationship between green area index and dry matter (grams per square metre) measured at 1st node (GS31), averaged for variety, nitrogen rate and timing, at Hart 2003 (◊), Mintaro 2003 (●) and Mintaro 2004 (■).....99

Figure 5.19. The relationship between green area index at GS49 in 2003 or GS37 in 2004 and dry matter (grams per square metre) at anthesis, averaged for variety, nitrogen rate and timing, at Hart 2003 (◊), Mintaro 2003 (●) and Mintaro 2004 (■). 99

Figure 5.20. The relationship between green area index and total crop nitrogen (kg N/ha) measured at 1st node (GS31), averaged for variety, nitrogen rate and timing, at Hart 2003 (◊), Mintaro 2003 (●) and Mintaro 2004 (■). 100

Figure 5.21. The relationship between green area index and total crop nitrogen (kg N/ha) measured at anthesis (GS65), averaged for variety, nitrogen rate and timing, at Hart 2003 (◊), Mintaro 2003 (●) and Mintaro 2004 (■). 100

Figure 5.22. Change in light interception with days after sowing until anthesis (GS65) for both Frame and H45, averaged for nitrogen rate and timing at a) Mintaro in 2003 and 2004 and b) Hart for 2003. Symbols represent Frame 2003 (●); H45 2003 (■); Frame 2004 (○); H45 2004 (□).....102

Figure 5.23. Light interception and nitrogen applied (kg N/ha) at Mintaro, measured at mid-tillering (GS22), for Frame and H45. Symbols represent sowing (●); mid-tillering (■); 1st node (GS31)(▲); T2 + T3 (○); T1+T2+T3 (+); T2 + T5 (□); T3 + T5 (△). Solid line represents 2003 and dashed line 2004. (LSDs [0.05] for nitrogen rate x timing are ns for 2003 and ns for 2004).....102

Figure 5.24. Light interception and nitrogen applied (kg N/ha) at Mintaro, measured at GS31, for Frame and H45. Symbols represent sowing (●); mid-tillering (■); 1st node (GS31)(▲); T2 + T3 (○); T1+T2+T3 (+); T2 + T5 (□); T3 + T5 (△). Solid line represents 2003 and dashed line 2004. (LSDs [0.05] for nitrogen rate x timing are 8.74 for 2003 and 7.78 for 2004). 103

Figure 5.25. Light interception and nitrogen applied (kg N/ha) at Mintaro, measured at GS49 in 2003 and GS37 in 2004, for Frame and H45. Symbols represent sowing (●); mid-tillering (■); 1st node (GS31)(▲); T2 + T3 (○); T1+T2+T3 (+); T2 + T5 (□); T3 + T5 (△). Solid line represents 2003 and dashed line 2004. (LSDs [0.05] for nitrogen rate x timing are ns for 2003 and 2.84 for 2004).....104

Figure 5.26. Light interception and nitrogen applied (kg N/ha) at Mintaro, measured at anthesis, for Frame and H45. Symbols represent sowing (●); mid-tillering (■); 1st node (GS31)(▲); T2 + T3 (○); T1+T2+T3 (+); T2 + T5 (□); T3 + T5 (△). Solid line represents 2003 and dashed line 2004. (LSDs [0.05] for nitrogen rate x timing are 2.89 for 2003 and 3.80 for 2004). 105

Figure 6.1. The effect of nitrogen rate on shoot number at stem elongation (GS30) for Frame and H45 for all application timing treatments at Hart in 2003 (+); Hart in 2004 (●); Mintaro in 2003 (■) and Mintaro in 2004 (▲). (LSDs [0.05] for nitrogen rate are ns for Hart in 2003, ns for Hart in 2004, 67 for Mintaro 2003 and 97.5 for Mintaro 2004).....116

Figure 6.2. The effect of nitrogen rate and application timing on shoot number (GS30) at Mintaro in a) 2003 and b) 2004. Symbols represent sowing (●); mid-tillering (■); 1st node (▲); T1+T2+T3 (+); T2+T3 (○); and T2+T5 (Δ). (LSDs [0.05] for nitrogen rate x timing are 86.5 for 2003 and 132.4 for 2004). 117

Figure 6.3. Relationship between shoot number at stem elongation (GS30) and total plant nitrogen uptake at 1st node (GS31) for both varieties at Hart in 2003 (○); Mintaro in 2003 (●); and Mintaro in 2004 (■).....117

Figure 6.4. Relationship between shoot number at stem elongation (GS30) and GAI at 1st node (GS31) for both varieties at Hart in 2003 (○); Mintaro in 2003 (●); and Mintaro in 2004 (■).....118

Figure 6.5. Relationship between grain yield response and shoot number at stem elongation (GS30) to either 40 or 100 kg N/ha for both varieties at Hart in 2003 (○); Mintaro in 2003 (●); Hart in 2004 (□) and Mintaro in 2004 (■).....118

Figure 6.6. The effect of nitrogen rate and application timing on head number at Hart in a) 2003 and b) 2004. Symbols represent sowing (●); mid-tillering (■); 1st node (▲); T1+T2+T3 (+); T2+T3 (○); T2+T5 (Δ); T3 + T4 (□); T3 + T5 (◆).(LSDs [0.05] for nitrogen rate x timing at Hart in 2003 and 2004 are ns). 120

Figure 6.7. The effect of nitrogen rate and application timing on head number at Mintaro in a) 2003 and b) 2004. Symbols represent sowing (●); mid-tillering (■); 1st node (▲); T1+T2+T3 (+); T2+T3 (○); T2+T5 (Δ); T3 + T4 (□); T3 + T5 (◆).(LSDs [0.05] for nitrogen rate x timing at Mintaro in 2003 are 47.8 and 64.0 in 2004). 121

Figure 6.8. Relationship between shoot number and head number for both varieties at Hart in 2003 (○); Mintaro in 2003 (●); Hart in 2004 (□) and Mintaro in 2004 (■). 121

Figure 6.9. Shoot mortality (%) for both Frame and H45 at Mintaro in a) 2003 and b) 2004. Symbols represent sowing (●); mid-tillering (■); 1st node (▲); T1+T2+T3 (+); T2+T3 (○); T2+T5 (Δ); T3 + T4 (□); T3 + T5 (◆). (LSDs [0.05] for nitrogen rate x timing are 11.1 % for 2003, and 18.6 % for 2004). 122

Figure 6.10. Relationship between shoot number and shoot mortality for both varieties at Hart in 2003 (○); Mintaro in 2003 (●); Hart in 2004 (□) and Mintaro in 2004 (■). 123

Figure 6.11. The response of grain number (grains/m^2) to nitrogen rate and application timing for both Frame and H45 at Hart in a) 2003 and b) 2004. Symbols represent sowing (●); mid-tillering (■); 1st node (▲); T1+T2+T3 (+); T2 + T3 (○); T2 + T5 (Δ). (LSDs [0.05] for nitrogen rate x timing are ns for 2003, and 802 for 2004). 124

Figure 6.12. The response of grain number (grains per square metre) with nitrogen rate for both Frame and H45 at a) Hart and b) Mintaro. Symbols represent Hart 2003 (●); Hart 2004 (■); Mintaro 2003 (▲); Mintaro 2004 (+). (LSDs [0.05] for nitrogen rate x timing are 767 for Hart 2003, ns for Hart 2004, 505 for Mintaro 2003 and 1357 for Mintaro 2004). 125

Figure 6.13. The response of grain number to nitrogen rate and application timing for a) Frame and b) H45 at Hart in 2003. Symbols represent sowing (●); mid-tillering (■); 1st node (▲); T1+T2+T3 (+); T2 + T3 (○); T2 + T5 (Δ). (LSDs [0.05] is 1434 for the variety x rate x timing interaction). 125

Figure 6.14. The response of grain number (grains per square metre) to nitrogen rate and application timing for both Frame and H45 at Mintaro in a) 2003 and b) 2004. Symbols represent sowing (●); mid-tillering (■); 1st node (▲); T1+T2+T3 (+); T2 + T3 (○); T2 + T5 (Δ). (LSDs [0.05] for nitrogen rate x timing are 668 for 2003, and ns for 2004). 127

Figure 6.15. Relationship between grains/m^2 and grain yield for variety, nitrogen rate and timing at Hart in 2003 (○); Mintaro in 2003 (●); Hart in 2004 (□) and Mintaro in 2004 (■). 127

Figure 6.16. Relationship between green area index at anthesis in 2003 and flag leaf emergence (GS37) in 2004 and grain number for variety, nitrogen rate and timing at Hart in 2003 (○); Mintaro in 2003 (●) and Mintaro in 2004 (■). 128

Figure 6.17. Grain weight (mg) for Frame and H45 at a) Hart and b) Mintaro in 2003 and 2004. Symbols represent Frame in 2003 (●); H45 in 2003 (■); Frame in 2004 (▲) and H45 in 2004 (+). (LSDs [0.05] for nitrogen rate x timing at Hart are ns in 2003 and 2004 and at Mintaro are ns in 2003 and 1.8 in 2004). 129

Figure 6.18. Grain weight (mg) for Frame and H45 at Mintaro in a) 2003 and b) 2004. Symbols represent sowing (●); mid-tillering (■); 1st node (▲); T1+T2+T3 (+); T2 + T3 (○); T2 + T5 (Δ). (LSDs [0.05] for nitrogen rate x timing are 1.67 for 2003, and 2.33 for 2004).....130

Figure 6.19. The relationship between grain weight and grain number for both varieties at Hart in 2003 (○); Mintaro in 2003 (●) and Mintaro in 2004 (■).....131

Figure 6.20. The relationship between light interception, at anthesis, and grain weight for both varieties at Hart in 2003 (○); Mintaro in 2003 (●); Hart in 2004 (□); and Mintaro in 2004 (■).....131

Figure 6.21. The response of grains per spike with nitrogen rate and application timing for Frame and H45 at Hart in a) 2003 and b) 2004. Symbols represent sowing (●); mid-tillering (■); 1st node (▲); T1+T2+T3 (+); T2 + T3 (○); T2 + T5 (Δ). (LSDs [0.05] for nitrogen rate x timing are ns for 2003, and 4.15 for 2004). 133

Figure 6.22. The relationship between head number and grains per spike at Hart in 2003 for H45 (●) and Frame (○), r = -0.92.....133

Figure 6.23. The relationship between head number and grains per spike at Mintaro for Frame in 2003 (●); H45 in 2003 (○); Frame in 2004 (■) and H45 in 2004 (□).....134

Figure 6.24. The relationship between grain number and grains per spike for both varieties at Hart in 2003 (○); Mintaro in 2003 (●); Hart in 2004 (□) and Mintaro in 2004 (■).....134

Figure 6.25. Relationship between grains per spike and light interception measured at anthesis for both varieties at Hart in 2003 (○); Mintaro in 2003 (●); Hart in 2004 (□) and Mintaro in 2004 (■).....135

Figure 6.26. The relationship between grain number and spikelets per head for both varieties at Hart in 2003 (○); Mintaro in 2003 (●) and Mintaro in 2004 (■).....136

Figure 6.27. The relationship between grain number and grains per spike for both varieties at Hart in 2003 (○); Mintaro in 2003 (●); Hart in 2004 (□) and Mintaro in 2004 (■).....137

Figure 6.28. The relationship between grains per spikelet and head number for both varieties at Hart in 2003 (○); Mintaro in 2003 (●) and Mintaro in 2004 (■).....138

LIST OF TABLES

Table 2.1a. A selection of rain-fed trials on wheat conducted in South Australia between 1981 and 2008. 15

Table 2.1b. A selection of rain-fed trials on wheat conducted in South Australia between 1981 and 2008. 16

Table 2.2a. A selection of rainfed trials on wheat conducted outside South Australia between 1981 and 2008. 17

Table 2.2b. A selection of rainfed trials on wheat conducted outside South Australia between 1981 and 2008. 18

Table 2.3. Comparison of the effects of 1 mm of evapotranspiration (ET) before or after anthesis on biomass production of low (no applied N) and high (80 kg N ha^{-1}) wheat crops (Angus and van Herwaarden 2001) 27

Table 3.1. Soil descriptions for three sample horizons for each trial site. 38

Table 3.3. Annual rainfall for 2003 and 2004 and the long term average rainfall (mm) for Hart and Mintaro sites, including the growing season (April-October) sub-total and long-term averages. 38

Table 3.2. Pre-sowing soil mineral nitrogen (kg/ha) (nitrate + ammonium) and total soil moisture (mm) for each site. 39

Table 3.4. Average monthly maximum and minimum temperatures (°C) for 2003, 2004 and the long term average at Hart and Mintaro trial sites 40

Table 3.5. Rain and temperature conditions compared to long term averages for key stages of the growing season at Hart and Mintaro during 2003 and 2004. 41

Table 3.6 The nitrogen treatments used at Hart 2003. The values are the percentage of the nitrogen applied at the specified growth stage and either 40 kg N/ha or 80 kg N/ha were applied at each treatment. 46

Table 3.7. The nitrogen treatments used at Mintaro 2003. The values are the percentage of the nitrogen applied at the specified growth stage and either 100 kg N/ha or 200 kg N/ha were applied at each treatment. 46

Table 3.8. Additional nitrogen treatments included at Hart 2004. The values are the percentage of the nitrogen applied at the specified growth stage and either 40 kg N/ha or 80 kg N/ha were applied at each treatment. 47

Table 3.9. The additional nitrogen treatments included at Mintaro 2004. The values are the percentage of the nitrogen applied at the specified growth stage and either 100 kg N/ha or 200 kg N/ha were applied at each treatment. 47

Table 3.10. Nitrogen application timing, days after sowing (DAS) and corresponding crop growth stages at Hart. 48

Table 3.11. Nitrogen application timing, days after sowing (DAS) and corresponding crop growth stages at Mintaro. 49

Table 4.1. Grain yield (t/ha) and nitrogen rate (kg N/ha) for both Frame and H45 at Mintaro and Hart in 2003 and 2004. Values for the control treatments are 2.24 and 2.68 for 2003 and 2004 at Mintaro, and 2.38 and 0.73 for 2003 and 2004 at Hart. 56

Table 4.2. Grain protein and nitrogen rate for both Frame and H45 at Mintaro and Hart in 2003 and 2004. Values for the control treatments are 8.5 and 7.0% for 2003 and 2004 at Mintaro, and 9.46 and 11.8% for 2003 and 2004 at Hart. 59

Table 4.3. Screenings (%) for variety (H45 and Frame) and nitrogen rate at Hart and Mintaro in 2003 and 2004. 62

Table 4.4. Harvest index (%) for variety and nitrogen rate at Hart and Mintaro in 2003 and 2004. 63

Table 4.5. Nitrogen harvest index (%) for nitrogen rate and timing at Mintaro in 2003 and 2004. Values are an average of Frame and H45. Values for the control treatments were 78.2 in 2003 and 71.5 in 2004 at Mintaro. 65

Table 4.6. Agronomic efficiency (kg/kg) for nitrogen timing and rate (kg N/ha) at Hart and Mintaro in 2003 and 2004. The values are an average of Frame and H45. 66

Table 4.7. The agronomic efficiency (kg/kg) of Frame and H45 wheat at 40 kg N/ha with nitrogen timing, at Hart in 2003. 67

Table 4.8. Apparent recovery (%) and nitrogen fertiliser application timing, averaged for variety and nitrogen rate at Hart and Mintaro in 2003 and 2004. 68

Table 4.9. Physiological efficiency (kg/kg) for nitrogen timing and rate at Hart and Mintaro in 2003 and 2004. The values are an average of Frame and H45. 70

Table 7a. Trial results for nitrogen management trials[1] conducted across Southern Australia between 2002 and 2008 in wheat. 151

Table 7b. Trial results for nitrogen management trials[1] conducted across Southern Australia between 2002 and 2008 in wheat. 152

LIST OF ABBREVIATIONS

AE	Agronomic efficiency
ANOVA	Analysis of variance
AR	Apparent recovery
DAS	Days after sowing
ET	Evapotranspiration
GAI	Green area index
HI	Harvest index
LAD	Leaf area duration
LAI	Leaf area index
LI	Light interception
LSD	Least significant difference
NHI	Nitrogen harvest index
NUE	Nitrogen use efficiency
PE	Physiological efficiency
WSC	Water soluble carbohydrate
WUE	Water use efficiency