Thermal Infrared
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I. Introduction
   a. Estimator of plant transpiration
   b. Indicator of plant water stress
   c. Easy to collect, log and non-destructive
   d. Equipment moderately expensive, durable, accurate
II. Thermal Infrared Basics
   a. Emitted radiation, wavelength/radiance relationships, emissivity
III. Thermal Infrared Sensor Performance & Characteristics
   a. Thermocouple, thermopile, microbolometers, thermistors
   b. Infrared Thermometer (IRT) Models available: Apogee, Everest, Fluke, etc. costs, accuracy, precision
   c. Wavelength sensitivity, atmospheric window
   d. Time scales, accuracy, uncertainty: time of day, measurement frequency, weather (clouds, wind, humidity)
   e. View angle, plant vs. soil temperatures
   f. Logging: microvolt sensitivity, time, location
   g. Ancillary data: air temperature, humidity , windspeed,
IV. Data analysis
   a. Atmospheric correction
   b. Maximizing signal: Plot averaging, reference temperature checks, temperature differencing to remove bias, diurnal correction
   c. Extensions: compute stress index, ET estimate
V. Conclusions
   a. Stress response detection with thermal sensors
   b. Durable, accurate, modest cost
   c. Select high quality sensors with known calibration
   d. Select 8-14 mum sensor window
   e. Select field-of-view to match platform needs and signal/noise
   f. Sensor response time < 1 s
   g. Sensor logger requirements
   h. Apply sky radiation correction
   i. Consider temperature and time-temperature differencing to reduce errors
   j. Collect reference temperatures at beginning and end of survey
   k. Minimize data collection period
   l. Watch the weather for uneven cloudiness and air temperature
   m. For variety evaluation use best estimate of plant temperature as first step, then can consider CWSI, ET estimates afterwards

References

www.apogeeinstruments.com/infraredradiometer
www.everestinterscience.com
Agaus, J.L, and Cairns, J.E. 2014. Field high-throughput phenotyping: the new crop breeding frontier, *Trends in Plant Science* 19(1): 52-61.
Fuchs, M. and Tanner, C.B. Infrared Thermometry of Vegetation, 1966. *Agronomy J.* 58:597-601.

Table 1. Characteristics of example thermal infrared sensors.

Manufacturer	Apogee Instruments	Everest Interscience	Omega
Sensor Name	Infrared radiometer	Enviro-Therm	Infrared thermocouple
Approximate Cost (USD)	700-800		300
Part Number	SI-xxx; 12 variations		OS36/80F
Web Site	www.apogeeinstruments.com	www.everestinterscience.com	www.omega.com
Temperature range	-30 to 60 °C		10 to 49 °C
Accuracy	0.2 °C	0.25 °C	0.8 c
Response time	0.2 s		0.08 s
Field-of-View	22°-44° circular; 64°x26° rectangular		60 °
Output	20-60 μV/°C; analog or digital	Digital, digital to analog (DAC)	
Power supply	2.5 V		None
Sensor type	Thermopile/thermistor		Thermocouple (type K or T typical, also J, E)
Spectral range	8-14 μm		6.5-14 μm
Logging	mV datalogger or SDI-12		mV datalogger
Cabling	5 m shielded twisted pair, 6 leads		2.4 m PFA coated, 3 leads
Dimensions	2.3 cm diameter, 6.0 cm length	5cm length?	1.27 cm diameter, 4.45 cm length
Housing shape	Cylindrical	Cylindrical	
Weight (g)	190 g with cable		15 g (sensor only)
Operating environment	-55 to 80 °C; 0-100% RH non-condensing		-18-85 °C
Comments	Selection by field-of-view, signal output type (analog or digital)		Short response time, no power needed, wide

	Check for dust		field of view, narrow calibration range, need stable cold junction