CHAPTER

2

Definitions of Physical Units and the International System

2.1 DEFINITIONS

In soil—plant—water relations, we will be using units based on physical definitions. Therefore, we need to review the definitions. We will define the following: force, weight, work, energy, power, pressure, and heat. The definitions come from Schaum (1961), but they can be found in any physics textbook.

2.1.1 Force

Force is a push or pull exerted on a body. If an unbalanced force acts on a body, the body accelerates in the direction of the force. Conversely, if a body is accelerating, there must be an unbalanced force acting on it in the direction of the acceleration. The unbalanced force acting on a body is proportional to the product of the mass and of the acceleration produced by the unbalanced force.

2.1.1.1 Newton's Laws of Motion

For completeness, we now review these three laws, even though the second law is the one we are interested in for the definition of force. (See the Appendix, Section 2.4, for a biography of Newton.)

1. A body will maintain its state of rest or of uniform motion (at constant speed) along a straight line unless compelled by some unbalanced force to change that state. In other words, a body accelerates only if an unbalanced force acts on it.
2. An unbalanced force F acting on a body produces in it an acceleration a which is in the direction of the force and directly

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proportional to the force, and inversely proportional to the mass m of the body.
In mathematical terms, this law states that $ka = F/m$ or $F = kma$, where k is a proportionality constant. If suitable units are chosen so that $k = 1$, then $F = ma$.

3. To every action, or force, there is an equal and opposite reaction, or force. In other words, if a body exerts a force on a second body, then the second body exerts a numerically equal and oppositely directed force on the first body. These two forces, although equal and oppositely directly, do not balance each other, because both are not exerted on the same body.

2.1.1.2 Units of Force

In the equation $F = ma$, it is desirable to make $k = 1$; that is, to have units of mass, acceleration, and force such that $F = ma$. To do this, we specify two fundamental units and derive the third unit from these two.

1. In the *meter-kilogram-second* or *mks absolute system*, the fundamental mass unit chosen is the kilogram and the acceleration unit is the m/s^2. The corresponding derived force unit, called the *newton* (nt or N), is the unbalanced force that will produce an acceleration of 1 m/s^2 in a mass of 1 kg.
2. In the *centimeter-gram-second* or *cgs absolute system*, the fundamental mass unit is the gram and the acceleration unit is the cm/s^2. The corresponding derived force unit, called the *dyne*, is that unbalanced force that will produce an acceleration of 1 cm/s^2 in a mass of 1 g.
3. In the *English gravitational system*, the fundamental force unit is the *pound* and the acceleration unit is the ft/s^2. The corresponding derived mass unit, called the *slug*, is the mass that when acted on by a 1 lb force acquires an acceleration of 1 ft/s^2.

Thus the following indicate three consistent sets of units that may be used with the equation $F = ma$ ($F = kma$ with $k = 1$):

- **mks system:** F (newtons) $= m$ (kilograms) $\times\, a$ (m/s^2)
- **cgs system:** F (dynes) $= m$ (grams) $\times\, a$ (cm/s^2)
- **English system:** F (pounds) $= m$ (slugs) $\times\, a$ (ft/s^2)

2.1.2 Mass and Weight

The mass m of a body refers to its inertia, and the weight w of a body is the pull or force due to gravity acting on the body which varies with location. (Inertia is the tendency of matter to remain at rest if at rest, or, if moving, to keep moving in the same direction, unless affected by some outside force.) Weight w is a force with a direction approximately toward the center of the earth.

If a body of mass m is allowed to fall freely, the resultant force acting on it is its weight, w, and its acceleration is that due to gravity, g. Then in any consistent system of units the equation $F = ma$ becomes

$$w = mg.$$

Thus

w (newtons) $= m$ (kilograms) $\times g$ (m/s^2)
w (dynes) $= m$ (grams) $\times g$ (cm/s^2)
w (pounds) $= m$ (slugs) $\times g$ (ft/s^2).

It follows that $m = w/g$. For example, if a body weighs 64 lb at a place where $g = 32$ ft/s^2, its mass is $m = w/g = 64$ lb/(32 ft/s^2) $= 2$ slugs. If a body weighs 49 N at a place where $g = 9.8$ m/s^2, its mass $m = w/g = 49$ N/(9.8 m/s^2) $= 5$ kg.

Problem: How many grams are there in one slug?

We remember that one pound = 454 g. We abbreviate pound as lb and gram as g.

One slug of mass = 32 lb of mass = 32 × 454 g of mass = 14,528 g of mass. The conversion was made by Don Kirkham (personal communication, February 15, 1994).

2.1.3 Work

A force does work on a body when it acts against a resisting force to produce motion in the body. Consider that a constant external force F acts on a body at an angle θ with the direction of motion and causes it to be displaced a distance d (Figure 2.1). Then the work W done by the force F on the body is the product of the displacement d and the component of F in the direction of d. Thus

$$W = (F \cos \theta)d.$$

If d and F are in the same direction, $\cos \theta = \cos 0° = 1$ and $W = Fd$.

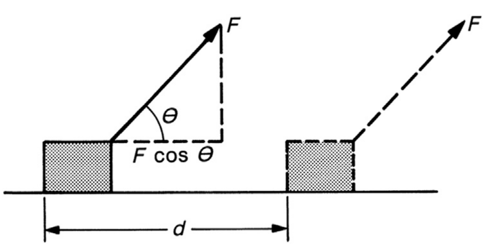

FIGURE 2.1 Illustration for definition of work. *Adapted from Schaum (1961, p. 49). This material is reproduced with permission of The McGraw-Hill Companies.*

2.1.3.1 Units of Work

Any unit of work equals a unit of force $\times$ a unit of length.

- One *foot-pound* (ft-lb) of work is done when a constant force of 1 lb moves a body a distance of 1 ft in the direction of the force.
- One *newton-meter* (Nm), called 1 joule (J), is the work done when a constant force of 1 N moves a body a distance of 1 m in the direction of the force. Because 1 N = 0.2248 lb and 1 m = 3.281 ft,

$$1 \text{ joule} = 1 \text{ newton} - \text{meter} = 0.7376 \text{ ft} - \text{lb}$$

$$1 \text{ ft} - \text{lb} = 1.356 \text{ joules.}$$

One *dyne-cm*, called 1 *erg*, is the work done when a constant force of 1 dyne moves a body a distance of 1 cm in the direction of the force. Since 1 N = 10^5 dynes and 1 m = 10^2 cm,

$$1 \text{ joule} = 10^7 \text{ ergs.}$$

2.1.4 Energy

The *energy* of a body is its ability to do work. Because the energy of a body is measured in terms of the work it can do, it has the same units as work.

The *potential energy* (PE) of a body is its ability to do work because of its position or state. The potential energy of a mass m lifted a vertical distance h, where g is the acceleration due to gravity, is

$$\text{PE} = mgh.$$

In the mks system: PE (joules) = m (kg) $\times$ g (m/s^2) $\times$ h (m). In the cgs system: PE (ergs) = m (grams) $\times$ g (cm/s^2) $\times$ h (cm).

Because $mg = w$, we may also write: PE = $mgh = wh$.

2.1.5 Power

Power is the time rate of doing work. Average power = (work done)/(time taken to do this work) = force applied $\times$ velocity of body to which force is applied, where the velocity of the body is in the direction of the applied force.

2.1.5.1 Units of Power

The unit of power in any system is found by dividing the unit of work in that system by the unit of time. Thus two units of power are the J/s (or watt, abbreviated W) and the ft-lb/s. Other practical units of power are the kilowatt and the horsepower.

- 1 W = 1 J/s
- 1 kilowatt (kW) = 1000 W = 1.34 horsepower
- 1 horsepower (hp) = 550 ft-lb/s = 33,000 ft-lb/min = 746 W.

The power of car engines is given in units of horsepower. My car has a 221-horsepower engine. Work done = power × time taken. Hence the total work done in 1 h, when the rate of doing work is 1 kW, is 1 kilowatt-hour (kWh). The total work done in 1 h, when the rate of doing work is 1 horsepower, is 1 horsepower-hour (hph). Every month, I receive a bill for electricity, and the meter readings on the bill, taken from the meter for my apartment, are in units of kilowatt-hours. This is a unit of work.

2.1.6 Pressure

Pressure or p is a force per unit area

$$p = \frac{(\text{force } F \text{ acting perpendicular to an area})}{(\text{area } A \text{ over which the force is distributed})}$$

or

$$p = F/A.$$

Some units of pressure are the lb/ft^2, lb/in^2, N/m^2, and $dyne/cm^2$. The $dyne/cm^2$ is a unit that we will use often in plant—water relations.

$$1 \times 10^6 \text{ dyne/cm}^2 = 1 \text{ bar}.$$

However, a bar is not an SI unit. The SI unit is the Pascal, and 10 bars = 1 MPa or 10 bars = 1 MPa. We will talk about the SI system of units in Section 2.2.

2.1.7 Heat

Heat is a form of energy. The three units most commonly used in measuring the quantity of heat are defined as follows.

1. **One calorie** (cal) = the quantity of heat required to raise the temperature of 1 g of water by 1 °C.
   Because the calorie was originally defined as stated earlier, it has been recognized that the energy requirement for raising the temperature of 1 g of water by 1° depends slightly on the temperature, with a variation of about half a percent over the interval from 0° to 100 °C. For work requiring an accuracy no greater than 1%, the above definition is satisfactory. For the most precise work, it has been agreed to define the calorie in terms of electrical units of energy, so that 1 calorie = 4.1840 J. This is very

close to the amount of energy required to raise the temperature of 1 g of water from 16.5 to 17.5 °C.
2. **1 kilocalorie** or **kilogram-calorie** (kcal or kg-cal) = 1000 cal.
3. **1 British thermal unit** (Btu) = the quantity of heat required to raise the temperature of 1 pound of water by 1°F. 1 Btu = 453.6 × 5/9 cal = 252 cal.

2.2 LE SYSTÈME INTERNATIONAL D'UNITÉS

Le Système International d'Unités, which is French for "The International System of Units" or SI units, is a listing of decisions promulgated since 1889 on units of measurement. The General Conference on Weights and Measures (CGPM) meets regularly to update the units. The document was originally written in French, and consequently the name of the system has a French name. CGPM stands for the French *La Conférence Générale de Poids et Mesures*. The goal of the CGPM is "to make recommendations on the establishment of a *practical system of units of measurement* suitable for adoption by all signatories to the Meter Convention" (United States Department of Commerce, 1977, p. 1). Another goal, in my opinion, is to have standard units worldwide, so that anybody reading an article in the world now or in the future will know exactly what the unit is. This allows replication of experiments. It is important that people understand published works even after the death of the authors of these works. I investigated buying a chlorophyll meter, also called an SPAD meter. The acronym stands for "soil plant analysis development" (Loh et al., 2002). I decided against buying the meter, because it does not read out in SI units. It reads out in SPAD units. The units will be used only as long as the meter can be bought. Someone 100 years from now could not replicate or understand experiments with an SPAD meter, unless the meter is used then. Graphs of absorption spectra of chlorophyll *a* and chlorophyll *b* (Steward, 1964, p. 51) can be replicated 100 years from now, because they are expressed in standard units for absorption coefficients and wavelengths.

The tenth CGPM (1954), by its Resolution 6, and the fourteenth CGPM (1971), by its Resolution 3, adopted as base units of this "practical system of units," the units of the following seven quantities: length, mass, time, electric current, thermodynamic temperature, amount of substance, and luminous intensity. The eleventh CGPM (1960), by its Resolution 12, adopted the name *International System of Units*, with the international abbreviation SI, for this practical system of units of measurements and laid down rules for the prefixes and the derived and supplementary units.

SI units are divided into three classes: base units, derived units, and supplementary units (Taylor, 1991, p. 1). The base units and their abbreviations are (United States Department of Commerce, 1977, p. 6; Taylor, 1991, pp. 3–5) (Table 2.1):

- 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)

The derived units are combinations of the base units. Examples of SI derived units expressed in terms of base units are (United States Department of Commerce, 1977, p. 6; Taylor, 1991, p. 6) (Table 2.2):

- 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)

Other derived units with special names are given by the United States Department of Commerce (1977) and Taylor (1991).

The class of supplementary units contains two purely geometrical units: the SI unit of plane angle, the *radian*, and the SI unit of solid angle, the *steradian*. (A radian is an arc of a circle equal in length to the radius or

TABLE 2.1 SI Base Units[1]

	SI Unit	
Quantity	**Name**	**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

[1]*From Taylor (1991, p. 5).*

TABLE 2.2 Example of SI Derived Units Expressed in Terms of Base Units[1]

	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	Reciprocal meter	m^{-1}
Density, mass density	Kilogram per cubic meter	kg/m^3
Specific volume	Cubic meter per kilogram	m^3/kg
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
Luminance	Candela per square meter	cd/m^2

[1]*From Taylor (1991, p. 6).*

the angle at the center of a circle formed by two radii cutting off such an arc, equal to 57.295+ degrees.) Another supplementary unit is the *astronomical unit*. This unit does not have an international symbol; abbreviations used, for example, are AU in English, UA in French, and AE in German. The astronomical unit of distance is "the length of the radius of the unperturbed circular orbit of a body of negligible mass moving round the Sun with a sidereal angular velocity of 0.017 202 098 950 radian per day of 86,400 ephemeris seconds" (United States Department of Commerce, 1977, p. 11). In the system of astronomical constants of the International Astronomical Union, the value adopted is

$$1 \text{ AU} = 149,597.870 \times 10^6 \text{ m}.$$

Notes about units: The appropriate unit should be used for each situation. For example, it would be inappropriate to use astronomical units to report the height of a corn plant, just as it would be inappropriate to use nanometers to report the distance from the earth to the sun. On graphs, sometimes data are reported on an axis as, for example, "$\times 10^3$". This notation is ambiguous, because the reader is not sure whether to multiply the number by 1000 or divide the number by 1000. It is best to use the prefixes to define a unit. The SI prefixes range from a factor of 10^{18} (exa) to 10^{-13} (atto) (United States Department of Commerce, 1977, p. 10). In addition, plant physiological data should not be normalized and given as a ratio. By normalization, we mean dividing values obtained in an experiment (e.g., value for transpiration or photosynthesis) by a common value. Normalization is used to smooth data (make the data less variable). But it should not be done. The ratio cancels out the units. A reader has no way to compare normalized data with values given in the literature, because no units are given. Units always should be given with data, so the data can be understood now and in the future. Normalized numbers with no units should not be confused with dimensionless numbers with no units. Dimensionless numbers, such as the Reynolds number (which we shall define in Chapter 15), are widely used by engineers. Haynes (2013, p. 2—12) lists dimensionless numbers and states that the SI unit for each of them is one.

2.3 EXAMPLE: APPLYING UNITS OF WORK AND PRESSURE TO A ROOT

Let us use our knowledge of the definitions of work and pressure to quantify the work done by a root as it pushes through the soil (Kirkham, 1973). When roots open up the soil, they expend energy. We can obtain a simple mathematical expression for the amount of work a root does as it grows. To make matters easy, let us first assume that, as the root moves along, only its end exerts forces, to push the root through the soil; and let us assume that the end of the root is blunt rather than rounded. By "blunt", let us mean that the end of the root is flat like the end of a solid right circular cylinder. Let us see what happens as we push such a solid cylinder through the soil. As we push the cylinder through the soil with a force, F, the resisting force of the soil will also have the value F, and, if we push the cylinder a distance, d, the work, W, done will be the product of the force and the distance, d:

$$W = Fd. \tag{2.1}$$

We now wish to get Eqn (2.1) in terms of the soil pressure. If we take r to be the radius of the cylinder that we are pushing in the soil, then the soil pressure P (force per unit area) on the end of the cylinder in contact with the soil will be

$$P = F/\left(\pi r^2\right). \tag{2.2}$$

So we divide both sides of Eqn (2.1) by the factor πr^2 and in the result substitute P for $F/(\pi r^2)$ to find that Eqn (2.1) becomes

$$W/\left(\pi r^2\right) = Pd \tag{2.3}$$

which may be written in the form

$$W/\left(\pi r^2 d\right) = P. \tag{2.4}$$

But $\pi r^2 d$ is the volume, say V, of soil displaced. So we may write Eqn (2.4) as

$$W/V = P \tag{2.5}$$

or

$$W = PV. \tag{2.6}$$

Equation (2.6) says that the work done by the root end as it pushes its way through the soil is equal to the product of root pressure and the volume of soil displaced by the root. Equation (2.6) gives us useful information. The equation says that, if the pressure, P, encountered by the roots in a soil of poor structure is twice as great as for a soil in good structure, the roots must do twice as much work to establish the same size root system in the poor soil as in the good soil.

2.4 APPENDIX: BIOGRAPHY OF ISAAC NEWTON

The following biographical material on Newton comes from Tannenbaum and Stillman (1959).

Newton was born on December 25, 1642, in Woolsthorpe, Lincolnshire, England. He was premature, and the midwife thought he would not live the night. He did not have the advantage of a happy, loving family. His father was said to be extravagant and wild, but he had no influence on Isaac, because he died more than two months before Isaac was born. His mother, Hannah, remarried to a Reverend Mr. Smith to avoid a life of poverty. After the marriage, Isaac lived in a separate house with his grandmother, but near his mother's home.

Because Isaac turned out to be a hopeless farmer, his family sent him to Cambridge in 1661. He became engaged to his childhood friend Catherine Storey, but they were never married. After Newton got his undergraduate degree, he wanted to get his master's degree with the support of a teaching assignment, but the rules of the University of Cambridge were strict and no members of the faculty could marry. Isaac and Catherine remained lifelong friends.

During the time of the great plague, Cambridge University was closed (the doors closed on August 8, 1665), and Newton went home and studied the movement of the planets. This is when the famous "apple" story occurred. There he reasoned that the moon does not fly off into space because the earth and the moon attract each other with a force that is directly proportional to the product of their masses. The same law holds the planets in orbit around the sun. Newton returned to Cambridge after the plague and started to study telescopes. His home headquarters at Cambridge served as his laboratory, because scientists did not have laboratories then.

On October 22, 1669, Isaac was appointed Lucasian Professor of Mathematics after his tutor, Dr. Isaac Barrow (1630–1677), stepped down so Newton could have the chair. As a professor he was expected to give lectures, but few students came to Newton's lectures. After his death, many people read his written versions of the lectures.

In 1671, Isaac was asked to build a telescope for the Royal Society, which had been formed in 1645. Members called themselves the "Invisible College" and they met in bars. The group welcomed Isaac's work on the telescope, and on January 11, 1672, Newton was elected to membership in the Royal Society and was invited to present more of his work, which he did. He also presented his theory of light and color, which some members, especially Robert Hooke (1635–1703), criticized because they had their own theories. Shy and studious Newton was deeply hurt by the criticism. He defended his work in several papers, but then gave up, saying he did not want to "become a slave to defend it." He submitted no more papers for publication to the Society. Newton then wrote the *Principia* (*Philosophiae Naturalis Principia Mathematica*; begun in 1684 and first published in 1687), which was an instant success and made him one of the most famous men at Cambridge.

About 1693, he became involved in an argument with Gottfried Wilhelm Leibniz (1646–1716), a philosopher and mathematician, who had independently discovered calculus in Germany. Leibniz's method of writing calculus was eventually the one that was universally accepted.

While the arguments between Leibniz and Newton were raging over who discovered calculus first, Newton's good friend Charles Montague was elected president of the Royal Society. On March 19, 1696, Montague got the king to make Newton Warden of the Mint. People used to chip pieces off of coins for the valuable metal, so coins got smaller and smaller as they circulated. During Newton's tenure, new coins were made and recoinage was complete in 1699. He was promoted to Master of the Mint, a position that provided a good salary that enabled him to help his poorer relatives. He believed that "they who gave away nothing till they died…, never gave". He also gave freely to many worthy causes such as the fund for building a new library at Trinity College, which was designed by Newton's friend Sir Christopher Wren. Newton also contributed money toward the purchase of a permanent building for the Royal Society.

Newton became president of the Royal Society on November 30, 1703, and remained president until his death. On April 16, 1705, Queen Anne knighted him. Of all his nieces and nephews, only one, Catherine, the daughter of his half-sister Hannah, was intellectually related to him.

Newton gave Catherine the best education available to a woman at that time, and she presided over his London home in his later years. To their home she attracted men such as Jonathan Swift (1667–1745) and Alexander Pope (1688–1744). John Dryden (1631–1700) wrote poems about her. Voltaire (1694–1778) also visited their house and was the first to publish the falling apple story. Newton had an excellent library in his study with over 1800 books, each with his bookplate "Philosophimur," meaning "let us seek knowledge." In the quiet of his study, he could pursue the religious studies that were so important to him.

Newton's last years were peaceful. His old enemies, Hooke and Leibniz, had died. Catherine had married, and her husband, John Conduit, took over the management of the Mint. The Conduits and their daughter lived with Newton, and this daughter inherited all of Newton's papers. Her son was the Earl of Portsmouth, and Newton's papers are known as the Portsmouth Collection. Newton developed gout, and, on the way back from a meeting of the Royal Society, became ill, and died on March 20, 1727. The inscription on his tomb reads, "Let Mortals rejoice/ That there has existed such and so great/AN ORNAMENT OF THE HUMAN RACE." Of his own place in history, Newton simply said, "If I have seen farther…, it is by standing on the shoulders of giants."

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