CHAPTER

26

Infrared Thermometers

Plant temperature and water use are related because, if a plant is well watered, the stomata are open, transpirational cooling occurs, and canopy temperature is cool. Conversely, as a plant becomes water stressed, stomata close, transpiration is reduced, and canopy temperature increases. Consequently, one can use canopy temperature to characterize the water status of a crop (Kirkham et al., 1983, 1984, 1985). In the 1970s, portable, commercially available infrared thermometers that measure thermal radiation were developed and refined (Jackson et al., 1980). They provide a means to measure remotely plant canopy temperatures, and measurements with them are easy because the instruments are hand-held and lightweight (Jackson et al., 1977). (Jackson and colleagues at the U.S. Water Conservation Laboratory in Phoenix, Arizona, did pioneering experiments with portable infrared thermometers. For a biography of Jackson, see the Appendix, Section 26.7.) In this chapter, we consider the theory and use of infrared thermometers.

26.1 INFRARED THERMOMETERS

Infrared thermometers have the advantage of measuring many leaves at one time. Before their development, it was difficult to determine the magnitude of the temperature difference either between plants or between plants and air, because there was no way of defining the temperature of a group of leaves. A leaf with the surface normal to incident solar radiation has a higher temperature than a leaf that has a surface parallel to the sun's rays or one that is shaded (Tanner, 1963). Severe sampling problems exist if one can make only a few measurements on individual leaves, such as one does when using thermocouples. The temperature that is measured depends on the location of the thermocouple (for example, base of leaf versus tip of leaf). Tanner (1963) said, "There is no single temperature value that represents the plant and which has been demonstrated to be useful for any given research problem".

Principles of Soil and Plant Water Relations
http://dx.doi.org/10.1016/B978-0-12-420022-7.00026-4

The developments in infrared thermometry have provided instruments that surmount the sampling problem. The thermal radiation from all plant surfaces in the field of view (F.O.V.) of the instrument is integrated into a single measurement. A temperature measurement with an infrared thermometer gives a temperature with a particular definition: the black-body temperature that would produce the radiation entering the instrument from plant parts in the F.O.V. (Tanner, 1963). Because the thermal radiation emissivity of green plants is high (0.95–0.97) (Tanner, 1963), the measured (apparent) radiation temperature can be converted to the plant temperature with little error. Most natural surfaces have high emissivities, ranging between 0.90 and 0.98 (Campbell, 1977; p. 49). Measurements made with infrared thermometers are particularly useful in studies of transpiration (water loss from plants), because the temperature measured with the instrument (radiated from the upper part of the plant) gives weight to the plant portions participating most actively in transpiration (Tanner, 1963).

As we noted in Chapter 25, a good approximation of a black body is a small hole in the wall of a hollow body (Figure 25.6). A beam of radiation that enters the hole and hits the inside wall is partly reflected to another part of the wall, where again a fraction is absorbed and so on. After a number of reflections, little radiant energy is left and the chance that some of it is reflected outward through the hole is exceedingly small. For similar reasons, a dense vegetative cover in which part of the leaves are seen on edge when viewed from above is much darker (i.e., has a lower reflection factor) than the surface of a single leaf (van Wijk and Scholte Ubing, 1966; p. 66).

26.2 DEFINITIONS

In Chapter 25, we defined black body and emissivity. Here we define other terms that are used in association with radiation and in the literature dealing with infrared thermometers. We shall use the definitions provided by van Wijk and Scholte Ubing (1966, pp. 62–63). *Radiant energy* is the energy traveling in the form of electromagnetic waves. It has the dimension of energy so that it is measured in joule, erg, calorie, or an equivalent quantity. The amount of radiant energy emitted, transferred, or received per unit time is called *radiant flux* Φ (Greek letter, capital phi). It has the dimension of energy per unit time. In physical literature, the watt (W) ($1\ \mathrm{W} = 1\ \mathrm{J/s}$) and the erg/s are commonly used as units; in meteorology, the unit cal/min is frequently employed. *Radiant flux density* $H = \mathrm{d}\Phi/\mathrm{d}A$ is the flux per unit of surface; it is expressed as $\mathrm{W/m^2}$, $\mathrm{erg/cm^2/s}$, $\mathrm{cal/cm^2/min}$ (=langley/min) (one langley $= 1\ \mathrm{cal/cm^2}$), or equivalent units. The units of radiant flux density (van Wijk and Scholte Ubing, 1966; p. 63) are the same as those for radiated power per unit area (Shortley and Williams, 1971; p. 324). When it is desired to point out that the radiant flux is directed toward the surface of observation, the term *irradiancy* or *irradiance* is used. If one wants to stress that the radiation is emitted by a source, the radiant flux density is sometimes called *radiancy* or *emittancy*. Emittancy is also called *radiant emittance* (Campbell, 1977; p. 48).

As noted in Chapter 25, the amount of radiant energy contained in thermal radiation depends strongly on the wavelength λ of the radiation that is emitted or received. It is often necessary to consider the energy, intensity, flux, etc. per unit of wavelength interval. Such quantities are called spectral quantities. They will be indicated by the subscript lambda (λ).

26.3 PRINCIPLES OF INFRARED THERMOMETRY

Let us now turn to the basic principles of infrared thermometers. We follow the analysis of Perrier (1971, p. 654). The energy emitted by a body that is not perfectly black is given by Eqn (25.5), $P = \alpha P_{\mathrm{Black}} = \alpha\sigma T^4$. For a perfect black body, $\alpha = 1$ and Eqn (25.5) reduces to Eqn (25.4), the Stefan–Boltzmann law. We apply Eqn (25.5) to the surface temperature, T_s, of leaves. If P is in units of $\mathrm{W/m^2}$, the surface temperature will be in °K, and the Stefan–Boltzmann constant σ will be $5.67 \times 10^{-8}\ \mathrm{W/m^2/K^4}$ (Campbell, 1977; p. 49). The term α (emissivity) is dimensionless. The emissivity, α, is sometimes abbreviated ε, the abbreviation used by Perrier (1971). Surface temperature can be calculated from Eqn (25.5) if surface emissivity is known and the flux of thermal radiation emitted is measured. [Perrier (1971, p. 654) uses the term "emittance," but most publications use the term "emissivity" for ε.]

A radiometer has a sensor that receives energy from the measured surface through the optics of the radiometer, which define the F.O.V. by use of a diaphragm, lens, and sometimes a mirror, and bring localized surface areas into focus. It is necessary to select the waveband of thermal energy emitted by the surface from the total energy received by the sensor and originating at the surface. Therefore, a filter with a sharp bandpass in the infrared region (Table 26.1) is used generally to eliminate the short-wave radiation. The bandpass of 8–14 μm is particularly suitable (Figure 26.1). This selected bandpass includes the peak of black body emission at normal temperature (9–10 μm) so that the maximum energy is measured. Moreover, water does not absorb radiation in this band; thus, the effect of water vapor on the measurement is minimized. But that part of the long-wave radiation emitted by the surroundings and reflected by the surface in this waveband cannot be eliminated directly (Figure 26.2; ϕ_r).

TABLE 26.1 The Electromagnetic Spectrum

Type of Radiation	Frequency Range (cycles/s)	Wavelength Range (cm)
Electric waves	$0-10^4$	Infinity-3×10^6
Radio waves	10^4-10^{11}	$3\times10^6-0.3$
Infrared	$10^{11}-4\times10^{14}$	$0.3-7.6\times10^{-5}$
Visible	$4\times10^{14}-7.5\times10^{14}$	$7.6\times10^{-5}-4\times10^{-5}$
Ultraviolet	$7.5\times10^{14}-3\times10^{18}$	$4\times10^{-5}-10^{-8}$
X-rays	$16\times10^{16}-3\times10^{22}$	$10^{-6}-10^{-12}$
Gamma rays	$3\times10^{18}-3\times10^{21}$	$10^{-8}-10^{-11}$

From Rosenberg (1974), p. 5. This material is used by permission of John Wiley & Sons, Inc.

Theoretically, a simple integration of the relation representing the response of infrared thermometers can be written as follows:

$$A = \varepsilon\sigma T_s^4 + (1-\varepsilon)B \quad \left[A \text{ in units of W/m}^2\right] \tag{26.1}$$

where A is the flux of long-wave radiation from the surface; T_s is the real temperature of the surface (leaves); B is the total incident long-wave (or thermal) radiation in units of W/m^2; $(1-\varepsilon)$ B is the reflected component influencing the thermometer output; ε is the surface emissivity; and σ is the Stefan–Boltzmann constant.

It is supposed that ε is independent of T_s over a narrow range (−15 to 60 °C) and is independent of wavelength over a narrow waveband (8–14 μm). This condition is important only in the second term $(1-\varepsilon)$ B. It

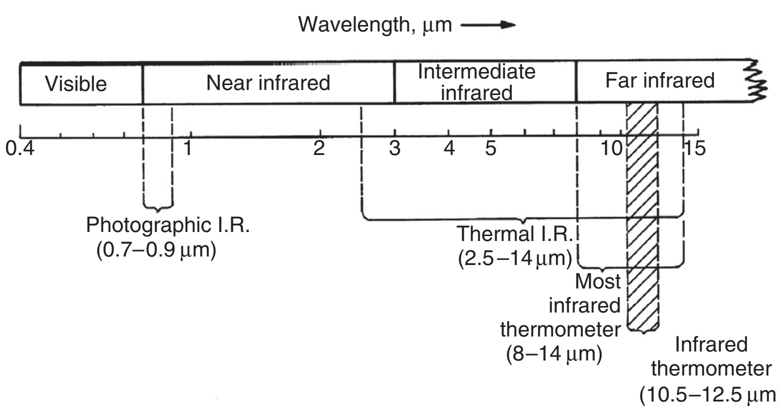

FIGURE 26.1 A portion of the electromagnetic spectrum relating photographic infrared, thermal infrared, and infrared thermometer ranges to the visible and infrared regions. *From Jackson et al. (1980), p. 5.*

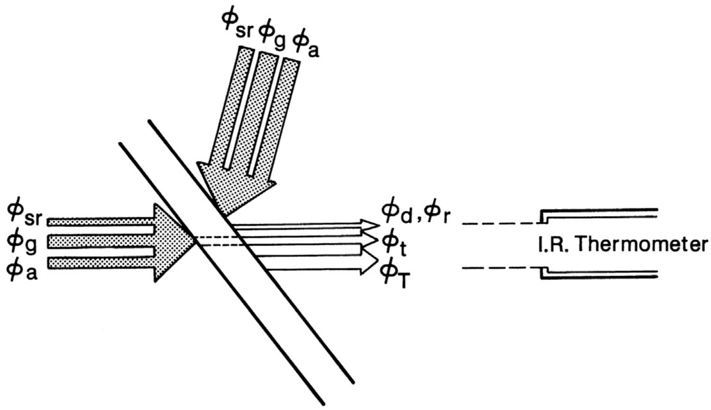

FIGURE 26.2 Scheme of fluxes of energy on a surface like a leaf. ϕ_T: energy emitted by the surface; ϕ_g: part of global radiation received by the surface; ϕ_a: part of long-wave radiation emitted by sky and received by the surface; ϕ_{sr}: radiation from the surroundings received by the surface; ϕ_r: reflected part of all these radiations; ϕ_d: diffused part of all these radiations; ϕ_t: transmitted part. *From Perrier (1971), Figure 17.7(C), p. 656. With kind permission of Kluwer Academic Publishers and Professor Alain Perrier.*

is supposed also that the filter function is practically independent of the temperature T_s (0–40 °C) and the temperature of the filter is constant. As a first approximation, since ε and B are known, by assuming that ε is close to unity (generally, for leaves $0.94 < \varepsilon < 0.98$), the real surface temperature (T_s) can be estimated (T) from the relation

$$A = \sigma T^4. \tag{26.2}$$

In Eqn (26.2) (compare with Eqn (26.1)), the calculated surface temperature (T) will be overestimated because the term containing B is neglected and also underestimated because ε is overestimated. This compensation between the two opposed deviations leads to a small overall error in the calculation of the surface temperature (T). Experience shows that B is most often less than A, and the maximum of B is reached in the evening (more scattering and reflection) or under a cloudy sky. The error generally varies between 0.5 and 1.5 °C.

26.4 USE OF A PORTABLE INFRARED THERMOMETER

Now let us turn to field use of infrared thermometers, following the description of Jackson et al. (1980, p. 52). To obtain representative canopy temperatures, it is desirable to point the infrared thermometer so that a maximum amount of vegetation is viewed by the sensor. This can be accomplished by viewing the target obliquely and at right angles to any structures which might be present in the field. It is best to take readings looking in several directions to minimize effects that the sun's angles (Kimes et al., 1980) (altitude angle; azimuth angle) may have on target temperature. The viewing angle used by Kirkham et al. (1984) was 30°, and they held the thermometer 1.2 m away from the crop (corn). Jackson et al. (1980) take measurements 1−2 h following solar noon, a time when a maximum difference between canopy and air temperature usually occurs. Routine weather observations, such as cloud cover, wind speed, precipitation, target conditions, and wet- and dry-bulb air temperatures, are recorded whenever canopy temperatures are measured. Wet- and dry-bulb air temperatures are essential in determining the Crop Water Stress Index (see Chapter 27). It is best to take measurements on cloud-free days to minimize errors due to reflection and scattering from clouds.

26.5 CALIBRATION OF INFRARED THERMOMETERS

Jackson et al. (1980) found that the readout temperature on most factory-calibrated instruments is not an accurate representation of apparent black-body temperatures. They calibrated all instruments under standardized conditions. Jackson et al. (1980) and Perrier (1971, p. 655) describe the calibration of an infrared thermometer. Let us use Perrier's description.

The unique relationship between the data supplied by the infrared thermometer (A_0) and the flux of long-wave radiation A (Eqn (26.1)) reaching the apparatus from the surface is obtained in the laboratory by measuring A_0 for many different surface temperatures (T) of a reference black body. The temperature (T) gives the flux A (Eqn (26.2)), so that it is possible to draw the curve relating A_0 to A or directly to T. For these measurements, the infrared thermometer is put either close to the surface of a sphere immersed in a temperature-controlled bath (Figure 26.3(A)) (thus obtaining a very good black body at known temperature T) or at the top of a perfectly reflecting cone placed on a reference surface (anodized aluminum) (Figure 26.3(B)), the temperature of which is controlled and varied. Such calibration curves relating A_0 to T are reproducible within a range of 0.3 °C. Some manufacturers provide a black-body plate with a thermometer imbedded in it to perform checks of the calibration. Sadler and van Bavel (1982) and Stigter et al. (1982) also describe calibration of infrared thermometers.

26.6 ADVANTAGES OF INFRARED THERMOMETERS

Infrared thermometers have three advantages. First, they are easy to use. The infrared thermometer is pointed at the canopy and a readout on

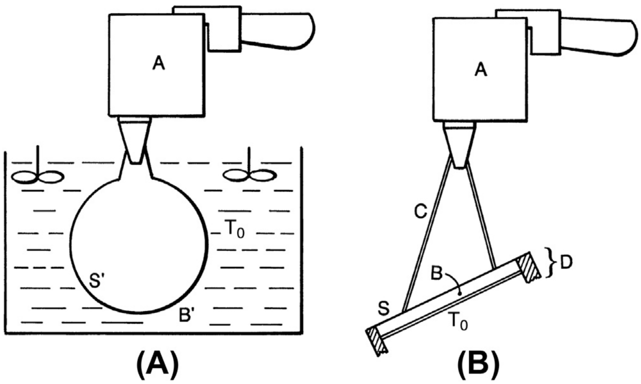

FIGURE 26.3 Schematic diagram of infrared thermometer being calibrated either using (A) a controlled temperature bath, B′, or (B) an aluminum block, B. Other abbreviations: A, radiation thermometer; T_0, controlled temperature; S′, spherical surface (black surface); S, anodized aluminum surface; C, cone (reflecting surface); D, reference surface system. *From Perrier (1971), Figure 17.7(C), p. 656. With kind permission of Kluwer Academic Publishers and Professor Alain Perrier.*

the back of the instrument, facing the viewer, immediately displays the temperature. The instruments can give either the temperature of the canopy or the difference in temperature between the air and the canopy. The latter temperature usually is preferred, because it indicates how stressed a crop is. Canopies with temperatures below ambient temperature are less water stressed than those with temperatures above ambient temperature. (The air temperature can be measured separately with a thermometer.) Infrared thermometers have been used to schedule irrigations of crops such as corn (Clawson and Blad, 1982). In such work it is important to measure the canopy temperature of a well-watered control for a standard, local reference.

A second advantage of infrared thermometers is that they can rapidly measure temperatures remotely and nondestructively. A third advantage is that they can integrate temperatures over an area (the F.O.V.) and thus avoid the sampling problem of single-point measurements made, for example, with thermocouples. Note that thermocouples used to measure leaf temperature touch the leaf directly and measure a different temperature than that determined with an infrared thermometer. The infrared thermometer measures a black-body temperature. Measurements made with thermocouples and infrared thermometers cannot be compared directly.

Canopies must be well developed and covering the soil before data can be collected with commercially available infrared thermometers (Figure 26.4). Measurements cannot be made on individual plants, such as those in pots in controlled environments. Amiro et al. (1983) describe a

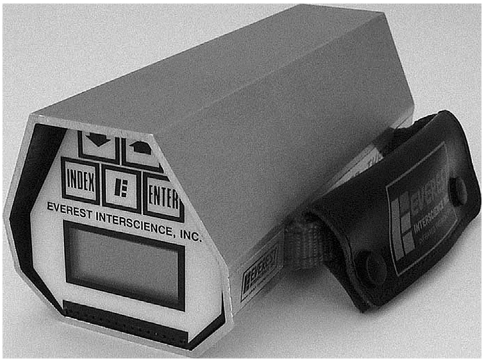

FIGURE 26.4 A commercially available, hand-held infrared thermometer. *From a brochure of Everest Interscience, Tucson, Arizona. Picture courtesy of Everest Interscience.*

small infrared thermometer that can be used on broad or narrow leaves grown under controlled environment or field conditions. A focusing system must be implemented for narrow leaves.

Of all the instruments available to measure water in plants (thermocouple psychrometers, pressure chambers, diffusion porometers, infrared thermometers), the infrared thermometer might have the most immediate, practical value. It provides an easy way to measure canopy temperature and to schedule irrigations. An elevated canopy temperature indicates water stress and a need for irrigation. Baker et al. (2007) found that canopy temperature minus air temperature provided a good predictor of the degree of drought stress in cotton and could be used to schedule irrigations. Producers might use the infrared thermometer on crops to detect water stress before damage occurs. This would be particularly important on high-value crops, such as those grown by horticulturists. Canopy temperature measurements can be made at different locations in a field to identify stressed areas. Consequently, infrared thermometers are valuable as a means to determine remotely spatial variability due to drought or any other stress that reduces the transpiration rate.

26.7 APPENDIX: BIOGRAPHY OF RAY JACKSON

Ray Dean Jackson, a soil physicist at the U.S. Water Conservation Laboratory (retired), was born in Shoshone, Idaho, on September 28, 1929. He married in 1952 and 1968 and has seven children (American Men and Women of Science, 1994). He served in the U.S. Marine Corps before receiving his B.S. degree at Utah State University in 1956. He earned an M.S. in soil physics from Iowa State University in 1957, and a PhD from Colorado State University in 1960. From 1957 to 1960 he was a soil scientist with the Soil and Water Conservation Research Division, Agriculture Research Service (ARS) of the United States Department of Agriculture (USDA), in Colorado. In 1960, he joined the U.S. Water Conservation Laboratory of the USDA in Phoenix, Arizona, as a research physicist, where he worked until retirement in 1992. He was research leader and the technical advisor for soil–plant–atmosphere relations for the Western Region of the ARS. He was an adjunct professor of soil and water science at the University of Arizona, Tucson. In the summer of 1964 he was an Organization for Economic Cooperation and Development (OECD) fellow at Rothamsted Experimental Station, England.

Jackson published on subjects relating to diffusion in porous media, soil–water evaporation, soil–water movement, heat transfer, simultaneous heat and water transfer, atmospheric radiation, and infrared thermometry. He was perhaps the first researcher to publish measured soil–water diffusivity data for the relatively dry water contents of the western United States, a region where water vapor diffusion predominates, and he showed that diffusion theory held at these low water contents. This work formed the basis for the development of the "desert survival still" developed by Jackson and van Bavel (1965). They demonstrated that a transparent plastic sheet covering a hole in the soil could be used to collect potable water from desert soils and plants. This technique is taught in survival courses worldwide (American Society of Agronomy, 1975).

Jackson received the Superior Service Unit Award from the USDA in 1963. He is a fellow of the American Society of Agronomy, Soil Science Society of America, and the American Association for the Advancement of Science (American Men and Women of Science, 1994). In 1992, he won the Outstanding Scientist of the Year Award from the USDA-ARS. The award recognized his leadership skills and his research, which resulted in the commercialization of hand-held infrared thermometers to measure remotely plant leaf temperatures for determination of a crop's water needs (American Society of Agronomy, 1992).

References

American Men and Women of Science, 1994. Nineteenth ed., vol. 4. J–L. R.R. Bowker, New Providence, New Jersey.

American Society of Agronomy, Jackson, Ray D., 1975. Agron. J. 67, 103.

American Society of Agronomy, 1992. People. USDA-ARS. Agronomy News December issue, 10.

Amiro, B.D., Thurtell, G.W., Gillespie, T.J., 1983. A small infrared thermometer for measuring leaf temperature in leaf chambers. J. Exp. Bot. 34, 1569–1576.

Baker, J.T., Gitz, D.C., Payton, P., Wanjura, D.F., Upchurch, D.R., 2007. Using leaf gas exchange to quantify drought in cotton irrigated based on canopy temperature measurements. Agron. J. 99, 637–644.

Campbell, G.S., 1977. An Introduction to Environmental Biophysics. Springer-Verlag, New York.

Clawson, K.L., Blad, B.L., 1982. Infrared thermometry for scheduling irrigation of corn. Agron. J. 74, 311–316.

Jackson, R.D., van Bavel, C.H.M., 1965. Solar distillation of water from soil and plant materials: simple desert survival technique. Science 149, 1377–1379.

Jackson, R.D., Reginato, R.J., Idso, S.B., 1977. Wheat canopy temperature: a practical tool for evaluating water requirements. Water Resour. Res. 13, 651–656.

Jackson, R.D., Pinter Jr, P.J., Reginato, R.J., Idso, S.B., 1980. Hand-held Radiometry. Agr Rev Manuals ARM-W-19. United States Department of Agriculture, Science and Education Administration, Western Region, Oakland, California.

Kimes, D.S., Idso, S.B., Pinter Jr, P.J., Reginato, R.J., Jackson, R.D., 1980. View angle effects in the radiometric measurement of plant canopy temperatures. Remote Sens. Environ. 10, 273–284.

Kirkham, M.B., Johnson, D.E., Kanemasu, E.T., Stone, L.R., 1983. Canopy temperature and growth of differentially irrigated alfalfa. Agr. Meteorol. 29, 235–246.

Kirkham, M.B., Suksayretrup, K., Wassom, C.E., Kanemasu, E.T., 1984. Canopy temperature of drought-resistant and drought-sensitive genotypes of maize. Maydica 29, 287–303.

Kirkham, M.B., Redelfs, M.S., Stone, L.R., Kanemasu, E.T., 1985. Comparison of water status and evapotranspiration of six row crops. Field Crops Res. 10, 257–268.

Perrier, A., 1971. Leaf temperature measurement. In: Šesták, Z., Čatský, J., Jarvis, P.G. (Eds.), Plant Photosynthetic Production. Manual of Methods. Dr W. Junk N.V, The Hague, The Netherlands, pp. 632–671.

Rosenberg, N.J., 1974. Microclimate: The Biological Environment. John Wiley and Sons, New York.

Sadler, E.J., van Bavel, C.H.M., 1982. A simple method to calibrate an infrared thermometer. Agron. J. 74, 1096–1098.

Shortley, G., Williams, D., 1971. Elements of Physics, fifth ed. Prentice-Hall, Englewood Cliffs, New Jersey.

Stigter, C.J., Jiwaji, N.T., Makonda, M.M., 1982. A calibration plate to determine performance of infrared thermometers in field use. Agr. Meteorol. 26, 279–283.

Tanner, C.B., 1963. Plant temperatures. Agron. J. 55, 210–211.

van Wijk, W.R., Scholte Ubing, D.W., 1966. Radiation. In: van Wijk, W.R. (Ed.), Physics of Plant Environment, second ed. North-Holland, Amsterdam, The Netherlands, pp. 62–101.