METHODS OF SOIL ANALYSIS

PART 2

Microbiological and Biochemical Properties
Soil Science Society of America Book Series

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FOREWORD

The methods pertinent to soil microbiology were formerly included in Part 2 of the Agronomy Monograph No. 9, Methods of Soil Analysis. Since the 2nd edition of this document, the number of biochemical and microbiological methods have expanded greatly. In addition because the clientele of scientists engaged in these efforts are primarily soils based, the ASA Board of Directors in 1993 elected to place this document in the SSSA Book Series. It is most refreshing and encouraging to see this stand-alone contribution specifically dedicated to soil microbiological and biochemical methods. This text will be well received by an ever-expanding spectra of biogeoscientists. It is very timely given the rise in public and private interests in soil and water quality, biodiversity, biodegradation, terrestrial ecology, environmental quality protection, sustainability of the biosphere and issues of global climatic change. For too long soil quality has been defined in terms of soil physical and chemical attributes with little or no regard to biological components. Part of this oversight has been a function of techniques available to accurately identify, define and quantify biological health and diversity. Another aspect is the rather recent explosion of interest and awareness among geoscientists in the functionality and import of soil microbiological and biochemical attributes in near-surface earth processes. The methods reported herein are at the cutting edge of science. Analytical techniques range in resolution from whole organisms to molecular fragments. In unravelling the identity and behavior of the complex soil biological system, temporal and dynamic diversity are considered in sampling methods. The authors represent a select spectra in biogeoscience expertise and career development. Such a synergistic assemblage of scientists assures that the methodology presented is current and relevant. The document is comprehensive in scope, interdisciplinary in character, and offers a high probability of acceptance among biologists. These methods will serve as the standard bearer for both professional and practicing biological scientists. It is the goal that common methodology will enhance collaboration and interchange among scientists and generate data sets using similar analytical approaches. We commend the authors and editors for their diligence and genius in bringing this new book to fruition in such a timely manner. This addition to the SSSA Book Series, will be well received and widely used by a growing number of biogeoscientist professionals wishing to document soil microbiological-biochemical attributes in near surface earth systems.

Larry P. Wilding, president
Soil Science Society of America
The books, *Methods of Soil Analysis*—Parts 1 and 2, published as Agronomy Monograph No. 9 have been the primary references on analytical methods used by soil scientists and persons in other disciplines involved with making measurements on soils. Part 2 of the second edition covered both methods on soil chemistry and soil microbiology. The need for more extensive coverage in both of these areas resulted in necessity of dividing Part 2 into two new books. One covering the topic of soil chemistry and the second covering soil microbiology and soil biochemistry. Revision was so extensive and involved so many new authors that it seemed best to consider this book a new publication rather than a third edition. It is published as one of the Soil Science of America Book Series.

Division of some subject matter between the book on chemical methods for soil analysis and this book was not always straightforward because some chemical methods are needed in measuring microbiological and biochemical processes. In such cases, a chemical method is provided within chapters of this book but the depth of coverage on theory is not complete nor are alternative methods presented as is the case for the book on soil chemical methods. Our desire was to make it possible to use the methods in this book independently without having to purchase both books.

Early in the book the topics of statistical methods, soil sampling, and measurement of soil moisture tension are covered. These chapters were not covered in the previous editions of Part 2 but are particularly important for investigations in soil microbiology and biochemistry. Several methods are provided on use of molecular techniques that were not in previous editions but are needed in many modern soil microbiology laboratories. The treatment of the material on molecular topics is such that a person would not need extensive training in molecular techniques to take advantage of the methods.

It is hoped that many laboratories outside of soil science will take advantage of the methods contained in this book. They will be particularly relevant and useful to laboratories with interest in environmental microbiology or bioremediation. Analytical methods are essential to progress in science and the methods presented in this book are recognized by soil scientists as being among the best currently available. All chapters were reviewed by persons having expertise on particular methods, by an associate editor, and by the editor. The help of the many reviewers,
efforts and patience of authors, and advice from the editorial board are all gratefully acknowledged. A book such as this one is very much a team effort and is beyond the capability of any individual or small group of individuals.

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Conversion Factors for SI and non-SI Units
# Conversion Factors for SI and non-SI Units

<table>
<thead>
<tr>
<th>To convert Column 1 into Column 2, multiply by</th>
<th>Column 1 SI Unit</th>
<th>Column 2 non-SI Unit</th>
<th>To convert Column 2 into Column 1, multiply by</th>
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<td>Length</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>0.621</td>
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<td>mile, mi</td>
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<td>1.094</td>
<td>meter, m</td>
<td>yard, yd</td>
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<tr>
<td>3.28</td>
<td>meter, m</td>
<td>foot, ft</td>
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<tr>
<td>3.94 × 10^-2</td>
<td>micrometer, μm (10^-6 m)</td>
<td>micron, μ</td>
<td>1.0</td>
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<tr>
<td>10</td>
<td>millimeter, mm (10^-3 m)</td>
<td>inch, in</td>
<td>25.4</td>
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<td>nanometer, nm (10^-9 m)</td>
<td>Angstrom, Å</td>
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<tr>
<td>Area</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.47</td>
<td>hectare, ha</td>
<td>acre</td>
<td>0.405</td>
</tr>
<tr>
<td>247</td>
<td>square kilometer, km^2 (10^3 m)^2</td>
<td>acre</td>
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<tr>
<td>0.386</td>
<td>square kilometer, km^2 (10^3 m)^2</td>
<td>square mile, mi^2</td>
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<tr>
<td>2.47 × 10^-4</td>
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<td>acre</td>
<td>4.05 × 10^3</td>
</tr>
<tr>
<td>10.76</td>
<td>square meter, m^2</td>
<td>square foot, ft^2</td>
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<td>1.55 × 10^-3</td>
<td>square millimeter, mm^2 (10^-3 m)^2</td>
<td>square inch, in^2</td>
<td>645</td>
</tr>
<tr>
<td>Volume</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9.73 × 10^-3</td>
<td>cubic meter, m^3</td>
<td>acre-inch</td>
<td>102.8</td>
</tr>
<tr>
<td>35.3</td>
<td>cubic meter, m^3</td>
<td>cubic foot, ft^3</td>
<td>2.83 × 10^-2</td>
</tr>
<tr>
<td>6.10 × 10^4</td>
<td>cubic meter, m^3</td>
<td>cubic inch, in^3</td>
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<tr>
<td>2.84 × 10^-2</td>
<td>liter, L (10^-3 m^3)</td>
<td>bushel, bu</td>
<td>35.24</td>
</tr>
<tr>
<td>1.057</td>
<td>liter, L (10^-3 m^3)</td>
<td>quart (liquid), qt</td>
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<td>liter, L (10^-3 m^3)</td>
<td>cubic foot, ft^3</td>
<td>28.3</td>
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<tr>
<td>0.265</td>
<td>liter, L (10^-3 m^3)</td>
<td>gallon</td>
<td>3.78</td>
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<tr>
<td>33.78</td>
<td>liter, L (10^-3 m^3)</td>
<td>ounce (fluid), oz</td>
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<tr>
<td>2.11</td>
<td>liter, L (10^-3 m^3)</td>
<td>pint (fluid), pt</td>
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### Mass

<table>
<thead>
<tr>
<th>Value</th>
<th>Unit Description</th>
<th>Value</th>
<th>Unit Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$2.20 \times 10^{-3}$</td>
<td>gram, $g$ ($10^{-3} \text{ kg}$)</td>
<td>$454$</td>
<td>pound, $lb$</td>
</tr>
<tr>
<td>$3.52 \times 10^{-2}$</td>
<td>gram, $g$ ($10^{-3} \text{ kg}$)</td>
<td>$28.4$</td>
<td>ounce (avdp), $\text{oz}$</td>
</tr>
<tr>
<td>$2.205$</td>
<td>kilogram, $\text{kg}$</td>
<td>$0.454$</td>
<td>pound, $lb$</td>
</tr>
<tr>
<td>$0.01$</td>
<td>kilogram, $\text{kg}$</td>
<td>$100$</td>
<td>quintal (metric), $\text{q}$</td>
</tr>
<tr>
<td>$1.10 \times 10^{-3}$</td>
<td>kilogram, $\text{kg}$</td>
<td>$907$</td>
<td>ton (2000 lb), $\text{ton}$</td>
</tr>
<tr>
<td>$1.102$</td>
<td>megagram, $\text{Mg}$ (tonne)</td>
<td>$0.907$</td>
<td>ton (U.S.), $\text{ton}$</td>
</tr>
<tr>
<td>$1.102$</td>
<td>tonne, $t$</td>
<td>$0.907$</td>
<td>ton (U.S.), $\text{ton}$</td>
</tr>
</tbody>
</table>

### Yield and Rate

<table>
<thead>
<tr>
<th>Value</th>
<th>Unit Description</th>
<th>Value</th>
<th>Unit Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0.893$</td>
<td>kilogram per hectare, $\text{kg \ ha}^{-1}$</td>
<td>$1.12$</td>
<td>pound per acre, $\text{lb \ acre}^{-1}$</td>
</tr>
<tr>
<td>$7.77 \times 10^{-2}$</td>
<td>kilogram per cubic meter, $\text{kg \ m}^{-3}$</td>
<td>$12.87$</td>
<td>pound per bushel, $\text{lb \ bu}^{-1}$</td>
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<tr>
<td>$1.49 \times 10^{-2}$</td>
<td>kilogram per hectare, $\text{kg \ ha}^{-1}$</td>
<td>$67.19$</td>
<td>bushel per acre, 60 $\text{lb}$</td>
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<td>$1.59 \times 10^{-2}$</td>
<td>kilogram per hectare, $\text{kg \ ha}^{-1}$</td>
<td>$62.71$</td>
<td>bushel per acre, 56 $\text{lb}$</td>
</tr>
<tr>
<td>$1.86 \times 10^{-2}$</td>
<td>kilogram per hectare, $\text{kg \ ha}^{-1}$</td>
<td>$53.75$</td>
<td>bushel per acre, 48 $\text{lb}$</td>
</tr>
<tr>
<td>$0.107$</td>
<td>liter per hectare, $L \text{ ha}^{-1}$</td>
<td>$9.35$</td>
<td>gallon per acre</td>
</tr>
<tr>
<td>$893$</td>
<td>tonnes per hectare, $t \text{ ha}^{-1}$</td>
<td>$1.2 \times 10^{-3}$</td>
<td>pound per acre, $\text{lb \ acre}^{-1}$</td>
</tr>
<tr>
<td>$893$</td>
<td>megagram per hectare, $\text{Mg \ ha}^{-1}$</td>
<td>$1.2 \times 10^{-3}$</td>
<td>pound per acre, $\text{lb \ acre}^{-1}$</td>
</tr>
<tr>
<td>$0.446$</td>
<td>megagram per hectare, $\text{Mg \ ha}^{-1}$</td>
<td>$2.24$</td>
<td>ton (2000 lb) per acre, $\text{ton \ acre}^{-1}$</td>
</tr>
<tr>
<td>$2.24$</td>
<td>meter per second, $m \text{ s}^{-1}$</td>
<td>$0.447$</td>
<td>mile per hour</td>
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</table>

### Specific Surface

<table>
<thead>
<tr>
<th>Value</th>
<th>Unit Description</th>
<th>Value</th>
<th>Unit Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10$</td>
<td>square meter per kilogram, $m^2 \text{ kg}^{-1}$</td>
<td>$0.1$</td>
<td>square centimeter per gram, $cm^2 \text{ g}^{-1}$</td>
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<tr>
<td>$1000$</td>
<td>square meter per kilogram, $m^2 \text{ kg}^{-1}$</td>
<td>$0.001$</td>
<td>square millimeter per gram, $mm^2 \text{ g}^{-1}$</td>
</tr>
</tbody>
</table>

### Pressure

<table>
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<tr>
<th>Value</th>
<th>Unit Description</th>
<th>Value</th>
<th>Unit Description</th>
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</thead>
<tbody>
<tr>
<td>$9.90$</td>
<td>megapascal, $\text{MPa}$ ($10^6 \text{ Pa}$)</td>
<td>$0.101$</td>
<td>atmosphere</td>
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<tr>
<td>$10$</td>
<td>megapascal, $\text{MPa}$ ($10^6 \text{ Pa}$)</td>
<td>$0.1$</td>
<td>bar</td>
</tr>
<tr>
<td>$1.00$</td>
<td>megagram per cubic meter, $\text{Mg \ m}^{-3}$</td>
<td>$1.00$</td>
<td>gram per cubic centimeter, $g \text{ cm}^{-3}$</td>
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<tr>
<td>$2.09 \times 10^{-2}$</td>
<td>pascal, $\text{Pa}$</td>
<td>$47.9$</td>
<td>pound per square foot, $\text{lb \ ft}^{-2}$</td>
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<tr>
<td>$1.45 \times 10^{-4}$</td>
<td>pascal, $\text{Pa}$</td>
<td>$6.90 \times 10^3$</td>
<td>pound per square inch, $\text{lb \ in}^{-2}$</td>
</tr>
</tbody>
</table>

(continued on next page)
**Conversion Factors for SI and non-SI Units**

<table>
<thead>
<tr>
<th>To convert Column 1 into Column 2, multiply by</th>
<th>Column 1 SI Unit</th>
<th>Column 2 non-SI Unit</th>
<th>To convert Column 2 into Column 1, multiply by</th>
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</thead>
<tbody>
<tr>
<td><strong>Temperature</strong></td>
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<td>1.00 (K – 273)</td>
<td>Kelvin, K</td>
<td>Celsius, °C</td>
<td>1.00 (°C + 273)</td>
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<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>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9.52 × 10⁻⁴</td>
<td>joule, J</td>
<td>British thermal unit, Btu</td>
<td>1.05 × 10³</td>
</tr>
<tr>
<td>0.239</td>
<td>joule, J</td>
<td>calorie, cal</td>
<td>4.19</td>
</tr>
<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>
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<tr>
<td>10⁻⁵</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>
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<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>
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<td>5.56 × 10⁻³</td>
<td>milligram (H₂O) per square meter second, mg m⁻² s⁻¹</td>
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<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>
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<tr>
<td>35.97</td>
<td>milligram per square meter second, mg m⁻² s⁻¹</td>
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<td><strong>Plane Angle</strong></td>
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<td>57.3</td>
<td>radian, rad</td>
<td>degrees (angle), °</td>
<td>1.75 × 10⁻²</td>
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</table>
### Electrical Conductivity, Electricity, and Magnetism

<table>
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<tr>
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<th>Equivalent Unit</th>
<th>Conversion Factor</th>
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<tr>
<td>10</td>
<td>siemen per meter, S m⁻¹</td>
<td>millimho per centimeter, mmho cm⁻¹</td>
<td>0.1</td>
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<tr>
<td>10⁴</td>
<td>tesla, T</td>
<td>gauss, G</td>
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### Water Measurement

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<tr>
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<tbody>
<tr>
<td>9.73 x 10⁻³</td>
<td>cubic meter, m³</td>
<td>acre-in</td>
<td>102.8</td>
</tr>
<tr>
<td>9.81 x 10⁻³</td>
<td>cubic meter per hour, m³ h⁻¹</td>
<td>cubic feet per second, ft³ s⁻¹</td>
<td>101.9</td>
</tr>
<tr>
<td>4.40</td>
<td>hectare-meters, ha-m</td>
<td>U.S. gallons per minute, gal min⁻¹</td>
<td>0.227</td>
</tr>
<tr>
<td>8.11</td>
<td>hectare-meters, ha-m</td>
<td>acre-feet, acre-ft</td>
<td>0.123</td>
</tr>
<tr>
<td>97.28</td>
<td>hectare-meters, ha-m</td>
<td>acre-feet, acre-ft</td>
<td>1.03 x 10⁻²</td>
</tr>
<tr>
<td>8.1 x 10⁻²</td>
<td>hectare-centimeters, ha-cm</td>
<td>acre-feet, acre-ft</td>
<td>12.33</td>
</tr>
</tbody>
</table>

### Concentrations

<table>
<thead>
<tr>
<th></th>
<th>SI Unit</th>
<th>Equivalent Unit</th>
<th>Conversion Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>centimole per kilogram, cmol kg⁻¹</td>
<td>milliequivalents per 100 grams, meq</td>
<td>1</td>
</tr>
<tr>
<td>0.1</td>
<td>gram per kilogram, g kg⁻¹</td>
<td>percent, %</td>
<td>10</td>
</tr>
<tr>
<td>1</td>
<td>milligram per kilogram, mg kg⁻¹</td>
<td>parts per million, ppm</td>
<td>1</td>
</tr>
</tbody>
</table>

### Radioactivity

<table>
<thead>
<tr>
<th></th>
<th>SI Unit</th>
<th>Equivalent Unit</th>
<th>Conversion Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.7 x 10⁻¹¹</td>
<td>becquerel, Bq</td>
<td>curie, Ci</td>
<td>3.7 x 10¹⁰</td>
</tr>
<tr>
<td>2.7 x 10⁻²</td>
<td>becquerel per kilogram, Bq kg⁻¹</td>
<td>picocurie per gram, pCi g⁻¹</td>
<td>37</td>
</tr>
<tr>
<td>100</td>
<td>gray, Gy (absorbed dose)</td>
<td>rad, rd</td>
<td>0.01</td>
</tr>
<tr>
<td>100</td>
<td>sievert, Sv (equivalent dose)</td>
<td>rem (roentgen equivalent man)</td>
<td>0.01</td>
</tr>
</tbody>
</table>

### Plant Nutrient Conversion

#### Elemental

<table>
<thead>
<tr>
<th></th>
<th></th>
<th>Oxide</th>
</tr>
</thead>
<tbody>
<tr>
<td>P</td>
<td>2.29</td>
<td>P₂O₅</td>
</tr>
<tr>
<td>K</td>
<td>1.20</td>
<td>K₂O</td>
</tr>
<tr>
<td>Ca</td>
<td>1.39</td>
<td>CaO</td>
</tr>
<tr>
<td>Mg</td>
<td>1.66</td>
<td>MgO</td>
</tr>
</tbody>
</table>