The international system of units and its particular application to soil chemistry[1]

S. J. Thien and J. D. Oster[2]

ABSTRACT

The International System of Units (SI) brings uniform style and terminology to world-wide communication of measurements. Because the American Society of Agronomy (ASA), Crop Science Society of America (CSSA) and Soil Science Society of America (SSSA) are international, they should adopt SI in their communications. This paper summarizes SI units, definitions, symbols, and rules of usage. Discussions of applying SI to agronomic parameters are included where new concepts are introduced. Tables of recommended units and conversion factors are presented so use of SI can begin immediately. It is proposed that a 2 to 3-year adaptation period begin with this printing, with authors beginning to use SI and including traditional units, as desired, in parenthesis.

Additional index words: **Metric, Conversion table, Publication style, Measurement.**

LE Systeme International d'Unites (SI) is being adopted around the world. Its purpose is to bring uniformity of style and terminology in communicating measurements. The world-wide impact of American Society of Agronomy (ASA) dictates the logic and essentiality of adopting SI in its journals. Using SI in ASA journals would aid communication among scientists within agronomic disciplines as well as among these and other disciplines, especially internationally and in the pure sciences. Scientists will find that SI does not differ greatly from the metric system now used, and it increases understanding of the units the authors use.

The General Conference on Weights and Measures (CGPM) adopted the International System of Units in 1960. The International Bureau of Weights and Measures (BIPM) and, in the USA, the National Bureau of Standards (NBS) published rules on its use (2). SI guidelines, besides being used in many foreign countries and international societies, are followed by several American societies and college textbooks (1). ASA members are not expected to adopt this new system immediately. Rather, the ASA SI Units committee (ACS 321.4) recommends adoption over 2 to 3 years after these guidelines are published. During the interim, it is strongly recommended that authors begin now to use SI

[1] Contribution No. 81-483-j from the Agronomy Dep., Kansas Agric. Exp. Stn., Kansas State Univ., Manhattan, KS 66506 and the U.S. Salinity Laboratory, AR-SEA, USDA, 4500 Glenwood Drive, Riverside, CA 92501. Current address of the junior author is Dep. of Soil and Environmental Sciences, Univ. of California, Riverside, CA 92521.

[2] Research soil scientist, and soil and water specialist, respectively.

Table 1. Base SI Units (2)

Quantity	Unit	Symbol
Length	meter	m
Mass	kilogram	kg
Time	second	s
Electric current	ampere	A
Thermodynamic temperature	kelvin	K
Amount-of-substance	mole	mol
Luminous intensity	candela	cd

Table 2. Examples of SI derived units expressed in terms of base units (2)

	SI Unit	
Quantity	Name	Symbol
Area	square meter	m^2
Volume	cubic meter	m^3
Speed, velocity	meter per second	m/s
Acceleration	meter per second squared	m/s^2
Wave number	1 per meter	m^{-1}
Density, mass density	kilogram per cubic meter	kg/m^3
Current density	ampere per square meter	A/m^2
Magnetic field strength	ampere per meter	A/m
Concentration (of amount of substance)	mole per cubic meter	mol/m^3
Specific volume	cubic meter per kilogram	m^3/kg
Luminance	candela per square meter	cd/m^2

Table 3. SI derived units with special names (2)

	SI unit			
Quantity	Name	Symbol	Expression in terms of other units	Expression in terms of SI base units
Frequency	hertz	Hz		s^{-1}
Force	newton	N		$m{\cdot}kg{\cdot}s^{-2}$
Pressure, stress	pascal	Pa	N/m^2	$m^{-1}{\cdot}kg{\cdot}s^{-2}$
Energy, work, quantity of heat	joule	J	N•m	$m^2{\cdot}kg{\cdot}s^{-2}$
Power, radiant, flux	watt	W	J/s	$m^2{\cdot}kg{\cdot}s^{-3}$
Quantity of electricity, electric charge	coulomb	C	A•s	s•A
Electric potential, potential difference, electromotive force	volt	V	W/A	$m^2{\cdot}kg{\cdot}s^{-3}{\cdot}A^{-1}$
Capacitance	farad	F	C/V	$m^{-2}{\cdot}kg^{-1}{\cdot}s^4{\cdot}A^2$
Electric resistance	ohm	Ω	V/A	$m^2{\cdot}kg{\cdot}s^{-3}{\cdot}A^{-2}$
Conductance	siemens	S	A/V	$m^{-2}{\cdot}kg^{-1}{\cdot}s^3{\cdot}A^2$
Celsius temperature	degree celsius	°C		K
Luminous flux	lumen	lm		cd•sr†
Illuminance	lux	lx	lm/m^2	$m^{-2}{\cdot}cd{\cdot}sr$†
Activity (of a radionuclide)	becquerel	Bq		s^{-1}
Absorbed dose, specific energy imparted, kerma, absorbed dose index	gray	Gy	J/kg	$m^2{\cdot}s^{-2}$

† In this expression the steradian (sr) is treated as a base unit.

and include traditional units, as desired, in parentheses.

Each scientific discipline presents unique circumstances regarding unit expressions. Hence, there may appear cases in crop or soil sciences where strict use of SI appears unsuitable. This paper addresses some of those considerations and the committee intends to remain active to consider future problems.

This paper is one of a series being prepared by members of the SI Units committee. It first describes SI in general and then discusses its particular application to ASA publications and the soil science discipline with emphasis on soil chemistry.

Table 4. Examples of SI derived units expressed by means of special names (2)

Quantity	Name	Symbol	Expression in terms of SI base units
Dynamic viscosity	pascal second	Pa•s	$m^{-1}{\cdot}kg{\cdot}s^{-1}$
Moment of force	newton meter	N•m	$m^2{\cdot}kg{\cdot}s^{-2}$
Surface tension	newton per meter	N/m	$kg{\cdot}s^{-2}$
Power density, heat flux density, irradiance	watt per square meter	W/m^2	$kg{\cdot}s^{-3}$
Heat capacity, entropy	joule per kelvin	J/K	$m^2{\cdot}kg{\cdot}s^{-2}{\cdot}K^{-1}$
Specific heat capacity, specific entropy	joule per kilogram kelvin	J/(kg•K)	$m^2{\cdot}s^{-2}{\cdot}K^{-1}$
Specific energy	joule per kilogram	J/kg	$m^2{\cdot}s^{-2}$
Thermal conductivity	watt per meter kelvin	W/(m•K)	$m{\cdot}kg{\cdot}s^{-3}{\cdot}K^{-1}$
Energy density	joule per cubic meter	J/m^3	$m^{-1}{\cdot}kg{\cdot}s^{-2}$
Electric field strength	volt per meter	V/m	$m{\cdot}kg{\cdot}s^{-3}{\cdot}A^{-1}$
Electric charge density	coulomb per cubic meter	C/m^3	$m^{-3}{\cdot}s{\cdot}A$
Electric flux density	coulomb per square meter	C/m^2	$m^{-2}{\cdot}s{\cdot}A$
Permittivity	farad per meter	F/m	$m^{-3}{\cdot}kg^{-1}{\cdot}s^4{\cdot}A^2$
Molar energy	joule per mole	J/mol	$m^2{\cdot}kg{\cdot}s^{-2}{\cdot}mol^{-1}$
Molar entropy, molar heat capacity	joule per mole kelvin	J/(mol•K)	$m^2{\cdot}kg{\cdot}s^{-2}{\cdot}K^{-1}{\cdot}mol^{-1}$
Exposure (x and γ rays)	coulomb per kilogram	C/kg	$kg^{-1}{\cdot}s{\cdot}A$
Absorbed dose rate	gray per second	Gy/s	$m^2{\cdot}s^{-3}$

Table 5. Supplementary SI Units (2)

Quantity	Unit	Symbol
Plane angle	radian	rad
Solid angle	steradian	sr

SI UNITS

SI units are divided into three classes: base units, derived units and supplementary units.

Base units are seven, well-defined units which by convention are regarded as dimensionally independent: the meter, the kilogram, the second, the ampere, the kelvin, the mole, and the candela (Table 1). Note that lower case is used for unit symbols except where the symbol is derived from a proper name, then a capital is used (unabbreviated units are not capitalized). Symbols do not change in the plural and are not followed by a period.

Derived units are expressed in algebraic terms of base units (Table 2). Some have been given special names and symbols (Table 3), which may be used to express other derived units (Table 4).

Supplementary units are those not yet classified as either base units or derived units. This class now contains only two units, radian and steradian (Table 5).

Punctuation of Derived Units. The product of two or more units is preferably indicated by a dot midway in relation to symbol height. The dot may be dispensed with when there is no risk of confusion with another symbol,

for example: N•m or N m

A solidus (oblique stroke, /), a horizontal line, or negative powers may be used to express a derived unit formed from two others by division, for example: m/s, $\frac{m}{s}$, or $m \cdot s^{-1}$.

Only one solidus may be used in combinations of units unless parentheses are used to avoid ambiguity,

for example: $m \cdot kg/s^3 \cdot A$, or

$m \cdot kg \cdot s^{-3} \cdot A^{-1}$,

but not, $m \cdot kg/s^3/A$.

Application of SI Prefixes. The prefixes and symbols listed in Table 6 are used to indicate orders of magnitude of SI units. Among the base units, the unit of mass (kilogram) is the only one whose name, for historical reasons, already contains a prefix. Names of decimal multiples and sub-multiples of the unit of mass are formed by attaching prefixes to the word "gram", for example mg, but not μkg because compound prefixes are not allowed.

Prefixes should be chosen to reduce nonsignificant digits or leading zeros in decimal fractions. A prefix preferably should be chosen so that the numerical value lies between 0.1 and 1000 and the same unit, multiple, or submultiple should be used throughout a text, including its tables and graphs. Exponential expression of numbers is acceptable. The prefix should only be attached to a unit in the numerator. An exponent attached to a symbol containing a prefix indicates that the unit with its prefix is raised to the power expressed by the exponent,

for example: $1\ cm^{-3} = (10^{-2}m)^3 = 10^{-6}m^3$

$1\ mm^2/s = (10^{-3}m)^2/s = 10^{-6}m^2/s$

$1\ ns^{-1} = (10^{-9}s)^{-1} = 10^9s^{-1}$.

Units from Different Systems. To preserve the advantage of SI as a system, it is advisable to minimize its use with units from other systems. The American Society for Testing and Materials (ASTM) (3) recommends that such use be limited to the units listed in Table 7. Another set of units whose use is temporarily acceptable with SI are given in Table 8.

Punctuation. Periods are not used after any SI unit symbol, except at the end of a sentence, nor are plurals used. For example, write 5 kg and not 5 kg. or 5 kgs. When writing numbers less than one, a zero should be written before the decimal. Use spaces instead of commas to group numbers into threes (thousands) counting from the decimal point toward the left and the right. For four-digit numbers, the space is not necessary except for uniformity in tables.

Examples: 2.141 596 73 722 7372 0.1335

Definitions of Base Units. Meter: The meter is the length equal to 1 650 763.73 wavelengths in vacuum of the radiation corresponding to the transition between the levels $2p_{10}$ and $5d_5$ of the krypton − 86 atom (2).

Table 6. SI Prefixes (2)

Multiplication factor	Prefix	Symbol
1 000 000 000 000 000 000 = 10^{18}	exa	E
1 000 000 000 000 000 = 10^{15}	peta	P
1 000 000 000 000 = 10^{12}	tera	T
1 000 000 000 = 10^{9}	giga	G
1 000 000 = 10^{6}	mega	M
1 000 = 10^{3}	kilo	k
100 = 10^{2}	hecto	h
10 = 10^{1}	deka	da
0.1 = 10^{-1}	deci	d
0.01 = 10^{-2}	centi	c
0.001 = 10^{-3}	milli	m
0.00 001 = 10^{-6}	micro	μ
0.000 000 001 = 10^{-9}	nano	n
0.000 000 000 001 = 10^{-12}	pico	p
0.000 000 000 000 001 = 10^{-15}	femto	f
0.000 000 000 000 000 001 = 10^{-18}	atto	a

Table 7. Units in use with SI (2)

Quantity	Unit	Symbol	Definition
Time	minute	min	1 min = 60 s
	hour	h	1 h = 60 min = 3,600 s
	day	d	1 d = 24 h = 86,400 s
Volume	liter	L	1 L = 1 dm^3 = 10^{-3} m^3
Mass	metric ton (tonne)	t	1 t = 10^3 kg = Mg
Area	hectare	ha	1 ha = 1 hm^2 = 10^4 m^2

Table 8. Units temporarily in use with SI (2)

Quantity	Unit	Symbol	Definition
Energy	kilowatt hour	kWh	1 kWh = 3.6 MJ
Pressure	bar	bar	1 bar = 10^5 Pa
Activity (of a radionuclide)	curie	Cr	1 Cr = 3.7×10^{10} Bq
Exposure (X and gamma rays)	roentgen	R	1 R = 2.58×10^{-4} C/kg
Absorbed dose	rad	rd	1 rd = 0.01 Gy

Kilogram: The kilogram is the unit of mass equal to the mass of the international prototype of the kilogram in the custody of the Bureau International des Poids et Mesures at Sevres, France (2).

Second: The second is the duration of 9 192 631 770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the cesium − 133 atom (2).

Ampere: The ampere is that current which, if maintained in two straight parallel conductors of infinite length, of negligible circular cross section, and place 1 meter apart in a vacuum, would produce between these conductors a force equal to 2×10^{-7} newton per meter of length (2).

Kelvin: The kelvin, unit of thermodynamic temperature, is the fraction 1/273.16 of the thermodynamic temperature of the triple point of water (2).

Mole: The mole is the amount of substance of a system which contains as many elementary entities as there are atoms in 0.012 kilogram of carbon 12. In use, the elementary entities must be specified and may be atoms, molecules, ions, electrons, other particles, or specified groups of such particles (2).

Candela: The candela is the luminous intensity, in the perpendicular direction, of a surface of 1/600 000 square meter of a blackbody at the temperature of freezing platinum under a pressure of 101 325 newtons per square meter (2).

ADAPTING SI TO SOIL CHEMISTRY

Length—Base and Derived Units

Soil scientists should find little difficulty in working with the base unit of length, meter (m). In derived units, meter is the preferred unit to be used in the denominator. For long distances, kilometer is preferred; but cm or mm is acceptable for short lengths associated with research measurements and line drawings. The familiar term, micron, is no longer acceptable, being replaced by micrometer ($\mu m = 10^{-6}m$). Interatomic distances are adequately described by either nanometer ($nm = 10^{-9}m$) or picometer ($pm = 10^{-12}m$). Another familiar term, Angstrom ($\AA = 10^{-10}m$), is unacceptable because it does not fit into a multiple-of-three exponent increment.

Area is a derived unit of the base unit for length expressed as m^2 (Table 2), with km^2 and mm^2 also recommended. Hectare ($ha = hm^2$) is an acceptable unit, and although m^2 is preferred in the denominator of an expression, ha also may be used. Thus, readers may find yields or application rates given in kg/ha easier to grasp because they are closely related to pounds per acre. Although acreage is an acceptable, commonly used noun in the English system, hectareage is not a word. The SI system uses the word area under such conditions.

Volume, expressed as m^3, is another derived unit of the base unit for length (Table 2). However, other accepted expressions of volumes include: cm^3, liter ($L = dm^3$), mL (cm^3), and μL ($10^{-9}m^3$). Use of liter (L) in the denominator of a derived unit will be permitted, although m^3 is often more convenient when manipulating units. This can be demonstrated in the conversion of amount-of-substance concentration in irrigation water to amount-of-substance applied:

$$(10\ mol/m^3) \times (1{,}000\ m^3/ha) = (10^4 mol/ha),$$

as opposed to

$$(10\ mmol/L) \times (1{,}000\ m^3/ha) \times (1{,}000\ L/m^3)$$

$$\div\ (1{,}000\ mmol/mol) = (10^4\ mol/ha)$$

(Note that $mol\ m^{-3}$ is numerically equal to $mmol\ L^{-1}$)

Acre-furrow slice is a quasi-volumetric relationship with no direct counterpart in SI because compound expressions such as hectare furrow slice, hectare-meter, or hectare-centimeter are unacceptable units. Instead, soil volume in this context is described in multiples or submultiples of m^3. Thus, whereas an acre-furrow slice (0.5 ft. deep) of 21 780 ft^3 becomes 618 m^3, the equivalent volumetric concept in SI for a hectare would be 0.15 m × 100 m × 100 m, or 1500 m^3.

Mass—Base and Derived Units

The kilogram is the unit of mass, equal to the mass of the international prototype of the kilogram. In the USA, the commonly used term for mass is weight, but that now should be avoided in technical communications. The weight of an object is a force (f), representing the product of its mass (m) and the acceleration due to gravity (a) in the equation: $f = ma$. A properly calibrated balance, with a set of standards of known mass, measures mass because the effect of acceleration due to gravity (which varies with altitude, longitude, and latitude) is accounted for by calibration.

Soil scientists should find little difficulty in meeting SI standards of usage for expressing mass. As the base unit already contains a prefix, remember to form names of decimal multiples and sub-multiples by attaching prefixes to the word "gram". Thus, we do not, for example, refer to a kilokilogram (kkg) or to a millikilogram (mkg) but to a megagram (Mg) or a gram (g).

Kilogram in the denominator of derived units is the accepted form, but it is the only instance when units containing a prefix are allowed.

A potentially confusing use involving SI expression of mass centers on the term ton. A metric ton (or tonne), denoted by the symbol "t", equals 10^3 kg (or megagram, Mg) in SI. But that definition does not equal the commonly understood meaning of ton (1 ton = 2000 pounds) in the USA. In written communication, spelling tonne avoids ambiguity, but in verbal communication megagram (1 t = 1 Mg) is suggested.

Time—Base and Derived Units

The base unit of time is the second (s), but equally acceptable units in SI are minute (60 s), hour (3 600 s), and day (86 400 s). Units of time that could vary in length should be avoided, for example, month or growing season.

Because plant growth phenomena have diurnal phases, it is acceptable to use day in the denominator of some agronomic expressions, for example, growth rate (mm/d) or evapotranspiration rate (cm/d).

Thermodynamic Temperature—Base and Derived Units

The base unit used to express thermodynamic temperature and temperature intervals is kelvin (K). However, temperature intervals also may be expressed in degrees Celsius (C). The kelvin scale is set by assigning the origin at absolute zero and 273.16 (exactly) to the triple point of water (the temperature and pressure of water at which ice, liquid, and vapor are all in equilibrium in the absence of air). The ice point (the temperature at which ice and water are in equilibrium in the presence of air and at one atmosphere) is zero on the Celsius scale (273.15 K). Thus Celsius temperature (C) is related to thermodynamic temperature (K) by the equation:

$$C = K - 273.15.$$

Amount of Substance—Base and Derived Units

The base unit for amount-of-substance is the mole. Any amount-of-substance that contains 6.02×10^{23} entities is a mole. This number, known as Avogadro's number, is the number of ^{12}C atoms in 0.012 kg of carbon 12. When the mole is used, elementary entities must be specified; they may be atoms, molecules, ions, electrons, other particles, or specified groups of such particles. Examples of type of entities used to describe a mole include:

1 mole of . . .
- . . .NaCl has 6.02×10^{23} molecules and a mass of 58.44 g,
- . . .Ca^{2+} has 6.02×10^{23} ions and a mass of 40.08 g,
- . . .½ Ca^{2+} has 6.02×10^{23} ½ Ca^{2+} units and a mass of 20.04 g,
- . . .positive charges (protons, p^+) has 6.02×10^{23} positive charges and a charge of 96.49 kC,
- . . .electrons (e^-) has 6.02×10^{23} electrons, a mass of 548.6 μg and a charge of −96.49 kC, or
- . . .photons (Υ) has 6.02×10^{23} particles whose frequency is 10^4 Hz and an energy of 39.90 kJ.

The emphasis in these examples is that the mole concept can refer to any specified particle, or grouping of particles (for example, ½ Ca^{2+}), convenient to fit the situation. Thus, the term mole in SI is not entirely synonymous with older terminologies. Many have learned to regard the mole as a definite mass; i.e. one mole of NaOH as one gram molecular weight (40 g) of sodium hydroxide, but now when describing an amount-of-substance, mole requires a more precise description.

Some basic chemical relationships restated in SI context follow:

Relative atomic mass (A_r), formerly atomic weight, is the average mass of one atom of the element (in its natural isotopic condition) compared to 1/12 of the mass of an atom of carbon 12,

$$\text{for example: } A_r(Ca^{2+}) = 40.08.$$

A_r values are unitless, being a ratio formed from two physical quantities of the same unit.

Relative molecular mass (M_r), formerly molecular weight, is the average mass per formula of the constituent atoms (in their natural isotope condition) compared to 1/12 of the mass of an atom of carbon 12. M_r values likewise are unitless,

$$\text{for example: } M_r(CaSO_4 \cdot 2H_2O) = 172.18.$$

Molar mass (M) is the mass divided by the amount-of-substance and has SI base units of kg mol^{-1}, but the practical unit g mol^{-1} is also used.

In a simple case of a pure substance composed of atoms, say Na^+, the molar mass is determined as follows:

$$M(Na^+) = (\text{mass of an atom of } Na^+/\text{mass of an atom of } ^{12}C) \times 0.012 \text{ kg mol}^{-1}$$

$$M(Na^+) = (22.99/12) \times 0.012$$

$$M(Na^+) = 0.02299 \text{ kg mol}^{-1}.$$

For molecules and compounds, a summation procedure of the above example for the separate constituents yields the molar mass.

When molar mass is expressed in units of g mol^{-1}, it is numerically identical to relative atomic mass, or relative molecular mass.

$$\text{For example: } M(Ca^{2+}) = 40.08 \text{ g mol}^{-1};$$

$$A_r(Ca^{2+}) = 40.08; M(CaSO_4 \cdot 2H_2O) = 172.18 \text{ g mol}^{-1};$$

$$M_r(CaSO_4 \cdot 2H_2O) = 172.18.$$

DERIVED UNITS

Pressure

The SI unit for pressure is the pascal (Pa), which is the pressure produced by a force of one newton on an area of one square meter. A standard atmosphere is equal to the pressure required to support 0.76 m of mercury at 0 C at a point on the earth where the acceleration of gravity is 9.806 m s^{-2}. As the density of mercury at 0 C is 13.595×10^3 kg m^{-3}, the unit force exerted by a standard atmosphere is calculated as follows:

$$1 \text{ atm} = 0.76 \text{ m} \times 13.595 \times 10^3 \text{ kg m}^{-3} \times 9.806 \text{ m s}^{-2}$$

$$1 \text{ atm} = 101\,300 \text{ N m}^{-2}$$

Thus a pressure of one atmosphere equals 101 300 N m^{-2} = 101 300 Pa = 101.3 kPa = 0.1013 MPa = 1.013 bar.

Pa, kPa, and MPa are recommended units, but bar, although temporarily acceptable, is strongly discouraged.

Amount of Substance Concentration

Chemists will normally be using the amount-of-substance concept (symbol n) in a concentration context. Amount-of-substance concentration (symbol c) then is correct terminology to describe the amount-of-substance divided by the volume of solution. SI base unit for this concept is mol m^{-3} where the molar mass (M) is known, and kg m^{-3} (in use, g m^{-3}) where it is not. Equally acceptable is the practical unit mol L^{-1} (≡ mol dm^{-3}). The "amount-of-substance concentration" concept can be replaced with "concentration" without creating confusion. Examples of correctly expressing concentration include:

$$c(HCl) = 0.1 \text{ mol L}^{-1} (= 0.1\, M\, HCl) \text{ and}$$

$$c(H_2PO_4^-) = 2.1 \text{ mol m}^{-3} (= 2.1 \text{ mmol L}^{-1}).$$

Note the acceptability of referring to the concentration 0.1 mol L^{-1} as a 0.1 *M* solution. While the concept and useage of molarity as previously used has been replaced by the amount-of-substance concentration concept, the descriptive symbol (*M*) is still permitted (7). Note, also, mmol L^{-1} (numerically identical to the base unit mol m^{-3}) nicely describes low solute concentrations often encountered in soil environments.

Thus, molarity is discarded in SI because the "amount-of-substance concentration" concept makes it redundant, but molality (mol kg^{-1}) remains the preferred unit for precise, nonisothermal conditions because molality, but not concentration, is independent of temperature (5).

The unit mole replaces such terms as gram-molecule, gram-atom and gram equivalent, and has led to a reevaluation of the concept of an equivalent and the corresponding amount of substance concentration, normality (5). The equivalent is defined (5) as that entity which in a specified reaction would combine with or be in any other appropriate way equivalent in

(a) an acid-base reaction to one entity of titratable hydrogen ions, H^+ or
(b) a redox reaction to one entity of electrons, e^-.

Thus:

1 equivalent of Cl^- would be stated as 1 mole of Cl^-;
1 equivalent of H_2SO_4 could be stated as 1 mole of $\frac{1}{2}H_2SO_4$;
1 equivalent of Al^{3+} could be stated as 1 mole of $1/3\ Al^{3+}$;
1 equivalent of MnO_4^- could be stated as 1 mole of $1/5\ MnO_4^-$.

Use of terms like $1/3\ Al^{3+}$, $\frac{1}{2}H_2SO_4$ and $1/5\ MnO_4^-$ is possible because the definition of the mole permits reference to any specified entity; a mole refers to 6.02×10^{23} units of that entity. The fractions ½, 1/3, and 1/5 in these examples are called equivalence factors (for Cl it is 1) and represent the entity of substance in question reacting with one entity of titratable hydrogen ions (or equivalent) at the equivalence point or one entity of electrons, e^-, in a redox reaction.

The concept of equivalence factors is illustrated as follows: For the reaction

$$2\,NaOH + H_2SO_4 = Na_2SO_4 + 2H_2O \quad [1]$$

one entity of H_2SO_4 reacts with two of NaOH allowing the reaction to be rewritten as

$$NaOH + \tfrac{1}{2}\,H_2SO_4 = \tfrac{1}{2}\,Na_2SO_4 + H_2O \quad [2]$$

making the two reactants equal when n (NaOH) = n (½ H_2SO_4), where n represents the number of moles. The equivalence factor varies with the nature of the reaction. Thus,

$$H_3PO_4 + KOH = KH_2PO_4 + H_2O \quad [3]$$

$$n(KOH) = n(H_3PO_4).$$

Whereas for

$$H_3PO_4 + 2KOH = K_2HPO_4 + 2H_2O \quad [4]$$

$$n(KOH) = n(\tfrac{1}{2}\,H_3PO_4).$$

And for

$$H_3PO_4 + 3AgOH = Ag_3PO_4(s) + 3H_2O \quad [5]$$

$$n(AgOH) = n(1/3\ H_3PO_4).$$

Now, consider the reaction

$$H_2SO_4 + Ca(OH)_2 = CaSO_4 + 2H_2O. \quad [6]$$

Then, at the acid-base end point,

$$n(H_2SO_4) = n\,(Ca(OH)_2) \quad [7]$$

and the equivalence factor for H_2SO_4 would appear to be 1 instead of ½ as was the case for reaction [1]. Recalling that the definition refers to titratable hydrogen it should be clear that the equivalence factor is ½. Another way of stating this definition would be to substitute the statement "the exchange between the reactants of one mole of protons" for the statement "one entity of titratable hydrogen ions."

A solution in which the amount of substance concentration of the reagent is 1 mol L^{-1} is a normal solution, symbol N. Thus for reaction [2], if c(½ H_2SO_4) equals 1 mol L^{-1}, the concentration of this 1 *N* solution of sulphuric acid is 0.049 kg L^{-1} [M (H_2SO_4) = 0.098 kg mol^{-1}]. Likewise for reaction [4] if c(½ H_3PO_4) equals 1 mol L^{-1}, the concentration of a 1 *N* solution of phosphoric acid is also 0.049 kg L^{-1} [M (H_3PO_4) = 0.098 kg mol^{-1}]. Because confusion may exist when a reagent has different equivalence factors depending on the specific reaction involved, any statements of solution concentration in terms of normality must include the equivalence factor, e.g.,

$$0.05\,N(H_3PO_4);\ 4.9\text{ g L}^{-1}\text{ of }H_3PO_4$$

$$0.10\,N(\tfrac{1}{2}\,H_3PO_4);\ 4.9\text{ g L}^{-1}\text{ of }H_3PO_4$$

$$0.15\,N(1/3\ H_3PO_4);\ 4.9\text{ g L}^{-1}\text{ of }H_3PO_4.$$

However, note that in each case the normality of the solution is being expressed on a molar basis e.g., 0.15*N* (1/3 H_3PO_4) = 0.15 *M* (1/3 H_3PO_4). It follows that normality and the amount of substance concentration formerly referred to as molarity, are the same. This is a direct consequence of the definition of a mole. Consequently, we strongly recommend that amount of substance concentrations expressed as normality be abandoned.

Redox Reactions. Since the mole can refer to any specified entity, it is convenient for redox reactions to relate the amount of reactant to the number of electrons per mole that it combines with or releases. To arrive at the appropriate equivalence factor, one must consider the stoichiometry of the overall redox reaction. For the reaction:

$$10FeSO_4 + 2KMnO_4 + 8H_2SO_4 = K_2SO_4 + 2MnSO_4 + 5Fe_2(SO_4)_3 + 8H_2O \quad [8]$$

the equivalent factor for $KMnO_4$ is 1/5, and for $FeSO_4$ it is 1. One mole of $KMnO_4$ is equivalent to 5 moles of $FeSO_4$ because, according to reaction [8], five moles of Fe^{2+} are oxidized for each mole of Mn^{7+} that is reduced:

$$MnO_4^- + 8H^+ + 5e = Mn^{2+} + 4H_2O \quad [9]$$

$$5Fe^{2+} - 5e = 5Fe^{3+}. \quad [10]$$

Likewise for the reaction involved in the biological oxidization of sulfur

$$2S + 3O_2 = 2SO_3 \quad [11]$$

$$n(1/6S) = n(\tfrac{1}{4}O_2), \text{ or}$$

$$n(2/3S) = n(O_2)$$

because

$$S - 6e = S^{6+} \quad [12]$$

$$O_2 + 4e = 2O^{2-}. \quad [13]$$

In summary, the recommended definition of the equivalent is as follows: the equivalent of a species X is the entity that in a specified reaction would combine with, or be in any other appropriate way, equivalent in: (a) an acid-base reaction to one entity of titratable hydrogen ions, H^+ or protons; or (b) a redox reaction to one entity of electrons, e^-. In both instances, the equivalent can be established from a knowledge of the equivalence factor and the chemical formula of the species. For a more detailed discussion of determining equivalence factors, see (5).

Cation Exchange Capacity

Historically, the soil scientist has expressed cation exchange capacity (CEC) in "equivalents per 100g". In SI, the unit becomes "specific amount-of-substance". "Specific" implies on a per-mass basis, and "amount-of-substance" selected as either plus charges (protons, p^+) or negative charges (electrons, e^-). In SI base units, charges per unit mass becomes mol $(p^+)\cdot kg^{-1}$ in reference to cationic charges neutralizing exchange sites, or mol $(e^-)\cdot kg^{-1}$ in reference to the negatively charged exchange sites. Values would be numerically equal because one proton (p^+), or its electrochemical equivalent, neutralizes one negatively charged exchange site. For example, let us assume a soil is reported to contain 4 milliequivalents each of exchangeable K^+ and Ca^{2+} per 100 g soil. The exchangeable cation composition and total cation exchange capacity (CEC) would be:

40 mmol $(K^+)\cdot kg^{-1}$,

40 mmol $(\tfrac{1}{2}\, Ca^{2+})\cdot kg^{-1}$, and

80 mmol $(+)\cdot kg^{-1}$, respectively.

As another example, consider that isomorphism (substituting of Al^{3+} for Si^{4+} and Mg^{2+} or Fe^{2+} for Al^{3+}) in Upton, Wyoming montmorillonite with a molecular mass of 0.7295 kg mol^{-1} results in 1 mole of excess electrons (6.02×10^{23}) per mole of clay (4, p. 578) or a specific charge density of

$$[1 \text{ mol}(-)/\text{mol (clay)}]\ [\text{mol(clay)}/0.7295 \text{ kg}] = 1.37 \text{ mol}(-)\cdot kg^{-1}$$

This charge is neutralized by cations whose positive charges sum to an equal number (1.37) (6.02×10^{23}). Consequently, the CEC is 1.37 mol(+) kg^{-1}.

This reasoning lends readily apparent stoichiometry to CEC calculations and has been demonstrated as a workable approach to teaching soil chemistry (6). If CEC is determined by the single-ion saturation technique, then the ion used should be specified. If the CEC for the Upton, Wyoming montmorillonite, in the example above, was determined using Na^+, its CEC should be expressed as 1.37 mol$(Na^+)\cdot kg^{-1}$. Likewise, if Mg^{2+} were used, the expression would be 1.37 mol$(\tfrac{1}{2}\, Mg^{2+})\cdot kg^{-1}$. One reason for specifying the saturating ion is that it can influence the CEC measured.

Converting CEC to surface charge density requires terms for specific surface area ($m^2\ kg^{-1}$) and molar charge, i.e., quantity of electrical charge per mole of charge entities [C$\cdot$mol$(-)^{-1}$], which is the Faraday constant. The surface charge density of the electrons in the sample of Upton, Wyoming montmorillonite is

$$[1.37 \text{ mol}(-)/\text{kg}]\ [\text{kg}/(766 \times 10^3 m^2)]$$

$$[(9.6485 \times 10^4 C)/\text{mol}(-)] = 0.17\ C\ m^{-2}$$

The surface charge density of the exchangeable cations would also be expressed as 0.17 C m^{-2}.

Conductivity

The SI unit of electrical conductance is siemens (S), so electrical conductivity of solutions is now expressed as S m^{-1}. To obtain a numerical value equal to that previously reported in units of mmho cm^{-1} and still retain base units in the denominator, it is recommended to report values in units of dS m^{-1} (1 dS m^{-1} = 1 mS cm^{-1} = 1 mmho cm^{-1}). The equivalent expression for μmho cm^{-1} would be 10^{-3} dS m^{-1} (10^{-1} mS m^{-1}), but because a symbol for a prefix of 10^{-4} is not defined in SI, using μmho cm^{-1} is unacceptable.

Radioactivity

SI uses the derived unit bequerel (Bq) to express radioactivity instead of the unit curie (Tables 3 and 8). The bequerel is expressed with the basic SI unit of time, the second.

Table 9. Examples of preferred units for expressing physical quantities in ASA journals

Quantity	Application	Unit	Symbol
Area	Specific surface area of soil	square meter per kilogram	$m^2 \cdot kg^{-1}$
	Pot area	square centimeter	cm^2
	Leaf area	square meter	m^2
	Land area	hectare	ha
Cation exchange capacity	Soil	mole per kilogram	$mol \cdot kg^{-1}$
Concentration†	In liquid media		
	molecular wt. known	mole per liter	$mol \cdot L^{-1}$
	molecular wt. unknown	gram per liter	$g \cdot L^{-1}$
	In plant material		
	molecular wt. known	mole per kilogram	$mol \cdot kg^{-1}$
	molecular wt. unknown	gram per kilogram	$g \cdot kg^{-1}$ ($mg \cdot kg^{-1}$)
	ion uptake	mole per liter	$mol \cdot L^{-1}$ ($mol \cdot m^{-3}$)
	Fertilizer	kilogram per hectare	$kg \cdot ha^{-1}$
	Gas	gram per cubic meter	$g \cdot m^{-3}$ ($mg \cdot m^{-3}$)
	Osmotic potential	joule per kilogram	$J \cdot kg^{-1}$
	Osmotic pressure	pascal	Pa
Density	Soil bulk density	megagram per cubic meter	$Mg \cdot m^{-3}$
Electrical conductivity	Salt tolerance	decisiemen per meter	$dS \cdot m^{-1}$
Evapotranspiration rate	Plant	meter per second	$m \cdot s^{-1}$
		millimeter per day	$mm \cdot d^{-1}$
Growth rate	Plant	meter per second	$m \cdot s^{-1}$
		millimeter per second	$mm \cdot s^{-1}$
		meter per day	$m \cdot d^{-1}$
Ion transport	Ion uptake	mole per square meter second	$mol \cdot m^{-2} \cdot s^{-1}$
	Velocity	mole per second	$mol \cdot s^{-1}$
Leaf area ratio	Plant	square meter per kilogram	$m^2 \cdot kg^{-1}$
Length	Soil depth	meter	m
		centimeter	cm
Photosynthetic rate	CO_2 mass flux density	milligram per square meter second	$mg \cdot m^{-2} \cdot s^{-1}$
	CO_2 amount of substance flux density	micromole per square meter second	$\mu mol \cdot m^{-2} \cdot s^{-1}$
Radiation	Light	hertz	s^{-1}
	Wave number	per meter	m^{-1}
	Wave length	nanometer	nm
	Irradiance	watt per square meter	$W \cdot m^{-2}$
	Photon flux density	mole per square meter second	$mol \cdot m^{-2} \cdot s^{-1}$
Resistance	Stomatal	second per meter	$s \cdot m^{-1}$
Transpiration rate	H_2O mass flux density	milligram per square meter second	$mg \cdot m^{-2} \cdot s^{-1}$
Water relations	Potential	joule per kilogram	$J \cdot kg^{-1}$
	Pressure	pascal	Pa
Yield	Grain or forage yield	megagram per hectare	$Mg \cdot ha^{-1}$
		gram per square meter	$g \cdot m^{-2}$
	Mass of plant or plant part	gram (gram per plant or per plant part)‡	$g(g \cdot plant^{-1}; g \cdot kernel^{-1})$

† If percent is used, the basis must be specified.
‡ Here the use of a non-basic unit in the denominator is an acceptable alternative. For example one can write either "the average yield per plant was 100 g" or "the average yield was 100 g•plant." Probably the latter usage would be restricted to table headings.

$$1 \text{ curie} = 3.7 \times 10^{10} \text{ Bq}$$

Thus a solution previously described as labelled with 30 μCr P^{32}, now is correctly described as labelled with 1.11×10^6 Bq P^{32}.

SUMMARY

The SI Units committee of the ASA is recommending adoption of SI in its journals. It is expected that SI usage will expand into textbooks and classrooms as well. Tables of recommended units (Table 9) and conversion factors (Table 10) are included so use of SI can begin immediately. Members are encouraged to begin using SI and include traditional units, if desired, in parenthesis. Problems arising with SI usage are solicited by the SI Units committee so that the system will be of greatest utility to our society.

Table 10. Factors for converting non-SI units to acceptable SI units, with parenthetic reference to SI base units where needed

Non-SI Units		SI Units
Multiply	By	To obtain
acre	4047	square meter, m^2
acre	0.405	hectare, ha (10^4 m^2)
acre	4.05×10^{-3}	square kilometer, km^2 (10^6 m^2)
Angstrom unit	10	nanometer, nm (10^{-9} m)
atmosphere	0.101	megapascal, MPa (10^6 Pa)
bar	10^{-1}	megapascal, MPa (10^6 Pa)
British thermal unit	1054	joule, j
calorie	4.19	joule, J
cubic feet	0.028	cubic meter, m^3
cubic feet	28.3	liter, L (10^{-3} m^3)
cubic inch	1.64×10^{-5}	cubic meter, m^3
cubic inch	16.4	cubic centimeter, cm^3 (10^{-6} m^3))
curie	3.7×10^{10}	becquerel, Bq
degrees (angle)	1.75×10^{-2}	radian, rad
dyne	10^{-5}	newton, N
erg	10^{-7}	joule, J
foot	0.305	meter, m
foot-pound	1.356	joule, J
gallon	3.785	liter, L (10^{-3} m^3)
gallon per acre	9.35	liter, per hectare, $L \cdot ha^{-1}$
gram per cubic centimeter	1.00	megagram per cubic meter, $Mg \cdot m^{-3}$
inch	25.4	millimeter, mm (10^{-3} m)
micron	1.00	micrometer, μm (10^{-6} m)
mile	1.61	kilometer, km (10^3 m)
miles per hour	0.477	meter per second, $m \cdot s^{-1}$
millimhos per centimeter	1.00	decisiemen per meter, $dS \cdot m^{-1}$
ounce	28.4	gram, g (10^{-3} kg)
ounce (fluid)	2.96×10^{-2}	liter, L (10^{-3} m^3)
pint (liquid)	0.473	liter, L (10^{-3} m^3)
pound	453.6	gram, g (10^{-3} kg)
pound per acre	1.12	kilogram per hectare, $kg \cdot ha^{-1}$
pound per acre	1.12×10^{-3}	megagram per hectare, $Mg \cdot ha^{-1}$
pounds per cubic foot	16.02	kilogram per cubic meter, $kg \cdot m^{-3}$
pounds per cubic inch	2.77×10^4	kilogram per cubic meter, $kg \cdot m^{-3}$
pounds per square foot	47.88	pascal, Pa
pounds per square inch	6.90×10^3	pascal, Pa
quart (liquid)	0.946	liter, L (10^{-3} m^3)
quintal (metric)	10^2	kilogram, kg
solid angle	12.57	steradian, sr
square centimeter per gram	0.1	square meter per kilogram, $m^2 \cdot kg^{-1}$
square feet	9.29×10^{-2}	square meter, m^2
square inch	645.2	square millimeter, mm^2 (10^{-6} m^2)
square mile	2.59	square kilometer, km^2
square millimeters per gram	10^{-3}	square meter per kilogram, $m^2 \cdot kg^{-1}$'
temperature (°F) − 32	0.5555	temperature, C
temperature (°C) + 273	1	temperature, °K
ton (metric)	10^3	kilogram, kg
ton (2000 lb)	907	kilogram, kg
tons (2000 lb) per acre	2.24	megagram per hectare, $Mg \cdot ha^{-1}$

ACKNOWLEDGMENTS

The authors are greatly appreciative of the laborious review talents and many helpful suggestions of Dr. Jan van Schilfgaarde. Likewise, we acknowledge the learned efforts of the entire ASA SI Units committee (ACS 321.4) to inform society members on this topic.

LITERATURE CITED

1. Alberty, R. A., and Farrington Daniels. 1980. Physical chemistry: SI Version. 5th ed. 692 p. John Wiley and Sons, Inc., New York.
2. Anonymous. 1977. National Bureau of Standards Special publication No. 330. 46 p. Superintendent of Documents; U.S. Gov't. Printing Office; Washington, D.C.
3. Anonymous. 1980. ASTM Standard for Metric Practice E380-79, 42 p. American Society for Testing and Materials; 1916 Race Street, Philadelphia, PA.
4. Grim, R. E. 1968. Clay Mineralogy. 2nd ed. McGraw-Hill, New York.
5. Irving, H. M. N. H. 1978. Recommendations on the usage of the terms 'equivalent' and 'normal'. Pure and Appl. Chem. 50:325–338.
6. Thien, S. J. 1977. Avogadro's concept of equivalents for teaching cation exchange capacity. J. Agron. Educ. 6:35–37.
7. Whiffen, D. H. 1979. Manual of Symbols and Terminology for Physiochemical Quantities and Units. International Union of Pure and Applied Chemistry. Permagon Press, New York.