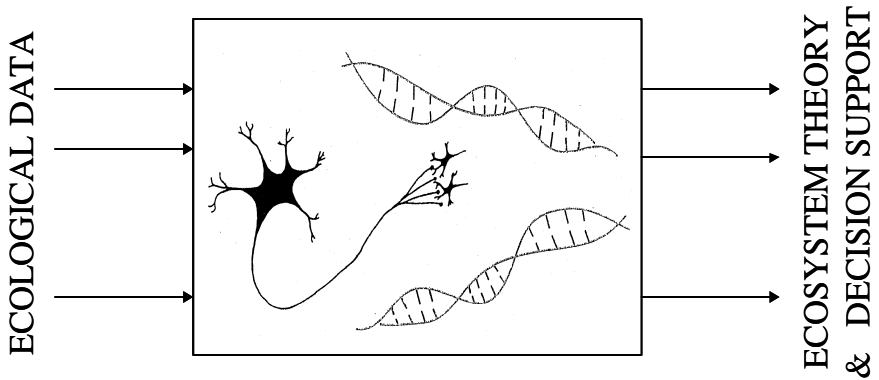


Friedrich Recknagel

Ecological Informatics

Understanding Ecology by Biologically-Inspired Computation

With 152 Figures and 43 Tables



Springer

Preface

In the 50s and 60s cross-sectional data of lake surveys were utilized for steady state assessments of the eutrophication status of lakes by univariate nonlinear regression. This *statistical approach* (see Table 1) became exemplary for river, grassland and forest models and - because of simplicity - widespread for classification of ecosystems.

In the 70s and 80s multivariate time series data were collected from ecosystems such as lakes, rivers, forests and grasslands in order to improve understanding of ecosystem dynamics. Process-based differential equations were used for the computer simulation of food web dynamics and functional group succession. This *differential equation approach* (see Table 1) is still widely used for scenario analysis.

Ecosystems analysis, synthesis and forecasting in the past ten years was very much influenced by inventions in computational technology such as high performance computing and biologically-inspired computation. This *computational approach* (see Table 1) allows to discover knowledge in complex multivariate databases for improving both ecosystem theory and decision support.

Table 1. Concepts for Ecosystems Analysis, Synthesis and Forecasting

	Statistical Regression Approach	Differential Equations Approach	Computational Approach
Ecosystem Representation	Steady States	Transitional States	Evolving States
Ecosystem Approximation	Univariate Nonlinear / Multivariate Linear	Multivariate Nonlinear	Multivariate Nonlinear
Ecosystem Complexity	Cross-Sectional Nutrient and Abundance Means	Nutrient Cycles and Food Web Dynamics	Species Succession and Ecosystem Evolution
Aquatic Examples	Phosphorus-Chlorophyll Relationship ^{1,2} ; External P-Loading Concept ³	AQUAMOD ⁴ ; MS-CLEANER ⁵ ; Bierman ⁶ ; Jorgensen ⁷ ; SALMO ⁸	Nonlinear Regression ⁹ ; Nonlinear PCA ¹⁰ ; DELAQUA ¹¹ ; ANNA ¹² ; Evolved Rules ¹³ ; Evolved Equations ^{14,15} ; ECHO ¹⁶ ; GECKO ¹⁷
Potential Applications	Ecosystem Classification	Scenario Analysis	Ecosystem Forecasting

¹ Sakamoto M (1966) Primary production by phytoplankton community in some Japanese lakes and its dependence on lake depth. Arch. Hydrobiol. 62, 1-28
² Dillon P, Rigler F (1974) The phosphorus-chlorophyll relationship in lakes. Limnol.Oceanogr. 19, 135-148
³ Vollenweider RA (1968) Scientific fundamentals of eutrophication of lakes and flowing waters with special reference to phosphorus and nitrogen. OECD, Paris. OECD/DAS/SCI/68.27

- ⁴ Straskraba M, Gnauck A (1985) *Freshwater Ecosystems: Modelling and Simulation*. Elsevier, Amsterdam
- ⁵ Park RA, O'Neill RV, Bloomfield JA, Shugart HH, Booth RS, Goldstein RA, Mankin JB, Koonce JF, Scavia D, Adams MS, Clesceri LS, Colon EM, Dettman EH, Hoopes JA, Huff DD, Katz S, Kitchell JF, Koberger RC, La Row EJ, McNaught DC, Petersohn L, Titus JE, Weiler PR, Wilkinson JW, Zahorcak CS (1974) A generalized model for simulating lake ecosystems. *Simulation* 33-50
- ⁶ Bierman VJ (1976) Mathematical model of the selective enhancement of blue-green algae by nutrient enrichment. In: Canale RP (eds) *Modelling Biochemical Processes in Aquatic Ecosystems*. Ann Arbor Science Publishers Inc., Ann Arbor, 1-32
- ⁷ Jorgensen SE (1976) A eutrophication model for a lake. *Ecol. Modelling* 2, 147-162
- ⁸ Recknagel F, Benndorf J (1982) Validation of the ecological simulation model SALMO. *Int. Revue Ges. Hydrobiol.* 67, 1, 113-125
- ⁹ Lek S, Delacoste M, Baran P, Dimonopoulos I, Lauga J, Aulagnier J (1996) Application of neural networks to modelling nonlinear relationships in ecology. *Ecol. Modelling* 90, 39-52
- ¹⁰ Chon TS, Park YS, Moon KH, Cha EY (1996) Patternizing communities by using artificial neural network. *Ecol. Modelling* 90, 69-78
- ¹¹ Recknagel F, Petzoldt T, Jaeke O, Krusche F (1995). Hybrid expert system DELAQUA - a toolkit for water quality control of lakes and reservoirs. *Ecol. Modelling* 71, 1-3, 17-36
- ¹² Recknagel F (1997) ANNA - artificial neural network model predicting species abundance and succession of blue-green algae. *Hydrobiologia*, 349, 47-57
- ¹³ Bobbin J, Recknagel F (2001) Knowledge discovery for prediction and explanation of blue-green algal dynamics in lakes by evolutionary algorithms. *Ecol. Modelling* 146, 1-3, 253-264
- ¹⁴ Whigham P, Recknagel F (2001) An inductive approach to ecological time series modelling by evolutionary computation. *Ecol. Modelling* 146, 1-3, 275-287
- ¹⁵ Whigham P, Recknagel F (2001) Predicting chlorophyll-a in freshwater lakes by hybridising process-based models and genetic algorithms. *Ecol. Modelling* 146, 1-3, 243-251
- ¹⁶ Holland JH (1992) *Adaptation in Natural and Artificial Systems*. Addison-Wesley, New York
- ¹⁷ Booth G (1997) Gecko: A continuous 2-D world for ecological modeling. *Artif. Life* 3, 147-163

The present book focuses on the *computational approach* for ecosystems analysis, synthesis and forecasting called *ecological informatics*. It provides the scope and case studies of ecological informatics exemplary for applications of biologically-inspired computation to a variety of areas in ecology.

Ecological Informatics is defined as interdisciplinary framework promoting the use of advanced computational technology for the elucidation of principles of information processing at and between all levels of complexity of ecosystems - from genes to ecological networks -, and the provision of transparent decisions targeting ecological sustainability, biodiversity and global warming.

Distinct features of ecological informatics are: data integration across ecosystem categories and levels of complexity, inference from data pattern to ecological processes, and adaptive simulation and prediction of ecosystems.

Biologically-inspired computation techniques such as fuzzy logic, artificial neural networks, evolutionary algorithms and adaptive agents are considered as core concepts of ecological informatics.

Fig. 1 represents the current scope of ecological informatics indicating that ecological data is consecutively refined to ecological information, ecosystem theory and ecosystem decision support by two basic computational operations: data archival, retrieval and visualization, and ecosystem analysis, synthesis and forecasting.

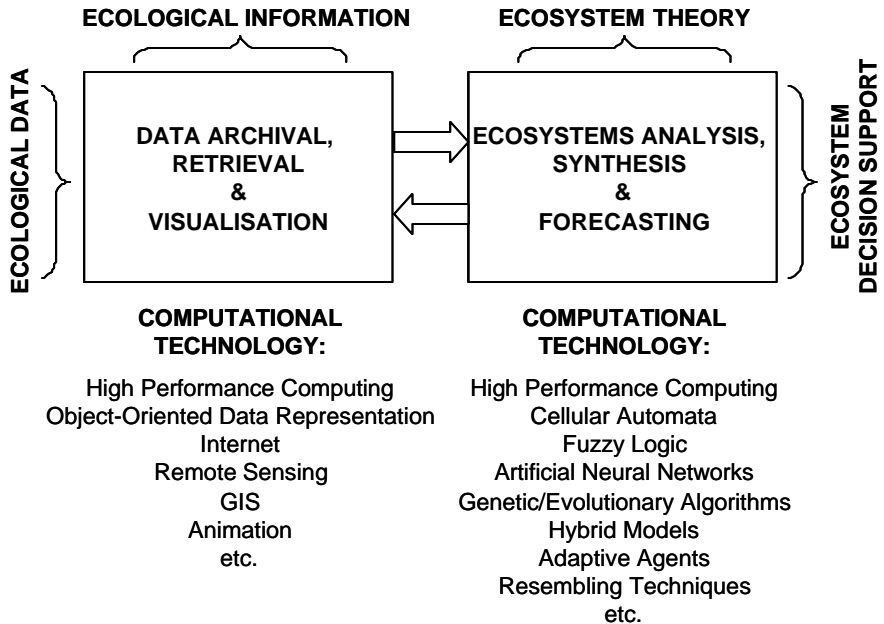


Figure 1. Scope of Ecological Informatics

Computational technologies currently considered being crucial for data archival, retrieval and visualization are:

- High performance computing to provide high-speed data access and processing, and large internal storage (RAM);
- Object-oriented data representation to facilitate data standardization and data integration by the embodiment of metadata and data operations into data structures;
- Internet to facilitate sharing of dynamic, multi-authored data sets, and parallel posting and retrieval of data;
- Remote sensing and GIS to facilitate spatial data visualization and acquisition;
- Animation to facilitate pictorial visualization and simulation.

Following computational technologies are currently considered to be crucial for ecosystems analysis, synthesis and forecasting:

- High performance computing to provide high-speed data access and processing and large internal storage (RAM), and to facilitate high speed simulations;
- Internet and www to facilitate interactive and online simulation as well as software and model sharing;
- Cellular automata to facilitate spatio-temporal and individual-based simulation;
- Fuzzy logic to represent and process uncertain data;
- Artificial neural networks to facilitate multivariate nonlinear regression, ordination and clustering, multivariate time series analysis, image analysis at micro and macro scale;
- Genetic and evolutionary algorithms for the discovery and evolving of multivariate nonlinear rules, functions, differential equations and artificial neural networks;
- Hybrid and AI models by the embodiment of evolutionary algorithms in process-based differential equations, the embodiment of fuzzy logic in artificial neural networks or knowledge processing;
- Adaptive agents to facilitate adaptive simulation and prediction of ecosystem composition and evolution.

The present book is an outcome of the *International Conference on Applications of Machine Learning to Ecological Modelling*, 27 November to 1 December 2000, Adelaide, Australia, which concluded with the foundation of the *International Society for Ecological Informatics (ISEI)* (<http://www.waite.adelaide.edu.au/ISEI/>). The chapters of the present book are based on selected papers of the conference, which are exemplary for current research trends in *ecological informatics*.

Chapters 1 to 5 address principles and ecological application of fuzzy logic, artificial neural networks, genetic algorithms, evolutionary computation and adaptive agents. Salski summarizes concepts of fuzzy logic and discusses applications for knowledge-based modeling, clustering and kriging related to ecotoxicological, geological and population dynamics data. Giraudel and Lek discuss the design and application of unsupervised artificial neural networks for the classification and visualization of multivariate ecological data. They demonstrate the potential of Kohonen-type algorithms by clustering data of forest communities in Wisconsin (USA). Morrall discusses origins and nature of genetic algorithms, and their suitability to induce numerical or rule-based models for ecological applications. Whigham and Fogel provide a scope of evolutionary algorithms and their potential for evolving rules, algebraic and differential equations relevant to ecology. They also address developments on individual and cooperative behaviour, prey-predator algorithms and hierarchical ecosystems based on evolutionary algorithms. Recknagel reflects on Holland's adaptive agents concept and its potential to more realistically simulate emergent ecosystem structures and behaviours. He distinguishes between individual-based and state variable-based agents, and emphasizes on the embodiment of evolutionary computation in state-variable based agents.

Chapters 6 to 9 provide case studies for the prediction and elucidation of stream ecosystems by means of machine learning techniques. Goethals, Dedecker, Gabriels and de Pauw demonstrate applications of classification trees and artificial neural networks for the bioassessment of the Zwalm river system in Belgium.

Schleiter, Obach, Wagner, Werner, Schmidt and Borchardt carried out a comprehensive study of the Breitenbach stream (Germany) based on a variety of unsupervised and supervised learning algorithms for artificial neural networks. They draw interesting conclusions regarding suitability of different algorithms for bioindication of stream habitats and input sensitivity of streams. Chon, Park, Kwak and Cha provide a summary of achievements in the structural classification and dynamic prediction of macroinvertebrate communities in Korean streams by artificial neural networks. They also discuss patterning of organizational aspects of macroinvertebrate communities. Huong, Recknagel, Marshall and Choy study relationships between environmental factors, stream habitat characteristics and the occurrence of macroinvertebrate taxa in the Queensland stream system (Australia) by means of a neural network based sensitivity analysis.

Chapters 10 to 12 contain examples of time series analysis of river water quality by artificial neural networks. Jeong, Recknagel and Joo apply recurrent neural networks to explain and predict the seasonal abundance and succession of different algae species in the River Nakdong (Korea). Validation results reveal a reasonable correspondence between seven days ahead forecasts and observations of algal abundance. Information on favouring conditions and processes for certain algal species discovered by a comprehensive sensitivity analysis comply well with domain knowledge. Bowden, Maier and Dandy combine super- and unsupervised artificial neural networks as well as genetic algorithms for automated input determination of neural networks in order to forecast the abundance of an algae species in the River Murray (Australia). Gevrey, Lek and Oberdorff apply two approaches of sensitivity analysis for the study of riverine fish species by means of artificial neural networks.

Chapters 14 to 17 provide case studies for the application of fuzzy logic, artificial neural networks and evolutionary algorithms to freshwater lakes and marine fishery systems. Karul and Soyupak compare results for the chlorophyll-a estimation in three Turkish lakes achieved by multiple regression and artificial neural networks. Wilson and Recknagel design a generic neural network model for forecasting algal blooms that is validated by means of six lake databases. It considers bootstrapping, bagging and time-lagged training as crucial techniques for minimising prediction errors. Bobbin and Recknagel apply evolutionary algorithms to discover rules for the abundance and succession of blue green algae species in the hypereutrophic Lake Kasumigaura (Japan). Resulting rules correspond with literature findings, reveal hypothetical relationships and are able to predict timing and magnitudes of algal dynamics.

Reick, Gruenewald and Page address the issue of data quality in the context of ecological time-series analysis and prediction. They describe cross-validation and automated training termination of neural networks applied for multivariate time-series predictions of marine zooplankton in the German Northern Sea. Chen combines fuzzy logic and artificial neural networks in order to classify fish stock-recruitment relationships in different environmental regimes near the West Coast Vancouver Island (Canada) and southeast Alaska (USA).

Chapters 18 to 20 provide examples for the classification of ecological images at micro and macro scale by artificial neural networks. Wilkins, Boddy and

Dubelaar demonstrate possibilities for the identification of marine microalgae by the analysis of flow cytometric pulse shapes with the help of neural networks. Robertson and Morison applied a probabilistic neural network for the automation of age estimation in three fish species. Thin-sections of sagittal otoliths viewed with transmitted light were used for all species, and the number of opaque increments used to estimate the age. The neural network correctly classified a larger range of age classes. Foody gives a representative summary of neural network algorithms currently used for the pattern recognition and classification of remotely sensed landscape images.

At this point I want to thank all of the authors who responded with great enthusiasm to my request for chapters to the theme of the book and delivered on time. I am also grateful to 24 colleagues and friends in Australia and overseas who significantly improved the quality of chapters by their critical reviews.

Finally I express my thanks to Dr. Christian Witschel and Agata Oelschlaeger of the Geosciences Editorial Team of the Springer Verlag for their close collaboration in producing the book.

Friedrich Recknagel
Adelaide, 15 April 2002

Contents

Part I Introduction	1
1. Ecological Applications of Fuzzy Logic	3
1.1 Fuzzy Sets and Fuzzy Logic	3
1.2 Fuzzy Approach to Ecological Modelling and Data Analysis	4
1.3 Fuzzy Classification: A Fuzzy Clustering Approach.....	6
1.4 Fuzzy Regionalisation: A Fuzzy Kriging Approach.....	9
1.5 Fuzzy Knowledge-Based Modelling.....	9
1.6 Conclusions.....	12
References.....	12
2. Ecological Applications of Unsupervised Artificial Neural Networks	15
2.1 Introduction.....	15
2.2 How to Compute a Self-Organizing Map (SOM) with an Abundance Dataset?.....	16
2.2.1 A Dataset for Demonstrations.....	16
2.2.2 The Self-Organizing Map (SOM) Algorithm.....	18
2.3 How to Use a Self-Organizing Map with an Abundance Dataset?.....	22
2.3.1 Mapping the Stations	22
2.3.2 Displaying a Variable	24
2.3.3 Displaying an Abiotic Variable	25
2.3.4 Clustering with a SOM	26
2.4 Discussion.....	29
2.5 Conclusion.....	31
References.....	32
3. Ecological Applications of Genetic Algorithms	35
3.1 Introduction.....	35
3.2 Ecology and Ecological Modelling	36
3.3 Genetic Algorithm Design Details	38
3.4 Applications of Genetic Algorithms to Ecological Modelling	40
3.5 Predicting the Future with Genetic Algorithms	43
3.6 The Next Generation: Hybrids Genetic Algorithms	44
References.....	45

4. Ecological Applications of Evolutionary Computation	49
4.1 Introduction	49
4.2 Ecological Modelling	50
4.2.1 The Challenges of Ecological Modelling	50
4.2.2 Summary	52
4.3 Evolutionary Computation	52
4.3.1 The Basic Evolutionary Algorithm	54
4.3.2 Summary	57
4.4 Ecological Modelling and Evolutionary Algorithms	57
4.4.1 Equation Discovery	57
4.4.2 Optimisation of Difference Equations	58
4.4.3 Evolving Differential Equations	59
4.4.4 Rule Discovery	60
4.4.5 Modelling Individual and Cooperative Behaviour	61
4.4.6 Predator-Prey Algorithms	64
4.4.7 Modelling Hierarchical Ecosystems	65
4.5 Conclusion	66
References	66
5. Ecological Applications of Adaptive Agents	73
5.1 Introduction	73
5.2 Adaptive Agents Framework	74
5.3 Individual-Based Adaptive Agents	76
5.4 State Variable-Based Adaptive Agents	78
5.4.1 Algal Species Simulation by Adaptive Agents	80
5.4.1.1 Embodiment of Evolutionary Computation in Agents	80
5.4.1.2 Adaptive Agents Bank	81
5.4.2 Pelagic Food Web Simulation by Adaptive Agents	85
5.5 Conclusions	86
Acknowledgements	86
References	87

Part II Prediction and Elucidation of Stream Ecosystems..... 89

6. Development and Application of Predictive River Ecosystem Models Based On Classification Trees and Artificial Neural Networks	91
6.1 Introduction	91
6.2 Study Sites, Data Sources and Modelling Techniques	92
6.2.1 The Zwalm River Basin	92
6.2.2 Data Collection	93
6.2.3 Classification Trees	94
6.2.4 Artificial Neural Networks	95

6.2.5	Model Assessment.....	96
6.3	Results	97
6.3.1	Classification Trees	97
6.3.1.1	Model Development and Validation	97
6.3.1.2	Application of Predictive Classification Trees for River Management.....	98
6.3.2	Artificial Neural Networks	100
6.3.2.1	Model Development and Validation	100
6.3.2.2	Application of Predictive Artificial Neural Networks for River Management	102
6.3.2.2.1	Prediction of Environmental Standards.....	102
6.3.2.2.2	Feasibility Analysis of River Restoration Options.....	103
6.4	Discussion.....	104
	Acknowledgements	105
	References	105
7.	Modelling Ecological Interrelations in Running Water Ecosystems with Artificial Neural Networks.....	109
7.1	Introduction.....	109
7.2	Materials and Methods	110
7.2.1	Data Base.....	110
7.2.2	Data Pre-Processing.....	110
7.2.3	Artificial Neural Network Types	111
7.2.4	Dimension Reduction	111
7.2.5	Quality Measures	111
7.3	Data Exploration with Unsupervised Learning Systems	112
7.4	Correlations and Predictions with Supervised Learning Systems	115
7.4.1	Correlations and Predictions of Environmental Variables	117
7.4.2	Dependencies of Colonisation Patterns of Macro-Invertebrates on Water Quality and Habitat Characteristics	117
7.4.2.1	Aquatic Insects in a Natural Stream, the Breitenbach.....	117
7.4.2.2	Anthropogenically Altered Streams	120
7.4.3	Biindication	121
7.5	Assessment of Model Quality and Visualisation Possibilities: Hybrid Networks	122
7.6	Conclusions.....	123
	Acknowledgements	125
	References	125
8.	Non-linear Approach to Grouping, Dynamics and Organizational Informatics of Benthic Macroinvertebrate Communities in Streams by Artificial Neural Networks	127
8.1	Introduction.....	127
8.2	Grouping Through Self-Organization.....	130
8.2.1	Static Grouping.....	130
8.2.2	Grouping Community Changes.....	143

8.3 Prediction of Community Changes	147
8.3.1 Multilayer Perceptron with Time Delay	147
8.3.2 Elman Network	151
8.3.3 Fully Connected Recurrent Network	154
8.3.4 Impact of Environmental Factors Trained with the Recurrent Network.....	158
8.4 Patterning Organizational Aspects of Community	161
8.4.1 Relationships among Hierarchical Levels in Communities	161
8.4.2 Patterning of Exergy	167
8.5 Summary and Conclusions.....	173
Acknowledgements	174
References.....	174

9. Elucidation of Hypothetical Relationships between Habitat Conditions and Macroinvertebrate Assemblages in Freshwater Streams by Artificial Neural Networks.....179

9.1 Introduction.....	179
9.2 Study Site.....	180
9.3 Materials and Methods	180
9.3.1 Data.....	180
9.3.2 Neural Network Modelling.....	181
9.3.3 Sensitivity Analysis.....	182
9.4 Results and Discussion.....	183
9.4.1 Elucidation of Hypothetical Relationships.....	183
9.4.2 Discovery of Contradictory Relationships.....	187
9.4.3 Limitations of the Method.....	188
9.5 Conclusions	189
References.....	190

Part III Prediction and Elucidation of River Ecosystems.....193

10. Prediction and Elucidation of Population Dynamics of the Blue-green Algae *Microcystis aeruginosa* and the Diatom *Stephanodiscus hantzschii* in the Nakdong River-Reservoir System (South Korea) by a Recurrent Artificial Neural Network.....195

10.1 Introduction.....	195
10.2 Description of the Study Site	196
10.3 Materials and Methods	197
10.3.1 Data Collection and Analysis	197
10.3.2 Modelling the Phytoplankton Dynamics	199
10.3.3 Neural Network Validation and Knowledge Discovery on Algal Succession.....	201

10.4 Results and Discussion.....	201
10.4.1 Limnological Aspects and Plankton Dynamics in the Lower Nakdong River	201
10.4.2 Configuring the Neural Network Architecture for Predictability	203
10.4.3 Elucidation of Ecological Hypothesis	205
10.4.3.1 <i>Microcystis aeruginosa</i>	207
10.4.3.2 <i>Stephanodiscus hantzschii</i>	208
10.5 Implications of Ecological Informatics for Limnology	208
10.6 Conclusions.....	210
Acknowledgements	210
References	210

11. An Evaluation of Methods for the Selection of Inputs for an Artificial Neural Network Based River Model..... 215

11.1 Introduction.....	215
11.2 Methods	217
11.2.1 Unsupervised Input Preprocessing	217
11.2.2 Supervised Input Determination	220
11.3 Case Study.....	222
11.4 Model Development	222
11.4.1 Performance Measures and Model Validation	223
11.4.2 Data Division.....	223
11.4.3 Determination of Model Inputs	224
11.5 Results and Discussion.....	224
11.6 Conclusions.....	230
Acknowledgements	230
References	231

12. Utility of Sensitivity Analysis by Artificial Neural Network Models to Study Patterns of Endemic Fish Species..... 233

12.1 Introduction.....	233
12.2 Contribution of Environmental Variables	234
12.3 Application to Ecological Data	235
12.4 Results	236
12.4.1 Predictive Power.....	236
12.4.2 Sensitivity Analysis	238
12.5 Discussion.....	242
12.6 Conclusions.....	244
References.....	244

Part IV Prediction and Elucidation of Lake and Marine Ecosystems.....247

13. A Comparison between Neural Network Based and Multiple Regression Models in Chlorophyll-a Estimation.....	249
13.1 Introduction.....	249
13.1.1 Eutrophication in Water Bodies and Relevant Models	249
13.1.2 Artificial Neural Networks	250
13.1.3 The Use of Artificial Neural Networks in Environmental Modelling	251
13.2 Data and Lakes.....	251
13.3 Methodology.....	253
13.3.1.1 Artificial Neural Network Approach.....	254
13.3.1.2 Training Method.....	254
13.3.1.3 Data Pre-Processing.....	256
13.3.1.4 Improving Generalisation.....	256
13.3.2 Multiple Regression Modelling Approach.....	257
13.4 Results	257
13.5 Conclusions and Recommendations.....	260
13.5.1 Conclusions.....	260
13.5.2 Recommendations.....	261
Acknowledgments.....	261
References.....	262
14. A Generic Artificial Neural Network Model for Dynamic Predictions of Algal Abundance in Freshwater Lakes.....	265
14.1 Introduction.....	265
14.2 Issues to be Addressed by Algal Bloom Models	266
14.2.1 Input Layer Design.....	266
14.2.2 Control of Overfitting	267
14.2.3 Linear versus Non-Linear Decision Boundaries	269
14.3 Implementation of the Generic ANN Algal Bloom Model.....	269
14.3.1 Input Layer Design	269
14.3.2 Model Approximation (Training	272
14.3.3 Control of Overfitting.....	273
14.3.4 Model Assessment	274
14.4 Results	275
14.5 Discussion.....	285
14.6 Conclusion	286
Acknowledgements.....	287
References	287
15. Predictive Rules for Phytoplankton Dynamics in Freshwater Lakes Discovered by Evolutionary Algorithms.....	291
15.1 Introduction.....	291

15.1.1	Knowledge Generalisation and Representation	292
15.2	Materials and Methods	292
15.2.1	Data	293
15.2.2	Evolutionary Learning.....	294
15.2.3	Greedy Partitioning Algorithms	296
15.3	Results	296
15.3.1	Prediction of Chlorophyll-a	296
15.3.2	Prediction of Algal Species Assemblages	304
15.4	Discussion.....	309
15.5	Conclusions.....	309
	Acknowledgements	310
	References	310
16.	Multivariate Time-Series Prediction of Marine Zooplankton by Artificial Neural Networks.....	313
16.1	Introduction.....	313
16.2	Generalisation	315
16.3	Automatic Termination of Training	318
16.4	Case Study: Zooplankton Prediction.....	322
16.5	Conclusions.....	325
	Acknowledgement.....	326
	References.....	326
17.	Classification of Fish Stock-Recruitment Relationships in Different Environmental regimes by Fuzzy Logic Combined with a Bootstrap Re-sampling Approach	329
17.1	Introduction.....	329
17.2	Fuzzy Stock-Recruitment Model.....	330
17.2.1	Traditional Stock-Recruitment Model.....	330
17.2.2	Fuzzy Stock-recruitment Model.....	332
17.2.2.1	Fuzzy Membership Function (FMF).....	333
17.2.2.2	Fuzzy Rules	334
17.2.2.3	Fuzzy Reasoning.....	335
17.3	Hybrid Optimal Learning and Bootstrap Re-sampling Algorithms	336
17.3.1	Hybrid Optimal Learning Algorithms	337
17.3.2	Bootstrap re-sampling Procedure	339
17.4	Two Real Data Analyses	340
17.4.1	West Coast Vancouver Island Herring Stock	340
17.4.1.1	Data Prescription and Preliminary Analyses	340
17.4.1.2	Fuzzy-SR Model Analysis	342
17.4.1.3	Bootstrap Re-sampling Analysis.....	344
17.4.2	Southeast Alaska Pink Salmon.....	345
17.4.2.1	Data Prescription and Preliminary Analysis	345
17.4.2.2	Fuzzy-SR Model Analysis	346
17.4.2.3	Bootstrap Re-sampling Analysis.....	347
17.5	Summary and Discussion.....	347

Acknowledgements	349
References.....	349

Part V Classification of Ecological Images at Micro and Macro Scale353

18. Identification of Marine Microalgae by Neural Network Analysis of Simple Descriptors of Flow Cytometric Pulse Shapes.....	355
18.1 Introduction.....	355
18.2 Materials and Methods	359
18.2.1 Pulse Shape Extraction	359
18.2.2 Data Filtering.....	359
18.2.3 Data Transformation	359
18.2.4 Principal Component Analysis.....	360
18.2.5 Neural Network Analysis	362
18.2.6 Hardware and Software	363
18.3 Results	363
18.4 Discussion.....	365
18.5 Conclusions.....	365
Acknowledgement.....	365
References.....	366
19. Age Estimation of Fish Using a Probabilistic Neural Network.....	369
19.1 Introduction.....	369
19.2 Traditional Methods of Age Estimation	369
19.3 Approaches to Automation in Fish Age Estimation	371
19.4 The Application of a Probabilistic Neural Network to Fish Age Estimation	372
19.5 Results	376
19.6 Discussion.....	378
Acknowledgements	380
References.....	380
20. Pattern Recognition and Classification of Remotely Sensed Images by Artificial Neural Networks	383
20.1 Introduction.....	383
20.2 Neural Networks in Remote Sensing.....	384
20.2.1 Classification Applications.....	384
20.2.2 Regression Applications.....	385
20.3 The Neural Networks Used in Remote Sensing.....	385
20.3.1 Feedforward Neural Networks	386
20.3.1.1 Multi-Layer Perceptron (MLP	387

20.3.1.2 Radial Basis Function (RBF.....	388
20.3.1.3 Probabilistic Neural Networks (PNN.....	390
20.3.1.4 Generalised Regression Neural Networks (GRNN.....	390
20.3.1.5 Other Network Types.....	391
20.4 Current Status.....	392
20.5 Conclusions.....	394
Acknowledgments.....	394
References.....	394
Index.....	399

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