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IN AGRICULTURE**

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CONTENTS

FOREWORD	ix
PREFACE	xi
CONTRIBUTORS	xiii
CONVERSION FACTORS FOR SI AND NON-SI UNITS	xv
Chapter 1 Geochemistry of Micronutrients	1
WARD CHESWORTH	
I. General Properties of the Elements	1
II. Specific Properties of the Elements	2
III. Geochemical Nature of Terrestrial Systems	7
IV. Natural Occurrences of the Elements	11
V. Soil Weathering System	14
VI. Summary	27
APPENDIX	28
REFERENCES	29
Chapter 2 Geographic Distribution of Trace Element Problems	31
ROSS M. WELCH, WILLIAM H. ALLAWAY, WILLIAM A. HOUSE, AND JOE KUBOTA	
I. Perspectives	31
II. Geographic Patterns of Trace Element Problems	32
III. Techniques for Mapping Trace Element Problem Areas	35
IV. Geographic Distribution of Problem Areas	36
V. Research Needs and Applications	52
REFERENCES	53
Chapter 3 Micronutrient Adsorption-Desorption Reactions in Soils	59
ROBERT D. HARTER	
I. Experimental Methods	59
II. Models	62
III. Adsorption Mechanisms	71
IV. Sorption Reactions of Individual Micronutrients	73
V. Summary and Future Research Needs	82
REFERENCES	83
Chapter 4 Inorganic Equilibria Affecting Micronutrients in Soils	89
W. L. LINDSAY	
I. Iron	90
II. Manganese	96
III. Zinc	99
IV. Copper	103
V. Boron	107
VI. Molybdenum	108
VII. Summary and Research Needs	109
REFERENCES	111

Chapter 5 Chemical Forms of Micronutrients in Soils	113
L. M. SHUMAN	
I. Pools of Micronutrients in Soils	114
II. Selective Chemical Extraction of Micronutrients from Soils	116
III. Redistribution Among Micronutrient Forms	125
IV. Summary	137
REFERENCES	138
Chapter 6 Organic Matter-Micronutrient Reactions in Soil	145
F. J. STEVENSON	
I. Significance of Complexation Reactions	145
II. The Micronutrient Cycle	146
III. Biochemical Compounds as Chelating Agents	156
IV. Trace Metal Interactions with Humic Substances	162
V. Stability Constants of Metal Complexes with Humic Substances	168
VI. Summary	180
REFERENCES	181
Chapter 7 Reactions of Metal Chelates in Soils and Nutrient Solutions	187
W. A. NORVELL	
I. Metal Chelate Equilibria	187
II. Adsorption of Chelating Agents	210
III. Biodegradation of Chelating Agents	214
IV. Photodegradation of Chelating Agents	220
V. Summary	222
REFERENCES	223
Chapter 8 Mechanisms of Micronutrient Uptake and Translocation in Plants	229
LEON V. KOCHIAN	
I. General Aspects of Ion Absorption and Translocation	230
II. Micronutrient Absorption into Roots	251
III. Micronutrient Transport within and between Cells	272
IV. Long-Distance Micronutrient Translocation	274
V. Conclusion: Future Prospects	284
ACKNOWLEDGMENTS	285
REFERENCES	285
Chapter 9 Function of Micronutrients in Plants	297
V. RÖMHELD AND H. MARSCHNER	
I. Iron	297
II. Manganese	302
III. Copper	306
IV. Molybdenum	309
V. Zinc	312
VI. Boron	316
VII. Chlorine	321
VIII. Summary	324
ACKNOWLEDGMENT	324
REFERENCES	324

CONTENTS	vii
Chapter 10 Micronutrients and Disease Resistance and Tolerance in Plants	329
ROBIN D. GRAHAM AND MICHAEL J. WEBB	
I. Resistance and Tolerance	329
II. Metabolic Pathways to Resistance	331
III. Roles of Individual Elements	333
IV. Summary and Conclusions	360
REFERENCES	361
Chapter 11 Environmental and Soil Factors Affecting Micronutrient Deficiencies and Toxicities	371
J. T. MORAGHAN AND H. J. MASCAGNI, JR.	
I. Environmental Factors	371
II. Soil Factors	387
III. Conclusions	408
ACKNOWLEDGMENTS	411
REFERENCES	411
Chapter 12 Micronutrient Soil Tests	427
J. T. SIMS AND G. V. JOHNSON	
I. Principles of Soil Testing	427
II. Chemistry of Micronutrient Soil Testing Extractants	431
III. Soil Tests for Micronutrients Essential to Plant Nutrition	439
IV. Soil Test Methods for Elements of Environmental Concern	464
REFERENCES	472
Chapter 13 Plant Tissue Analysis in Micronutrients	477
J. BENTON JONES, JR	
I. Procedures for Plant Analysis	478
II. Micronutrient Concentrations in Plants	490
III. Interpretation of the Results	509
IV. Practical Application and Future	511
REFERENCES	513
Chapter 14 Micronutrient Fertilizer Technology	523
JOHN J. MORTVEDT	
I. Micronutrient Sources	523
II. Industrial By-Products as Micronutrient Fertilizers	528
III. Methods of Applying Micronutrients with N-P-K Fertilizers	529
IV. Micronutrient Marketing and Use	540
V. Summary	545
REFERENCES	546
Chapter 15 Fertilizer Applications for Correcting Micronutrient Deficiencies	549
D. C. MARTENS AND D. T. WESTERMANN	
I. Boron	549
II. Copper	554

III. Iron	559
IV. Manganese	565
V. Molybdenum	572
VI. Zinc	575
VII. Other Micronutrients	581
VIII. Summary	583
REFERENCES	584
Chapter 16 Trace Elements in Animal Nutrition	593
ELWYN R. MILLER, XINGEN LEI, AND DUANE E. ULLREY	
I. Essential Trace Elements	593
II. Iron	594
III. Zinc	601
IV. Copper	609
V. Manganese	616
VI. Selenium	622
VII. Iodine	627
VIII. Cobalt	632
IX. Molybdenum	636
X. Fluorine	640
XI. Prospectus	645
REFERENCES	645
Chapter 17 Trace Elements in Human Nutrition	663
DARRELL R. VAN CAMPEN	
I. Iron	663
II. Zinc	669
III. Copper	673
IV. Manganese	677
V. Chromium	680
VI. Selenium	682
VII. Iodine	687
VIII. Other Trace Elements	689
IX. Research Needs	692
REFERENCES	693
Chapter 18 Beneficial Elements, Functional Nutrients, and Possible New Essential Elements	703
COLIN J. ASHER	
I. Concepts and Definitions	703
II. Sodium	706
III. Aluminum	708
IV. Silicon	710
V. Nickel	713
VI. Cobalt	716
VII. Lanthanum and Cerium	717
VIII. Need for Further Research	719
REFERENCES	719
Glossary	725
Subject Index	731

FOREWORD

The sustenance and well being of humankind are inexorably linked to the stocks of essential nutrients in the bio-geosphere and their capacity for cycling and manipulation. Nutrient management is fundamental to agriculture and its ability to minimize environmental impacts.

The capacity to produce usable plant biomass depends upon the adequacy and balance of mineral nutrients. Well-managed agricultural ecosystems require knowledge about native nutrient stocks, the chemical form(s) in which nutrients occur, protocols for determining nutrient levels in soils and plants, the functions and interactions of nutrients in plants and animals, the mechanisms of nutrient uptake, sorption-desorption and equilibria reactions in soils, diagnosis of nutrient deficiencies in plants and animals, plant responses to nutrient deficiencies and management, and manipulation of nutrients through formulations and application technologies.

This publication is an updated and revised version of the first edition of *Micronutrients in Agriculture* published in 1972. It includes current thinking and knowledge on the concepts of mineral essentiality in plants with reference to the beneficial role or significance of such elements as sodium, nickel, aluminum, lanthanum, and cerium. Future research agendas are also identified.

Fred P. Miller, *president*
Soil Science Society of America

PREFACE

In 1971, the Soil Science Society of America and the Tennessee Valley Authority cosponsored a symposium to review micronutrient problems in soils and in plant and animal nutrition. The papers were published as the first edition of *Micronutrients in Agriculture* by SSSA in 1972. The book has been used throughout the world as a reference and textbook since that time. It is primarily intended for graduate students and researchers in agricultural, biological, environmental, and nutritional sciences interested in the subject matter comprising each chapter who already have a thorough understanding of biochemistry, physiology, and soil science. However, it will serve as an excellent up-to-date reference book for everyone interested in the micronutrients—boron, chlorine, copper, iron, manganese, molybdenum, and zinc.

This book, the second edition, contains information primarily obtained since the first edition was published, although some material from the first edition was repeated where no new information was available. While the general subject matter is similar to that in the first edition, emphasis was changed to address newly emerging areas in micronutrient research. The 18 chapters in this book were written by outstanding scientists who are authorities on micronutrient problems in soils and in plant, animal, and human nutrition. Eleven chapters of the first edition were deleted or combined and three new subject areas were included in this revision. The previously published subject areas covered in this edition are: (1) Chemistry of micronutrients in soils, (2) Micronutrient uptake, translocation, functions and interactions in plants, (3) Diagnosis and correction of micronutrient deficiencies, (4) Micronutrient fertilizer technology, and (5) Trace elements in animal nutrition. The new subject areas are: (1) Micronutrients and disease resistance or tolerance in plants, (2) Trace elements in human nutrition, and (3) Beneficial elements, functional elements, and possible new essential elements.

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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 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)	454	pound, lb
3.52×10^{-2}	gram, g (10^{-3} kg)	28.4	ounce (avdp), oz
2.205	kilogram, kg	0.454	pound, lb
0.01	kilogram, kg	100	quintal (metric), q
1.10×10^{-3}	kilogram, kg	907	ton (2000 lb), ton
1.102	megagram, Mg (tonne)	0.907	ton (U.S.), ton
1.102	tonne, t	0.907	ton (U.S.), ton

Yield and Rate

0.893	kilogram per hectare, kg ha ⁻¹	1.12	pound per acre, lb acre ⁻¹
7.77×10^{-2}	kilogram per cubic meter, kg m ⁻³	12.87	pound per bushel, bu ⁻¹
1.49×10^{-2}	kilogram per hectare, kg ha ⁻¹	67.19	bushel per acre, 60 lb
1.59×10^{-2}	kilogram per hectare, kg ha ⁻¹	62.71	bushel per acre, 56 lb
1.86×10^{-2}	kilogram per hectare, kg ha ⁻¹	53.75	bushel per acre, 48 lb
0.107	liter per hectare, L ha ⁻¹	9.35	gallon per acre
893	tonnes per hectare, t ha ⁻¹	1.12×10^{-3}	pound per acre, lb acre ⁻¹
893	megagram per hectare, Mg ha ⁻¹	1.12×10^{-3}	pound per acre, lb acre ⁻¹
0.446	megagram per hectare, Mg ha ⁻¹	2.24	ton (2000 lb) per acre, ton acre ⁻¹
2.24	meter per second, m s ⁻¹	0.447	mile per hour

Specific Surface

10	square meter per kilogram, m ² kg ⁻¹	0.1	square centimeter per gram, cm ² g ⁻¹
1000	square meter per kilogram, m ² kg ⁻¹	0.001	square millimeter per gram, mm ² g ⁻¹

Pressure

9.90	megapascal, MPa (10^6 Pa)	0.101	atmosphere
10	megapascal, MPa (10^6 Pa)	0.1	bar
1.00	megagram per cubic meter, Mg m ⁻³	1.00	gram per cubic centimeter, g cm ⁻³
2.09×10^{-2}	pascal, Pa	47.9	pound per square foot, lb ft ⁻²
1.45×10^{-4}	pascal, Pa	6.90×10^3	pound per square inch, lb in ⁻²

(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 Unit	To convert Column 2 into Column 1, multiply by
		Temperature	
		Celsius, °C Fahrenheit, °F	
1.00 (K - 273) (9/5 °C) + 32	Kelvin, K Celsius, °C		1.00 (°C + 273) 5/9 (°F - 32)
9.52 × 10 ⁻⁴ 0.239 10 ⁷ 0.735 2.387 × 10 ⁻⁵ 10 ⁵ 1.43 × 10 ⁻³	joule, J joule, J joule, J joule, J joule per square meter, J m ⁻² newton, N watt per square meter, W m ⁻²	Energy, Work, Quantity of Heat	1.05 × 10 ³ 4.19 10 ⁻⁷ 1.36 4.19 × 10 ⁴ 10 ⁻⁵ 698
		British thermal unit, Btu calorie, cal erg foot-pound calorie per square centimeter (langley) dyne calorie per square centimeter minute (irradiance), cal cm ⁻² min ⁻¹	
		Transpiration and Photosynthesis	
3.60 × 10 ⁻² 5.56 × 10 ⁻³ 10 ⁻⁴ 35.97	milligram per square meter second, mg m ⁻² s ⁻¹ milligram (H ₂ O) per square meter second, mg m ⁻² s ⁻¹ milligram per square meter second, mg m ⁻² s ⁻¹ milligram per square meter second, mg m ⁻² s ⁻¹	gram per square decimeter hour, g dm ⁻² h ⁻¹ micromole (H ₂ O) per square centi- meter second, μmol cm ⁻² s ⁻¹ milligram per square centimeter second, mg cm ⁻² s ⁻¹ milligram per square decimeter hour, mg dm ⁻² h ⁻¹	27.8 180 10 ⁴ 2.78 × 10 ⁻²
57.3	radian, rad	Plane Angle	1.75 × 10 ⁻²
		degrees (angle), °	

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-inches, acre-in	102.8
9.81×10^{-3}	cubic meter per hour, $m^3\ h^{-1}$	cubic feet per second, $ft^3\ s^{-1}$	101.9
4.40	cubic meter per hour, $m^3\ h^{-1}$	U.S. gallons per minute, $gal\ min^{-1}$	0.227
8.11	hectare-meters, ha-m	acre-feet, acre-ft	0.123
97.28	hectare-meters, ha-m	acre-inches, acre-in	1.03×10^{-2}
8.1×10^{-2}	hectare-centimeters, ha-cm	acre-feet, acre-ft	12.33

Concentrations

1	centimole per kilogram, $cmol\ kg^{-1}$ (ion exchange capacity)	milliequivalents 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