

Published 2000

**LAND APPLICATION OF
AGRICULTURAL, INDUSTRIAL,
AND MUNICIPAL BY-PRODUCTS**

Soil Science Society of America Book Series

Books in the series are available from the Soil Science Society of America,
677 South Segoe Road, Madison, WI 53711 USA.

1. MINERALS IN SOIL ENVIRONMENTS. Second Edition. 1989.
J. B. Dixon and S.B. Weed, *editors* R. C. Dinauer, *managing editor*
2. PESTICIDES IN THE SOIL ENVIRONMENT: PROCESSES, IMPACTS,
AND MODELING. 1990.
H. H. Cheng, *editor* S. H. Mickelson, *managing editor*
3. SOIL TESTING AND PLANT ANALYSIS. Third Edition. 1990.
R. L. Westerman, *editor* S. H. Mickelson, *managing editor*
4. MICRONUTRIENTS IN AGRICULTURE. Second Edition. 1991.
J. J. Mortvedt et al., *editors* S. H. Mickelson, *managing editor*
5. METHODS OF SOIL ANALYSIS: PHYSICAL AND MINERALOGICAL
METHODS. Part 1. Second Edition. 1986.
Arnold Klute, *editor* R. C. Dinauer, *managing editor*
METHODS OF SOIL ANALYSIS: MICROBIOLOGICAL
AND BIOCHEMICAL PROPERTIES. Part 2. 1994.
R. W. Weaver et al., *editor* S. H. Mickelson, *managing editor*
METHODS OF SOIL ANALYSIS: CHEMICAL METHODS. Part 3. 1996.
D. L. Sparks, *editor* J. M. Bartels, *managing editor*
6. LAND APPLICATION OF AGRICULTURAL, INDUSTRIAL, AND
MUNICIPAL BY-PRODUCTS. 2000.
J. F. Power and W.A. Dick, *editors* J. M. Bartels, *managing editor*

Land Application of Agricultural, Industrial, and Municipal By-Products

Editorial Committee:
James F. Power, *chair*
Warren A. Dick, *chair*
Richard M. Kashmanian
J. Thomas Sims
Robert J. Wright
Michael D. Dawson
David Bezdicek

Managing Editor: J.M. Bartels

Editor-in-Chief SSSA: Warren A. Dick

Number 6 in the Soil Science Society of America Book Series

**Published by: Soil Science Society of America, Inc.
Madison, Wisconsin, USA**

2000

Copyright © 2000 by the Soil Science Society of America, Inc.

ALL RIGHTS RESERVED UNDER THE U.S. COPYRIGHT LAW OF 1976
(P.L. 94-553)

Any and all uses beyond the “fair use” provision of the law require written permission from the publishers and/or author(s); not applicable to contributions prepared by officers and employees of the U.S. Government as part of their official duties.

The views expressed in this publication represent those of the individual authors and editors. These views do not necessarily reflect endorsement by the Publisher(s). In addition, trade names are sometimes mentioned in this publication. No endorsement of these products by the Publisher(s) is intended, nor is any criticism implied of similar products not mentioned.

Soil Science Society of America, Inc.
677 South Segoe Road, Madison, Wisconsin 53711 USA

Library of Congress Catalog Card Number: 00-131536

Printed in the United States of America

TABLE OF CONTENTS

FOREWORD	vii
PREFACE	ix
CONTRIBUTORS	xi
CONVERSION FACTORS FOR SI AND NON-SI UNITS.....	xv
1 Chemical, Physical, and Biological Characteristics of Agricultural and Forest By-Products for Land Application J. H. Edwards and Arun V. Someshwar	1
2 Description of Food Processing By-Products Allen V. Barker, Tara A. O'Brien, and Margie L. Stratton	63
3 Characterization of Industrial By-Products D. M. Miller, W. P. Miller, S. Dudka, and M. E. Sumner	107
4 Quantities, Characteristics, Barriers, and Incentives for Use of Organic Municipal By-Products Richard M. Kashmanian, Daniel Kluchinski, Tom L. Richard, and John M. Walker	127
5 Soil and By-Product Characteristics that Impact the Beneficial Use of By-Products Allen V. Barker, Margie L. Stratton, and Jack E. Rechcigl	169
6 Sustainable Use of By-Products in Land Management Leslie R. Cooperband	215
7 Assessing the Impacts of Agricultural, Municipal, and Industrial By-Products on Soil Quality J. Thomas Sims and Gary M. Pierzynski	237
8 Potential Impact of Land Application of By-Products on Ground and Surface Water Quality William F. Ritter	263
9 Odor and Other Air Quality Issues Associated with Organic and Inorganic By-Products P. D. Millner and L. L. McConnell	289
10 Composting and Beneficial Utilization of Composted By-Product Materials Harold M. Keener, Warren A. Dick, and Harry A. J. Hoitink	315
11 Combining By-Products to Achieve Specific Soil Amendment Objectives S. Brown and R.L. Chaney	343

12	Estimating the Benefits of Agricultural Use of Municipal, Animal, and Industrial By-Products Wen-Yuan Huang and Yao-Chi Lu	361
13	Examples and Case Studies of Beneficial Reuse of Beef Cattle By-Products B. A. Stewart, C. A. Robinson, and David B. Parker	387
14	Liquid Dairy Manure Utilization in a Cropping System: A Case Study Deanne Meyer and Lawrence J. Schwankl	409
15	Beneficial Use of Poultry By-Products: Challenges and Opportunities Miguel L. Cabrera and J. Thomas Sims	425
16	Beneficial Uses of Swine By-Products: Opportunities for the Future Robert L. Mikkelsen	451
17	Examples and Case Studies of Beneficial Reuse of Municipal By-Products Nicholas T. Basta	481
18	Beneficial Uses of Flue Gas Desulfurization By-Products: Examples and Case Studies of Land Application Warren A. Dick, Richard Stehouwer, Jerry M. Bigham, William E. Wolfe, Yueli Hao, Domy C. Adriano, Joel H. Beeghly, and Ralph J. Haefner	505
19	Properties and Examples of Beneficial Use of Gypsumlike By-Products K. D. Ritchey, R. B. Clark, Moustafa A. Elrashidi, and V. C. Baligar	537
20	Beneficial Use of Wood Ash as an Agricultural Soil Amendment: Case Studies from the United States Forest Products Industry Eric D. Vance and Charles C. Mitchell	567
21	Beneficial Reuse of Aggregate Mineral Fines and Scrap New Construction Wallboard R. F. Korcak, R. Meininger, and Peter A. Yost	583
22	Case Studies of Municipal and On-Farm Composting in the United States of America Lawrence J. Sikora and Dan M. Sullivan	605
	Subject Index	625

FOREWORD

Environmental quality is one of the major issues and concerns worldwide. Of particular importance is the protection and sustainability of valuable soil and water resources. With increasing human populations, concentrated animal production areas, and expanding industries, safe disposal of by-product materials is becoming a greater challenge. Often, agricultural, industrial, and municipal by-products are applied to land. While they can be beneficial to plants and soils, there can be negative impacts on soil, water, and air quality. For example, there is intense controversy as we enter the 21st century on the impacts of animal wastes on water quality and resulting effects on aquatic life and human health. Arguably, the application of by-product materials to land will be a leitmotif for decades to come.

This SSSA book provides a wealth of information by leading experts on land application of agricultural, industrial, and municipal by-products including characteristics of an array of by-product materials, benefits and hazards in applying by-products, and actual case studies. The book will be a contemporary and useful resource for professionals, students, and policymakers.

Donald L. Sparks, *president*
Soil Science Society of America

PREFACE

Increased concerns these last several decades about protecting the environment and moving toward a more sustainable culture have stimulated interest in recycling by-products from the agricultural, industrial, and municipal sectors of our society. Land application is a dominant method of recycling (or reuse) of many such by-products. Past experiences have demonstrated repeatedly and revealed acceptable and inappropriate ways for land application of by-products. Consequently in 1995, the Soil Science Society of America appointed an Organizing Committee to investigate the need and feasibility of publishing a comprehensive monograph on land application of agricultural, industrial, and municipal by-products. The Organizing Committee recommended that the SSSA Board of Directors proceed with the development and production of such a monograph, and an Editorial Committee was selected.

The Editorial Committee solicited authors for 26 chapters for this monograph. Later several chapters were combined or eliminated, resulting in 22 manuscripts remaining for publication. Authors were invited to present their chapters orally or by poster at a symposium on this subject at the 1997 Meeting of the Soil Science Society of America.

The chapters in this monograph address most of the major concerns associated with application of various types of by-products to land. The fundamental processes involved in recycling by-products through land application are discussed, providing the reader with a basic understanding of the science involved. Problems and potential benefits from land application are outlined. Finally, a number of case studies and examples of successful land application technologies and programs are presented. The chapters of this monograph are designed to provide readers with a comprehensive reference source on land application of by-product materials.

Information on best management practices, regulations, properties of by-products, etc., can rapidly change, and new information continually becomes available. The information contained in the different chapters was relatively current at the time the chapters were written.

The Editorial Committee thanks the SSSA Board of Directors and the Headquarters staff for their support and cooperation in preparing this monograph. Also thanks are due to the authors for their cooperative efforts in making this publication a reality.

James F. Power (deceased), *co-editor*
University of Nebraska
Lincoln, Nebraska

Warren A. Dick, *co-editor*
Ohio Agricultural Research and Development Center
Ohio State University
Wooster, Ohio

CONTRIBUTORS

- Domy C. Adriano** Professor of Environmental Soil Science, Savannah River Ecology Lab., University of Georgia, Aiken, SC 29803
- V. C. Baligar** Research Scientist, USDA-ARS-AFSRC, Beaver, WV 25813
- Allen V. Barker** Professor, Department of Plant and Soil Sciences, University of Massachusetts, Amherst, MA 01003
- Nicholas T. Basta** Associate Professor of Soil Chemistry, Oklahoma State University, Stillwater, OK 74078
- Joel H. Beeghly** Project Manager, Dravo Technology Center, Pittsburgh, PA 15225
- Jerry M. Bigham** Professor of Soil Science, School of Natural Resources, Ohio State University, Columbus, OH 43210
- S. Brown** Assistant Professor, Ecosystem Sciences Division, College of Forest Resources, University of Washington, Seattle, WA 98195
- Miguel L. Cabrera** Agroecologist, Crop and Soil Sciences, University of Georgia, Athens, GA 30602-7272
- R. L. Chaney** Research Agronomist, USDA-ARS, Environmental Chemistry Lab., Bldg. 007, BARC-W, Beltsville, MD 20705
- R. B. Clark** Research Scientist, USDA-ARS-AFSRC, Beaver, WV 25813
- Leslie R. Cooperband** Assistant Professor, Waste Management Specialist, Department of Soil Science, University of Wisconsin, Madison, WI 53706
- Warren A. Dick** Professor of Soil Science, School of Natural Resources, Ohio State University, Wooster, OH 44691
- S. Dudka** Postdoctoral Associate, Department of Crop and Soil Sciences, University of Georgia, Athens, GA 30602-7272
- J. H. Edwards** Soil Scientist, USDA-ARS, National Soil Dynamics Lab., Auburn, AL 36832-5806
- Moustafa A. Elrashidi** Soil Scientist, CREC, University of Florida, Lake Alfred, FL 33850-2299
- Ralph J. Haefner** Hydrologist, U.S. Geological Survey, Columbus, OH 43229
- Yueli Hao** Soil Scientist, School of Natural Resources, Ohio State University, Columbus, OH 43210
- Harry A. J. Hoitink** Professor of Plant Pathology, OARDC/Ohio State University, Wooster, OH 44691-4096
- Wen-Yuan Huang** Agricultural Economist, Economic Research Service, Washington, DC 20036-5831
- Richard M. Kashmanian** Senior Economist, USEPA, Office of Policy, Washington, DC 20460
- Harold M. Keener** Associate Professor, Department of Food, Agricultural, and Biological Engineering, OARDC/Ohio State University, Wooster, OH 44691-4096

- Daniel Kluchinski** Associate Professor/County Agricultural Agent, Rutgers Cooperative Extension, Rutgers-The State University of New Jersey, Trenton, NJ 08648-4584
- R. F. Korcak** Associate Area Director, USDA-ARS, Beltsville Area, Beltsville, MD 20705
- Yao-Chi Lu** Senior Economist, USDA-ARS, Beltsville, MD 20705
- Laura L. McConnell** Research Chemist, Environmental Chemistry Lab., USDA-ARS, Bldg. 007, Rm. 225, BARC-W, Beltsville, MD 20705-2350
- Richard C. Meininger** Executive Director (Retired), National Aggregates Assoc., Columbia, MD 21044
- Deanne Meyer** Livestock Waste Management Specialist, One Shields Ave., Department of Animal Science, University of California, Davis, CA 95616
- Robert L. Mikkelsen** Associate Professor, Department of Soil Science, North Carolina State University, Raleigh, NC 27695-7619
- D. M. Miller** Associate Professor, Department of Agronomy, University of Arkansas, Fayetteville, AR 72701
- W. P. Miller** Professor, Department of Crop and Soil Sciences, The University of Georgia, Athens, GA 30602-7272
- Patricia D. Millner** Research Microbiologist, Soil Microbial Systems Lab., USDA-ARS, Bldg. 001, Rm. 140, BARC-W, Beltsville, MD 20705-2350
- Charles C. Mitchell** Extension Agronomist-Soils and Professor, Department of Agronomy and Soils, Auburn University, Auburn, AL 36849
- Tara A. O'Brien** Earth Sciences Teacher, Hampshire Regional High School, Westhampton, MA; mailing address is Department of Plant and Soil Sciences, University of Massachusetts, Amherst, MA 01002
- David B. Parker** Assistant Professor, West Texas A&M University, Canyon, TX 79016-0001
- Gary M. Pierzynski** Professor of Soil and Environmental Chemistry, Department of Agronomy, Kansas State University, Manhattan, KS 66506-5501
- Jack E. Rechcigl** Professor of Soil and Environmental Sciences, University of Florida, Ona, FL 33865s
- Tom L. Richard** Assistant Professor, Department of Agricultural and Biosystems Engineering, Iowa State University, Ames, IA 50011
- K. D. Ritchey** Research Scientist, USDA-ARS-AFSRC, Beaver, WV 25813
- William F. Ritter** Professor of Bioresources, Civil and Environmental Engineering, Biore-sources Engineering Department, University of Delaware, Newark, DE 19717
- C. A. Robinson** Assistant Professor, West Texas A&M University, Canyon, TX 79016-0001
- Lawrence J. Schwankl** Irrigation Specialist, University of California, LAWR-Veihmeyer Hall, One Shields Ave., Davis, CA 95616

- Lawrence J. Sikora** Research Microbiologist, Soil Microbial Systems Lab., USDA-ARS, Beltsville Agricultural Research Center, Beltsville, MD 20705
- J. Thomas Sims** Professor of Soil and Environmental Chemistry, Department of Plant and Soil Sciences, University of Delaware, Newark, DE 19717
- Arun V. Someshwar** Principal Research Engineer, NCASI, Gainesville, FL 32614-1020
- Richard Stehouwer** Assistant Professor of Soil Chemistry, Pennsylvania State University, State College, PA 16801
- B. A. Stewart** Director, Dryland Agriculture Institute, West Texas A&M University, Canyon, TX 79016
- Margie L. Stratton** Postdoctorate, University of Florida, Ona, Florida; mailing address is Department of Plant and Soil Sciences, University of Massachusetts, Amherst, MA 01003
- Dan M. Sullivan** Extension and Research Soil Scientist, Department of Soil Science, Oregon State University, Corvallis, OR 97331
- M. E. Sumner** Regents Professor, Department of Crop and Soil Sciences, University of Georgia, Athens, GA 30602-7272
- Eric D. Vance** Project Leader, National Council for Air and Stream Improvement, Inc., P.O. Box 13318, Research Triangle Park, NC 27709-3318
- John M. Walker** Physical Scientist, USEPA, Office of Wastewater Management, Washington, DC 20460
- W. E. Wolfe** Professor of Civil Engineering, Ohio State University, Columbus, OH 43210
- Peter A. Yost** Research Analyst, National Association of Home Builders-Research Center, Upper Marlboro, MD 20772

Conversion Factors for SI and non-SI Units

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 Units	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)	square mile, mi^2	4.05×10^{-3}
0.386	square kilometer, km^2 (10^3 m^2)	acre	2.590
2.47×10^{-4}	square meter, m^2	square foot, ft^2	4.05×10^3
10.76	square meter, m^2	square inch, in^2	9.29×10^{-2}
1.55×10^{-3}	square millimeter, mm^2 (10^{-3} m^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
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

Pressure

9.90	megapascal, MPa (10 ⁶ Pa)	atmosphere	0.101
10	megapascal, MPa (10 ⁶ Pa)	bar	0.1
1.00	megagram, per cubic meter, Mg m ⁻³	gram per cubic centimeter, g cm ⁻³	1.00
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

(continued on next page)

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 Units	To convert Column 2 into Column 1, multiply by
	Temperature		
	kelvin, K	Celsius, °C	
1.00 (K - 273)	(9/5 °C) + 32	Celsius, °C	1.00 (°C + 273)
	Celsius, °C	Fahrenheit, °F	5/9 (°F - 32)
		Energy, Work, Quantity of Heat	
	joule, J	British thermal unit, Btu	1.05 × 10 ³
9.52 × 10 ⁻⁴	joule, J	calorie, cal	4.19
0.239	joule, J	erg	10 ⁻⁷
10 ⁷	joule, J	foot-pound	1.36
0.735	joule per square meter, J m ⁻²	calorie per square centimeter (langley)	4.19 × 10 ⁴
2.387 × 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	
	milligram per square meter second, mg m ⁻² s ⁻¹	gram per square decimeter hour, g dm ⁻² h ⁻¹	27.8
3.60 × 10 ⁻²	milligram (H ₂ O) per square meter second, mg m ⁻² s ⁻¹	micromole (H ₂ O) per square centi- meter second, μmol cm ⁻² s ⁻¹	180
5.56 × 10 ⁻³	milligram per square meter second, mg m ⁻² s ⁻¹	milligram per square centimeter second, mg cm ⁻² s ⁻¹	10 ⁴
10 ⁻⁴	milligram per square meter second, mg m ⁻² s ⁻¹	milligram per square decimeter hour, mg dm ⁻² h ⁻¹	2.78 × 10 ⁻²
35.97			
	Plane Angle		
	radian, rad	degrees (angle), °	1.75 × 10 ⁻²
57.3			

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

Concentrations

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

	<i>Elemental</i>	<i>Oxide</i>	
2.29	P	P ₂ O ₅	0.437
1.20	K	K ₂ O	0.830
1.39	Ca	CaO	0.715
1.66	Mg	MgO	0.602