Published 2008

Nitrogen in Agricultural Systems

Nitrogen in Agricultural Systems

J. S. Schepers and W. R. Raun, Co-editors

Agronomy Monograph 49

American Society of Agronomy
Crop Science Society of America
Soil Science Society of America

American Society of Agronomy, Inc.
Crop Science Society of America, Inc.
Soil Science Society of America, Inc.
677 South Segoe Road, Madison, WI 53711-1086 USA

ISBN: 978-0-89118-164-4

Library of Congress Control Number: 2008926541

Cover photos: USDA-ARS

Printed in the United States of America.

Contents

Foreword

The American Society of Agronomy, the Crop Science Society of America, and the Soil Science Society of America are pleased to publish this highly relevant and comprehensive review of the principles and management of nitrogen in the earth's environment, *Nitrogen in Agricultural Systems*.

Nitrogen supply is of great importance to the food supply and to the health of the world's population, but mismanagement of the nitrogen supply can create environmental hazards. The nitrogen management principles described in this book promote judicious global management of our nitrogen resources. Co-editors, James Schepers and William Raun have done an excellent job of assembling this monograph.

The authors contributing to this book are highly regarded scientists who work at the forefront of research in nitrogen management, and their expertise brings great credibility to this book. Research scientists, land managers, and students from a broad range of disciplines will benefit greatly from this assemblage of in-depth knowledge of nitrogen management.

The Societies certainly appreciate the efforts of the editors, Drs. Schepers and Raun, who chose an outstanding group of authors, and who skillfully and carefully guided the development of the book. Thank you also to the members of the editorial committee, which included Drs. Ron Follett, Richard Fox, and Giles Randall.

The editors, along with the highly qualified authors, provide a truly excellent book, one of which all three Societies can be justly proud. We anticipate that the readers will find this book to be a highly valued resource.

Kenneth Moore, President of the American Society of Agronomy

William Wiebold, President of the Crop Science Society of America

Gary A. Peterson, President of the Soil Science Society of America

Preface

Nitrogen in Agricultural Systems provides an extensive review of the principles and management implications related to nitrogen in the soil–plant–water system. The volume supersedes Agronomy Monograph 22 *Nitrogen in Agricultural Soils* published in 1982 and Agronomy Monograph 10 *Soil Nitrogen* published in 1965. Advances in scientific techniques and instrumentation used to study the various interactions and relationships between nitrogen and the environment in the past several decades have prompted this analysis and compilation of current knowledge. Authors participating in this edition have introduced new concepts as well as updated and broadened understandings presented in earlier editions. New chapters have been added to address growing concerns over environmental protection and the efficient use of resources. Significant advances in analytical devices and computational tools have broadened the perspective from which authors present and discuss their specific views on each aspect of the nitrogen cycle.

This volume combines several chapters from previous editions dealing with the sources and forms of nitrogen in the environment and expands discussion of nitrogen loss mechanisms from soil and vegetation. Nitrogen transformations remain a common thread throughout in the discussion of biological, chemical, physical, and weather-related interactions. New research tools and advanced management concepts are presented and discussed from a holistic perspective that emphasizes the complexity of the nitrogen cycle. The subjects of accountability and nitrogen budgeting are emphasized because they have a strong bearing on management decisions and the environmental implications. The concept of soil–plant resiliency is introduced as a framework from which to better understand and appreciate how climate, soils, and plants interact to broadly delineate cropping eco-regions. The ensuing nitrogen management schemes reflect crop responses, as well as how producers assess and are able to respond to risks. Sections on economic considerations and the water quality implications of nitrogen management are included. The literature on nitrogen in agricultural systems is vast and continues to expand, which precludes including all references. The editors and authors apologize for the omission of any pertinent citations and contributing research.

The editorial committee is grateful to the authors for their dedication, cooperation, patience, and support in the completion of this revision. Thanks are extended to the many individuals who graciously reviewed the manuscripts and offered constructive comments. Special acknowledgement is given to the Headquarters staff for editing and assistance in preparation of this manuscript for publication.

The Editorial Committee

J. S. Schepers, Co-editor, USDA-ARS, Lincoln, Nebraska

W. R. Raun, Co-editor, Oklahoma State University, Stillwater, Oklahoma

R. F. Follett, USDA-ARS, Fort Collins, Colorado

R. H. Fox, Pennsylvania State University, University Park, Pennsylvania

G. W. Randall, University of Minnesota, Waseca, Minnesota

Contributors

Beegle, D.B.	Pennsylvania State University, Dep. of Crop and Soil Sciences, 116 Ag Sciences & Industries Building, University Park, PA 16802-3504 (dbb@psu.edu)
Bottomley, P.J.	Dep. of Microbiology, Oregon State University, 220 Nash Hall Campus Way, Corvallis, OR 97331-7306 (peter.bottomley@orst.edu)
Bronson, K.F.	Texas Agricultural Experiment Station, 1102 E FM 1294, Lubbock, TX 79403 (k-bronson@tamu.edu)
Buresh, R.J.	IRRI, DAPO Box 7777, Metro Manila, Philippines (r.buresh@cgiar.org)
Cabrera, M.L.	Dep. of Crop & Soil Sciences, 3111 Miller Plant Sciences Bldg., University of Georgia, Athens, GA 30602 (mcabrera@uga.edu)
Calderón, F.J.	USDA-ARS, Central Great Plans Research Station, 40335 County Rd. GG, Akron, CO 80720 (francisco.calderon@npa.ars.usda.gov)
Coyne, M.S.	Dep. of Plant and Soil Sciences, N-122N Agricultural Sciences Bldg., 500 S. Limestone, University of Kentucky, Lexington, KY 40546-0091 (mark.coyne@uky.edu)
Daberkow, S.	USDA Economic Research Service, 1800 M Street NW, Washington, DC 20036-5831 (daberkow@ers.usda.gov)
Delgado, J.A.	USDA-ARS-Soil Plant Nutrient Research, 2150 Center Avenue, Bldg D, Suite 100, Fort Collins, CO 80526 (jorge.delgado@ars.usda.gov)
Derry, D.	University of Guelph, 49 Hillholm Road, Guelph, ON Canada
Doering, O.	Dep. of Agricultural Economics, Purdue University, 403 W. State St., West Lafayette, IN 47907-2056 (doering@purdue.edu)
Fox, R.H.	retired, formerly Pennsylvania State University
Francis, D.D.	USDA-ARS, University of Nebraska, 241 Keim Hall, P.O. Box 830934, Lincoln, NE 68583-0934 (dfrancis1@unl.edu)
Griffin, T.S.	USDA-ARS-NEPSWL, University of Maine, Room 23, Orono, ME 04469 (tim.griffin@ars.usda.gov)
Groffman, P.M.	Cary Institute of Ecosystem Studies, Box AB, 65 Sharon Turnpike, Millbrook, NY 12545 (groffmanP@ecostudies.org)
Jenkinson, D.S.	Rothamsted Research, Harpenden, Herts, UK AL52JQ (davids_jenkinson@tiscali.co.uk)
Kelling, K.A.	Dep. of Soil Science, 1525 Observatory Dr., University of Wisconsin, Madison, WI 53706-1299 (kkelling@wisc.edu)
Kissel, D.E.	University of Georgia, Soil, Plant & Water Laboratory, 2400 College Station Rd., Athens, GA 30602-9105 (dkissel@uga.edu)
Meisinger, J.J.	USDA-ARS, BARC-East, Bldg. 163F Room 6, 10300 Baltimore Ave., Beltsville Agricultural Research Center, Beltsville, MD 20705-2350 (John.Meisinger@ars.usda.gov)
Molina, J.-A.	Univ. of MN-439 Borlaug Hall, 1991 Upper Buford Circle, St. Paul, MN 55108 (jamolina@umn.edu)

Mosier, A.R.	retired, formerly USDA-ARS and University of Florida
Mulla, D.J.	Dep. of Soil, Water, and Climate, University of Minnesota, 1991 Upper Buford Circle, St. Paul, MN 55108 (dmulla@soils.umn.edu)
Mulvaney, R.L.	University of Illinois at Urbana-Champaign, S-220 Turner Hall, 1102 S. Goodwin Ave., Urbana, IL (mulvaney@uiuc.edu)
Myrold, D.D.	Dep. of Crop and Soil Science, Agric. Life Sci. Bldg. 3017, Oregon State University, Corvallis, OR 97331-7306 (david.myrold@oregonstate.edu)
Norton, J.M.	Dep. Plants, Soils, and Climate, 4820 Old Main Hill, Utah State University, Logan UT 84322-4820 (jennnyn@cc.usu.edu)
Olk, D.C.	USDA-ARS, National Soil Tilth Laboratory, 2110 University Blvd., Ames, IA 50011-3120 (dan.old@ars.usda.gov)
Paramasivam, S.	Savannah State University, Box 20600, 122 Drew Griffith Hall, Savannah, GA 31404 (siva@savstate.edu)
Randall, G.W.	University of Minnesota, Southern Research and Outreach Center, 35838 120th St., Waseca, MN 56093-4521 (grandall@umn.edu)
Raun, W.R.	Oklahoma State University, Dep. of Plant and Soil Sciences, 368 Agricultural Hall, Stillwater, OK 74078-0507 (bill.raun@okstate.edu)
Reddy, K.R.	University of Florida, Soil and Water Science Dep., 106 Newell Hall; PO Box 110510, Gainesville, FL 32611-0510 (krr@ufl.edu)
Ribaudo, M.	USDA Economic Research Service, 1800 M Street NW, Washington, DC 20036-5831 (mribaudo@ers.usda.gov)
Russelle, M.P.	USDA-ARS Plant Science Research Unit, 1991 Upper Buford Circle Room 439, St. Paul, MN 55108-6028 (Michael.Russelle@ars.usda.gov)
Schepers, J.S.	University of Nebraska-Lincoln, 113 Keim Hall, Lincoln, NE 68583-0915 (jim.schepers@ars.usda.gov)
Schmitt, M.A.	University of Minnesota, 240 Coffey Hall, 1420 Eckles, St. Paul, MN 55108 (schmi009@umn.edu)
Sims, J.T.	College of Agriculture and Natural Resources, University of Delaware, 531 S. College Avenue, Newark, DE 19717-2103 (jtsims@udel.edu)
Stehouwer, R.C.	Penn State University, 116 ASI Bldg., University Park, PA 16802-3504 (rcs15@psu.edu)
Strock, J.S.	Dep. of Soil, Water, and Climate, Southwest Research and Outreach Center, University of Minnesota, Lamberton, MN 56152 (jstrock@umn.edu)
van Kessel, C.	University of California-Davis, Dep. of Plant Sciences, 1210A PES Bldg., Davis, CA 95616-8515 (cvankessel@ucdavis.edu)
Vigil, M.F.	Central Plains Resources Management Research, 40335 County Rd. GG, Akron, CO, 80720-0400 (merle.vigil@ars.usda.gov)
Voroney, P.	Dep. of Land Resource Science, Ontario Agricultural College, University of Guelph, Guelph, ON, Canada N1G 2W1 (pvoroney@ uoguelph.ca)
Walthall, C.L.	USDA-ARS, 5601 Sunnyside Ave., Rm. 4-2278, Beltsville, MD 20705-5140 (charlie.walthall@ars.usda.gov)

Conversion Factors for SI and Non-SI Units

To convert Column 1 into Column 2 multiply by	Column 1 SI unit	Column 2 non-SI unit	To convert Column 2 into Column 1 multiply by
		Length	
0.621	kilometer, km (10^3 m)	mile, mi	1.609
1.094	meter, m	yard, yd	0.914
3.28	meter, m	foot, ft	0.304
1.0	micrometer, μm (10^{-6} m)	micron, μ	1.0
3.94×10^{-2}	millimeter, mm (10^{-3} m)	inch, in	25.4
10	nanometer, nm (10^{-9} m)	Angstrom, Å	0.1
		Area	
2.47	hectare, ha	acre	0.405
247	square kilometer, km^2 $(10^3\ m)^2$	acre	4.05×10^{-3}
0.386	square kilometer, km^2 $(10^3\ m)^2$	square mile, mi^2	2.590
2.47×10^{-4}	square meter, m^2	acre	4.05×10^{3}
10.76	square meter, m^2	square foot, ft^2	9.29×10^{-2}
1.55×10^{-3}	square millimeter, mm^2 $(10^{-3}\ m)^2$	square inch, in^2	645
		Volume	
9.73×10^{-3}	cubic meter, m^3	acre-inch	102.8
35.3	cubic meter, m^3	cubic foot, ft^3	2.83×10^{-2}
6.10×10^{4}	cubic meter, m^3	cubic inch, in^3	1.64×10^{-5}
2.84×10^{-2}	liter, L (10^{-3} m^3)	bushel, bu	35.24
1.057	liter, L (10^{-3} m^3)	quart (liquid), qt	0.946
3.53×10^{-2}	liter, L (10^{-3} m^3)	cubic foot, ft^3	28.3
0.265	liter, L (10^{-3} m^3)	gallon	3.78
33.78	liter, L (10^{-3} m^3)	ounce (fluid), oz	2.96×10^{-2}
2.11	liter, L (10^{-3} m^3)	pint (fluid), pt	0.473
		Mass	
2.20×10^{-3}	gram, g (10^{-3} kg)	pound, lb	454
3.52×10^{-2}	gram, g (10^{-3} kg)	ounce (avdp), oz	28.4
2.205	kilogram, kg	pound, lb	0.454
0.01	kilogram, kg	quintal (metric), q	100
1.10×10^{-3}	kilogram, kg	ton (2000 lb), ton	907
1.102	megagram, Mg (tonne)	ton (U.S.), ton	0.907
1.102	tonne, t	ton (U.S.), ton	0.907
		Yield and Rate	
0.893	kilogram per hectare, kg ha^{-1}	pound per acre, lb $acre^{-1}$	1.12
7.77×10^{-2}	kilogram per cubic meter, kg m^{-3}	pound per bushel, lb bu^{-1}	12.87
1.49×10^{-2}	kilogram per hectare, kg ha^{-1}	bushel per acre, 60 lb	67.19
1.59×10^{-2}	kilogram per hectare, kg ha^{-1}	bushel per acre, 56 lb	62.71

Table cont.

To convert Column 1 into Column 2 multiply by	Column 1 SI unit	Column 2 non-SI unit	To convert Column 2 into Column 1 multiply by
1.86×10^{-2}	kilogram per hectare, kg ha^{-1}	bushel per acre, 48 lb	53.75
0.107	liter per hectare, L ha^{-1}	gallon per acre	9.35
893	tonne per hectare, t ha^{-1}	pound per acre, lb $acre^{-1}$	1.12×10^{-3}
893	megagram per hectare, Mg ha^{-1}	pound per acre, lb $acre^{-1}$	1.12×10^{-3}
0.446	megagram per hectare, Mg ha^{-1}	ton (2000 lb) per acre, ton $acre^{-1}$	2.24
2.24	meter per second, m s^{-1}	mile per hour	0.447
	Specific Surface		
10	square meter per kilogram, m^2 kg^{-1}	square centimeter per gram, cm^2 g^{-1}	0.1
1000	square meter per kilogram, m^2 kg^{-1}	square millimeter per gram, mm^2 g^{-1}	0.001
	Density		
1.00	megagram per cubic meter, Mg m^{-3}	gram per cubic centimeter, g cm^{-3}	1.00
	Pressure		
9.90	megapascal, MPa (10^6 Pa)	atmosphere	0.101
10	megapascal, MPa (10^6 Pa)	bar	0.1
2.09×10^{-2}	pascal, Pa	pound per square foot, lb ft^{-2}	47.9
1.45×10^{-4}	pascal, Pa	pound per square inch, lb in^{-2}	6.90×10^3
	Temperature		
1.00 (K – 273)	kelvin, K	Celsius, °C	1.00 (°C + 273)
(9/5 °C) + 32	Celsius, °C	Fahrenheit, °F	5/9 (°F – 32)
	Energy, Work, Quantity of Heat		
9.52×10^{-4}	joule, J	British thermal unit, Btu	1.05×10^3
0.239	joule, J	calorie, cal	4.19
10^7	joule, J	erg	10^{-7}
0.735	joule, J	foot-pound	1.36
2.387×10^{-5}	joule per square meter, J m^{-2}	calorie per square centimeter (langley)	4.19×10^4
10^5	newton, N	dyne	10^{-5}
1.43×10^{-3}	watt per square meter, W m^{-2}	calorie per square centimeter minute (irradiance), cal cm^{-2} min^{-1}	698
	Transpiration and Photosynthesis		
3.60×10^{-2}	milligram per square meter second, mg m^{-2} s^{-1}	gram per square decimeter hour, g dm^{-2} h^{-1}	27.8
5.56×10^{-3}	milligram (H_2O) per square meter second, mg m^{-2} s^{-1}	micromole (H_2O) per square centimeter second, μmol cm^{-2} s^{-1}	180
10^{-4}	milligram per square meter second, mg m^{-2} s^{-1}	milligram per square centimeter second, mg cm^{-2} s^{-1}	10^4
35.97	milligram per square meter second, mg m^{-2} s^{-1}	milligram per square decimeter hour, mg dm^{-2} h^{-1}	2.78×10^{-2}
	Plane Angle		
57.3	radian, rad	degrees (angle), °	1.75×10^{-2}

Table cont.

To convert Column 1 into Column 2 multiply by	Column 1 SI unit	Column 2 non-SI unit	To convert Column 2 into Column 1 multiply by
	Electrical Conductivity, Electricity, and Magnetism		
10	siemen per meter, S m^{-1}	millimho per centimeter, mmho cm^{-1}	0.1
10^4	tesla, T	gauss, G	10^{-4}
	Water Measurement		
9.73×10^{-3}	cubic meter, m^3	acre-inch, acre-in	102.8
9.81×10^{-3}	cubic meter per hour, m^3 h^{-1}	cubic foot per second, ft^3 s^{-1}	101.9
4.40	cubic meter per hour, m^3 h–1	U.S. gallon per minute, gal min^{-1}	0.227
8.11	hectare meter, ha m	acre-foot, acre-ft	0.123
97.28	hectare meter, ha m	acre-inch, acre-in	1.03×10^{-2}
8.1×10^{-2}	hectare centimeter, ha cm	acre-foot, acre-ft	12.33
	Concentration		
1	centimole per kilogram, cmol kg^{-1}	milliequivalent per 100 grams, meq 100 g^{-1}	1
0.1	gram per kilogram, g kg^{-1}	percent, %	10
1	milligram per kilogram, mg kg^{-1}	parts per million, ppm	1
	Radioactivity		
2.7×10^{-11}	becquerel, Bq	curie, Ci	3.7×10^{10}
2.7×10^{-2}	becquerel per kilogram, Bq kg^{-1}	picocurie per gram, pCi g^{-1}	37
100	gray, Gy (absorbed dose)	rad, rd	0.01
100	sievert, Sv (equivalent dose)	rem (roentgen equivalent man)	0.01
	Plant Nutrient Conversion		
	Elemental	Oxide	
2.29	P	P_2O_5	0.437
1.20	K	K_2O	0.830
1.39	Ca	CaO	0.715
1.66	Mg	MgO	0.602