

Copyright is owned by the Author of the thesis. Permission is given for a copy to be downloaded by an individual for the purpose of research and private study only. The thesis may not be reproduced elsewhere without the permission of the Author.

**EFFECT OF ROOTZONE COMPOSITION AND
CULTIVATION/AERATION TREATMENT ON
THE PERFORMANCE OF GOLF GREENS
UNDER NEW ZEALAND CONDITIONS**

**A thesis submitted in partial fulfilment
of the requirements for the degree of
Doctor of Philosophy in Turfgrass Science
at Massey University
New Zealand**

Cunqi Liu

2004

DECLARATION

This is to certify that the research carried out for my Doctoral thesis entitled "EFFECT OF ROOTZONE COMPOSITION AND CULTIVATION/AERATION TREATMENT ON THE PERFORMANCE OF GOLF GREENS UNDER NEW ZEALAND CONDITIONS" in the Institute of Natural Resources, Massey University, Palmerston North, New Zealand is my own work and that the thesis material has not been used in part or in whole for any other qualification.

Cunqi Liu

Cunqi Liu

PhD Candidate

Date: 02/08/04

DECLARATION

This is to certify that the research carried out in the Doctoral thesis entitled "EFFECT OF ROOTZONE COMPOSITION AND CULTIVATION/AERATION TREATMENT ON THE PERFORMANCE OF GOLF GREENS UNDER NEW ZEALAND CONDITIONS" was done by Cunqi Liu in the Institute of Natural Resources, Massey University, Palmerston North, New Zealand. The thesis material has not been used in part or in whole for any other qualification, and I confirm that the candidate has pursued the course of study in accordance with the requirements of the Massey University regulations.

Professor Peter D. Kemp

Chief Supervisor 

Date: 3/8/2004

Dr. Richard J. Gibbs
Co-supervisor



Date: 2/8/04

Martin P. Wrigley
Co-supervisor

Date: 3/8/04



CERTIFICATE OF REGULATORY COMPLANCE

This is to certify that the research carried out for the Doctoral thesis entitled EFFECT OF ROOTZONE COMPOSITION AND CULTIVATION/AERATION TREATMENT ON THE PERFORMANCE OF GOLF GREENS UNDER NEW ZEALAND CONDITIONS in the Institute of Natural Resources at Massey University, New Zealand:

- (a) is the original work of the candidate, except as indicated by appropriate attribution in the text and/or in the acknowledgements;
- (b) that the text, excluding appendices/annexes, does not exceed 100,000 words;
- (c) all the ethical requirements applicable to this study have been complied with as required by Massey University, other organisations and/or committees (the New Zealand Sports Turf Institute), which had a particular association with this study, and relevant legislation.

Cunqi Liu *Cunqi Liu*
PhD Candidate
Date: 02/08/04

Professor Peter D. Kemp
Chief Supervisor *P.D. Kemp*
Date: 3/8/2004

Dr. Richard J. Gibbs *R.J. Gibbs*
Co-supervisor
Date: 2/8/04

Martin P. Wrigley
Co-supervisor
Date: 3/8/04 *M. Wrigley*

EFFECT OF ROOTZONE COMPOSITION AND CULTIVATION/AERATION TREATMENT ON THE PERFORMANCE OF GOLF GREENS UNDER NEW ZEALAND CONDITIONS

Cunqi Liu, *Institute of Natural Resources, Massey University, Palmerston North, New Zealand*

ABSTRACT

The performance of golf greens in terms of rootzone physical properties, sward characteristics and playing quality is highly dependent upon the original rootzone composition and subsequent management. Such performance also continuously changes with time under usage. A study to this performance was conducted from April 1998 to January 2003 at the research site of the New Zealand Sports Turf Institute. This thesis reports results of both the field measurements made of rootzone physical properties, sward characteristics and playing quality of five alternative golf green rootzones during the first five years after sowing, and of the simulation modeling of their performance predicted for the first 30 years after sowing. Rootzone treatments were partially amended sand rootzone, soil rootzone, pure sand rootzone, fully amended sand rootzone, and partially amended sand + zeolite rootzone. A split-plot design was superimposed on the rootzone treatments consisting of twice-yearly cultivation/aeration treatments (control, HydroJect, scarification and Verti-drain).

Results showed that performance of golf greens could be objectively, quantitatively and comprehensively assessed and monitored over the long-term at the rootzone level by using an Integrated Rate Methodology (IRM) model through computing the Comprehensive Golf Green Performance Index (CGGP_I).

The performance of golf greens showed a gradual improvement during the first two years after sowing. It then deteriorated progressively over the remainder of the 30 years predicted for all rootzone and cultivation/aeration treatments. This general trend was reflected mainly by a gradual decrease with time in water infiltration rate, oxygen diffusion rate, air-filled porosity and deep rooting. Also, there was a gradual increase in green speed, surface hardness, root mass and organic matter content near the surface profiles. By the 14th and 27th year after sowing, the IRM model predicted that the

CGGP_I for all the three amended sand rootzones and the pure sand rootzone were below the minimum acceptable threshold.

The key factor that caused the general deterioration in green performance of all the sand-based rootzones appeared to be excess accumulation of organic matter in the surface of the profiles.

Whilst there were marked differences in the performance of golf greens between the rootzone types, it was only the conventional soil rootzone that consistently performed unacceptably. Quantitative benefits of upgrading from a soil-based to a sand-based rootzone were evident in terms of improved infiltration rate, increased oxygen diffusion rate and macroporosity, reduced organic matter accumulation near the surface, better root growth and distribution, more stable turfgrass sward, lower weed cover and less fluctuation with seasons in surface hardness.

Among the four sand-based rootzones, the pure sand rootzone had the highest incidence of dry patch disorder, poorest turf visual quality, greatest changes over time in the relative balance of *Festuca* and *Agrostis*, and largest fluctuation with seasons in surface hardness. However, it contained the best root growth distribution. After the fifth year from sowing, the green performance of the pure sand rootzone remained significantly better than the three amended sand rootzones.

There was negligible difference in the performance of golf greens between the three amended sand rootzones on all measured or predicted occasions. The supposed benefits of burying a zeolite-amended sand layer at 100-200 mm depth, ostensibly for encouraging deep rooting, were not apparent under the experimental conditions used, possibly because the experimental plots were never managed under nutrient or moisture stress conditions.

Beneficial effects of twice-yearly cultivation/aeration treatments on rootzone physical properties, sward characteristics and playing quality were evident, although these effects were extremely short-lived. Verti-drain treatment with hollow tines tended to be most effective in controlling surface organic matter accumulation and the resultant rootzone physical deterioration. In contrast, the scarification treatment gave variable response, reducing root mass, hence organic matter accumulation, near the surface on the one hand, but on the other decreasing infiltration rate and turfgrass cover.

HydroJect treatment, although tending to induce a higher incidence of disease and pest damage, appeared particularly effective in minimizing the occurrence of dry patch disorder on sand-based rootzones when used in conjunction with a proprietary wetting agent. None of the cultivation/aeration treatments could effectively halt the general deterioration with time in the performance of golf greens under the twice-yearly treatment frequency used. It was concluded that:

- (a) The performance of sand-based rootzones for golf greens will be limited in the long term by excess accumulation of organic matter near the surface of the profile;
- (b) Cultivation/aeration treatments will need to commence immediately after full turf establishment and should be carried out more than twice per year on golf greens under New Zealand conditions;
- (c) HydroJect treatment, when used in conjunction with wetting agent application, is an effective management tool for prevention of dry patch disorder on sand-based golf greens; while scarification should not be used in isolation of other physical cultivation;
- (d) Upgrading from a conventional soil rootzone to a high-grade, sand-based rootzone will greatly improve golf green performance;
- (e) The practice of constructing only the top 100 mm of the sand rootzone with organic-amended sand is an alternative method that can be used successfully for putting green construction instead of the fully amended, standard USGA-type profile; the pure sand rootzone system is also an appropriate alternative for rootzone construction of golf greens, provided the initial establishment can be managed successfully;
- (f) The integrated rate modeling approach is potentially an effective decision-making tool for rootzone upgrading, surface preparation planning, performance assessment and monitoring, professional consultancy, and seasonal management of golf greens.

KEYWORDS: Comprehensive Golf Green Performance Index (CGGP_I), compost, golf green construction, HydroJect, Integrated Rate Methodology (IRM) model, playing quality, pure sand, rootzone physical properties, sward characteristics, scarification, Verti-drain and zeolite.

ACKNOWLEDGEMENTS

My sincere thanks go to my chief supervisor, Associate Professor Peter D. Kemp, for his great supervision, warm guidance, advice and patience throughout this study, and to my co-supervisors, Dr. Richard J. Gibbs (formerly Scientific Services Manager of the New Zealand Sports Turf Institute, but now Manager of Sports Surface Design & Management Division, Recreational Services, Auckland, New Zealand) and Martin P. Wrigley, for their enthusiastic encouragement, constructive suggestions, critical comments and friendly help on experimental design, proposals, conduct, thesis writing and financial assistance, which made this study productive as well as possible.

I would like to express my special thanks to Prof. John Hodgson and Keith W. McAuliffe (CEO, the New Zealand Sports Turf Institute, Palmerston North) for their invaluable suggestions and critical comments on the validation of the mathematical model used in this thesis; to Dr. Ian L. Gordon for his generosity in sharing his knowledge and critical advice on data interpretation and statistical analysis; to Mr. John Dando (Landcare Research, Palmerston North) for his assistance on the measurement of Oxygen Diffusion rate.

My deep gratefulness is extended to the New Zealand Sports Turf Institute (NZSTI) for employing me on a part-time basis during this study; to the Toro Foundation, New Zealand Golf Association and the NZSTI for partial funding of this research project; and to the financial assistance from Massey University through a Helen E. Akers PhD Scholarship, Professor Ren Jizhou Scholarship and Sports Turf Bursary for this study.

Many thanks to current and former staff of the NZSTI for their friendship and help during this study, in particular Brendan Hannan, Edward Hall, the late Mark Williams, Mark Hooker, Spencer Myer and Tom Ragg, for constructing and managing the plots. I wish to thank all other persons who offered assistance to me during this study but who have not been individually named here.

Lastly, my immense appreciation is to my parents for their lifetime education and support, to my wife Jianhua Qin for her encouragement and support in many ways, and to my son Xuchang Liu and my daughter Katie Liu, who always brings us cheer and happiness.

STRUCTURE OF THESIS

All chapters in this thesis, except Chapter One (Introduction), Two (Review of the Literature), Three (Materials and Methods), Eight (General Discussion) and Nine (Conclusions), are based on a series of papers that have been published or submitted for publication. The two papers in Chapter Seven (model section), which have been submitted for publication, are presented here as scientific papers but in thesis format. These two submitted papers are saved in the supplied disc in the appendix. The references relevant to individual chapters are at the end of each chapter. All the materials and methods used in this research are integrated into one chapter (Chapter Three) due to the similarity. The results are discussed in detail in each experimental chapter and integrated into a general discussion in Chapter Eight. The main findings from the research in this thesis are summarized separately in Chapter Nine.

TABLE OF CONTENTS

ABSTRACT.....	<i>i</i>
ACKNOWLEDGEMENTS	<i>iv</i>
STRUCTURE OF THESIS.....	<i>v</i>
TABLE OF CONTENTS.....	<i>vi</i>
LIST OF TABLES.....	<i>xi</i>
LIST OF APPENDIX TABLES.....	<i>xii</i>
LIST OF FIGURES.....	<i>xiii</i>
LIST OF APPENDIX FIGURES.....	<i>xv</i>
 1. INTRODUCTION.....	 <i>1</i>
1.1 INTRODUCTION.....	<i>2</i>
1.2 REFERENCES.....	<i>5</i>
 2. REVIEW OF THE LITERATURE.....	 <i>8</i>
2.1 INTRODUCTION.....	<i>9</i>
2.2 EFFECT OF ROOTZONE COMPOSITION AND	
CULTIVATION/AERATION TREATMENT ON ROOTZONE PHYSICAL	
PROPERTIES OF GOLF GREENS.....	<i>10</i>
2.2.1 Background and overview	<i>10</i>
2.2.2 Effect of rootzone composition on rootzone physical properties of golf greens	
.....	<i>13</i>
2.2.2.1 Water infiltration rate (IR).....	<i>13</i>
2.2.2.2 Oxygen diffusion rate (ODR)	<i>14</i>
2.2.2.3 Rootzone porosity.....	<i>15</i>
2.2.2.4 Water retention (WR).....	<i>16</i>
2.2.2.5 Organic matter content (OMC)	<i>16</i>
2.2.2.6 Bulk density (D_b).....	<i>18</i>
2.2.3 Effect of cultivation/aeration treatment on rootzone physical properties of	
golf greens.....	<i>19</i>
2.2.3.1 HydroJect (HJ).....	<i>20</i>

2.2.3.2 Scarification (S).....	21
2.3.3.3 Verti-drain (VD).....	21
2.2.4 Summary.....	22
2.3 EFFECT OF ROOTZONE COMPOSITION AND CULTIVATION/AERATION TREATMENT ON SWARD CHARACTERISTICS OF GOLF GREENS.....	23
2.3.1 Introduction.....	23
2.3.2 Species composition and turf cover	24
2.3.3 Root development.....	26
2.3.4 Dry patch severity	28
2.3.5 Summary.....	30
2.4 EFFECT OF ROOTZONE COMPOSITION AND CULTIVATION/AERATION TREATMENT ON PLAYING QUALITY OF GOLF GREENS.....	31
2.4.1 Introduction.....	31
2.4.2 Ball roll distance (green speed)	32
2.4.3 Green surface hardness	34
2.4.4 Summary.....	36
2.5 A DYNAMIC MATHEMATICAL MODEL FOR COMPREHENSIVE ASSESSMENT AND MONITORING OF THE LONG-TERM PERFORMANCE OF GOLF GREENS.....	37
2.5.1 Introduction.....	37
2.5.2 The general approach of integrated rate methodology (IRM)	38
2.5.3 Summary.....	40
2.6 SUMMARY AND CONCLUSIONS	41
2.7 REFERENCES.....	43
 3. MATERIALS AND METHODS.....	 57
3.1 EXPERIMENTAL DESIGN.....	58
3.2 ESTABLISHMENT AND MAINTENANCE.....	59
3.3 SAMPLING PROTOCOL	62
3.4..... GUIDELINES USED FOR ASSESSMENT OF GOLF GREEN PERFORMANCE	62
3.5 STATISTICAL ANALYSIS.....	62
3.6 REFERENCES.....	68

4. EFFECT OF ROOTZONE COMPOSITION AND CULTIVATION/AERATION TREATMENT ON ROOTZONE PHYSICAL PROPERTIES OF GOLF GREENS	70
4.1 ABSTRACT	71
4.2 INTRODUCTION	73
4.3 MATERIALS AND METHODS	73
4.4 RESULTS.....	74
4.4.1 Water infiltration rate (IR).....	74
4.4.2 Oxygen diffusion rate (ODR)	77
4.4.3 Water and air retention	80
4.4.4 Organic matter content (OMC).....	87
4.4.5 Bulk density (D_b)	92
4.5 DISCUSSION	95
4.5.1 Water infiltration rate (IR)	95
4.5.2 Oxygen diffusion rate (ODR).....	96
4.5.3 Water and air retention	98
4.5.4 Organic matter content (OMC).....	100
4.5.5 Bulk density (D_b)	101
4.6 SUMMARY AND CONCLUSIONS	102
4.7 REFERENCES	104
 5. EFFECT OF ROOTZONE COMPOSITION AND CULTIVATION/AERATION TREATMENT ON SWARD CHARACTERISTICS OF GOLF GREENS.....	 109
5.1 ABSTRACT	110
5.2 INTRODUCTION.....	112
5.3 MATERIALS AND METHODS	113
5.4 RESULTS.....	113
5.4.1 Species composition and stability.....	113
5.4.2 Root growth and distribution	114
5.4.3 Visual turf qualities.....	123
5.5 DISCUSSION	128
5.5.1 Species composition and stability.....	128
5.5.2 Root growth and distribution	129
5.5.3 Visual turf qualities.....	131
5.6 SUMMARY AND CONCLUSIONS	133

5.7 REFERENCES	135
 6. <i>EFFECT OF ROOTZONE COMPOSITION AND CULTIVATION/AERATION TREATMENT ON PLAYING QUALITY OF GOLF GREENS</i>.....	139
6.1 ABSTRACT	140
6.2 INTRODUCTION.....	141
6.3 MATERIALS AND METHODS	142
6.4 RESULTS.....	142
6.4.1 Ball roll distance (green speed)	143
6.4.2 Surface hardness	145
6.5 DISCUSSION	149
6.5.1 Ball roll distance (green speed)	149
6.5.2 Surface hardness	150
6.6 SUMMARY AND CONCLUSIONS	152
6.7 REFERENCES.....	153
 7. <i>A MATHEMATICAL MODEL FOR COMPREHENSIVE ASSESSMENT AND DYNAMIC MONITORING OF THE LONG-TERM PERFORMANCE OF GOLF GREENS</i>.....	155
7.1 ABSTRACT	156
7.2 INTRODUCTION.....	158
7.3 STRUCTURES AND PARAMETERIZATION OF THE INTEGRATED RATE METHODOLOGY (IRM) MODEL.....	160
7.3.1 The general Integrated Rate Methodology (IRM) model	160
7.3.2 The Rootzone sub-model	164
7.3.2.1 Determination of factor weightings.....	168
7.3.3 The Sward sub-model	170
7.3.3.1 Determination of factor weightings.....	174
7.3.4 The Playing Quality sub-model	176
7.3.4.1 Determination of factor weightings.....	179
7.3 RESULTS.....	181
7.4.1 Rootzone Index (R_I).....	181
7.4.2 Sward Index (S_I)	185
7.4.3 Playing Quality Index (P_I)	189

7.4.4 The Comprehensive Golf Green Performance Index (CGGP ₁)	193
7.5 DISCUSSION	196
7.5.1 Rootzone Index (R ₁).....	196
7.5.2 Sward Index (S ₁)	198
7.5.3 Playing Quality Index (P ₁)	199
7.5.4 Comprehensive Golf Green Performance Index (CGGP ₁)	200
7.6 SUMMARY AND CONCLUSIONS	202
7.7 REFERENCES.....	204
 8. GENERAL DISCUSSION.....	 209
8.1 GENERAL TREND OVER TIME IN GOLF GREEN PERFORMANCE	210
8.2 KEY FACTORS CAUSING THE GENERAL DETERIORATION TREND IN GOLF GREEN PERFORMANCE	210
8.3 EFFECT OF ROOTZONE TYPE ON GOLF GREEN PERFORMANCE	211
8.4 EFFECT OF CULTIVATION/AERATION TREATMENT ON GOLF GREEN PERFORMANCE	213
8.5 POTENTIAL APPLICATIONS OF THE IRM MODEL IN GOLF GREEN MANAGEMENT PRACTICES	214
8.6 REFERENCES	217
 9. CONCLUSIONS.....	 220
 APPENDICES.....	 223

LIST OF TABLES

Table 2-1 USGA classification of green speed for regular membership and tournament play	34
Table 2-2 Proposed limits for interpreting the playing quality of golf greens under British conditions.....	34
Table 3-1 Selected physical and chemical characteristics of rootzone media.....	60
Table 3-2 Cultivation/aeration treatments	61
Table 3-3 Details of trial management	64
Table 3-4 Sampling protocol for measurement of rootzone physical properties	65
Table 3-5 Protocol for measurement of playing quality and sward characteristics	66
Table 3-6 Adopted and adjusted guidelines for performance assessment of golf greens... ..	67
Table 4-1 Changes with time in mean soil porosity values measured at -3 kPa moisture potentials averaged over all rootzones	85
Table 4-2 Changes with time in organic matter content (% w/w) averaged over all rootzones.....	91
Table 5-1 Changes with time in species composition (% w/w) averaged over all rootzones.....	117
Table 5-2 Changes with time in dry root mass (g m^{-2}) and root mass percentage (%) averaged over all rootzones	121
Table 5-3 Mean visual scores of turf uniformity and density in relation to rootzone type and cultivation/aeration treatment	125
Table 5-4 Mean visual scores of dollar spot and sod webworm incidence in relation to rootzone type and cultivation/aeration treatment	126
Table 6-1 Changes with time in mean green surface hardness (gravities) averaged over all rootzones.....	148
Table 7-1 Justification of all statistic models and scaling factors used in the general IRM model and three IRM sub-models.....	163
Table 7-2 Factor weightings of the IRM model for golf green ecosystems	180

LIST OF APPENDIX TABLES

Appendix Table 7-1 Calculation of weighting factors of the general IRM model for a golf green ecosystem	226
Appendix Table 7-2a Effects of season and climate, daily maintenance and cultivation/aeration treatment on soil physical performance of rootzones for golf greens (i.e. infiltration rate)	227
Appendix Table 7-2b Effects of season and climate on sward characteristics of rootzones for golf greens	228
Appendix Table 7-2c Effects of season and climate on playing quality of rootzones for golf greens	229
Appendix Table 7-3a Scaled effects of each cultivation/aeration treatment on each factor of the physical properties of the golf green rootzones	230
Appendix Table 7-3b Scaled effects of each cultivation/aeration treatment on each factor of the sward characteristics of the golf green rootzones	231
Appendix Table 7-3c Scaled effects of each cultivation/aeration treatment on each factor of the playing quality of the golf green rootzones	232

LIST OF FIGURES

Fig. 3-1 Experimental plots	57
Fig. 3-2 Rootzone design.....	58
Fig. 4-1 Changes in infiltration rate over the long-term in relation to each rootzone type and cultivation/aeration treatment	75
Fig. 4-2 Changes in infiltration rate over the short-term after cultivation in relation to each rootzone type and cultivation/aeration treatment	76
Fig. 4-3 Changes in oxygen diffusion rate with time in relation to each rootzone type and cultivation/aeration treatment	79
Fig. 4-4 Changes in air-filled porosity at -3 kPa with time in relation to each rootzone type and cultivation/aeration treatment	82
Fig. 4-5 Changes in water-filled porosity at -3 kPa with time in relation to each rootzone type and cultivation/aeration treatment	83
Fig. 4-6 Changes in total porosity with time in relation to each rootzone type and cultivation/aeration treatment.....	84
Fig. 4-7 Changes in organic matter content with time in relation to each rootzone.....	89
Fig. 4-8 Changes in organic matter content with time in relation to each cultivation/aeration treatment.....	90
Fig. 4-9 Changes in bulk density with time in relation to each rootzone type and cultivation/aeration treatment.....	94
Fig. 5-1 Changes in species composition (%) with time in relation to rootzone type and cultivation/aeration treatment.....	115
Fig. 5-2 Changes in species composition (%) with time in relation to rootzone type and cultivation/aeration treatment.....	116
Fig. 5-3 Changes in root mass and percentage root distribution with time in relation to rootzone type and cultivation/aeration treatment in the 0-50 mm rootzone depth.....	119
Fig. 5-4 Changes in root mass and percentage root distribution with time in relation to rootzone type and cultivation/aeration treatment in the 50-250 mm rootzone depth...	120
Fig. 5-5 Changes in mean visual scores of dry patch severity with time in relation to rootzone type and cultivation/aeration treatment	124
Fig. 6-1 Changes in ball roll distance with time in relation to each rootzone type and cultivation/aeration treatment.....	144

Fig. 6-2 Changes in green surface hardness with time in relation to each rootzone type ..	146
Fig. 6-3 Changes in green surface hardness with time in relation to each cultivation/aeration treatment.....	147
Fig. 7-1 A schematic representation of a general Integrated Rate Methodology model for a golf green ecosystem.....	162
Fig. 7-2 A conceptual Rootzone sub-model for a golf green ecosystem.....	166
Fig. 7-3 A conceptual Sward sub-model for a golf green ecosystem.....	173
Fig. 7-4 A conceptual Playing Quality sub-model for a golf green ecosystem.....	178
Fig. 7-5 Changes in the Rootzone Index with time in relation to each rootzone type .	182
Fig. 7-6 Changes in the normalized values of soil physical factors with time in relation to each rootzone type.....	183
Fig. 7-7 Changes in the Rootzone Index with time in relation to each rootzone type managed under different cultivation/aeration treatment.....	184
Fig. 7-8 Changes in the Sward Index with time in relation to each rootzone type	186
Fig. 7-9 Changes in the normalized values of each sward factor with time in relation to each rootzone type.....	187
Fig. 7-10 Changes in the Sward Index with time in relation to each rootzone type managed under different cultivation/aeration treatment.....	188
Fig. 7-11 Changes in the Playing Quality Index with time in relation to each rootzone type	190
Fig. 7-12 Changes in the normalized values of each Playing Quality factor with time in relation to each rootzone type.....	191
Fig. 7-13 Changes in the Playing Quality Index with time in relation to each rootzone type managed under different cultivation/aeration treatment.....	192
Fig. 7-14 Changes in the Comprehensive Golf Green Performance Index with time in relation to each rootzone type.....	194
Fig. 7-15 Changes in the Comprehensive Golf Green Performance Index with time in relation to each rootzone type managed under different cultivation/aeration treatment	195
Fig. 8-1 A schematic representation of the decision-making process using an IRM model for seasonal management of golf greens	215

LIST OF APPENDIX FIGURES

Appendix Fig. 3-1 Mean rainfall during the experimental period (1998-2003) for Palmerston North region.....	223
Appendix Fig. 3-2 Mean air temperature during the experimental period (1998-2003) for Palmerston North region	223
Appendix Fig. 4-1 Changes in air-filled porosity at -4 kPa with time in relation to each rootzone type and cultivation/aeration treatment	224
Appendix Fig. 4-2 Changes in air-filled porosity at -5 kPa with time in relation to each rootzone type and cultivation/aeration treatment	225
Appendix Fig. 4-3 Changes in water-filled porosity at -4 kPa with time in relation to each rootzone type and cultivation/aeration treatment	226
Appendix Fig. 4-4 Changes in water-filled porosity at -5 kPa with time in relation to each rootzone type and cultivation/aeration treatment	227
Appendix Fig. 7-1a Development of statistical models for normalization of measurement values of each modeling factor	235
Appendix Fig. 7-1b Development of statistical models for normalization of measurement values of each modeling factor	236
Appendix Fig. 7-1c Development of statistical models for normalization of measurement values of each modeling factor	237
Appendix Fig. 7-1d Development of statistical models for normalization of measurement values of each modeling factor	238
Appendix Fig. 7-2 Changes in Comprehensive Golf Green Performance Index with frequency of cultivation/aeration treatment in relation to each rootzone type and cultivation/aeration treatment by the 15th year after sowing	239
Appendix Fig. 7-3a Natural diminishing equations for water infiltration rate after sowing in relation to each rootzone type.....	240
Appendix Fig. 7-3b Natural diminishing equations for water infiltration rate after sowing in relation to each cultivation/aeration treatment.....	241
Appendix Fig. 7-4a Natural diminishing equations for organic matter content measured at 0-35 mm rootzone depth after sowing in relation to each rootzone type	242
Appendix Fig. 7-4b Natural diminishing equations for organic matter content measured at 0-35 mm rootzone depth after sowing in relation to each cultivation/aeration treatment	243

Appendix Fig. 7-4c Natural diminishing equations for organic matter content measured at 35-70 mm rootzone depth after sowing in relation to each rootzone type	244
Appendix Fig. 7-4d Natural diminishing equations for organic matter content measured at 35-70 mm rootzone depth after sowing in relation to each cultivation/aeration treatment	245
Appendix Fig. 7-5a Natural diminishing equations for air-filled porosity measured at -3kPa in 35-70 mm rootzone depth after sowing in relation to each rootzone type.....	246
Appendix Fig. 7-5b Natural diminishing equations for air-filled porosity measured at -3kPa in 35-70 mm rootzone depth after sowing in relation to each cultivation/aeration treatment	247
Appendix Fig. 7-6a Natural diminishing equations for water-filled porosity measured at -3kPa in 35-70 mm rootzone depth after sowing in relation to each rootzone type.....	248
Appendix Fig. 7-6b Natural diminishing equations for water-filled porosity measured at -3kPa in 35-70 mm rootzone depth after sowing in relation to each cultivation/aeration treatment	249
Appendix Fig. 7-7a Natural diminishing equations for root mass percentage (percentage of root mass at 50-250 mm rootzone depth in the total) after sowing in relation to each rootzone type	250
Appendix Fig. 7-7b Natural diminishing equations for root mass percentage (percentage of root mass at 50-250 mm rootzone depth in the total) after sowing in relation to each cultivation/aeration treatment	251
Appendix Fig. 7-8a Natural diminishing equations for species composition after sowing in relation to each rootzone type	252
Appendix Fig. 7-8b Natural diminishing equations for species composition after sowing in relation to each cultivation/aeration treatment	253
Appendix Fig. 7-8c Natural diminishing equations for relative balance of two sown turfgrasses in the sward after sowing in relation to each rootzone type.....	254
Appendix Fig. 7-8d Natural diminishing equations for relative balance of two sown turfgrasses in the sward after sowing in relation to each cultivation/aeration treatment	255
Appendix Fig. 7-9a Natural diminishing equations for dry patch severity after sowing in relation to each rootzone type	256
Appendix Fig. 7-9b Natural diminishing equations for dry patch severity after sowing in relation to each cultivation/aeration treatment	257
Appendix Fig. 7-10a Natural diminishing equations for visual turf quality (uniformity and density) after sowing in relation to each rootzone type.....	258
Appendix Fig. 7-10b Natural diminishing equations for visual turf quality (uniformity and density) after sowing in relation to each rootzone type.....	259

Appendix Fig. 7-10c Natural diminishing equations for visual turf quality (uniformity and density) after sowing in relation to each cultivation/aeration treatment.....	260
Appendix Fig. 7-10d Natural diminishing equations for visual turf quality (uniformity and density) after sowing in relation to each cultivation/aeration treatment.....	261
Appendix Fig. 7-11a Natural diminishing equations for green surface hardness after sowing in relation to each rootzone type.....	262
Appendix Fig. 7-11b Natural diminishing equations for green surface hardness after sowing in relation to each cultivation/aeration treatment.....	263
Appendix Fig. 7-12a Natural diminishing equations for green speed after sowing in relation to each rootzone type.....	264
Appendix Fig. 7-12b Natural diminishing equations for green speed after sowing in relation to each cultivation/aeration treatment	265