Phosphorus: 
Agriculture and the Environment
DEDICATION

Phosphorus: Agriculture and the Environment is dedicated to the memories of Dr. Les Lanyon and Dr. Regis Simard, whose untimely deaths have left great voids in the scientific, agricultural, and environmental communities.

Les was a Professor of Soil Science and Management at Pennsylvania State University, where he held teaching, research, and extension responsibilities for 27 yr. His research focused on the development of agricultural management practices that integrated the protection of natural resources with successful agricultural production. He was internationally known for his work to protect water quality, especially significant national resources such as the Chesapeake Bay.

Regis was Professor and Head of the Soil Science Department of the University of Manitoba and an outstanding soil scientist for Agriculture and Agri-Food Canada for 15 yr, where the focus of his research was soil chemistry, nutrient management, and environmental quality. He studied nutrient dynamics in relation to soil fertility and water quality, developed new methods of soil analyses in the laboratory, and implemented novel approaches to measure the impact of nutrient management at the field and watershed scales. His outstanding work on phosphorus (P), which received international recognition, highlighted the potential problem of P accumulation in watersheds and soils and established preferential infiltration as an important pathway of P loss to water.

Throughout their careers, these two individuals contributed greatly to our scientific understanding of the relationship between agricultural P use and environmental quality. They were internationally recognized scientists, leaders, thinkers, and wonderful colleagues. Their dedication, foresight, and unique enthusiasm touched everyone who met or worked with them.

Dr. Les E. Lanyon

Dr. Regis R. Simard
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FOREWORD

The American Society of Agronomy (ASA), Crop Science Society of America (CSSA), and Soil Science Society of America (SSSA) place an emphasis on advancing the disciplines and practices of agronomic, crop, and soil sciences by fostering excellence in the acquisition of new knowledge, in the training of scientists, in the education of citizens, and in the applications of knowledge to challenges facing society. In addition, our scientific societies facilitate the teaching, research, and outreach programs that contribute to the long-term sustainability of food and fiber production systems and promote informed and wise stewardship of soil, water, and air resources.

This book entitled Phosphorus: Agriculture and the Environment provides an interdisciplinary view of the fate of phosphorus (P) entering the environment from plant and animal agriculture and the subsequent impact of P on ecosystems. The editors have succeeded in developing a comprehensive monograph that addresses P in a diversity of agricultural production systems since P is a major nutrient input. Phosphorus in plant and animal agriculture is intimately connected and this volume incorporates diverse expertise in soil, crop, animal, and environmental sciences. The goal of this monograph is to summarize our current knowledge of the fate and function of P in the ecosystem. It integrates agronomic, environmental, and animal science research that provides the essential foundation for understanding P management impacts on agricultural productivity and environmental quality. We believe that this comprehensive volume on P attains these goals and will contribute to ongoing interdisciplinary efforts to understand the complex issues facing science and society.

Lee Sommers
President, ASA

James Coors
President, CSSA

John Havlin
President, SSSA
PREFACE

Phosphorus: Agriculture and the Environment provides a comprehensive, systematic review of the varied aspects of phosphorus (P) use in crop and livestock production and of the relationship between agricultural P management and water quality. This monograph draws upon the expertise of leading international scientists to present a contemporary analysis of the forms and cycling of P in soils and the agricultural and environmental management practices used today to optimize crop production while preventing nonpoint P pollution of our surface and ground waters. This publication builds upon the scientific understanding of P in agricultural settings presented in the 1980 American Society of Agronomy-Crop Science Society of America-Soil Science Society of America Monograph The Role of Phosphorus in Agriculture edited by F.E. Khasawneh, E.C. Sample, and E.J. Kamprath.

In the 25 yr that have passed since that seminal publication, we have seen major advances in our understanding of how to best manage P for agricultural production, vitally important given the increasing pressures agriculture faces to provide food for a rapidly growing world population. We have also seen growing concern about the impacts of agricultural P on our environment, particularly our surface waters where accelerated eutrophication is now a worldwide environmental issue. In response, scientists, land managers, and advisory and regulatory agencies have worked diligently with the agricultural community to develop improved approaches to P management. As this has occurred, we have come to recognize that some agricultural systems cannot remain sustainable without major changes. Crop production in vast areas of the world is limited by P-deficient soils—new strategies are required to remove this limitation and provide an adequate food supply. In contrast, in many developed countries, we often find agricultural P surpluses that have led to the accumulation of P in soils, and to P losses in runoff and leaching which, in turn, degrade our surface waters, threatening habitats, fisheries, and even human health. The problems facing animal agriculture, often concentrated geographically in a manner that leads to large P surpluses on farms and in watersheds, are especially acute today. These challenges have led to a greater emphasis on the integration of multi-disciplinary science into agri-environmental policy as we seek to increase agricultural productivity while protecting, or remediating, our water supplies.

Encouragingly, we have made great strides in our understanding of the basic principles of P chemistry/biochemistry and are able to apply this knowledge more effectively than ever before. New technologies, such as advanced spectroscopic methods (e.g., P$^{31}$ NMR—Nuclear Magnetic Resonance; XANES—X-ray Absorption Near Edge Structure), now allow us to quantitatively identify inorganic and organic P species in soils, sediments, plants, by-products, and water bodies. This knowledge is now being used to develop management practices that will increase agricultural productivity and protect water quality. Also of great importance have been the advances in geo-spatial management of information critical to our
ability to apply advances in P management at large scales, such as watersheds. Technologies useful for improving the land management of P have mushroomed in the last decade, and we can now use digitized soil survey data, hydrologic information, GPS (Global Positioning System) assisted variable rate fertilizer and manure applicators, and specialized and sophisticated farm machinery (e.g., tillage, subsurface manure applicators and injectors) to better manage P in a wide range of agricultural settings.

*Phosphorus: Agriculture and the Environment* contains chapters on P as a natural resource, P cycling in soils and management in fertilizers and livestock feeds, transport pathways for P loss to water, and ways to improve future sustainability of profitable agricultural and livestock production systems, while protecting water quality. Sections include: (1) production, characteristics, and changing technologies of P for agriculture from natural sources to fertilizers; (2) P reactions and cycling in soils in inorganic and organic forms, soil testing for crop production and environmental impacts, fertilizer and by-product reaction in soils, P dynamics in tropical, flooded, and wetland soils and trace element interactions; (3) soil P interactions in terms of plant nutrition and crop production, plant tissue testing, rhizosphere microorganisms and plant P uptake, and P nutrition of agronomic crops, vegetables, and forests; (4) P nutrition of dairy, beef, swine and poultry animals; (5) agricultural management of fertilizer and by-product P in terms of crop yield response, low input farming, organic farming, and precision farming; and (6) P and the environment, its mobility in the landscape, risk assessment of P losses, best management practices for P, and long-term strategies of sustainable P use.

As Editors, we thank all the authors who contributed their time and expertise to this monograph. Clearly, a wide breadth and depth of knowledge is needed to understand and resolve the complex agricultural and environmental problems associated with P management. The disciplines and scientific expertise of the authors—soil scientists, agronomists, aquatic ecologists, hydrologists, animal scientists, and economists, from academia, government, and industry—reflect that breadth and provide the depth needed for the comprehensive reviews provided in this book. We also particularly thank our Section Editors:

Gary Pierzynski, Kansas State University, Manhattan, KS.
Dale Westermann, USDA-ARS, Kimberly, ID.
Miguel Cabrera, University of Georgia, Athens, GA.
Mark Powell, USDA-ARS, Madison, WI.
Tommy Daniel, University of Arkansas, Fayetteville, AR.
Paul Withers, ADAS, Nottingham, England.

They ensured continuity and minimized overlap among chapters in each section. Their diligent effort, support, and time played a major role in the successful completion of this book. Finally, we are all extremely grateful to the external reviewers, who devoted much time and effort to provide constructive critiques of each chapter, and who helped ensure this publication was timely and complete.

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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 Units | To convert Column 2 into Column 1, multiply by
--- | --- | --- | ---
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, \(\mu\text{m}\) (10^{-6} m) | micron, \(\mu\) | 1.0
3.94 \times 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 \times 10^{-3}
0.386 | square kilometer, km^2 (10^3 m)^2 | square mile, mi^2 | 2.590
2.47 \times 10^{-4} | square meter, m^2 | acre | 4.05 \times 10^{3}
10.76 | square meter, m^2 | square foot, ft^2 | 9.29 \times 10^{-2}
1.55 \times 10^{-3} | square millimeter, mm^2 (10^{-3} m)^2 | square inch, in^2 | 645

**Volume**

| 9.73 \times 10^{-3} | cubic meter, m^3 | acre-inch | 102.8
35.3 | cubic meter, m^3 | cubic foot, ft^3 | 2.83 \times 10^2
6.10 \times 10^4 | cubic meter, m^3 | cubic inch, in^3 | 1.64 \times 10^5
2.84 \times 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 \times 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 \times 10^{-2}
2.11 | liter, L (10^{-3} m^3) | pint (fluid), pt | 0.473
## Mass

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<td>gram, g (10^{-3} kg)</td>
<td>pound, lb</td>
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<td>gram, g (10^{-3} kg)</td>
<td>ounce (avdp), oz</td>
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<td>2.205</td>
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<td>0.01</td>
<td>kilogram, kg</td>
<td>quintal (metric), q</td>
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<td>ton (2000 lb), ton</td>
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<td>megagram, Mg (tonne)</td>
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<tr>
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## Yield and Rate

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<tr>
<td>2.24</td>
<td>meter per second, m s^{-1}</td>
<td>mile per hour</td>
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## Specific Surface

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<td>square meter per kilogram, m^{2} kg^{-1}</td>
<td>square centimeter per gram, cm^{2} g^{-1}</td>
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<tr>
<td>1000</td>
<td>square meter per kilogram, m^{2} kg^{-1}</td>
<td>square millimeter per gram, mm^{2} g^{-1}</td>
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## Density

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<td>1.00</td>
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## Pressure

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</tr>
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<td>10</td>
<td>megapascal, MPa (10^{6} Pa)</td>
<td>bar</td>
</tr>
<tr>
<td>2.09 × 10^{-2}</td>
<td>pascal, Pa</td>
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</tr>
<tr>
<td>1.45 × 10^{-4}</td>
<td>pascal, Pa</td>
<td>pound per square inch, lb in^{-2}</td>
</tr>
</tbody>
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(continued on next page)
### Conversion Factors for SI and non-SI Units

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<thead>
<tr>
<th>To convert Column 1 into Column 2, multiply by</th>
<th>Column 1 SI Unit</th>
<th>Column 2 non-SI Units</th>
<th>To convert Column 2 into Column 1, multiply by</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Temperature</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.00 (K – 273)</td>
<td>kelvin, K</td>
<td>Celsius, °C</td>
<td>1.00 (°C + 273)</td>
</tr>
<tr>
<td>(9/5 °C) + 32</td>
<td>Celsius, °C</td>
<td>Fahrenheit, °F</td>
<td>5/9 (°F – 32)</td>
</tr>
<tr>
<td><strong>Energy, Work, Quantity of Heat</strong></td>
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<tr>
<td>9.52 × 10⁻⁴</td>
<td>joule, J</td>
<td>British thermal unit, Btu</td>
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<td>0.239</td>
<td>joule, J</td>
<td>calorie, cal</td>
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<tr>
<td>10⁻⁷</td>
<td>joule, J</td>
<td>erg</td>
<td>10⁻⁷</td>
</tr>
<tr>
<td>0.735</td>
<td>joule, J</td>
<td>foot-pound</td>
<td>1.36</td>
</tr>
<tr>
<td>2.387 × 10⁻⁵</td>
<td>joule per square meter, J m⁻²</td>
<td>calorie per square centimeter (langley)</td>
<td>4.19 × 10⁴</td>
</tr>
<tr>
<td>10⁵</td>
<td>newton, N</td>
<td>dyne</td>
<td>10⁻⁵</td>
</tr>
<tr>
<td>1.43 × 10⁻³</td>
<td>watt per square meter, W m⁻²</td>
<td>calorie per square centimeter minute (irradiance), cal cm⁻² min⁻¹</td>
<td>698</td>
</tr>
<tr>
<td><strong>Transpiration and Photosynthesis</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.60 × 10⁻²</td>
<td>milligram per square meter second, mg m⁻² s⁻¹</td>
<td>gram per square decimeter hour, g dm⁻² h⁻¹</td>
<td>27.8</td>
</tr>
<tr>
<td>5.56 × 10⁻³</td>
<td>milligram (H₂O) per square meter second, mg m⁻² s⁻¹</td>
<td>micromole (H₂O) per square centimeter second, μmol cm⁻² s⁻¹</td>
<td>180</td>
</tr>
<tr>
<td>10⁻⁴</td>
<td>milligram per square meter second, mg m⁻² s⁻¹</td>
<td>milligram per square centimeter second, mg cm⁻² s⁻¹</td>
<td>10⁴</td>
</tr>
<tr>
<td>35.97</td>
<td>milligram per square meter second, mg m⁻² s⁻¹</td>
<td>milligram per square decimeter hour, mg dm⁻² h⁻¹</td>
<td>2.78 × 10⁻²</td>
</tr>
<tr>
<td><strong>Plane Angle</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>57.3</td>
<td>radian, rad</td>
<td>degrees (angle), °</td>
<td>1.75 × 10⁻²</td>
</tr>
</tbody>
</table>
### Electrical Conductivity, Electricity, and Magnetism

<table>
<thead>
<tr>
<th>Unit</th>
<th>Conversion Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 siemen per meter, S m⁻¹</td>
<td>millimho per centimeter, mmho cm⁻¹</td>
</tr>
<tr>
<td>10⁴ tesla, T</td>
<td>gauss, G</td>
</tr>
</tbody>
</table>

### Water Measurement

<table>
<thead>
<tr>
<th>Unit</th>
<th>Conversion Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>9.73 × 10⁻³ cubic meter, m³</td>
<td>acre-inch, acre-in</td>
</tr>
<tr>
<td>9.81 × 10⁻³ cubic meter per hour, m³ h⁻¹</td>
<td>cubic foot per second, ft³ s⁻¹</td>
</tr>
<tr>
<td>4.40 cubic meter per hour, m³ h⁻¹</td>
<td>U.S. gallon per minute, gal min⁻¹</td>
</tr>
<tr>
<td>8.11 hectare meter, ha m</td>
<td>acre-foot, acre-ft</td>
</tr>
<tr>
<td>97.28 hectare meter, ha m</td>
<td>acre-inch, acre-in</td>
</tr>
<tr>
<td>8.1 × 10⁻² hectare centimeter, ha cm</td>
<td>acre-foot, acre-ft</td>
</tr>
</tbody>
</table>

### Concentrations

<table>
<thead>
<tr>
<th>Unit</th>
<th>Conversion Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 centimole per kilogram, cmol kg⁻¹</td>
<td>milliequivalent per 100 grams, meq</td>
</tr>
<tr>
<td>0.1 gram per kilogram, g kg⁻¹</td>
<td>percent, %</td>
</tr>
<tr>
<td>1 milligram per kilogram, mg kg⁻¹</td>
<td>parts per million, ppm</td>
</tr>
</tbody>
</table>

### Radioactivity

<table>
<thead>
<tr>
<th>Unit</th>
<th>Conversion Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.7 × 10⁻¹¹ becquerel, Bq</td>
<td>curie, Ci</td>
</tr>
<tr>
<td>2.7 × 10⁻² becquerel per kilogram, Bq kg⁻¹</td>
<td>picocurie per gram, pCi g⁻¹</td>
</tr>
<tr>
<td>100 gray, Gy (absorbed dose)</td>
<td>rad, rd</td>
</tr>
<tr>
<td>100 sievert, Sv (equivalent dose)</td>
<td>rem (roentgen equivalent man)</td>
</tr>
</tbody>
</table>

### Plant Nutrient Conversion

#### Elemental

<table>
<thead>
<tr>
<th>Nutrient</th>
<th>Oxide</th>
</tr>
</thead>
<tbody>
<tr>
<td>P</td>
<td>P₂O₅</td>
</tr>
<tr>
<td>K</td>
<td>K₂O</td>
</tr>
<tr>
<td>Ca</td>
<td>CaO</td>
</tr>
<tr>
<td>Mg</td>
<td>MgO</td>
</tr>
</tbody>
</table>