Contents

	Foreword	**xiii**
	Preface	**xv**
	Acknowledgements	**xix**
	Introduction	**xxi**
	About the Companion Website	**xxv**
1	**Spatial Simulation Models: What? Why? How?**	**1**
1.1	What are simulation models?	2
1.1.1	Conceptual models	4
1.1.2	Physical models	7
1.1.3	Mathematical models	7
1.1.4	Empirical models	8
1.1.5	Simulation models	9
1.2	How do we use simulation models?	12
1.2.1	Using models for prediction	13
1.2.2	Models as guides to data collection	13
1.2.3	Models as 'tools to think with'	14
1.3	Why do we use simulation models?	15
1.3.1	When experimental science is difficult (or impossible)	16
1.3.2	Complexity and nonlinear dynamics	18
1.4	Why dynamic and spatial models?	23
1.4.1	The strengths and weaknesses of highly general models	23
1.4.2	From abstract to more realistic models: controlling the cost	27
2	**Pattern, Process and Scale**	**29**
2.1	Thinking about spatiotemporal patterns and processes	30
2.1.1	What is a pattern?	30

2.1.2 What is a process? 31
2.1.3 Scale 32
2.2 Using models to explore spatial patterns and processes 38
2.2.1 Reciprocal links between pattern and process: a spatial model of forest structure 39
2.2.2 Characterising patterns: first- and second-order structure 40
2.2.3 Using null models to evaluate patterns 43
2.2.4 Density-based (first-order) null models 46
2.2.5 Interaction-based (second-order) null models 48
2.2.6 Inferring process from (spatio-temporal) pattern 49
2.2.7 Making the virtual forest more realistic 53
2.3 Conclusions 56

3 Aggregation and Segregation 57

3.1 Background and motivating examples 58
3.1.1 Basics of (discrete spatial) model structure 59
3.2 Local averaging 60
3.2.1 Local averaging with noise 63
3.3 Totalistic automata 64
3.3.1 Majority rules 65
3.3.2 Twisted majority annealing 68
3.3.3 Life-like rules 69
3.4 A more general framework: interacting particle systems 70
3.4.1 The contact process 71
3.4.2 Multiple contact processes 73
3.4.3 Cyclic relationships between states: rock–scissors–paper 76
3.4.4 Voter models 78
3.4.5 Voter models with noise mutation 80
3.5 Schelling models 83
3.6 Spatial partitioning 86
3.6.1 Iterative subdivision 86
3.6.2 Voronoi tessellations 87
3.7 Applying these ideas: more complicated models 88
3.7.1 Pattern formation on animals' coats: reaction–diffusion models 89
3.7.2 More complicated processes: spatial evolutionary game theory 91
3.7.3 More realistic models: cellular urban models 93

4 Random Walks and Mobile Entities 97

4.1 Background and motivating examples 97
4.2 The random walk 99
4.2.1 Simple random walks 99
4.2.2 Random walks with variable step lengths 102
4.2.3 Correlated walks 103
4.2.4 Bias and drift in random walks 108
4.2.5 Lévy flights: walks with non-finite step length variance 109

4.3 Walking for a reason: foraging and search 111
4.3.1 Using clues: localised search 115
4.3.2 The effect of the distribution of resources 116
4.3.3 Foraging and random walks revisited 119
4.4 Moving entities and landscape interaction 119
4.5 Flocking: entity–entity interaction 121
4.6 Applying the framework 125
4.6.1 Animal foraging 126
4.6.2 Human 'hunter-gatherers' 128
4.6.3 The development of home ranges and path networks 129
4.6.4 Constrained environments: pedestrians and evacuations 129
4.6.5 Concluding remarks 131

5 Percolation and Growth: Spread in Heterogeneous Spaces 133

5.1 Motivating examples 133
5.2 Percolation models 137
5.2.1 What is percolation? 137
5.2.2 Ordinary percolation 138
5.2.3 The lost ant 142
5.2.4 Invasion percolation 145
5.3 Growth (or aggregation) models 148
5.3.1 Eden growth processes: theme and variations 149
5.3.2 Diffusion-limited aggregation 155
5.4 Applying the framework 158
5.4.1 Landscape pattern: neutral models and percolation approaches 158
5.4.2 Fire spread: Per Bak's 'forest fire model' and derivatives 162
5.4.3 Gullying and erosion dynamics: IP + Eden growth + DLA 166
5.5 Summary 168

6 Representing Time and Space 169

6.1 Representing time 170
6.1.1 Synchronous and asynchronous update 170
6.1.2 Different process rates 172
6.1.3 Discrete time steps or event-driven time 173
6.1.4 Continuous time 174
6.2 Basics of spatial representation 175
6.2.1 Grid or lattice representations 175
6.2.2 Vector-based representation: points, lines, polygons and tessellations 177
6.3 Spatial relationships: distance, neighbourhoods and networks 179
6.3.1 Distance in grids and tessellations 179
6.3.2 Neighbourhoods: local spatial relationships 181
6.3.3 Networks of relationships 183

6.4 Coordinate space: finite, infinite and wrapped 185
6.4.1 Finite model space 185
6.4.2 Infinitely extensible model space 186
6.4.3 Toroidal model space 187
6.5 Complicated spatial structure without spatial data structures 188
6.6 Temporal and spatial representations can make a difference 190

7 Model Uncertainty and Evaluation 193

7.1 Introducing uncertainty 193
7.2 Coping with uncertainty 194
7.2.1 Representing uncertainty in data and processes 195
7.3 Assessing and quantifying model-related uncertainty 198
7.3.1 Error analysis 200
7.3.2 Sensitivity analysis 200
7.3.3 Uncertainty analysis 202
7.3.4 Analysis of model structural uncertainty 204
7.3.5 Difficulties for spatial data and models 206
7.3.6 Sensitivity and uncertainty analysis for a simple spatial model 207
7.4 Confronting model predictions with observed data 211
7.4.1 Visualisation and difference measures 212
7.4.2 Formal statistical tests 214
7.5 Frameworks for selecting between competing models 216
7.5.1 Occam's razor 216
7.5.2 Likelihood 217
7.5.3 Multi-model inference 220
7.6 Pattern-oriented modelling 222
7.6.1 POM case-study: understanding the drivers of treeline physiognomy 224
7.7 More to models than prediction 226

8 Weaving It All Together 229

8.1 Motivating example: island resource exploitation by hunter-gatherers 230
8.2 Model description 231
8.2.1 Overview 232
8.2.2 Design concepts 236
8.2.3 Details 238
8.3 Model development and refinement 244
8.3.1 The model development process 244
8.3.2 Model refinement 246
8.4 Model evaluation 247
8.4.1 Baseline dynamics 247
8.4.2 Sensitivity analysis 254
8.4.3 Uncertainty analysis 258
8.5 Conclusions 262

9 In Conclusion **265**

9.1 On the usefulness of building-block models 265
9.2 On pattern and process 266
9.3 On the need for careful analysis 268

References **271**

Index **299**