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Applications of Thermal Imaging in Agriculture – A Review

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Abstract.

In thermal imaging, the invisible radiation pattern of an object is converted into a visible image. This two-dimensional temperature mapping technique has potential for characterizing products during several operations of agricultural and food industries. Thermal imaging has been successfully adopted for studying plant physiology, irrigation scheduling, and yield forecasting in agricultural fields. Likewise maturity evaluation, detection of bruises in fruits and vegetables, detection of spoilage in agricultural produces by microbial activities, and detection of foreign materials are the potential post-harvest operations to use thermal imaging. This paper presents the fundamentals of infrared thermal imaging and a review of applications of thermal imaging in pre-harvest and post-harvest operations of agriculture.

Keywords: Thermal imaging, pre-harvest operations, farm machinery, post-harvest operations

INTRODUCTION

Temperature measurement is an important phenomenon in almost all industrial and agricultural sectors. Several instruments and methods have been developed to measure the temperature of objects. Temperature measurements in the agricultural and food industries have mostly relied on conventional contact methods such as thermocouples, thermometers, and thermistors, which provide limited information (Nott and Hall 1999). Non-contact methods and temperature mapping techniques are becoming popular due to higher temporal and spatial resolutions. Several techniques such as x-ray tomography, infrared thermography, electrical impedance tomography, ultrasound imaging, microwave radiometry, and magnetic resonance imaging (MRI) are available to map the temperatures of biological materials (Nott and Hall 1999; Sun et al. 1993,1994; Kantt et al. 1997,1998; Hulbert et al. 1995). However, infrared thermal imaging has great potential for both pre-harvest and post-harvest operations in agriculture due to the portability of the equipment and simple operational procedure. This paper describes the fundamentals of the infrared thermal imaging method and a review of its applications in agriculture.

The region in the infrared band with wavelengths from 3 to 14 μm is called the thermal infrared region. This band is useful in imaging applications that use heat signatures (Gonzalez and Woods 2002). Thermal imaging is a non-contact technique to convert the radiation pattern of an object into a visible image called a thermogram or thermal image (Agerskans 1975). By this method, the surface temperature of any object can be mapped at a high resolution. Thermal imaging is a passive technique which does not require any external source of illumination. Another advantage of this technique is the penetration capacity of thermal radiation through smoke and mist (Davis and Lettington 1988). However, many factors such as sun, wind, fog, and rain affect the performance of the thermal imaging method while measuring the temperature of outdoor objects (Davis and Lettington 1988).

FUNDAMENTALS OF THERMAL IMAGING

Infrared radiation was discovered by an astronomer, Sir William Herschel, in 1800 (Anonymous 2002). He measured the temperature of different colors in sunlight to determine the color which was responsible for heating. Herschel discovered that the hottest temperature existed beyond the red region and it was not visible. He named this radiation as “calorific rays” and it is now known as infrared radiation. Many characteristics of infrared radiation are similar to visible light. For instance, infrared radiation can be focused, refracted, reflected, and transmitted. All objects with a temperature greater than absolute zero (–273°C) emit infrared radiation (Anonymous 2002). The emissivity, absorptivity, transmissivity, and reflectivity of infrared radiation vary for different materials. In general, the objects which are good absorbers of infrared radiation are also good emitters. Examples of materials that have good and poor infrared radiation properties are shown in Table 1.

Table 1. Materials with good and poor infrared radiation properties.

Property	Good	Poor
Transmissivity	Sodium chloride, germanium, zinc selenide, diamond	Biological materials
Reflectivity	Clean metals, aluminum foil	Paper, rubber
Emissivity/ Absorptivity	Black electric tape, water, paper, rubber, non-metalic flat paints	Clean metals, aluminum foil

Source: Anonymous (2002)

The relationship between absorptivity (α), reflectivity (ρ), and transmissivity (τ) of an object is expressed by Kirchhoff's law as:

$$\alpha + \rho + \tau = 1 \qquad (1)$$

At thermal equilibrium of an object, the absorption is equal to emission. In many thermographic applications, the law can further be simplified for opaque objects ($\tau = 0$) as:

$$\alpha + \rho = 1 \qquad (2)$$

or

$$\epsilon + \rho = 1 \qquad (3)$$

where ϵ is emissivity.

The infrared sensors in a thermal camera receive the total infrared radiation emitted from the surface of objects. According to Stefan-Boltzmann law (Eqn 4), the total amount of radiation emitted by an object per unit area is directly related to the emissivity of the object and its temperature:

$$E = \sigma \epsilon T^4 \qquad (4)$$

where:

E = total amount of radiation emitted by an object per square meter ($W\ m^{-2}$)
σ = Stefan-Boltzman constant = 5.67×10^{-8} ($W\ m^{-2}\ K^{-4}$)
ϵ = emissivity of the object, decimal
T = temperature of the object (K)

Therefore, if the total radiation emitted and the emissivity of a material are known, it's temperature can be calculated. For quantitative temperature measurement, the emissivity of the objects must be known but for qualitative differentiation, the emissivity may be neglected (Hellebrand et al. 2002).

Infrared detectors in a thermal camera sense the radiation emitted from the surface of the object in the spectral range of 3-5 µm (short wave) or 8-12 µm (long wave). These two wavelength regions are selected for infrared radiation measurement as these wave bands have good transmission in the atmosphere (Anonymous 2002). Broadband cameras (sensitive to 3-12 µm) and dual-wave band (long and short wave) cameras with two types of detectors are also available in the market.

APPLICATIONS

An infrared thermal imaging system provides the surface temperature of any object and these data may be used directly or indirectly for many applications. However, this method is suitable for making quality determination of surface temperature than quantitative measurement (Davis and Lettington 1988). This technique has been used in various fields such as medicine, electrical, mechanical, and civil engineering for a long time (Agerskans 1975). The reductions in cost of the equipment and simple operational procedure have created opportunities for the application in several fields of the agricultural and food industries. This technology can be used in all agricultural materials and processes, where heat is generated or lost in space and time (Hellebrand et al. 2002). Small variations (below 1°C) can also be successfully measured with proper equipment and methodology. If the temperature difference is too small, a suitable environment should be created such as increasing or decreasing the temperature of the sample and measuring the rate of cooling or heating (Danno et al. 1980).

Pre-harvest Operations

Plant leaves possess a complex heterogeneous internal structure and because of this different parts of the leaf contain different amounts of water per unit area, affecting thermal properties. The important parameters in plant physiology such as transpiration rate, heat capacity per unit area of the leaf, and the water flow velocity can be measured to high temporal and spatial resolution by thermal imaging techniques (Christoph et al. 2002). Identification of diseases in the field nursery before visible symptoms occur, irrigation scheduling based on soil moisture content and plant parameters, detection of fruits and vegetables on the plants to guide mechanical harvesting, and yield forecasting are the potential areas in which thermal imaging methods may be utilized effectively in the agricultural fields.

Field nursery Local microclimatic changes in the field nursery will cause severe damage to the tender seedlings. Early detection of dampness and disease in a nursery is very important to take early control measures. The microclimatic changes inside the nursery site can be mapped with great spatial accuracy using infrared thermography. In a field nursery, significant positive correlation was found between seedling temperature and degree of damage (Hellebrand et al. 2002). The warmest seedlings had a lower survival rate than the cooler seedlings (Egnell and Orlander 1993). Kim and Lee (2004) developed algorithms to detect the quality of potato transplants using visual and thermal imaging. Potato transplants were grown at three photosynthetic photon flux (PPF) levels of 50, 150, 250 μmol.m^{2}s^{-1} and four electrical conductivity levels of 700, 1400, 2100, 2800 μs.cm^{-1}. The leaf temperature was higher (by about 0.5 to 2.0^{o}C) for the transplants grown at PPF of 50 μmol.m^{2}s^{-1} than the other two treatments. The authors stated that thermal and visual characteristics of potato transplants can be used to monitor the transplants' grown at low PPF.

Irrigation scheduling Infrared thermometry may be used to schedule irrigation based on soil moisture content and plant parameters such as evapo-transpiration, stomatal conductance, and closing of stomata (Jones 1999). Inoue et al. (1990) determined the transpiration and stomatal conductance using infrared thermometry. Temperature of the canopy was taken with the help of a handheld infrared thermal camera in a cotton field. Transpiration rate and stomatal conductance were calculated using canopy temperature and other meteorological data in a model. A porometer was used to measure transpiration and stomatal conductance in the field simultaneously. Crop stress indices calculated by remote infrared thermometry were linearly related with porormeter values and R^2 of 0.79 and 0.93 for transpiration and stomatal resistance, respectively. Berliner et al. (1984) determined the crop stress for wheat using infrared thermometry. A thermal camera was installed on a platform located on the top of a pole (3.3 m height) in the field. In addition to canopy temperature, wet and dry bulb temperatures, wind speed, and solar radiation were also recorded simultaneously. Stomatal resistance and water potential had a linear relationship with canopy temperature and the R^2 were 0.64 and 0.65, respectively. For the implementation of canopy temperature as a water stress index, no meteorological data other than infrared measurement is required. Landsat thermal bands could be used to study the irrigation status of the field and different stages of growth of crops (Perdikou et al. 2002). Kalma and Jupp (1990) used infrared thermometry data to develop a model for estimating the evaporation from a pasture. All metabolic activities of a plant cause variation in temperature and hence, research on the quantification of changes in temperature on the canopy with respect to various plant parameters would yield valuable information required for precision farming.

Yield forecasting Time series data models are the commonly used methods to estimate yield for many crops in almost all parts of the world. But most of the time, high deviation is observed in the actual yield from the forecasted yield. Smith et al. (1985) analyzed the relationship between wheat yield and one-time measurement (daytime) of temperature difference between foliage and ambient air temperature (T_f-T_a). For foliage temperature measurement, they used a thermal camera (3^o field of view lens) which received the infrared radiation in the spectral wavelength of 8-14 μm. The camera was held at 1.5 m height in the field and focused on the foliage at 30^o. In addition to ambient and foliage temperatures, associated micrometeorological data were collected during the wheat growing stages from jointing to maturity. The experiment was conducted for two crop seasons (1982 and 1983) on a red-brown soil in Australia. Transpiration and the associated aerodynamic characteristics and canopy stomatal resistances to water vapor transport were predicted from the collected temperature data. They determined that the predicted transpiration and CO_2 assimilation rates were closely related to yield within each year but not between years. The regression coefficients for T_f-T_a and various yield parameters are shown in Table 2. It was stated that infrared thermometry would be a useful technique for studying yield variations in agronomic experiments.

Table 2. Relationship between yield parameters of wheat and mean T_f-T_a for years 1982 and 1983.

Period	yield parameter	R^2	
		1982	1983
Jointing to maturity	Grain yield	0.94	0.87
Jointing to anthesis + 7 days	Kernel numbers	0.88	0.75
Grain filling	Kernel weight	0.57	0.40

Source: Smith et al. (1985)

In Europe around 20% deviations were observed in the harvested yield of apple from the forecasted yield using a time series data model during the 2000 crop season (Stajnko et al. 2004). An algorithm with thermal imaging was developed by Stajnko et al. (2004) to count the number and measure the diameter of fruits in an apple orchard. Thermal images of the apple trees were taken five times during the vegetation period. Each time around 120 images of 20 apple trees were taken from both the sunny and shadowy side of the tree from a distance of 2 m. The acquired images were processed to obtain the number and diameter of fruits. At the same time, on each imaged tree, all fruits were manually counted and diameters of the fruits were measured with sliding calipers. The R^2 values between thermal imaging and manual methods were in the range of 0.83 to 0.88 in fruit number and 0.68 to 0.70 in fruit diameter measurement. The R^2 value increased during the ripening period for both number and diameter of the fruits. It was suggested that thermal imaging techniques may be employed to provide an objective and easy counting of apples and measurement of their diameters required in calculating the apple yield. Since the accuracy of yield forecasting by thermometry is very promising, this technique may be used as a complementary method to other methods.

Harvesting Mechanical harvesting requires precise determination of the location of fruits on trees. Xu and Ying (2003) suggested infrared thermal imaging to identify citrus fruits in a tree canopy. Around 1^{o}C difference was observed between the temperature distribution of citrus, leaves, and branches. It was stated that infrared thermal imaging would be the easiest and most accurate method in locating the citrus for mechanical harvesting as opposed to other machine-vision methods.

Green houses The environmental conditions inside a greenhouse chamber should be maintained carefully because the small plants and seedlings are sensitive to small changes in the microclimate. Thermography is a useful tool to detect temperature anomalies at various locations inside the greenhouse. Ljungberg and Jonsson (2002) conducted an infrared survey to investigate the temperature profile at various locations inside a greenhouse such as surface of the tables used for plant production, radiation tubes, and plants at different stages of growth. The survey was conducted in greenhouses under conditions, production benches without plants and with plants. A thermal camera (wavelength 8-12 µm), mounted on a two wheeled cart was used for the survey. In the greenhouse with plants, the difference between maximum and minimum temperatures on the production benches was 4.3^{o}C, whereas it was 11^{o}C in the greenhouse without plants. The difference was more than 100^{o}C on the radiation pipes in the greenhouse with plants and only 6.5^{o}C in the greenhouse without plants. The authors suggested that thermography can be used as a tool to calibrate heating systems, evaluate its function, and to indicate anomalies in the growth process of plants inside a greenhouse. Infrared thermography may be used as an effective tool in research and evaluation of the growth process of plants at different energy related greenhouse conditions.

Termite attack In tropical countries termites are the major problems for coconut and other trees. Failure to timely detect termites and not taking a preventive measure often leads to the death of the perennial trees. Termites are also a serious problem in farm buildings and in all wooden structures in domestic buildings. In Australia, the estimated economic loss in buildings by termites is around $70 million (James and Rice 2002). Thermal imaging can be used as a non-destructive and fast method to detect termites in trees and buildings, compared to the traditional methods such as knocking and drilling in wood (James and Rice 2002).

Farm machinery Unexpected failure of farm equipment during peak operational season can result in severe economic losses. All mechanical and electrical equipment can be inspected by a thermal camera for wear and tear. By this method, it is possible to identify the excessive heat produced by components due to friction or any other reason. For instance, hay making equipment, planters, combines, tractors, and other mechanical equipment may be inspected by infrared thermography and proactive steps can be taken to change parts before they fail or cause an interruption in production (Hellebrand et al. 2002). Utter (2003) demonstrated the use of infrared thermography to identify the backfiring and oil leakage in agricultural aircraft.

In many developing countries, millions of people are involved in agricultural field operations. To maximize work efficiency and field safety, ergonomic factors are being considered in the design of farm machinery and work environment. Thermography would be an excellent choice to map the body temperature of workers during field work.

Post-harvest Operations

Maturity evaluation Maturity evaluation of fruits and vegetables is a crucial operation in both pre-harvest and post-harvest stages. Even though several automatic methods are available for this purpose, visual inspection is followed in many parts of the world. This manual method of maturity evaluation is a time consuming process and human fatigue frequently influences the results (Danno et al. 1980). The maturity of tomato, Japanese pear, and Japanese persimmon were evaluated using infrared thermometry by Danno et al. (1980). Fruits and vegetables were divided into three grades of maturity such as, immature, mature, and over-ripe based on color, firmness, and sugar content. Since the difference in surface temperatures of fruits and vegetables at different stages of maturity was small at a steady state (before treatment), the produces were kept at high (30^{o}C) and low (5^{o}C) temperatures in constant temperature rooms for more than 24 h before temperature measurement. The surface temperature of fruits and vegetables was different in three grades of maturity and the difference was in the range of 0.5 to 1.0^{o}C. The surface temperature of immature fruits stored at lower temperature was slightly higher than that of mature and over-ripe fruits. Whereas, the surface temperature of immature fruits stored at higher temperature was slightly lower than that of mature and over-ripe fruits.

Bruise detection Bruises and scratches are the most common damage on the surface of fruits and vegetables during transportation and handling. Danno et al. (1978) determined the effect of surface defects on temperature distribution for apple, Satsuma mandarin, and natsudaidai (similar to grape) fruits. Artificial bruises were made on the fruits by pressing and scratching. The bruised fruits were kept at high (30^{o}C) and low (10^{o}C) temperatures in temperature-regulated rooms for more than 24 h. Then the fruits were imaged with a thermal camera (wavelength 8-14 μm). In all fruits, the temperature at the bruises was slightly lower than that of unbruised skin. A temperature difference of 0.2 to 1.0^{o}C was measured between sound and bruised skin.

While detecting the bruises in apple manually, the dark-colored skin easily confuses and misleads human vision (Varith et al. 2003). The capability of the thermal imaging method to detect bruises in apple was determined by Varith et al. (2003). Red delicious, Fuji, and Macintosh varieties were bruised by dropping them from 0.46 m onto a smooth concrete floor. After creating bruises, the apples were kept at 26°C and 50% relative humidity for 48 h for the development of bruises. Then the apples were refrigerated at 3°C for at least 3 h. Apples were subjected to two heating and one cooling treatments (Treatment A- heating with forced convection in ambient air at 50% relative humidity, 26°C; Treatment B- heating with forced convection in the same air heated to 37°C; Treatment C- cooling with forced convection in ambient air at 50% relative humidity, 26°C after heating in 40°C water for 2 to 3 min). After treatments the apples were thermally imaged for 3 min using a thermal camera with 3.4 to 5 µm spectral bands. It was determined that at steady state (before treatment) thermal imaging could not detect the bruises in apple. But after treatment the bruised tissue showed at least 1 to 2°C difference from sound tissue within 30 to 180 s after treatment. The authors stated that the temperature difference between sound and bruised tissue was possibly due to the differences in thermal diffusivity and not due to the emissivity. The correctly identified bruises by thermal imaging method in different treatments are shown in Table 3. Vanlinden et al. (2003) used thermal imaging method to detect bruises in tomato. Artificially bruised tomatoes were heated in microwave oven for 14 s and then thermally imaged. The temperature difference between the intact and bruised parts was in the range of 0.5 to1.0°C.

Table 3. Correctly identified bruises in apple by thermal imaging after heating and cooling treatments (n=15).

Variety	Treatment*	Successful bruise detection (%)
Fuji	A	100.0
	B	86.7
	C	86.7
Macintosh	A	100.0
	B	100.0
	C	86.7
Red Delicious	A	66.6
	B	40.0
	C	60.0

* A- heating with forced convection in ambient air (26°C and 50% relative humidity)
B- heating with forced convection in the heated air (37°C)
C- cooling with forced convection in ambient air (26°C and 50% relative humidity), after heating in 40°C water for 2– 3 min

Source: Varith et al. (2003)

Detection of foreign substances in food The thermo graphic technique may be used as a supplementary method to detect foreign materials, which could not be separated by mechanical and optical methods. Meinlschmidt and Margner (2003) developed a thermal imaging system to detect foreign materials (rotten nuts, hard shells, and stones) in hazelnuts (Fig. 1). Algorithms were developed for pulse and online thermography using three image processing techniques namely histogram analysis, texture analysis, and an object-oriented method. The quality of detection was related to the physical behavior of the food and the foreign body, their form, and the noise of the images.

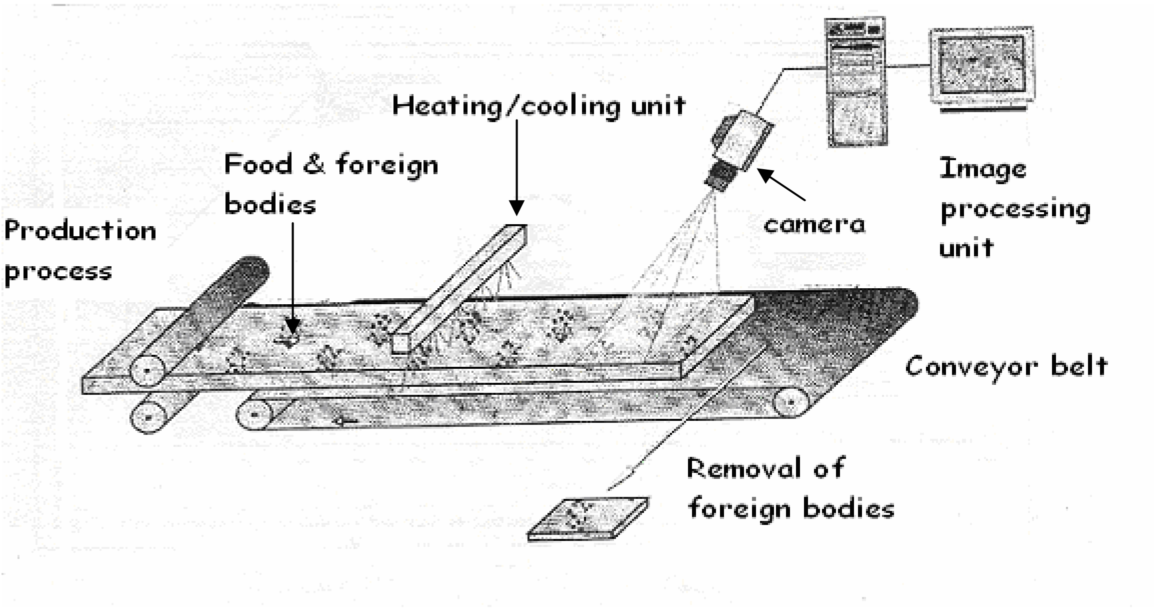

Fig.1. Online thermography apparatus for detecting foreign bodies in a moving food stream (Meinlschmidt and Margner 2003).

Wood Drying Thermal imaging has potential to evaluate the heating pattern in various heating methods. For instance, it is possible to make continuous measurement of the uniformity of heating by microwaves. Antti and Perre (1999) evaluated a microwave applicator used for online wood drying. Thermal camera and CT-scan were used to map the surface temperatures and moisture distribution, respectively, in wood during the drying operation. Dry and wet specimens of birch, pine-heartwood, and pine-sapwood were used in this experiment. Before drying, the moisture content was 6 and 50% for dry and wet birch, 6 and 29% for dry and wet pine-heartwood, and 6 and 19% for dry and wet pine-sapwood. The initial temperature was 22°C for the dry specimen and between 5 and 12°C for the wet specimens in all types of wood. The temperature gradient at the surface of wood in dry specimens was 6°C after 1 min heating and reached 25°C after 7 min whereas the temperature gradient in the surface of wet specimens was 13 and 30°C after 1 and 7 min of heating, respectively. The authors stated that accurate determination of microwave power consumed for drying may be possible with the help of measured temperature using an infrared camera.

Other applications The damage to fruits and vegetables due to microbial activities may be evaluated by thermography (Hellebrand et al. 2002). The quality and palatability of beef are directly related to the stress level of animals and hence, it is necessary to separate highly stressed animals in the slaughter house. Infrared imaging can be used to segregate stressed animals before being slaughtered (Wurzbach 2003).

CONCLUSIONS

The thermal imaging method has potential to be used in many pre-harvest and post-harvest operations of agriculture. However, the opportunities are still in the experimental stage. Intensive research should be conducted for the real-time applications to increase the productivity and ultimately the net profit to farmers. Plant, soil, and water relationship by thermal imaging has been studied in detail by several researchers and the outcome of this kind of research would yield valuable data required for the site specific management and precision farming. Similarly in post harvest operations, thermal imaging methods can be used for classification of agricultural produce based on certain criteria which would otherwise not be detected by visual methods. Unlike other methods, with thermal imaging it may not be possible to develop universal methodologies for agricultural operations because the thermal behavior of plants and agricultural produces vary with climatic conditions. It may be required to develop different protocols for similar operations under different growing regions.

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REFERENCES

Agerskans, J. 1975. Thermal imaging-A technical review. In *Proceedings of Temperature Measurement*, 375-388. London. April 9-11.

Anonymous. 2002. Infrared training: Level 1 course manual. North Billerica, MA: Infrared Training Centre.

Antti, A.L. and P. Perre. 1999. A microwave applicator for on line wood drying: Temperature and moisture distribution in wood. *Wood Science and Technology* 33:123-138.

Berliner, P., D.M. Oosterhuis and G.C. Green. 1984. Evaluation of the infrared thermometer as a crop stress detector. *Agricultural and Forest Meteorology* 31:219-230.

Christoph, S.G., U. Schurr and B. Jahne. 2002. Thermographic measurements on plant leaves. In *Proceedings of Thermosense XXIV*, 407-416. Bellingham, WA: SPIE.

Danno, A., M. Miyazato and E. Ishiguro. 1978. Quality evaluation of agricultural products by infrared imaging method: Grading of fruits for bruise and other surface defects. *Memoirs of the Faculty of Agriculture*, Kagoshima University 14:123-138.

Danno, A., M. Miyazato and E. Ishiguro. 1980. Quality evaluation of agricultural products by infrared imaging method: Maturity evaluation of fruits and vegetables. *Memoirs of the Faculty of Agriculture*, Kagoshima University 16:157-164.

Davis, A.P. and A.H. Lettington. 1988. Principles of thermal imaging. In *Applications of Thermal Imaging,* ed. S.G. Burnay, T.L. Williams and C.H. Jones, 1-34. Bristol: IOP Publishing Ltd.

Egnell, G. and G. Orlander. 1993. Using infrared thermography to access viability of *Pinus sylvestris* and *Picea abies* seedlings before planting. *Canadian Journal of Forest Research* 23(9):1737-1743.

Gonzalez, R.C. and R.E. Woods. 2002. *Digital Image Processing*, 2nd edition. 44-45. Delhi, India: Pearson Education private limited.

Hellebrand, H.J., H. Beuche and M. Linke. 2002. Thermal imaging: A promising high-tec method in agriculture and horticulture. In *Physical Methods in Agriculture: Approach to Precision and Quality*, ed. J. Blahovec and M. Kutilek, 411-427. New York, NY: Kluwer Academic/Plenum Publishers.

Hulbert, G.J., J.B. Litchfield and S.J. Schmidt. 1995. Temperature mapping in carrot using T_1 weighted magnetic resonance imaging. *Journal of Food Science* 60:780-785.

Inoue, Y., B.A. Kimball, R.D. Jackson, P.J. Pinter and R.J. Reginato. 1990. Remote estimation of leaf transpiration rate and stomatal resistance based on infrared thermometry. *Agricultural and Forest Meteorology* 51:21-33.

James, K. and D. Rice. 2002. Finding termites with thermal imaging. Paper No. ITC 035A. North Billerica, MA: Infrared Training Centre.

Jones, H.G. 1999. Use of infrared thermometry for estimation of stomatal conductance as a possible aid to irrigation scheduling. *Agricultural and Forest Meteorology* 95:139-149.

Kalma, J.D. and D.L.B. Jupp. 1990. Estimating evaporation from pasture using infrared thermometry: Evaluation of a one layer resistance model. *Agricultural and Forest Meteorology* 51:223-246.

Kantt, C.A., A.G. Webb and J.B. Litchfield. 1997. Temperature measurement of foods using chemical shift magnetic resonance imaging as compared with T1- weighted temperature mapping. *Journal of Food Science* 62(5):1011-1016.

Kantt, C.A., S.J. Schmidt, S.E. Sizer, S. Palaniappan and J.B. Litchfield. 1998. Temperature mapping of particles during aseptic processing with magnetic resonance imaging*. Journal of Food Science* 63(2):305-311.

Kim, Y.H. and S.H. Lee. 2004. Thermal and visual image characteristics of potato transplants as affected by photosynthetic photon flux and electrical conductivity. ASAE Paper No. 044101. St. Joseph, MI: ASAE.

Ljungberg, S.A. and O. Jonsson. 2002. Infrared thermography: A tool to map temperature anomalies of plants in a green house heated by gas fired infrared heaters. In *Proceedings of Thermosense XXIV,* 399-406. Bellingham, WA: SPIE.

Meinlschmidt, P. and V. Margner. 2003. Thermographic techniques and adopted algorithms for automatic detection of foreign bodies in food. In *proceedings of Thermosense XXV, 168*-177. Bellingham, WA: SPIE.

Nott, K.P. and L.D. Hall. 1999. Advances in temperature validation of foods. *Trends in Food Science and Technology* 10: 366-374.

Perdikou, P., C. Clayton and D. Hadjimitsis. 2002. Use of ETM + thermal band to identify irrigation patterns in the Aral sea basins, Kazakhstan. In *Proceedings of SPIE* 4879, 62-71. Bellingham, WA: SPIE.

Smith, R.C.G., H.D. Barrs, J.L. Steiner and M. Stapper. 1985. Relationship between wheat yield and foliage temperature: Theory and its application to infrared measurements. *Agricultural and Forest Meteorology* 36:129-143.

Stajnko, D., M. Lakota and M. Hocevar. 2004. Estimation of number and diameter of apple fruits in an orchard during the growing season by thermal imaging. *Computer and Electronics in Agriculture* 42(1):31-42.

Sun, X.Z., J.B. Litchfield and S.J. Schmidt. 1993. Temperature mapping in a model food gel using magnetic resonance imaging. *Journal of Food Science* 58:168-172, 181.

Sun, X.Z., S.J. Schmidt and J.B. Litchfield. 1994. Temperature mapping in a potato using half fourier transform MRI of diffusion. *Journal of Food Process Engineering* 17:423-437.

Utter, O.J. 2003. Inspection on agricultural aircraft. *In Abstracts of Inframation, Infrared Camera Application Conference.* NV. North Billerica, MA: Infrared Training Centre. Available at: http://www.inframation.org/abstracts.asp Accessed on: May 28, 2005.

Vanlinden, V., R. Vereycken, C. Bravo, H. Ramon and J.D. Baerdemaeker. 2003. Detection technique for tomato bruise damage by thermal imaging. In *Proceedings of Post-harvest Unlimited,* 389-394. Leuven, Belgium: ISHS.

Varith, J., G.M. Hyde, A.L. Baritelle, J.K. Fellman and T. Sattabongkot. 2003. Non- contact bruise detection in apples by thermal imaging. *Innovative Food Science and Emerging Technologies* 4:211-218.

Wurzbach, R.N. 2003. Infrared applications in farming: vision of things to come. In *Proceedings of Thermosense XXV*, No. 5073,154-159. Bellingham, WA: SPIE.

Xu, H. and Y. Ying. 2003. Detection citrus in a tree canopy using infrared thermal imaging. In *Proceedings of SPIE No.* 5271B, 321-327. Bellingham, WA: SPIE.