

Akira Okubo, with Simon A. Levin

Diffusion and Ecological Problems: Modern Perspectives

Second Edition

With 114 Illustrations



Springer

Simon A. Levin
Department of Ecology and
Evolutionary Biology
Princeton University
Princeton, NJ 08544
USA
slevin@eno.princeton.edu

Editors

S.S. Antman
Department of Mathematics
and
Institute for Physical Science and Technology
University of Maryland
College Park, MD 20742-4015
USA

J.E. Marsden
Control and Dynamical Systems
Applied Mathematics
California Institute of Technology
Pasadena, CA 91125
USA

L. Sirovich
Division of Mail Code 107-81
Brown University
Providence, RI 02912
USA

S. Wiggins
Control and Dynamical Systems
Mail Code 107-81
California Institute of Technology
Pasadena, CA 91125
USA

Mathematics Subject Classification (2000): 92A17, 35K55

Library of Congress Cataloging-in-Publication Data

Diffusion and ecological problems : modern perspectives / [edited by] Akira Okubo,
Simon A. Levin.—2nd ed.

p. cm. — (Interdisciplinary applied mathematics ; 14)

Rev. ed. of: Diffusion and ecological problems / Akira Okubo. 1980.

Includes bibliographical references.

ISBN 978-1-4419-3151-1

ISBN 978-1-4757-4978-6 (eBook)

DOI 10.1007/978-1-4757-4978-6

1. Ecology—Mathematical models. 2. Diffusion—Mathematical models.

3. Biogeography—Mathematical models. I. Okubo, Akira. II. Levin, Simon A.

III. Okubo, Akira. Diffusion and ecological problems. IV. Interdisciplinary applied
mathematics ; v. 14.

QH541.15.M3 O38 2001

577'.01'5118—dc21

00-052258

Printed on acid-free paper.

© 2001, 1980 Springer Science+Business Media New York

Originally published by Springer-Verlag New York, Inc. in 2001

All rights reserved. This work may not be translated or copied in whole or in part without the written permission of the publisher Springer Science+Business Media, LLC.

except for brief excerpts in connection with reviews or scholarly analysis. Use in connection with any form of information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed is forbidden.

The use of general descriptive names, trade names, trademarks, etc., in this publication, even if the former are not especially identified, is not to be taken as a sign that such names, as understood by the Trade Marks and Merchandise Marks Act, may accordingly be used freely by anyone.

Production managed by Steven Pisano; manufacturing supervised by Erica Bresler.

Typeset by Asco Typesetters, Hong Kong.

9 8 7 6 5 4 3 2 1

ISBN 978-1-4419-3151-1

SPIN 10700945

3.3	Diffusion of Spores.....	62
3.3.1	Settling Velocity	63
3.3.2	Diffusion Model	67
3.3.3	Experiments on Spore Dispersal	73
3.3.4	Vertical Distributions over Wide Regions	76
3.3.5	Wind and Water Pollination	79
3.4	Dispersal of Gametes and Organisms	84
3.4.1	Broadcast Spawners and External Fertilization.....	85
3.4.2	The Dispersal of Fish Eggs and Larvae in the Sea ..	88
3.5	Transport Across the Solid Interface	91
3.5.1	Fluid Exchange in Animal Burrows.....	92
3.5.2	Bioturbation and Related Effects	104
3.5.3	Notes on Solute Transport in Soils and Sediments	105
4.	Diffusion of “Smell” and “Taste”: Chemical Communication ..	107
	<i>Akira Okubo, Robert A. Armstrong, and Jeannette Yen</i>	
4.1	Diffusion of Insect Pheromones.....	107
4.1.1	Instantaneous Emission in Still Air	108
4.1.2	Continuous Emission in Still Air.....	110
4.1.3	Continuous Emission from a Moving Source.....	111
4.1.4	Continuous Emission of Pheromone in a Wind.....	112
4.2	A Diffusion Problem Concerning the Migration of Green Turtles	115
4.3	Chemical Communication in Aquatic Organisms	119
4.3.1	Temporal and Spatial Scales for Chemical Communication	119
4.3.2	Models of Chemical Communication in Aquatic Organisms	123
4.3.3	An Inverse Problem: Estimating the “Statistical Funnel” of Sediment Traps	124
5.	Mathematical Treatment of Biological Diffusion	127
	<i>Akira Okubo and Daniel Grünbaum</i>	
5.1	Animal Motion and the Balance of Acting Forces.....	128
5.2	Taxis and the Equation of Motion	131
5.3	Extension of the Random Walk Model and the Equation of Biodiffusion.....	133
5.3.1	Correlated Random Walks.....	137
5.3.2	Patlak’s Model	140
5.3.3	The Fokker–Planck Equations.....	143
5.4	Application to Taxis	151
5.5	Simulation of Taxis	157
5.6	Advection–Diffusion Models for Biodiffusion.....	158
5.7	Internal State-mediated Taxis.....	161
5.7.1	An Example: Receptor Kinetics-based Taxis	162

6. Some Examples of Animal Diffusion	170
<i>Akira Okubo and Peter Kareiva</i>	
6.1 Population Pressure and Dispersal	170
6.2 Horizontal and Vertical Distributions of Insects in the Atmosphere: Insect Dispersal.....	172
6.2.1 Dispersal of Insects	173
6.2.2 Mathematical Models for Insect Dispersal	181
6.3 Diffusion Models for Homing and Migration of Animals.....	186
6.4 Model for Muskrat Dispersal and Biological Invasions in General.....	191
6.5 The Dispersal of Animal-Borne Plants	194
6.6 Diffusion Models as a Standard Tool in Animal Ecology	195
7. The Dynamics of Animal Grouping	197
<i>Akira Okubo, Daniel Grünbaum, and Leah Edelstein-Keshet</i>	
7.1 Physical Distinction Between Diffusion and Grouping	197
7.2 Formulation of Swarming by a Generalized Diffusion Equation.....	200
7.3 Insect Swarming	202
7.3.1 Locust Swarms.....	202
7.3.2 Experimental Techniques	203
7.3.3 Mosquitoes, Flies, and Midges	204
7.3.4 Marine Zooplankton Swarming	208
7.4 Fish Schooling.....	209
7.5 Simulation Model for Animal Grouping.....	215
7.6 The Split and Amalgamation of Herds.....	219
7.7 The Ecological or Evolutional Significance of Grouping.....	222
7.8 Linking Individuals, Groups, and Populations: The Biological Context of Mathematical Models of Grouping.....	227
7.9 Continuum Approximations for Density Distributions Within Social Group.....	229
7.9.1 Energy-Potential Analogy.....	230
7.9.2 Integral Equations for Group Dynamics	231
7.9.3 Poisson-Point Assumption	232
7.10 Dynamics of Groups in Social Grouping Populations	234
7.10.1 Spatially Explicit Group-Size Distribution Models	235
8. Animal Movements in Home Range.....	238
<i>Akira Okubo and Louis Gross</i>	
8.1 The Size of the Home Range and Its Relation to Animal Weight and Energy Requirements	239

8.2	Mathematical Models for Animal Dispersal in Home Ranges	240
8.3	Simulation of Animal Movement in Home Ranges	242
8.4	Animal Dispersal and Settling in New Home Ranges.....	248
8.5	Strategies of Movement for Resource Utilization	250
8.6	Data on Animal Movements	258
	8.6.1 Case Study: Florida Panther	259
8.7	Home-Range Estimation.....	261
8.8	Allometric Relations Between Body Size and Home Range	261
8.9	Individual-based Models of Movement.....	262
	8.9.1 Corridors and Movement	263
	8.9.2 Food Density and Home-Range Size	264
8.10	Diffusion Models.....	264
	8.10.1 Boundary Effects	265
	8.10.2 Movement in Heterogeneous Environments	266
	8.10.3 Multiple Scales and Foraging.....	266
9.	Patchy Distribution and Diffusion	268
	<i>Akira Okubo and James G. Mitchell</i>	
9.1	Role of Diffusion in Plankton Patchiness.....	269
9.2	Spectra of Turbulence and Patchiness	274
9.3	Plankton Distribution in Convection Cells	280
9.4	Bioconvection	287
9.5	Microscale Patchiness.....	291
9.6	Diffusion and the Entropy of Patchiness	294
10.	Population Dynamics in Temporal and Spatial Domains.....	298
	<i>Akira Okubo, Alan Hastings, and Thomas Powell</i>	
10.1	Mathematical Representation of Intra- and Interspecific Interactions in Temporal and Spatial Domains: Advection–Diffusion–Reaction Equations	299
10.2	Single-Species Population Dynamics with Dispersal	304
	10.2.1 Some Simple Population Models and Associated Travelling Frontal Waves	304
	10.2.2 The Critical Size Problem	310
	10.2.3 Population Balance with Diffusion and Direct Immigration-Emigration: Invasion and Settlement of New Species	317
10.3	Two- and Multispecies Population Dynamics with Dispersal	321
	10.3.1 Lotka–Volterra Predator–Prey Model.....	322
	10.3.2 Travelling Waves	326
	10.3.3 The Effect of Cross-Diffusion	333
	10.3.4 The Effect of Advective Flow on Predator–Prey Systems	334

10.4 The Effect of Density-Dependent Dispersal on Population Dynamics.....	336
10.5 The Effect of Dispersal on Competing Populations.....	343
10.6 Pattern-Developing Instability in Diffusion–Reaction Systems: The Development of Patchiness.....	348
10.7 Nonlinear Stability Analysis for Diffusion–Reaction Systems.....	357
10.8 Models of Age-Dependent Dispersal.....	364
References.....	374
Author Index.....	443
Subject Index.....	459