गेहूं की फसल के थर्मल छवि विश्लेषण नमी तनाव की स्थिति के अधीन हो

Thermal image analysis of wheat crop grown under moisture stress conditions

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A Thesis

By

Koushik Banerjee

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Approved by:

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CERTIFICATE

This is to certify that the thesis entitled, **"Thermal image analysis of wheat crop grown under moisture stress conditions"** submitted to the Faculty of Post Graduate School, Indian Agricultural Research Institute, New Delhi, by **Mr. Koushik Banerjee**, Roll No. 20514 in partial fulfilment of the requirements for the award of the degree of **Master of science in Agricultural Physics**, is a record of bonafide research work carried out by him under my guidance and supervision and that no part of the thesis has been submitted anywhere for the publication or for any other degree or diploma.

I further certify that the assistance and help received during the course of this investigation have been duly acknowledged.

Place: IARI, New Delhi
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DEDICATED TO MY

CHAIRMAN

& MY PARENTS

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Date : *Koushik Banerjee*
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ABSTRACT

In view of the global climate change and burgeoning population there is a greater constraint on the availability of water for agriculture. Wheat crop growth and yield are much affected by the availability of water during the growing season. Experiments were conducted during the year 2014-15 and 2015-16, to characterize the effects of moisture stress on wheat crop using thermal image analysis. The goal of the study is to apply the principles of infrared thermometry and image analysis to characterise the changes in growth and yield of wheat crop raised under moisture stress condition. Wheat cultivar HD 2967 was grown in the research fields of Indian Agricultural Research Institute, New Delhi under four different levels of moisture stress. Periodic observations on biophysical parameters and thermal imagery were made. Three thermal indices namely CWSI, IG and I3 were estimated based on the canopy temperature measured through thermal image and infrared thermometer (IRT). Results showed that the thermal image based indices were more consistent than IRT based indices. This is because the thermal camera captures the crop canopies of many plants in a plot and thus helps to minimize the error due to sampling in comparison to the spot measurements made using the infrared thermometers. In addition the thermal indices calculated by the thermal images correlated significantly with the crop canopy based parameters like NDVI and LAI.

As a further application of this technology, an attempt was made to estimate the Leaf Area Index (LAI) of the wheat crop grown under different moisture stress conditions using Thermal Image Analysis. Thermal Images were analysed with five different supervised image classification techniques namely Maximum likelihood, Mahalanobis, Minimum distance to mean, Parallepiped and Spectral angle mapper methods using ENVI - image analysis software. Results showed that the best estimation of LAI was possible using Maximum likelihood method, due to its higher overall classification accuracy and Kappa coefficient. This is further supported by the statistical analysis based on the observed LAI. In general Maximum likelihood method estimated the wheat crop LAI from the thermal image meaningfully with high R^2 *value of around 0.624 and low values of RMSE and MBE. Thus the present study clearly showed that thermal image analysis could be applied as a non-destructive, rapid, less erroneous technique to characterise the crop canopy temperature and also estimate the LAI of the wheat crop grown under moisture stress conditions.*

आर्द्र तनाव परिस्थिति में उगाये गए गेहूं का थर्मल बिम्ब विश्लेषण

सारांश

वैश्विक जलवायु परिवर्तन तथा तेज़ी से बढ़ती हुई जनसंख्या के कारण कृषि के लिए उपलब्ध जल में आए दिन भारी कमी होने वाली है। उपयुक्त मौसम में पानी की कमी के कारण गेहूं में वृद्धि, विकास तथा उत्पादन पर काफी असर पड़ता है। 2014-15 तथा 2015-16 में गेहूं पर आर्द्र तनाव के प्रभाव को विश्लेषित करने के लिए थर्मल बिम्ब विश्लेषण का उपयोग कर प्रयोग किए गए। प्रयोग का उद्देश्य इंफ्रारेड थर्मोमेटेरी के सिद्धांतों का इस्तेमाल कर बिम्ब विश्लेषण द्वारा आर्द्र तनाव परिस्थिति में गेहूं की वृद्धि तथा उत्पादन का अध्ययन करना था। इसके लिए गेहूं की किस्म HD 2976 को भारतीय कृषि अनुसंधान संस्थान के अनुसंधान प्रक्षेत्र में 4 अलग अलग आर्द्र तनाव परिस्थितियों मे उगाया गया। जैवभौतिकी तथा थर्मल बिम्ब का सामयिक अवलोकन किया गया। तीन उष्ण सूचकांकों (CWSI, IG तथा I3) का आकलन थर्मल बिम्ब तथा इंफ्रारेड थर्मोमीटर द्वारा कैनोपी तापमान को मापकर किया गया। परिणाम से पता चला कि थर्मल बिम्ब पर आधारित सूचकांक IRT पर आधारित सूचकांकों की तुलना में ज्यादा संगत थे। ऐसा इसलिए हुआ क्योंकि थर्मल कैमरा किसी क्षेत्र के काफी संख्या में पौधों के कैनोपी के बिम्ब को लेता है तथा इस प्रकार सैम्प्लिंग के द्वारा उत्पन्न हुई त्रुटि को कम करता है, जबकि इंफ्रारेड थर्मोमीटर किसी एक ही स्थान को मापता है। इसके अलावा थर्मल बिम्ब के आधार पर लिए गए थर्मल सूचकांक पौधों के कैनोपी संबन्धित पारामीटर (NDVI तथा LAI) से काफी संगत में पाये गए।

इस तकनीक की एक और उपयोगिता को इंगित करने के लिए अलग-अलग आर्द्र तनाव परिस्थितियों में गेहूं में LAI को थर्मल बिम्ब विश्लेषण द्वारा आकलित करने का प्रयास किया गया। थर्मल बिंबों को 5 अलग-अलग संचालित बिम्ब वर्गीकरण विधियों यथा- मैक्सिमम लाईक्लिहूड, महलानोबिस, मिनिमम डिस्टन्स टू मीन, परलेपिपेड तथा स्पेक्ट्रल एंगल मैपर का प्रयोग ENVI बिम्ब विश्लेषण सॉफ्टवेयर के माध्यम से किया गया। परिणाम से पता चला कि मैक्सिमम लाईक्लिहूड विधि द्वारा सर्वोत्तम LAI का आकलन हो सकता है क्योंकि इसकी वर्गीकरण यथार्थता तथा कप्पा गुणक काफी ज्यादा हैं। इसको आगे सांख्यिकी विश्लेषण द्वारा भी समर्थित किया गया जो कि LAI पर आधारित था। सामान्य तौर पर मैक्सिमम लाईक्लिहूड तकनीक द्वारा गेहूं के LAI का आकलन थर्मल बिम्ब द्वारा सार्थक रूप से अधिक R2 मान (0.624) तथा कम RMSE तथा MBE मान के साथ हुआ। अतः वर्तमान अध्ययन दर्शाता है कि थर्मल बिम्ब विश्लेषण का उपयोग एक बिना विनाशकारी, तेज़, कम त्रुटिपूर्ण विधि के रूप में फसल कैनोपी तापमान को विवरित करने के लिए तथा गेहूं में LAI का आकलन आर्द्र तनाव परिस्थिति में करने के लिए किया जा सकता है।

1. INTRODUCTION

The environment within which agricultural crops and agronomic practices developed over the past 10,000 years is rapidly changing due to human-induced climate change (IPCC, 2014). Global climate models predict an increase in mean ambient temperatures between 1.8 and 5.8°C by the end of this century (IPCC, 2014). The effects of climatic change on crop growth and productivity in field have also been documented based on historical long-term field experiments data (Tao *et al*., 2006; Lobell *et al.*, 2011) and reported harvest data (Lobell and Asner, 2003; Tao *et al.*, 2008a). Future climate change is projected to be one of major challenges for regional agricultural production in broad regions of the world (Tao *et al.*, 2003; IPCC, 2007a; Lobell *et al.*, 2008; Battisti and Naylor, 2009). About 21% of the world's food depends on the wheat (*Triticum aestivum*) crop, which grows on 200 million hectares of farmland worldwide. Although wheat is traded internationally and developing countries are major importers (43% of food imports), the reality is that 81% of wheat consumed in the developing world is produced and utilized within the same country, if not the same community (CIMMYT, 2005). In these circumstances, many poor households depend on increased wheat production on their own farms for improved household food security. In the period leading up to 2020, demand for wheat for human consumption in developing countries is expected to grow at 1.6% per annum, and for feed at 2.6% per annum. The global average wheat yield will have to increase during the coming 25 years from 2.6 to 3.5 tonnes ha-1. This yield increase, essential to maintain global food security, requires a continuing supply of improved germplasm and appropriate agronomy in order to sustain enhanced productivity and preserve the natural resource base. Wheat is the 2nd largest crop grown in India after rice with current annual production of more than 90 MT and climate change negatively affects wheat grain yield, which potentially increases food insecurity and poverty (Mohammadi *et al*., 2012).

Leaf temperature is important to plants both because of the subtle effects of small temperature changes on the rates of key physiological processes such as biochemical reactions and cell growth and division and because of the damaging effects of extreme temperatures. Any study of physiological processes needs to take account of the temperature sensitivity of the process in relation to the likely natural variation (spatial and temporal) of temperature. It has been well known for many years (Brown and Escombe, 1905; Huber, 1935; Jackson, 1982; Raschke, 1960) that leaf temperature depends on stomatal opening, with temperatures decreasing as stomata open and as evaporation rates increase. The use of leaf temperature as an indicator of stomatal conductance or transpiration, however, is confounded by the fact that leaf temperature is also affected by a wide range of other plant and environmental characters according to the leaf energy balance. Furthermore, as the environment is constantly changing, at least for plants in the field, it also becomes necessary to consider the dynamic behavior of leaf temperature in any precise study of leaf temperature. An extensive literature developed over 30 years or so, making use of the temperature rise as stomata close under drought as an indicator of crop ‘‘stress.’’ This was greatly facilitated by the increasing availability of infrared -thermometers. Most studies in this field have been based on infrared thermometry rather than on thermography, which is the process of obtaining thermal images.

The rate of evaporation is only one of many components of the canopy energy balance that affect canopy temperature: factors such as radiation, wind speed, air temperature, and air humidity also have major effects (Jones, 1992). Without sufficient information about these factors, measurements of leaf temperature alone are not enough to allow estimates of the transpiration rate or the stomatal conductance. One solution is to make use of `dry' and `wet' reference surfaces, where the observed leaf temperature is compared with the temperature that the same leaves would attain under the conditions of zero and maximum transpiration at the same environment (Jones *et al.*, 1997). The dry surface represents the situation without transpiration and the wet surface represents the maximum potential rate of transpiration. Throughout the 1970s and 1980s in particular, there was much effort on the development of thermal crop water stress indices that could be used for irrigation scheduling purposes (Idso *et al.*, 1981; Idso, 1982; Jackson, 1982; Jones and Leinonen, 2003). These were based on the measurement of canopy temperature using infrared thermometers. A major problem with such measurements, however, is that it is common for the field of view of the detector to include some background (e.g. soil or sky) in addition to the leaves of the crop of interest, especially before full ground cover is achieved. As an alternative to the estimation of crop water stress from the mean temperature of the canopy, it has been proposed that the variability of canopy temperature may provide important information about the degree of stomatal closure (Fuchs, 1990). By contrast with infrared thermometry, thermal imaging allows information on the temperatures of all areas in a scene to be obtained simultaneously in one image. Therefore, thermal imagery provides an ideal approach for the collection of the large number of individual leaf temperatures that are necessary for methods based on temperature frequency distributions. Thermal imaging also allows leaves to be distinguished from the background. If done manually, however, the necessary image processing can be rather labour-intensive and may also be dependent on subjective image interpretation.

Common application of thermal imaging depends on alteration in plant water relation. Although many application of thermography in the areas of plant response to biotic & abiotic stress have been reported, in all such application the perceived response can be attributed to alteration in leaf conductance due to change in stomatal aperture.

The Greek Physician, Hippocrates, wrote in 400 B.C. "In whatever part of the body excess of heat or cold is felt, the disease is there to be discovered." The ancient Greeks immersed the body in wet mud, identified the warmed region as the area that dried more quickly and considered that as diseased tissue. Latter on the first non-contact way of measuring temperature of a surface by using infrared radiation was achieved long back in 1800 by the astronomer, Sir William Herschel, in Bath, England. His son John Herschel recorded the heating waves and created an evaporigraph image using carbon suspension in alcohol and termed this image as a thermogram (Krishnan, 2014). Study of plant water relations was done using thermal image by Jones and Leinonen in the year of 2003. Infrared sensing of the canopy temperature can be used to monitor stomatal conductance or to estimate the transpiration rate of plants (Merlot *et al.,* 2002). Prashar and Jone, 2014 also studied the negative correlation between transpiration rate and leaf temperature. Some studies in relation to digital infrared thermography of horticulture have been done regarding the control of diseases, but few studies propose the use of thermography for an early diagnosis of the distribution system for fertigation or to diagnose salt tolerance in crops (Kim *et al.,* 2014). Soon it was found that there is a real need for sensitive, easy, economic and robust techniques for detection of salinity, water and other stress in plant (Costa *et al.,* 2013). The major advantage of infrared thermal imaging is the non-invasive, non-contact and non-destructive nature of the technique to determine the temperature distribution of any object or process of interest in a short period of time (Ishimwe *et al*., 2014; Urrestarazu, 2013). Thermal imaging is a useful tool in forward genetics, large scale screening and mutant characterization and help in rapid development in molecular plant physiology and functional genomics (Krishnan, 2014).

Objectives

1. Characterization of crop condition using thermometry and crop bio-physical parameters under different moisture stress conditions in wheat

2. To estimate the crop stress index based on thermal image and correlate with biophysical parameter

2. Review of Literature

2.1 Wheat crop

2.1.1 Scenario of wheat crop

Wheat, *Triticum sp*, is one of the widely cultivated cereals mainly originated in N-E Asia. It is a type of edible grass whose fruit is called caryopsis under the family Poaceae or Gramineae. Domestication of wheat crop was started far back around 8000 BC, since from then it is considered one of the principal food for the zone of North Africa, West Asia and Europe. At present, area under wheat crop has been further expanded than other commercial crop due to its sole importance in human diet. It is one of the rich contributors of vegetable protein in human diet. It also ranks second in terms of production just behind the rice but ahead of maize. 21% of global population depends on wheat (CIMMYT, 2005). Even though, the most outstanding growth of wheat was achieved around the latitude located 30-60° N and 27-40° S (Nuttonson, 1955), but further research from CIMMYT have shown that cultivation of wheat can also be achieved in warmer belt by the aid of viable and sophisticated technology (Saunders and Hettel, 1994). Typical temperature for growth and development of wheat is around 25°C with maximum tolerable temperature of 30-32°C and minimum being 3-4° C (Briggle, 1980). Adequate availability of moisture at root zone specially during critical growth stage is utmost important for achieving good production, but luxurious presence of this resource can create congenial environment for disease to break through.

2.1.2 Wheat in India

Triticum Sphaerococcum is familiarly known as Indian wheat, but at present its cultivation is substituted by *Triticum aestivum*, which is commonly known as bread wheat, *Triticum durum* called as Marconi wheat and Emmer wheat as *Triticum dicoccum*. During the era of early independency, most of the wheat was imported to meet the demand in India. But the continuous effort of Dr. N. E. Borlaug, the father of green revolution, made India to become a wheat surplus country with improved Norin 10, the dwarfing gene of wheat. India saw an abrupt change in respect of wheat production from 6.46 million ton to 93 million ton during the period of 1950-51 to 2011-12 respectively. During the period of 2010-11, India was the second largest wheat producer country after China with a share of 12% in total world. According to statistical year 2015 report, India is third largest wheat producer country with average production of 88.94 million metric ton in the world following European Union (157.98 million metric ton), China (130.19 million metric ton) (USDA 2016) and world's average production of wheat was estimated as 699 million tons during the tear 2014-15.

2.1.3 Wheat and Global warming

According to the result of IPCC 2014 climatic model, global mean atmospheric temperature will increase by 1.8 to 5.8 °C at the end of this century. Upcoming climate will also deviate from its normal with fluctuating behaviour of temperature and will be cursed by the more frequent hot days (Pittock, 2003). So, understanding the response pattern of crop under higher temperature condition and their forbearance to heat will provide us the idea about acclimatization pattern of newly developed variety in upcoming period (Halford, 2009). Temperature above the tolerance limit can cause irrecoverable yield loss for a crop which can be called as Heat stress (Wahid *et al*., 2007). Heat stress is a combined effect of temperature elevation in respect of their rate and magnitude and the duration in days the crop faced this higher temperature condition (Wahid *et al*., 2007). Phenological progress of wheat is very much sensitive to temperature condition (Slafer and Satorre, 1999) and continuous trend, of increase in ambient temperature throughout the wheat growing season has been reported by many researcher (Alexander *et al.*, 2006; Hennessy *et al*., 2008). Sensitization of high temperature stress in wheat vary according to different phonological stage, but it has been found that reproductive stage is more vulnerable to high temperature stress than vegetative stage as far as the number of grain and the biomass is concerned (Wollenweber *et al*., 2003). Effect of enhanced temperature on wheat at the time of grain development stage is ultimately linked with final yield and its quality. Ideal temperature range for wheat anthesis and grain development phase is found to be 12-22 °C. Prevalence of temperatures over this can altogether diminish grain yield (McDonald *et al*., 1983, Mullarkey and Jones, 2000; Tewolde *et al*., 2006). High temperature stress at the time of anthesis expands floret premature birth (Wardlaw and Wrigley, 1994). High temperature stress at the time of conceptive stage can bring about pollen or dust sterility, tissue drying out, lower CO_2 absorption and enhanced photorespiration. Albeit high temperatures quicken development (Fischer, 1980; Kase and Catsky, 1984) they additionally decrease the phenology, which is not made up for by the expanded development rate (Wardlaw and Moncur, 1995; Zahedi and Jenner, 2003). Enhanced daily minimum temperature seems to have more prominent effect on wheat net production as grain yield is more firmly adversely related with expanding minimum temperature than daily increasing maximum temperature (Lobell *et al*., 2005). Prasad *et al*., 2008a, found that night temperature more than 20°C can adversely minimizes spikelet viability and simultaneously this also reduces the grain number and their size.

2.2 Moisture temperature stress on plant

Moisture stress amid crop growth and development restricts the crop yield particularly in the tropics. Due to decrease in the availability of water for agriculture in the course of the most recent three decades have lessened yields in numerous crops. The uncertainity in the occurrence of rainfall has made the irrigation an essential requirement for crop cultivation (Long and Ort, 2010). Continuous changes in rainfall pattern and uncertainity in the occurrence of rain at the right stages of the crop growth have made the need for proper characterisation of moisture stress effects on crop plants.

Limited availability of moisture during crop growth period causes canopy temperature to be significantly higher than that of ambient temperature. When the balance between lost and gain of water throughout the system is not maintained, overheating of leaf takes place. Moisture stress situation is usually or occasionally associated with depleted water condition or during higher solar irradiance situation. The impact of moisture stress in principle cereal crop like wheat is found to be serious. The effect changes relying upon the formative phase of the plants and among this stage flowering stage is found to be most unsafe. Appearance of moisture stress before flowering can bring about floret sterility, creating reduction in yield due to decreased grain number. This impact is most intense when stress happens at or soon after pollen meiosis, when sugar supply to the formative pollen grains seems to be most important. Size of the grain size in moisture stressed plants can be extremely lessened, predominately from a decrease in starch, which constitute a large portion of the grain mass.

2.3 Impact of moisture stress on Wheat

2.3.1 Photosynthesis

Photosynthesis is generally the most sensitive crop parameter as compared to other plant physiological processes under moisture stress condition (Wahid *et al.*, 2007). Any kind of inhibition of photosynthesis process influences development and ultimately grain yield of wheat (Al-Khatib and Paulsen, 1990, 1999). Moisture stress causes lowering in photosynthesis by interrupting the structure and activity of chloroplasts and diminishing the chlorophyll content (Xu *et al*.,1995). The restraint of photosynthesis due to moisture stress is regularly ascribed to increments in the rate of photorespiration, this happens because of reduction in solubility of CO_2 and O_2 along with decline in activity of Rubisco (Ogren, 1984; Long *et al*., 2004). Sensitivity of Rubisco under moisture deficit and high temperature condition is much higher that other enzymes which are associated with carboxylation process. Relatively higher activity of PEP carboxylase lower activity of Rubisco was found in non-green photosynthic part like awn, compare to flag leaf portion of wheat (Xu *et al*., 2004). Higher PEP carboxylase/ Rubisco proportions were kept up, especially in non-leaf organs, which had higher PEP carboxylase/Rubisco proportions than the banner leaf at all times (Xu *et al*., 2004). Through consequences for PSII- and PSI- intervened electron exchange, and performance of Calvin cycle, submission to high temperature stress (40 °C) harms the photosynthetic equipment (Baker, 1991; Sharkey, 2005). PSII gives off an impression of being impacted by moisture stress, however, is not seriously influenced by tolerably high temperatures (<40°C) (Allakhverdiev *et al.*, 2008). Prasad *et al.* 2008b, found that the most critical reason behind the PSII affectability under high temperature are heat induced increment in thylakoid layer smoothness and dependency of electron-transport of PSII.

2.3.2 Leaf Senescence

Gradual and steady loss of green leaf portion during reproductive phase of a crop is normally called leaf senescence (Nood´en, 1988). Moisture stress aggravated the process of leaf senescence by catalyzing the senescence related metabolic process in wheat (Al-Khatib and Paulsen, 1984; Paulsen, 1994). Biosynthesis of chlorophyll retard the leaf senescence process, but prevalence of higher moisture deficit situation along with high temperature 42°C (Tewari and Tripathy, 1998) inhibits this biosynthesis mechanism, hence leaf senescence is accelerated. Harding *et al*., 1990 also found inactivity of thylakoid component coupled with high temperature and moisture stress further enhances the leaf senescence process.

2.3.3 Water Relations

Leaf stomatal conductance, its water potential and rate of transpiration are directly determined by the moisture availability around root system (Farooq *et al*., 2009a). Limited availability of moisture around the root zone environment causes leaf temperature of the plant to increase. However, attainment of high temperature over the plant canopy is to some extent checked by the process of evaporation and transpiration from the leaf surface which left a cooling effect. Even though an equal mode of balance is always maintained between leaf temperature, stomatal conductance and continuously diminishing soil water, it has been found that the typical nature of most of the plant is to maintain or conserve a moisture stack within it when surrounding temperature crosses 30 °C (Mart´ınez-Ballesta, 2009). Hydraulic conductivity of plant cell membrane and its tissue is found to be increased with the elevation of ambient temperature due to reduction of viscocity of water (Cochard *et al*., 2007) increased membrane fluidity, permeability and most importantly due to activity of aquaporin (Mart´ınez- Ballesta, 2009).

2.3.4 Grain Growth and Development

Higher degree of moisture stress along with abnormal temperature rise not only affects the wheat grain number but also it has a significance effect in reducing grain weight (Ferris *et al*., 1998). But this unpleasant phenomena mainly depends on the time period during the crop growth and its phonological stage on which high temperature become prevalent than the moisture deficit. For example, ambient temperature above 20 °C having the well potentiality to cause substantial reduction in grain number per spike between the stage spike initiation and anthesis in wheat (Saini and Aspinall, 1982). Spike development is accelerated under the limited availability of moisture (Porter and Gawith, 1999), which in turn reduce the spikelet number per plant, that results in reduce number of grain per spike (Saini and Aspinall, 1982). A negative correlation has been noticed between high temperature stress and grain number during the double ridge formation and flag leaf initiation stage in wheat by Rawson and Bagga, 1979. Even though high temperature (>30°C) during floret development brings complete sterility (Saini and Aspinall, 1982), but dissimilarity among various wheat genotype has also been noticed (Anjum *et al*., 2008; Zhao *et al.*, 2008). Accessibility of carbohydrates during the floral development stage is taken as a determining element for obtaining higher grain number (Demotes-Mainard and Jeuffroy, 2004). Wheat plants when subjected a temperature of 30°C along with moisture stress situation continuously for 3 days during the partioning phase of pollen mother cells, causes considerable diminution of grain set and hence finally grain yield (Saini and Aspinall, 1982). Moisture stress also harms the viability of anther and pollen cell and brings a poor fertilization set (Saini and Aspinall, 1982; Ferris *et al.*, 1998). Prevalence of moisture stress and high temperature, likewise, brings shrinkage in grain structure by physiological modification of aleurone layer and endosperm cell when day temperature elevated from 25-31°C and night temperature from 14-20°C (Dias *et al*., 2008).

2.3.5 Grain Quality

Amount of protein present in grain and grain size are the most essential attributes for deciding grain quality in wheat (Coles *et al.*, 1997). Moisture stress at the time of grain filling stage influence the protein concentration (Wardlaw *et al*., 2002; Gooding et al., 2003) through decrease in starch accumulation which affect protein content by permitting more nitrogen per unit of starch (Stone and Nicolas, 1998). In spite of the fact that the day by day uptake of carbon and also, nitrogen into grain makes their gradual increments with availability of moisture along with rising temperature, but it has been found that carbon uptake diminishes per degree-day (Wardlaw *et al.*, 1980; Daniel and Triboi, 2000). As a result size of the grain is more dependent on availability of moisture and ambient temperature rise than quantity of nitrogen applied or up taken by the crop in their grain (Uhlen *et al.*, 1998; Daniel and Triboi, 2000). Negative relation has been established between grain protein concentration and its size (Guttieri *et al*., 2000; Erekul and Kohn, 2006).

2.3.6 Leaf membrane stability

Despite the fact that imperviousness to large water deficit includes a few complex resilience and shirking systems, one of the place of essential physiological damage by moisture stress is thought to be the cell membrane (Blum, 1988). As a consequence of this, movement of ions, organic solutes and water is hampered (Christiansen, 1978). The extent of membrane damage can be evaluated by the membrane thermos-stability (MT), which assess the spillage of electrolyte from the leaves which is under moisture stressed condition (Reynolds *et al*., 1994). It has been found very useful for assessing the yield performance under high moisture stress situation (Reynolds *et al*., 1994). Electrolyte spillage from cells was utilized to gauge heat injury to plasma layers in different field crops including spring wheat (Reynolds *et al*., 1994). Shanahan et al. (1990) acquired a huge increment in yield of spring wheat in warmer areas by selecting MT methodology, as controlled by estimations on flag leaves at anthesis. Current report suggest that, existence of both additive and dominant gene action is accountable for MT in wheat (Dhanda and Munjal, 2012).

2.3.7 Starch Synthesis

Starch is the principle component of wheat grain which makes up to 70% on dry weight basis, cessation of starch accumulation is the main cause behind the reduction of wheat grain weight (Bhullar and Jenner, 1985). Production of starch depends on activity of three major enzyme sucrose synthase, soluble starch synthase (SSS) and granule-bound starch synthase (Hawker and Jenner, 1993). Among this three, SSS has the direct role in production of starch and at lower availability of moisture activity of this enzyme is seriously inhibited (Rijven, 1986; Keeling *et al*., 1993, 1994) as a consequence of this, biogenesis of starch and wheat grain development is prohibited (Prakash *et al.*, 2003, 2004) and finally net yield reduced significantly (Labuschagne *et al*., 2009). Temporary prevalence of moisture deficit along with elevated temperature, >30 °C, affect biogenesis of starch due to its inhibitory effect over SSS activity (Jenner, 1994).

2.3.8 Canopy Temperature Depression

Canopy temperature depression (CTD), may be defined as the difference of temperature between normal ambient condition and plant canopy, it is positive when temperature within the plant system is much lower than that of its surrounding, so for this it is considered as one of the handy indices for monitoring stress condition of a plant (Royo *et al.,* 2002). However, usefulness of CTD as an indicator of stress forbearance and crop yield is strictly depends on respective environment in which crop is grown. So, higher value of CTD can be utilized as selection norm for improving forbearance against high temperature (Ayeneh *et al*., 2002; Balota *et al.*, 2007; Reynolds *et al*., 1994, 1998).

Canopy temperature is important to crop due to its subtle effects on the rates of key physiological processes with variation in temperature. Spatial and temporal variation of temperature is needed to be taken into account for the study of physiological processes in plant. Dependence of leaf temperature on stomatal opening is well known for many years, (Brown and Escombe, 1905, Huber, 1935; Jackson,1982; Raschke, 1960. Study of dynamic nature of leaf temperature in association with leaf energy balance in constantly changing environment is further-more important. Before the invention of remote infrared sensor leaf temperature measurement was limited by the use thermocouples. Scientific understanding of plant water relationship was achieved by measuring the canopy temperature using infrared thermometry by Tanner, 1963 and Fuchs and Tanner, 1966. Stress degree day (Jackson *et al*. 1977) can be taken as one of the important milestone for irrigation management in the area of thermal sensing. Latter further normalization was done by taking into account of differences in atmospheric humidity and the comparison with a well-watered crop by means of the CWSI (Idso, 1982; Idso *et al*., 1981; Jackson *et al*., 1981). Addition of wet reference (as fully transpiring leaf) and dry reference (non-transpiring leaf) surfaces makes normalization of current ambient conditions (Jones, 1999b; Jones *et al.*, 1997) and allow near accurate estimation of conductance. Most recent introduction of thermography, which is basically a process of taking thermal images by using thermal camera makes the area of thermometry more enhanced and more fertile.

2.3.9 Leaf energy balance

Practical implication of thermal imaging for understanding the plant physiological processes depends mainly on leaf energy balance. Molecular transfer of mass (water vapour) and heat to atmosphere from leaf surface is carried out by combination of conduction, diffusion and convection (Campbell and Norman, 1998;

Jones, 1992; Monteith and Unsworth, 1990). General format of energy balance for a leaf surface may be presented as follows

$$Rn + M - \lambda E - C = S$$

Where Rn represent net radiant flux at the leaf, M is the heat evolved due to metabolic activity, λE is the lattent heat of evaporation and transpiration to the environment from the leaf, C is the heat loss due to conduction and evaporation and finally S is the rate of heat increase in the leaf tissue. By splitting net radiation we can revise the above equation as follows

$$Rs + RLa - RLe + \lambda E - C = S$$

Where the subscript s, Le is the emitted long wave radiation and La represent absorbed short wave and long wave radiation. This equation can be further modified by introducing leaf temperature (T_{leaf}) and putting the value of λE, C and S from empirical relation (Penman, 1948), so the modified equation is as follows,

$$Rs + RLa - \epsilon\sigma T^4_{leaf} + M - \lambda^*gw^*(D + s(T_{leaf} - Ta))/pa - gaH\ cp(T_{leaf} - Ta) = (\rho^* c_p^*\ l\ ^*)^* d\ T_{leaf}/dt$$

Where gw and gaH represent the overall conductances of mass and heat and ρ*cp* l * are the leaf density (kg/m^3), leaf's specific heat (J/Kg/K), and leaf thickness (m) respectively and D is the atmospheric vapour pressure deficit. Solution of this equation was done by (Gates and Papain, 1971). Now in the above equation Rn is replaced by R ni which is called net isothermal radiation and that include T^4_{leaf}. Rni can be defined as,

$$Rn = Rs + RLa - \epsilon\sigma T^4_{leaf} = Rni - \epsilon\sigma(T^4a - T^4_{leaf}) = Rni - cp\ gr\ (T_{leaf} - Ta)$$

Where radiative conductance is denoted as gr. After rearranging the above equation one can calculate the leaf temperature if sufficient information of Ta, D, gw and ga H are there. So,

$$T_{leaf} = Ta + [\ (Rni + M) - \lambda^*gw\ ^*D/\ pa] / [cp\ gHR + \lambda gw\ s/pa\ ]$$

2.4 Sensor technology for stress monitoring

Availability thermal scanners in the 1960s abolish the limitation of the use thermographic Techniques. Earliest in the 1970s and early 1980s Omasa and colleagues (Hashimoto *et al.*, 1984; Omasa *et al.*, 1981a, b) had used thermal imagery for observing the temperature distribution pattern in leaf and applied this in relation to stomatal conductance in laboratory systems. In that period instruments were heavy and liquid nitrogen was needed to cool sensor of the cameras. Infrared thermographic technique introduces uncooled, handheld cameras with better thermal resolution (0.1°C) in reasonable price. Other techniques which give information of internal structure, such as x-ray or nuclear magnetic resonance (NMR) tomography, visible reflectance (red/green/blue) images familiar from standard digital cameras to fluorescence images.

2.4.1 Thermal sensing

Thermal sensing technique can be well applied for studying stomatal conductance in relation with plant water uptake. Transpirational cooling of leaf due to latent heat of vaporization is a determining factor for leaf temperature. Heat may also be generated due system respiration (Seymour, 1999) or may be due to freezing of water over the leaf surface (Wisniewski *et al*., 1997), but their effect can be neglected due to their meagre effect on canopy temperature. Leaf temperature (Tl) at any time depends on temperature air (Ta), ambient humidity (e), wind speed (u) and net radiation (Rn) that is absorbed by the canopy as given by equation 1 (Leinonen *et al*., 2006)

$$Tl - Ta = [rHR*(raW + rs)*\gamma*Rni - \rho*cp*rHR*D]/ [\rho*cp[\gamma(raW + rs) + s*rHR]]$$

Where rs - leaf resistance to water vapour (s m^{-1}), raW-the boundary layer resistance to water vapour (s m^{-1}), Rni- the net isothermal radiation (W m^{-2}), ρ - density of air (kg m^{-3}), cp- specific heat capacity of air (J kg^{-1} K^{-1}), s - slope of the curve relating saturating water vapour pressure to temperature (Pa$^{\circ}C^{-1}$), γ - psychrometric constant (Pa K^{-1}) and rHR the parallel resistance to heat and radiative transfer (s m^{-1}) and D the air vapour pressure deficit (Pa) and this constitute the main problem regarding use of thermal sensing for estimating stomatal conductance. Crop water stress index (CWSI) is one of the most important stress monitoring indices was given by Idso *et al*. 1981 and can be represented in following manner

$$CWSI = (T_{canopy} - T_{nws}) / (T_{max} - T_{nws})$$

where T_{max} – dry leaf temperature, T_{nws} - non-water-stressed baseline temperature and this gives an effective measurement of stomatal opening rather than water stress.

2.4.2 Fluorescence imaging

Fluorescence emissions have the better potentiality to give more information about the leaf stress monitoring. When a leaf is excited by UV-A, the following bands namely Blue, Green, Red and Far red will be responsible for the fluorescence emission at the wavelength of 440 nm, 520 nm, 690 nm, and 740 nm respectively. Photosynthetic process is mainly associated with chlorophyll-a fluorescence which gives peak at red and far-red, while ferulic acid and chlorogenic acid, which constitute other phenolic compounds in the leave gives peak at the shorter wavelength (e.g. Lichtenthaler and Miehé, 1997; Buschmann *et al*., 2000). Most commonly used parameters for chlorophyll fluorescence is the ratio of Fv/Fm indicating the maximum efficiency of production of quantum yield by Photosynthesis-II under steady state of photosynthesis (Maxwell and Johnson, 2000). Fluorescence imaging is useful in extracting the above mentioned information in a sophisticated way which will also produce an indication of variation of leaf surface properties. Application of Fluorescence imaging is not only limited to study of photosynthetic response to stress, but also its applicability can be extended in the study of biotic stresses by fungi, viruses and bacteria by using multicolour and the chlorophyll (Chaerle *et al*., 2006; Pineda *et al*., 2008; Rodriguez-Moreno *et al*., 2008).

2.4.3 Reflectance imaging

Reflected light help us to view leaves under normal condition and the detected colour gives information about leaf health. Reflectance spectrum furnishes the composite effect of plant pigment system which includes chlorophylls, carotenoids and flavonoids. A good indicator of plant stress is leaf chlorophyll content which will reduce as plant goes towards senescence and this reduction of leaf chlorophyll concentration can be well detected by spectrophotometer. Deficiencies or toxicities of mineral, diseases have differentiating characteristic colour pattern. As example interveinal browning and yellowing occurs due to Zinc and Magnesium deficiency respectively but Sulphur deficiency causes purpling of veins (Taiz *et al*., 2015).

2.4.4 Multi-sensor imaging

Single imaging sensor can give limited information, but amalgamation of more than one imaging sensor technologies can greatly enhance the diagnosing ability to stress having particular importance. Thermal imaging can give useful information about change in evaporation rate which is caused due to stomatal aperture change, but on the other hand closure of stomata may happen due to composite effect of drought, salinity stress or it may come due to pathogenic attack and many more. And we need this kind of multisensory imaging technique so that we can detect the exact reason. Merging of reflectance and thermal sensors (e.g. Chaerle et al., 2001; Leinonen and Jones, 2004), or fluorescence and visible reflectance (Lenk et al., 2007) leads to the stress detection processes in higher accuracy level.

2.5 Image analysis

Meaningful images come into work when proper image analysis has been done. Following are some of the procedures followed in image analysis.

2.5.1 Image enhancement

Noise, especially random noise is most important and unavoidable part of an image which must be reduced by image enhancement. In thermal image each pixel of a particular area shows a particular temperature value which is assigned with DN value. It is usually preferred to use a grey scale to represent the differential temperature values visually. Here black represent lower value while higher values are represented by white colours. For improving visual discrimination and for contrast enhancement in dull image, (which have small dynamic range of grey value) it is generally preferred to use contrast stretch or some time more refined histogram equalization technique (Mather and Koch, 2010). Other possible methods for improving visual interpretation and for more accurate discrimination of temperature in thermal image, arbitrary colour scale may be used and the resulting image will be called a pseudo colour image. Again to minimize the effect of noise and to improve image sharpness high pass filter may be used, for this some application software are also developed for agriculture purpose (Ewing and Horton, 1999).

2.5.2 Thresholding

Thermal imaging gives an accurate estimation of temperature over a large area at one click and this constitutes its prime advantage over temperature measurement by infrared thermometers (IRT). IRTs give point measurement of leaf temperature which is susceptible to change very quickly with the change of ambient temperature, so thermal image can provide a comprehensive temperature distribution of the crop field

(Fuchs, 1990). Another important disadvantage regarding conventional infrared thermometers is its restricted view angle and for this they commonly capture some unwanted background with them along with canopy, so biasness also comes automatically. This background elimination can be done by thermal imaging. Use of black polyethylene sheet as a false or artificial background behind the orchard trees was suggested by Guiliani and Flore ,2000 , by this way they had attempted to reduce soil, sky and other background effect. Use of black polyethylene under sunny conditions guide it to warm-up sharply due to their higher absorptivity which is above the leaf temperature under study and this permit them to remove background pixel by using thresholding techniques. Another improved thresholding technique was suggested by Jones *et al*. 2002, the use of wet and dry reference surface in the same image which together act as evaporating and non-evaporating surface respectively. Any pixel having temperature above and below this threshold range which was specified by the reference surfaces will be treated as background.

2.5.3 Image Classification

Use of image analysis software is a sophisticated approach for removing irrelevant pixels and for identifying actual pixels which constitute leaves (Casa, 2003; Jones and Casa, 2001; Jones and Leinonen, 2003). Two main image classification schemes are unsupervised and supervised classifications. Unsupervised classification is an automatic technique, which having the ability to group each pixel element based on their spectral characteristics. But this failed to classify each element into direct distinguishable classes. Where the supervised methods are more frequently used in plant-physiological applications, while accurate training area can classify the other same area having similarity in spectral classes present in the same image (Mather and Koch, 2010).

2.5.4 Image ratios

Rationing of some specific spectral band is useful for generating new extracted image. Ratio of Red reflected region to NIR reflected region is the most frequently used indices for studying vegetation or leaf which is the main concerned area for plant scientist (Leprieur *et al*., 1996; Steven, 1998). Many other ratio indices frequently are also frequently employed by agricultural scientists, such as

$$NDVI= (\rho_{NIR} - \rho_{RED})/(\rho_{NIR} + \rho_{RED})$$

where ρ is the reflectance at red and NIR wavelength. Another comparable indices is SAVI (soil adjusted vegetation indices). These two bands are mainly used due to their contrasting behaviour in reflectance and absorption. It is well known that vegetation reflect more at NIR and absorb more at red due to their strong photosynthetic correlation and the higher value of this index is usually associated with full vegetative coverage.

2.6 Applications of thermography

Two atmospheric windows, ranging from 3-5 µm and from 8-14 µm, allows the thermal imaging to visualize the differences in the surface bound object by sensing infrared radiation coming out from their body which is proportional to their kinetic temperature in non-invasive way (Ludwig, 2013). Capabilities of thermography in monitoring soil salinity, pest–crop-disease interaction, estimation of yield, assessing maturity (Ishimwe *et al.*, 2014) have all been already established. Detection of minute differences in seed temperature can be done with the help of thermal profile of seed (Zhang *et al*. 2012). Ishimwe *et al.*, 2014, have found significant effective correlations between seedling temperatures with its level of damage. So, the seedling viability which relay upon its internal disorders and other external damage can be well measured by IR thermography. Assessing the canopy temperature through infrared thermographic techniques can reveal broad implication of both abiotic and biotic stress (Jones *et al.,* 2009; Ballester *et al*., 2013). Comparison between sap flow within the system along with the canopy temperature under drought condition was done for predicting result of water shortage on fresh weight of fruit during harvesting (Ballester *et al*., 2013). They have taken thermal images around midday and analyzed images automatically at weekly interval and their result reveals good relationship between canopy temperature, estimated by thermal image, and final harvest weight of fruit. Application of high doses of pesticides for managing pest in the field raises the level of pesticide residues in the agricultural product and dissimilar spectral response was observed from healthy and affected plant by Moshou *et al.,* 2004. Impact of downy mildew disease over cucumber leaves was done by Oerke *et al.,*2006.

2.6.1 Pathogen Detection

Potentiality of thermal imaging for detecting pathogenic severity in grapevine under different moisture condition was investigated by Stoll *et al*., 2008. Thermal images were taken by using handheld thermal camera under differently irrigation treated plant. After thermal image analysis, it was found that an increment of leaf temperature on the leaf where pathogen was inoculated in irrigated vines and the water stressed plant showed lesser degree of canopy temperature rise at the location of pathogen inoculation. Alteration in metabolic rate along with transpiration rate is found in cucumber leaf, affected by downy mildew disease caused by *Pseudoperonospora cubensis*. Deleterious effect of this disease was detected by thermal imaging technique by Oerke *et al*., 2006. They made a green-house experiment, where cucumber leaf was inoculated with the above mentioned agent and they found higher canopy temperature difference between healthy and diseased leaf from thermal image which were recorded day by day for up to 8 days after inoculation. Effect of fungal inoculation of *Plasmopara viticola* on grapevine leaves with the spatial inconsistency of temperature was studied by thermal imagery (Lindenthal *et al.*, 2005).

2.6.2 Determination of Fruit Yield

Observation of citrus fruits was done by inspecting temporal variation of citrus canopy with the aid of thermal imaging technique (Bulanon *et al.* 2008). The motto of this study was on identification of fruit from leaf for improving robotic harvesting of fruit which is an alternate way of hand-made harvesting. Images were taken throughout the day at an interval of 15 minutes and then image analysis was done of the selected region of interest and it was found that fruit temperature was higher in comparison to citrus canopy by a magnitude of 1.6^{o}C from evening to early morning of next day, but this temperature variation is more or less 0.6^{o}C during other time of the experiment. Their findings indicated that thermal imaging has a capability to discriminate fruit from its canopy from end of afternoon to midnight time. Stajnko *et al.*, 2004, also showed that thermal imaging is useful in determination of diameter of apple fruit and its number in an orchard and from this they were able to predict possible yield of that orchard. Thermal images were taken by hand held thermal camera at consecutive five stages of fruit growth. Later, different image processing design or algorithim, thresholding technique, image filtering process were applied in order to separate fruit from its background. Their findings presented a good correlation (R^2=0.83–0.88) between image derived fruit number and the number of fruit that is obtained from manual harvesting and a R^2 = 0.68 - 0.70 was obtained between image analysis derived apple diameter and the diameter that has been found by manual measurement. This showed another potential capability of thermal imaging

2.6.3 Bruise Detection in Fruits

Bruising is one of the consideration for dismissing natural products amid sorting, because bruised or lessoned fruit has its own capability to make another undamaged fruit to become bruised during the time of fruit storing. For detecting this trait Baranowski *et al*., 2009, derived a method for sorting early bruising in apple by using pulsed-phase thermography (PPT). Observation showed that lessoned part of the fruit possess lower temperature than the non-lessoned portion, hence capability of this PPT technique is well established from their study. Varith *et al*., 2003, also developed a methodology based on thermal imaging technique for detection of bruise in apple by determining the thermal diffusivity of bruised and un bruised part of the fruit.

2.6.4 Maturity Evaluation of Fruits

Firmness and development or maturity, are critical properties with respect to the nature of leafy foods and vegetables. Thermographic technique is shown to be potential in detecting mechanical injury and fruit maturity (Hellebrand *et al*., 2000). Maturity evaluation of Japanese pear (*Pyrus serotina* Rehder), and tomato (*Lycopersicon esculentum* Mill) was done with the help of Infra-Eye 102A thermal camera by Danno *et al.*,1980.

2.6.5 Detection of Foreign Bodies in Food

The existence of foreign materials in food is a noteworthy security concern and different strategies are utilized in the food processing industry. Although, there are many methods like sieving, X-ray machines, optical sensors, but there is no universal methods for detecting all kinds of foreign materials regardless of their size and shape. Warmann and Märgner (2005) examined the presence of foreign materials in hazelnuts and output of thermal image analysis of single nuts revealed the nature of individual nuts by using a Thermosensorik CMT 384, warm camera. The study showed that thermal imaging could be utilized to recognize foreign body and decide the nature of individual hazel nuts.

2.6.6 Plant physiology and Agronomy

Plant physiology and agronomy are the two major fields where thermal imaging can play a big role based on some level of modification of plant water relation. Nevertheless, thermography had also showed its potentiality in the study of chemical, pathogenic and pollutants interaction with stomatal conductance and other physiological behaviour of plant. Accurate assessment of alteration of water loss, which depends on stomatal behaviour, by thermography, decides the usefulness of thermal imaging in the study of physiological function of plant (Inoue, 1986, 1990). In addition to above, thermal image analyses can estimate contrast in photosynthetic rate (Inoue, 1990), due to its dependence on stomatal regulation (Jones, 1995). Nilsson, 1995, showed the potentiality of thermal imagery for diagnosing and studying plants with various agronomic treatments.

2.6.7 Thermography in Forestry

Usefulness of thermal imaging in almond trees under water-deficit conditions was carried out by García-Tejero *et al.*,2012. And a good estimation was derived from thermal image analyses, which showed proper correlation between water stress and young plant. Number of apple fruits along with their diameter were studied using thermal imagery by Stajnko *et al*., 2004, and a thermal gradient between fruit from its background was estimated. Sankaran *et al.*, 2013, highlighted the usefulness of thermal imaging in proximal remote sensing for daily disease observation in citrus orchard.

2.6.8 Genetic screening

Screening of huge numbers of genotypes in relation to water availability in the area of genetics and plant breeding is also possible by thermal imaging. First fruitful attempt in plant genetic screening for isolating mutant through thermal imaging was carried out by Raskin and Ladyman, 1988. Recent study showed that, thermal imaging, have the capability of isolating Arabidopsis from a lot of 85,000 m^2 (Merlot *et al*., 2002; Mustilli *et al*., 2002).

2.7 Potential, Limitation and future prospect of thermal imaging

The after effects of this study affirm past discoveries that infrared thermography offers extraordinary potential in assessing water stress level in crop. In comparison to thermometry, thermal image provide temperature values for each pixels in the field of view. Thus it makes very easy differentiation of various component of image like sunlit and shaded portion of canopy and sunlit and shaded soil area etc. Thermal cameras are not complex gadgets furthermore, can be utilized by farmers for enhancing watering system under limited water condition. Nevertheless, currently available thermal cameras are essentially intended for non-agriculture purpose, mostly for inspecting building and industrial machinery. A broad utilization of thermography by agriculturists may give motivating force to producers to create improved cameras that are more proper for farming applications.

Quality cameras are expensive and cheaper have less resolution. Images are difficult to interpret when it contains too many objects with erratic temperature pattern. Accurate temperature measurement is not maintained by too many emissive objects and their different pattern of reflectivity. Most of the cameras have the accuracy of 2% which is not so similar as obtained from contact temperature measurement. It is only able to detect surface temperature. Thermal imaging cameras cannot be used to see object under water and through a glass or from any reflective surface as IR images reflected much like a mirror. Viewing range of thermal camera is also less than any other cameras and human eyes. In spite of all these due to its quick and reproducible results thermal imaging has immense potential for its application in agriculture, especially in crop stress monitoring.

3. MATERIALS AND METHODS

Common materials and methods used in the study are described in following sections of this chapter.

3.1 Experimental site

Field experiments were conducted at the experimental farm (Main Block 4C) of Division of Agricultural Physics of Indian Agricultural Research Institute, New Delhi, located at $28^{o}38'23''$ North latitude and $77^{o}09'27''$ East longitude and having altitude of 228.6 m above mean sea level. The climate is subtropical and semiarid characterized by hot dry summer and cold winter. The soil at the experimental site is classified under the major group of Indo-Gangetic alluvium (Typic Haplustept), non-calcareous and slightly alkaline in nature. The mean monthly maximum temperature in the rabi season (November to April) ranges from 20 to 36°C and mean monthly minimum temperature from 6 to 19°C. Mean annual rainfall (30 years average) is 769.3 mm, of which 75% is received during the south west monsoon season between July to September and very little rain is received in *rabi* season.

3.2 Treatment and crop management

The field experiments on wheat based cropping system was commenced in 2014-15 and 2015-16 at IARI research farm (MB 4C) to study the effect of moisture stress on crop performance and characterise different crop biophysical parameters like leaf area index (LAI), normalized deviation vegetation index (NDVI), photosynthesis, stomatal conductance, leaf stem and panicle biomass along with its yield. The treatment comprises of 4 levels of moisture stresses, I1, I2, I3, I4. Irrigations were given on IW/CPE ratio, and the respective values of this ratio for different moisture stress levels are furnished in the table.

Wheat crop under I1 irrigation treatment is considered to be non-stressed condition while crop under irrigation I4 is supposed to be under highly stressed condition. For proper growth of the crop N, P and K were applied at the rate of 150, 60 and 40kg/ha respectively. Nutrients were applied as, urea for N, SSP for phosphorus and Muriate of potash for K. Nitrogen was applied in two split, 50kg N was applied at the time of sowing and rest portion was applied during late tillering stage. Field was kept weed free by employing manual weeding 3-4 times during crop growth stage.

Table 3.1 Moisture stress treatments

Treatment	Amount of water (cm) irrigated	IW/CPE
I1	25	1
I2	20	0.8
I3	15	0.6
I4	5	0.4

3.3 Observations and Measurements.

3.3.1 Daily meteorological data

Daily weather parameters (maximum and minimum temperatures, rainfall, relative humidity, wind speed, bright sunshine hours) for the crop growth period (2014-15 and 2015-16) were obtained from meteorological observatory present near the field, at the Division of Agricultural Physics, IARI, New Delhi.

3.3.2 Soil physical parameter

3.3.2.a Soil Moisture

Soil moisture at different depths (0-15, 15-30, 30-45, 45-60 cm) was estimated by gravimetric method. Soil samples were collected by screw-auger in aluminium cans and were weighed and kept in hot air oven and was allowed to dry at 105^{o}C until a constant weight is achieved for two days. Dried samples were weighed and the moisture content on mass basis was calculated using the following formula:

Mass wetness= (Fresh weight-Dry weight)/Dry weight ……… (1)

Thereafter, this mass wetness value was multiplied with BD to get volumetric moisture content. Soil moisture was also measured by tube moisture meter, which gives profile moisture measurement by displaying count number. It can measure moisture up to 90 cm depth at 15 cm interval. The count number which was obtained by this instrument was put in a mathematical equation to get moisture content at respective depth.

3.3.2.b Soil temperature

Soil temperature at different depths (0, 30cm) was measured with the help of soil thermometer (Thermotech TH044) at 2.30 pm.

3.3.2.c Soil Bulk Density

The core sampler was pushed into the soil to the desired depth in such a way that soil core is collected from the centre of the given depth (e.g. 0-15, 15-30, 30-60, 60-90 and 90-120 cm). Core with soil samples were dried in oven at 105^{o}C for 48 hrs. Bulk density (g cm^{-3}) was calculated by dividing weight of dried soil by the volume of core used (Veihmeyer and Hendrickson, 1948) by using the formula:

$$BD = (X - Y) / V \qquad \text{……….} (2)$$

Where, BD is the bulk density in g cm^{-3}, X is the weight of core with oven dry soil (g), Y is the weight of empty core (g) and V is the volume of core (cm^{3}). For each soil depth, three core soil samples were taken and their bulk density values averaged.

3.3.2.d Mechanical composition - Textural analysis

The percent sand, silt and clay contents were determined by hydrometer method (Bouyoucos, 1962), and soil texture was determined with the help of textural triangle as proposed by USDA.

3.3.3. Soil chemical property

3.3.3.a Soil EC and pH

Soil EC and pH were measured (0-15, 15-30, 30-60 cm) by preparing a soil-water suspension (1:2.5) by weighing 10 g air-dry soil (<2 mm) into a beaker containing 25 ml deionised water. Sample was mechanically shaken at 15 rpm for 1 hour to dissolve soluble salts. EC of the soil suspension was measured using a conductivity meter (Model No.-2300, Hanna instrument, Germany) and pH meter (Model No. 2215, Hanna instrument, Germany).

3.3.3.b Soil Organic Carbon (SOC)

Soil organic carbon at different depths (Surface, 0-15, 15-30, 30-60 cm) was determined for initial field conditions, using titration method (Walkley and Black, 1934). For calculation of % Organic carbon following formula was used:

$$Soil\ Organic\ Carbon\ (\%) = \frac{10(B-S)}{B} * 0.003 * \frac{100}{weight\ of\ sample\ (g)} \quad \ldots\ldots (4)$$

Where, B and S stands for the titer values of blank and Sample respectively.

3.3.3.c Soil Ammonium and Nitrate-N content

For estimation of ammonium and nitrate-N, for different depths, 10 g dry soil was extracted with 100 ml of 2M KCl solution. The content of NH_4^+ and NO_3^-- N were estimated by following the method given by Keeney and Nelson, (1982).

Table 3.2 Soil physical characteristics of experimental site

Soil depth	BD	Field capacity	Depth of water at FC	Wilting Point	Depth of water at WP	Available WHC	Depth of WHC
cm	(g/cc)	fraction	cm	fraction	cm	fraction	cm
0-15	1.52	0.24	5.472	0.07	1.596	0.17	3.876
15-30	1.66	0.23	5.727	0.08	1.992	0.15	3.735
30-60	1.68	0.25	12.6	0.09	0.4536	0.16	12.1464
60-90	1.72	0.25	12.9	0.09	0.4644	0.16	12.4356
90-120	1.75	0.26	27.3	0.10	0.1050	0.16	16.8

Table 3. 3: Soil Chemical Properties

Depth	Organic Carbon content		Available Nitrogen	pH	EC
(cm)	%	g/Kg	Kg/ha		ds/m
0-15	0.47	4.70	221.19	7.2	0.45
15-30	0.34	3.38	171.85	7.1	0.28
30-60	0.22	2.23	160.12	7.4	0.25

3.3.4 Biophysical parameters

3.3.4 a Phenological growth stages

Phenological development of the wheat crop was closely observed visually and their accurate dates were recorded. The phenological stages identified were:

emergence, crown-root initiation (CRI), tillering, jointing, anthesis, dough, and physiological maturity. Following Penning de Vries *et al*., 1989, the representation of crop development is made in a very simple way, by using a quantitative scale from 0 (emergence) to 1 (flowering) and 2 (maturity).

3.3.4 b Leaf Area Index

Leaf Area Index (LAI) was measured using Plant Canopy Analyzer (LAI-2200, LICOR inc., Nebraska) following the standard procedure given by Welles and Norman (1991). LI 2200 provide immediate LAI estimation by measuring simultaneously diffuse radiation by means of a fish eye light sensor in the five distinct zenith angle of 7, 23, 38, 53 and 68 degrees. Multiple LAI observations (at least five) on each date at different locations within each plot were recorded and their average were calculated to represent LAI of that plot on that day. A quarter view cap, was placed on sensor to exclude the operator, and the rest of the hemispherical view was used to calculate LAI.

3.3.4 c Biomass

Number of plants that were obtained from a 30cm scale were counted from each plot. The site which was selected for biomass sampling was identical one which was chosen based on the visual observation. After that, different plant parts like plant number, tiller number, leaf, stem and panicle were separated depending on the growth stages (CRI, Tillering, Flowering, and maturity). These plant materials were oven-dried at 65^{o} C for 48 hours or more until constant weight was achieved as recommended. Dry biomass produced was expressed as g m^{-2}. At harvest panicle number, leaf weight, stem weight, 1000 seed weight, total weight of grains for treatment were recorded. After threshing and winnowing, grains were weighed to estimate grain yield for whole plot.

3.3.4 d Photosynthesis and associated parameters

Rate of photosynthesis was measured using portable Infrared Gas Analyzer (IRGA), model LI-6400XT Model (Li-COR Ltd., Lincoln, Nebraska, USA) equipped with air supply unit and a broad chamber. The rate of photosynthesis, respiration, stomatal conductance and transpiration rate were measured by operating the IRGA in the closed mode. The parameters were expressed in the following units; rate of photosynthesis (µmol CO_2 m^{-2} s^{-1}), stomatal conductance (mol H_2O m^{-2} s^{-1}), transpiration rate (mmol m^{-2} s^{-1}). Measurements were made on the topmost fully expanded leaf between 10.00 hrs to 12:30 hrs IST when photosynthetically active radiation is maximum.

3.3.4 e Normalized Difference Vegetative Index (NDVI)

NDVI measurements were taken with the GreenSeeker™ Handheld Optical Sensor Unit (NTech Industries, Inc., USA) in the central rows of all plots. The instrument gives the NDVI as it is calculated from reflectance measurements in the red and near infrared (NIR) portion of the spectrum:

$$NDVI = \frac{R_{NIR} - R_{RED}}{R_{NIR} + R_{RED}} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (7)$$

Where, R_{NIR} is the reflectance of NIR radiation and R_{Red} is the reflectance of visible red radiation.

3.3.5 Canopy thermal properties

3.3.4 a Infra Red Thermometer (IRT) measurements

Canopy temperature was measured by a hand-held infrared thermometer (EXTECH, New Hampshire, USA) with 8° field of view. Canopies emit long wave radiation as a function of their kinetic temperature. Infrared thermometer senses this radiation and converts it into electrical signal. The readings were taken during the time of 2.30 pm when the crop was supposed to be under maximum ambient temperature condition.

3.3.4 b Thermal image acquisition

Thermal images were taken by using hand held and robust thermal camera (Testo 890-1). This camera contains the following features, high-quality wide angle lens 42° x 32°, detector 640 x 480, it has the thermal sensitivity (NETD) < 40 mK at 30°C (86°F), the minimum focusing distance is 0.1 m and having the geometric resolution (IFOV) 1.13 mrad (standard lens). It works between the spectral range 8 - 14 µm. It can sense a broad range of temperature from -20 to 100°C with accuracy of ±2°C. The images were available in.bmt, format file format, but were possible export to .bmp, .jpg, .png, .csv, .xls format type. Detector type is FPA (Focal plane array).

Camera can provide an image of 640 x 480 pixels. This camera can provide both thermal and visible images. Thermal images were taken during crop growth stage wise and were taken from nadir view angle. Images were taken around 1.30 to 2.30 pm, when the plant is supposed to be under maximum temperature stress condition. Representative canopy portion was selected before taking the images and the thermal image contains dry reference leaf (leaf covered with petroleum jelly), wet reference (leaf sprinkled with water 1 minute before taking the image) and the normal leaf. Thermal images which were obtained from this camera contain leaf area and from this region of interest we can get temperature of this canopy by selecting their corresponding pixels.

3.4. Indices based on leaf/canopy temperature

Thermal images are highly employed to detect water stress in several crops, since drought promotes stomatal closure, reducing transpiration and evaporative cooling, while increasing leaf temperature. Thermal normalized thermal indices (CWSI, IG and I3) were developed to avoid the variability produced by environmental parameters affecting the relationship between stress and plant temperature (Jones, 1999; Leinonen *et al*., 2006). Crop water stress index was determined by applying the algorithm suggested by Jones, 1992, which is improved version of the equation as proposed by Idso (1982). CWSI (crop water stress index) ranges from 0 to 1 (values close to 1 are related to high levels of stress) (Idso *et al*., 1981), IG directly increased with stomatal conductance and the I3 positively correlated with stomatal resistance (Jones, 1999; Leinonen *et al.*, 2006), taking into account surface temperatures under wet and dry conditions as follows:

$$CWSI = (T_{canopy} - T_{wet}) / (T_{dry} - T_{wet})$$

$$IG = (T_{dry} - T_{canopy}) / (T_{canopy} - T_{wet})$$

$$I3 = (T_{canopy} - T_{wet}) / (T_{dry} - T_{canopy})$$

Where, T_{canopy} is the surface temperature of the canopy and T_{wet} and T_{dry} are reference surfaces that are completely wet or dry to simulate maximum and minimal leaf transpiration under the exposed environmental conditions. T_{wet} and T_{dry} represent the two reference leaf, T_{wet} is wet reference which is painted with water and transpire continuously and T_{dry} represents canopy temperature of the leaf which is covered with petroleum jelly and act as non-transpiring leaf respectively (Idso 1982; Jones 1992).

Details about thermal indices, are available in Jones (1999) and Jones and Vaughan, 2010.

3.5. Image classification through ENVI

Image classification technique assigns the picture elements into various land cover classes. For this, it uses the pixel by pixel spectral information for this categorizing various classes. Image classification is based on statistical decision theory. The decision to categorize a particular pixel into various classes depends on statistical analysis. It mainly works based on the algorithm that was assigned in respective image classification process. The most renowned sorts classifying an image includes unsupervised method which needn't bother with an earlier information of the region and the supervised classification method which needs earlier information of the region in which the process going on (Lillesand and Kiefer, 2000). In unsupervised classification opportunity for human error is much less. Unsupervised classification techniques are mainly used when number of classes that has to be separated is large and there is no ground truth data. But apart from these advantages it has some shortcomings too. Unsupervised classification identifies spectrally homogeneous classes within the data; these classes do not necessarily correspond to the informational categories that are of interest to analyst. Here in this case our main aim is to classify the image into two broad classes that is crop area and ground area and number of classes are very much less in the raw image. Here, image classification was done using ENVI 4.8 supervised classification methods. Selection of region of interest (ROI) will be separate for various land cover classes. If the number of ROI is more classification will be good. In ROI selection process we have picked respective color in which we want to get our classified image for several classes. If a pixel value lies above the lower threshold but below the upper threshold, the pixel will be included into this class. In supervised Maximum likelihood method, Mahalanobis method, Minimum distance method, Parallelepiped method and Spectral angle mapper method were used. Here a solitary pixel that is illustrative for preparing training set is characterized, then the system framework makes an inspection between the seed pixel and the bordering pixels, taking into account a few parameters determined by the expert. When one or a greater amount of the neighbouring pixels is acknowledged, the mean of the sample is computed from the unknown pixels, and after that the pixels coterminous to the example are thought about similarly. This procedure rehashes until no pixels that are coterminous to the example fulfil the spectral parameters.

3.5.1 Maximum likelihood method

Maximum likelihood method is well known for its excellence in classifying images based on the probability that an unknown pixel which is to be grouped into an image class. The fundamental hypothesis believe that these probabilities are equivalent for all classes, and that the input groups are normally distributed (Al-Ahamadi, F. S. and Hames, A.S 2009). This Classification method utilizes the training data to calculate means and variances of each and individual classes for assessing the probabilities, it furthermore considers the variability of brightness qualities in every class. This makes its wider in use in classifying when accurate training data set are provided (Perumal, K and Bhaskaran, R 2010).

3.5.2 Minimum distance to mean classifier method

Minimum distance to mean classifier is the simplest classification technique, which is based on the minimum distance conclusion rule that estimate the spectral distance between an unknown pixel and the mean vector for each sample class (Perumal, K and Bhaskaran, R 2010). Here at first mean value of each training classes were computed. Then to categorize an unknown pixel into a specific land cover class Euclidian distance of the pixel to the mean value will be computed. The pixel will be assigned to that class whose distance is nearest to mean.

3.5.3 Mahalanobis method

Mahalanobis method of image classification is more or less same as minimum distance method except that the previous includes covariance matrix for each classes. This strategy also considers variability of classes into account. And it is found to be more helpful functional where statistical criteria are considered (Al-Ahamadi, F. S. and Hames, A.S 2009). Algorithm that support this classification procedure also assume that the histogram of the bands are obeying Gaussian distribution (Perumal, K and Bhaskaran, R 2010).

3.5.4 Parallelepiped method

Parallelepiped classification uses a simple decision rule to classify multispectral data. The decision boundary forms an n dimensional parallelepiped classification in the image data space. The dimension of the parallelepiped is based upon a standard deviation threshold from the mean of the selected class. In both of the above process training step is regarded as sole of the image classification. Here, we have to first supervise the software by selecting several region of interest (ROI) of the image that we are going to classify (Lillesand and Kiefer 1987). The main disadvantage of this method is that it leaves some unclassified area which makes them not wide acceptability (Perumal, K and Bhaskaran, R 2010).

3.5.5 Spectral angle mapper method

Spectral angle mapper is another method which is based on physical perception for separating spectral classes that mostly utilizes an n dimensional angle to match an unknown pixel to reference pixel. The algorithm which works behind this classification technique decides similarity between two spectra by determining the angle between two spectra (Perumal, K and Bhaskaran, R 2010)

3.6. Evaluation of Classification

The target of supervised image classification scheme is not only to prepare a land cover map but also the area coverage by different classes. This classification scheme also shows how the selected ROI had performed in classifying the image by identifying the potential misclassified area. ENVI's confusion matrix function allows comparison of two classified images (the classification and the truth image) or a classified image and ROI's. The relation between these two compared information is generally pictured in confusion matrix or error matrix. The column number and row number in the confusion matrix should be equivalent to the quantity of classes whose characterization precision is being evaluated (Lillesand and Kiefer, 2000). In confusion matrix two accuracy are determined i.e., Producer's accuracy and the User's accuracy. Omission error compute the likelihood of a pixel of being precisely classified or grouped (Producer's accuracy). This shows how good a training data set is well classified. Error of Commission decides the likelihood that a pixel depicts to the class for which it has been appointed (User's accuracy). The value which is obtained by dividing the total number of correctly classified pixel to the total number of tested pixel gives the measurement of overall accuracy or total accuracy (Lillesand and Kiefer, 2000, and USACE, 2003). Another trademark coefficient that can be gotten from confusion matrix is Kappa coefficient (K) which is a marker of the degree to which the percentage right estimations of a confusion matrix are because of "genuine" understanding versus "chance" accordance, and it ranges from 0 (most noticeably awful) to 1(best). Here in this case the number of region of interest that has been taken for accuracy assessment was 45 to 55 depending on image that has been classified. Formulas of the above said parameter are given below (Hasmadi et all 2009).

Producer's accuracy (%) = 100(%) – error of omission (%)

User's accuracy (%) = 100(%) – error of commission (%)

$$\text{Overall accuracy (\%)} = \frac{total\ number\ of\ correctly\ classified\ pixels * 100}{total\ number\ of\ sample\ pixels}$$

$$\text{Kappa coefficient, } k = \frac{\theta 1 - \theta 2}{1 - \theta 2}$$

$$\theta_1 = \frac{\sum_{i=1}^{N} x_{ii}}{N} \qquad \theta_2 = \frac{\sum_{i=1}^{N} x_{i+} x_{+i}}{N^2}$$

Where X_{ij} = number of count in the ijth cell of the confusion matrix.

N= total number of counts in the confusion matrix

X_{i+} = marginal total of row i

X_{+I} = marginal total of column i

3.7. Post-Classification Processes

It is regularly advantageous to smooth the final classified images to indicate just the prevailing probably right classification or characterization**.** Post classification image processing was done just for getting less noisy appearance, the processes which were applied for this purpose are Sieve and Clump. This two post classification activity was done for all the five methods of classified images. Sieve method investigate neighbouring 4 to 8 pixel for determining whether all the pixels are grouped or classified into right section or else. If the number of the pixel for a specific class that has been grouped as assigned by the analyst is less than that of being classified then the corresponding pixel will be removed. It is sometime encountered that the classified images suffers from spatial coherency (speckles and holes appearance), to avoid this type of untoward effect clump method is followed after image classification (Al-Ahamadi, F. S. and Hames, A.S 2009). At first a dilate operation is conducted on the classified image for clumping the classes together, then another step called erode operation is done for finalizing the whole post classification processing.

3.8. End product

At the end the classified image was obtained, where two or classes were there. As our main target is to get the two broad classes after classifying the image that is crop area and ground area. But t has been found that the resulting classified image giving at least four classes i.e., sunlit leaf, shaded leaf, sunlit soil and shaded soil. Hence the pixel that are related to each of two classes like sunlit and shaded leaf were merged into crop as a broad class and the same thing was done for ground class where sunlit and shaded soil area were merged together. To get the percentage coverage by these two classes the statistical parameter of this classified image from ENVI 4.8 Quick stat was derived. Here the percentage coverage by this two classes including the number of pixel that are confined by this two classes were obtained that also include the mean and standard deviation value of the particular band. Then leaf area index was calculated using the information obtained above by dividing one sided leaf area to ground area. Latter correlation was calculated between instrumental LAI value with image derived leaf area index for all the five image classifying method.

3.9. Statistical Analysis

Analysis of Variance (ANOVA) under a Randomized Completed Block Deign design setup was used to assess the significant difference among the various factors as well as their interactions. Further, Tukey's HSD was used to assess pair-wise significance among the various factors as well as their interactions wherever significance were noted through ANOVA.

4. RESULTS

Objective 1: Characterization of crop condition using thermometry and crop biophysical parameters under different moisture stress conditions in wheat

4.1 Weather

Weekly mean maximum and minimum temperature, total weekly rainfall and weekly mean Relative Humidity and wind speed, for the 2014-15 and 2015-16 *rabi* seasons are shown in the Fig.4.1. Maximum and minimum temperature during the two years showed similar trend of initially decreasing till mid - January and then steadily increasing till April. Mean maximum temperature was highest in the month of April and lowest in January. Mean minimum temperature also showed similar pattern. In general, the average maximum temperature was about 22.9°C and 25.0°C during crop season of 2014-15 and 2015-16 with minimum temperature of about 9.19°C and 8.88°C respectively. There were considerable differences in the amount of rainfall received during the two crop years. In 2014-15, total rainfall of 264 mm was received during the entire crop season while in 2015-16 it was only 19.2 mm. The year 2014-15 was abnormally wet in terms of rainfall and its distribution. During the end of the season considerable amount of rainfall was received in both the years. However significant differences were not observed in wind speed and sun shine hours.

4.2 Leaf Area Index

The seasonal profile of wheat LAI for different treatments in 2014-15 and 2015-16 are shown in the Fig. 4.2. In case of all the four treatments in both the years, LAI profile showed a typical pattern of first increasing during greening phase, then reaching a peak near maximum vegetative growth stage and then decreasing due to senescence. LAI was highest in both years 2014-15 and 2015-16 for I1 followed by I2, I3 and lowest in I4. The peak LAI values were 5.6, 5.08, 4.77, 4.27 in 2014-15 and 5.73, 5.09, 5.03.4.62 in 2015-16 for I1, I2 I3 and I4 treatments respectively. In general under stress condition peak LAI was found to be earlier than those observed in ambient condition. Under the treatment I4 which is having the maximum moisture stress, peak LAI was obtained 4-5 days earlier than ambient condition in both the years.

The differences in LAI among the treatments were not significant at the beginning and end of the crop growth. Maximum differences among treatment were observed during the panicle initiation and flowering stages. During grain filling stage rapid reduction in LAI was observed with maximum rate of reduction observed under treatment I4. These results indicate that moisture stress condition resulted in significant growth loss and reducing the leaf area. In both the years, a rapid decline in LAI was observed during senescence phase for plants grown under I4 – stress treatment than plants grown under I2 or I3 conditions. Thus moisture stress results in lower growth and LAI as well as it caused early maturity thus causing peak or maximum LAI to be reached earlier.

4.3 Normalised Difference Vegetation Index (NDVI)

The variation of normalised difference vegetation index under different treatments across both the years 2014-15 and 2015-16 is shown in fig 4.3 Significant decrease in NDVI during tillering and flowering stages were observed under different moisture stress treatments during both the years under study. In general NDVI decreased by 4.5-5.5%, 4-5% and 2.5-3.5% under I4, I3 and I2 treatments respectively over both years. During flowering stage NDVI decreased by 11-12%, 5.5-6.5% and 7.5-8.5% respectively under I4, I3 and I2 stress conditions when compared with I1 over both years. Thus individual m treatments as well as crop growth stages were found to be significant (p value <0.01) across both the years.

4.4 Soil Moisture content

The temporal and spatial distribution of mean volumetric soil moisture content (SMC) in each treatment is shown in Fig. 4.4 & 4.5**.** The effects of different moisture stress were clearly seen on the profile of SMC among different treatments. During the initial period, there was not much of a difference in profile SMC among the different treatments but with the progress of season and crop growth, the moisture content remained at its highest in I1 followed by I2, I3 and then in I4 in both the years 2014-15 and 2015-16. During 2014-15, due to high rainfall received, the profile moisture content remained at its high as compared to that in 2015-16. Under ambient moisture condition volumetric moisture content varied within Field capacity to Permanent wilting point in both years. Under extreme stress conditions like I3 and I4 moisture content was below permanent wilting point (6.02-6.43 cm) in 2015-16 but only in I4 (7.23 cm) in 2014-15 as this year received higher rainfall at the end of season as compared to 2014-15. In case of non-stressed moisture treatments, the profile moisture content started decreasing from 30 DAS and similar trend was observed till 45-48 DAS and then again increasing till 60 DAS. At the end of the season a peak in moisture content was noticed due to the occurrence of rainfall especially during the year 2014-15. Under moisture stressed condition, profile moisture content increased upto 30-33 DAS and then decreased, although a sudden small rise was noticed at the end of season.

4.5 Soil Temperature

The temporal and spatial distribution of soil temperature changes in each treatment as shown in Fig. 4.6 for both the two year of study. It was generally observed that the soil temperature was lowest in the top layers (15 and 30 cm) during the initial stages of the season and crop development. But with the progress of the season and the crop development the temperature in the top layers increased significantly and attained higher temperature than those of the bottom layers at the end of season. This appeared at around grain filling stage in ambient condition. However temperature change from lower value to higher values occurred at earlier stage of the crop growth (50% flowering stage) in crops under moisture stress condition. In general the surface layer temperature varied between 15.21 to 22.23 °C in 2014-15 and 14.87°C to 23.63 °C in 2015-16. The treatment effects were found to be significant in both years. Under high moisture stress the surface average temperature increased by 32-34% in 2014-15 and by 25-26% in 2014-15. However the average temperature up-to 60 cm, increased by 13-15% in 2014-15 and 11-12% in 2015-16. This shows that effect of moisture was more seen in surface layers than in the underground soil layers. In general the average temperature pattern was I4 > I3 > I2 ~ I1 in both the years. The soil layer profile showed the least soil temperature at 30 cm i.e., the damping depth irrespective of the temperature stress in all the treatments.

4.6 Temperature measurement by IRT and Thermal Image

IRT canopy temperature measurements were significantly lower than the thermal camera measurements during both the years. In general, the IRT canopy temperature measurements were significantly lower than those taken by Thermal camera under moisture stress condition in the afternoon but significantly higher than those taken on the normal irrigation treatment I1. On the normal irrigation treatment I1, the average IRT measurements was 0.05 degrees warmer than the air temperature, this was anticipated when solar radiation, transpiration, and evaporative cooling are minimum. On the other hand, average measurements by the Thermal camera during the same time was 2.24°C degrees lesser than air temperature. This might be due to be the result of greater shading within the plants. In general, thermal camera was at the nadir position directly above the plot during the measurement. When the Thermal camera was held above the plot it captured a maximum greater expanse of shaded plant area compared to that of the IRT, which was observed at a 45-degree angle at eye-level. This is because, when the sun is directly overhead in the afternoon, no shading was visible from the point-of-view of the Thermal Camera.

4.7 Thermal Image of the wheat crop

Thermal images were taken with a Thermo vision camera (model Testo-876) from a 3-m step ladder above the plots (Fig.4.7, 4.8, 4.9, 4.10 for different crop growth stage). IRT measurements were also taken at eye-level using an EXTECH brand thermometer. The thermal images were post-processed using custom software to filter out background soil and to calculate the canopy temperature mean and standard deviation of each plot.

4.8 Crop Canopy Temperature

For all the treatments the crop canopy temperatures (CCT) were found to be non-significant at tillering stage (p value > 0.05) (Fig. 4.11). At tillering stage the crop canopy temperature was the least (around 10^{o}C). However with the advancement in crop developmental stage the canopy temperature also showed a steady increase. For example at flowering stage the crop canopy temperature was about 27^{o}C during both the years. Moisture stress treatments had significant effect on crop canopy temperatures. Among the different treatments, I4 showed consistently highest CCT of about 26-27^{o}C in 2014-15 but was around 27-28^{o}C in 2015-16. These differences may be due to greater rainfall in 2014-15 as compared to 2015-16. In general individual treatment mean effect of all the treatment was found to be significant in both years. But interaction effect was found to be insignificant between I1 and I2 in 2014-15.

4.8.1Crop Canopy Temperature Depression

Canopy Temperature Depression (CTD) is usually expressed as air temperature minus canopy temperature, and this value is higher and a positive number in a well irrigated wheat crop. CTD measurement during the crop growth showed (Fig. 4.12) variations depending on the occurrence of rain and irrigation given to the crop as per the different moisture stress treatments. However the differences in CTD were prominently noticed during the crop vegetative stages and flowering. In general wheat crop grown during 2014-15 showed less CTD than those grown during 2015-16. In both the years the minimum CTD value was observed in treatment I4 and CTD values were mostly high and positive in treatment I1. In general, treatment I1 showed the highest CTD values and treatment I4 showed the least CTD values. Among the years tested in this study, during the year 2014-15 the CTD values were 30% higher than those observed during 2015-16. Moisture stress treatment had significant effect on the CTD values. The difference in CTD values of I2, I3 and I4 in comparison to I1 were 0.223, 0.676 and 1.343 times respectively during 2014-15 and were about 0.321, 0.915 and 2.74 times during 2015-16. Among the different crop growth stages observed in this study differences in CTD were insignificant during the initial and final stages of the crop.

4.8.2 Photosynthesis

Photosynthesis over both years was found to be lower under moisture stress conditions compared to normal irrigation during all stages of the crop (Fig 5.3). The maximum photosynthetic rate observed in different treatments were 25.47, 23.60, 21.92 and 21.26 μmol CO_2 m^{-2} $s^{-1}$for the treatments I1, I2, I3 and I4 respectively during the year 2014-15 and were about 24.78, 23.90, 20.85 and 20.76 μmol CO_2 m^{-2} $s^{-1}$for the treatment I1, I2, I3 and I4 respectively during the year 2015-16. In both the years at the photosynthetic rate showed a steady increase till flowering stage of the crop. At flowering stage photosynthetic rate decreased by 15.28, 25.25 and 37.28 % under treatments I2, I3 and I4 respectively. In general the effects of treatment and growth stages were found to be significant (p value < 0.001).

4.8.3 Leaf Temperature

Leaf Temperature (°C) was found to be increased under moisture stress treatments during both the years (Fig 4.14). Individual main treatment effects were found to be significant during both the years. Leaf temperature increased maximum under I4 (22-23%), followed by I3 (19.0-20.8%) and lowest in I1 (4.0-5.51%) in both the years. Among the two years of study the average leaf temperature under different moisture stress treatments and crop growth stages was 20.54 and 24.65°C respectively in 2014-15 and 2015-16. This was higher by about 16.74%.

4.8.4 Stomatal conductance (Cond) and Transpiration rate (Trmmol)

The variation of stomatal conductance and transpiration rate under different treatments across both the years 2014-15 and 2015-16 is shown in fig 4.13. Moisture stress effect was found to be significant for transpiration rate but the individual crop growth stages effect was found to be insignificant in both the years. Also transpiration rate was found to decrease under different moistures stress.

Similar to transpiration rate, stomatal conductance also decreased under moisture stress. But here also individual growth stage effect was found to be in-significant. Compared to the normal irrigation treatment (I1), under different moisture stress condition the stomatal conductance decreased by 19.05, 32.25 and 57.27% respectively under I2, I3 and I4 treatments during 2014-15 and by 38.9. 51.40 and 56.19% respectively during 2015-16.

4.9 Grain Yield and Biomass

Wheat grain yield and above ground biomass observed under different treatments in both the years is given in (Fig 4.15). In general during the study period - 2014-15 and 2015-16, the changes in grain yield and biomass were significantly decreased by moisture imposed in the different treatments. Overall the treatment effects for yield were found to be significant in both the years 2014-15 and 2015-16. But interaction between I1 and I2 was found to be insignificant in 2014 - 15. Per cent yield reduction under moisture stress under I2, I3 and I4 were 7.0 to 8.26, 37.385 to 42.947 and 62.59 to 63.39% respectively in both the years. In 2014-15 biomass varied from 704 to 1218 g/m^2 with a mean value of 999 g/m^2. The per cent reduction in biomass under I2, I3 and I4 were 7.1 to 7.3, 22.432 to 28.92 and 42.19 to 44.04% respectively in both the years. Greater reduction (24.65 – 26.75%) in biomass was found in 2015-16 as compared to 2014-15 (22.31 – 23.92% reduction) under pooled moisture stress treatments. This may be due to greater rainfall in 2014-15 reduced the moisture stress intensity and produced greater vegetative growth also lead to the crop lodging during grain filling stage. Harvest Index varied by 0.27 to 0.42 with a mean value of 0.37 in 2015-16 and 0.29 to 0.43 in 2014-15 with a mean value of 0.38. In general harvest index decreased with increase in moisture stress.

Significant reduction in tiller no was recorded under I2, I3 and I4 treatments compared to normal irrigation treatment I1. However, the percentage of reductions in I4 was higher than the reductions detected in I2. Similarly tiller no/m^2 showed considerable reduction with moisture stress. Treatment I2, I3 and I4 showed 6.0 to 11.46%, 12.68 to 14.87% and 21.11 to 22.23% in both years. Moisture stress had significant effects on panicle number / m^2. Treatment I1 had 300 panicles/m^2, however it reduced to about 100/m^2 in treatment I4. In 2014-15, the panicle no. under severe moisture stress treatment I4 was about 101/m^2 with a mean value of 189/m^2 across treatments. In 2015-16, the grain yield varied from 207.88 to 555.72 g/m^2 with a mean value of 344.90 g/m^2 across treatments and biomass varied 708 to 1266 g/m^2 with a mean value of 1006.05 g/m^2. However the harvest parameter 1000 seed weight though showed decrease with moisture stress, the effect was significant only for the treatment I3 and I4 which showed a decrease of about 19.23% and 34.21% respectively in both years. Treatment I2 was not significantly different from I1 as both the treatments showed around 43.10 to 43.36g of 1000 seed weight.

Objective 2: To estimate the crop stress index based on thermal image and correlate with biophysical parameter

Three thermal indicex namely crop water status index (CWSI), IG and I3 were characterised from the temperature data obtained by the thermal image and by infrared thermometer

(i) Thermal Stress Index 1 - Crop Water Stress Index by Thermal Image (TI) and Infrared thermometry (IRT)

Crop Water Status Index was calculated based on the temperature of the wet and dry reference temperature using thermal Image (TI) and Infrared thermometer (IRT). The changes in CWSI before irrigation under different treatments during the cropping season are given in Fig 4.17. CWSI values close to 1 are related to high levels of stress. CWSI based on TI and IRT increased with increase in moisture stress. In the I4 treatment the values of CWSI – TI ranged from 0.734 to 0.948 and CWSI – IRT ranged from 0.186 to 1.262. In normal irrigated treatment I1 CWSI – TI ranged from 0.249 to 0.666 and CWSI – IRT ranged from -0.165 to 0.897. Thus CWSI values increased with increasing moisture stress. The trends in the values for the different treatments were same in both the years. The seasonal mean of CWSI – TI for I1, I2, I3 and I4 were 0.489, 0.558, 0.696 and 0.794 respectively and that of CWSI – IRT was 0.643, 0.680, 0.662 and 0.922 respectively. However the CWSI – IRT showed huge variance and standard error the treatment effects were not significant for CWSI – IRT, nevertheless the treatment effects were significant for CWSI – TI.

(ii) Thermal Index IG - by Thermal Image (TI) and Infrared thermometry (IRT)

Thermal index IG was calculated from the thermal image (TI) and by IRT as described under materials and methods (Fig 4.18). IG directly increased with stomatal conductance. IG calculated both by Thermal Image and IRT show variations with the moisture stress treatments. IG is low for moisture stress treatments (I4, I3 and I2) and high for treatment I1. Among the two years tested IG values were higher in 2015-16 compared to 2014 -15 with a seasonal average of 1.101 and 0.763 respectively. The average Thermal index - IG values for I1, I2, I3 and I4 for the year 2014-15 were 2.458, 1.132, 0.576 and 0.237 respectively and that of 2015 – 16 were 1.305, 0.974, 0.477 and 0.296 respectively.

(iii) Thermal stress Index 3 (TSI3) – by TI and IRT

Thermal Stress Index TSI3, which is related stomatal resistance was estimated using the canopy temperature determined by the Thermal Image and Infrared thermometer (4.19). Values of TSI3 increased with increase in moisture stress. Mean seasonal values of TSI3 during 2014-15 was higher (3.085) than that of 2015-16 (-0.008). This is due to heavy rains received during 2014-15 than 2015-16. Irrespective of the method of determination (Thermal Image or IRT), the average TSI3 - values increased with increase in moisture stress treatment. For the year 2014-15, TSI3-TI for the treatments I1, I2, I3 and I4 were 1,165, 1.940, 3.094 and 5.893 respectively and it was 0.441, 0.933, 1.841 and 5.390 respectively for the year 2015-16..Similarly the TSI3 –IRT for the treatments I1, I2, I3 and I4 were -2.019, 2.794, 2.723 and 4.805 respectively for the year 2014-15 and it was -0.242, -0.172, 0.0702 and 0.312 respectively for the year 2015-16.

The inter relationship between different thermal indices, biophysical parameters and yield are shown in Table 4.1. Result showed that under moisture stress, treatments correlation between NDVI and LAI showed the maximum (0.961***). Among the three thermal indices tested, CWSI was highly correlated with Thermal Stress Index 2 – IG followed by TSI3. Similarly thermal stress indices calculated from thermal image based temperature were significantly correlated with the biophysical parameters than those of IRT based indices. In general thermal indices were negatively correlated with NDVI, LAI, PN, cond. and transpiration. Among the different thermal indices CWSI-TI calculated from thermal image based canopy temperature showed the highest correlation -0.733***, -0.823***, -0.785***, -0.799*** and -0.802*** with NDVI, LAI, PN, Cond and Trmmol respectively. Similarly with yield, thermal Image based indices were better correlated than IRT based thermal indices. Among the different indices calculated yield was best correlated with CWSI ,

Table 4.1: Correlation among All derived indices TSI3, IG, CWSI from TI and IRT and crop biophysical parameter

	TSI3- TI	*TSI3-IRT*	*IG- TI*	*IG - IRT*	*CWSI-TI*	*CWSI - IRT*	*NDVI*	*LAI*	*PN*	*Cond*	*Trmmol*
TSI3-TI	1										
TSI3-IRT	0.809***	1									
IG- TI	0.595**	0.575**	1								
IG - IRT	0.169^{ns}	0.450*	0.356	1							
CWSI - Thermal	0.710***	0.649**	0.870***	0.439*	1						
CWSI - IRT	0.604**	0.371^{ns}	0.820***	0.212^{ns}	0.849***	1					
NDVI	-0.817**	-0.760***	-0.620**	-0.382^{ns}	-0.733***	-0.647**	1				
LAI	-0.774***	-0.761***	-0.734***	-0.425^{ns}	-0.823***	-0.701***	0.961***	1			
PN	-0.692***	-0.571**	-0.633**	-0.455**	-0.785***	-0.654**	0.616**	0.616**	1		
Cond	-0.641**	-0.548**	-0.716***	-0.318^{ns}	-0.799***	-0.698***	0.530*	0.556**	0.939***	1	
Trmmol	-0.624**	-0.495*	-0.670***	-0.281^{ns}	-0.802***	-0.764***	0.576*	0.587**	0.922***	0.952***	1
Yield	-0.693***	-0.713***	-0.812***	-0.460*	-0.870***	-0.715***	0.872***	0.770***	0.622**	0.588**	0.593**

*** Significant at the p value < 0.01 level, ** Significant at the p value < 0.01 level, * Significant at the p value < 0.05 level, ns – non significant

PN- photosynthesis rate, Cond- stomatal conductance, Trmmol- transpiration,

4.10 Image classification and estimation of LAI from Thermal Image

Leaf Area index is an important indicator of crop stress status. Hence in this study efforts were made to characterise the Leaf Area Index (LAI) using thermal image analysis by applying image classification techniques.

Thermal image classification method utilised in this study uses algorithms that is applied systematically to the entire thermal image and it group pixels into meaningful categories. Further supervised classification method was used in this study, it required input from a ground truth, which was used as a training set. Thus identifying proper training set is the most essential factor in using this supervised classification for the thermal image. Therefore the accuracy of this method is highly dependent on the samples used for training. Samples used for training were of two types, one used for the actual classification and the other is used for supervising the accuracy of the classification.

Two set of categories namely green leaf, and soil were used to compare the accuracy of the five different supervised classification methods for analysing the thermal image. In order to determine the accuracy of each method in two categories, error matrices were generated. From this error matrices Kappa, coefficient value, overall accuracy, the producer's and user's accuracy were determined. In general overall accuracy and Kappa coefficient value showed the ratio of pixels correctly identified. The ratio of the verified pixels of a particular category that is rightly classified is given by producer's accuracy. User's accuracy is not important when methods of classification are evaluated. Thus overall accuracy, Kappa coefficient and producer's accuracy of error matrices are considered to evaluate each of the supervised classification methods used in this study.

Thus thermal images were evaluated by supervised classification using five methods (Fig 4.20) namely Maximum likelihood, Mahalanobis, Minimum distance to mean, Parallepiped and Spectral angle mapper methods. The accuracy evaluation of the five supervised classification methods for the two classed (leaf and soil) is given in Table 5. Overall accuracy and Kappa coefficient values of Spectral angle mapper method was not high in comparison with other four methods namely Maximum likelihood, Mahalanobis, Minimum distance to mean and Parallepiped. In particular, the producer's accuracies of Spectral angle mapper method were low for both the classes - crop and soil. On the other hand, overall accuracy and Kappa coefficient values of Maximum likelihood and Mahalanobis methods showed almost the same results with higher accuracy. On an average, the producer's accuracies of Maximum likelihood were higher for all categories. In comparison with the results obtained with Maximum likelihood, the producer's accuracies of Minimum distance to mean and Parallepiped were relatively low for soil. The K value was the highest (0.998) in Minimum likelihood followed by Mahalanobis, Minimum distance to mean and Parallepiped, with the least observed in Spectral angle mapper (0.432).

An instance of the image processing of the wheat crop under moisture stress treatments is presented in Fig.4.20 In this thermal image the shades closer to blue colour represent cool / low temperature and the shades of colour closer to yellow colour represents warm / high temperature. It can be seen that the wheat crop is cooler than the background soil. Thus soil was warmer than any of the wheat plant. Manually selected Ground Control Points (GCPs) such as green leaves and soil are shown in image Fig 4.21. The classification results are shown in Fig. 4.22. Visual evaluation of the results indicates that, in general, the wheat crop and soil are perfectly separated. In some classification methods (Fig.4.22), some parts of the actual leaf or soil were not classified properly. This area was observed mainly in the edge pixels, i.e., the pixels that are mixed with the background. Thus depending on the method the parameters were adjusted to minimise this effect. For example in the ENVI Spectral Angle Mapper classification procedure, the maximum acceptable angle between vectors of the training class and any pixel to be classified was increased. Thus more 'actual' (according to the visual classification) leaf pixels were classified as leaves. On the other hand, more pixels that were visually classified as background soil were wrongly classified as leaves when automated classification of the software was used.

The relationship between the LAI calculated based on the thermal image using the five different classification techniques is given in Fig.4.23 The maximum likelihood method gave the highest correlation between the predicted LAI with the observed LAI and the spectral angle mapper showed the least correlation. There was good agreement between estimated and observed LAI for methods Maximum likelihood followed (R^2 = 0.624) by Minimum distance to mean. Parallelpiped, Mahalabonis and least for spectral angle mapper (R^2 = 0.180)).

The image classification using different statistical techniques responded well to different moisture stress treatments with significant R^2 values between those observed and predicted. In pooled statistical analysis, the R^2 values were lower for spectral angle mapper (R^2 = 0.180) (Table 6). Also other statistical tools viz., RMSE, MBE were much higher (1.489 and 1.405 respectively) for spectral angle mapper method than any other method. Values of statistical analysis revealed that Maximum likelihood method had the highest R^2 and prediction efficiency (58.44%) and the least in other statistical parameters like RMSE (0.431) and MBE (0.187). RMSE for MLH, MLB, MDM, PLP and SAM was 24.71, 57.08, 35.99, 30.88 and 283% respectively. Thus of all the different image classification methods tested in this study Maximum Likelihood method was the better predictor of LAI from thermal image of wheat crop.

Table 4.2 Accuracy evaluation of crop & soil by five different methods

SLNo.	Method	CLASS					
		Crop		Soil			
		Producer's accuracy (%)	User's accuracy (%)	Producer's accuracy (%)	User's accuracy (%)	Over all accuracy	K
1	Maximum likelihood	98.978	99.831	99.986	99.533	98.769	0.998
2	Mahalanobis	99.956	99.978	93.669	99.973	99.972	0.967
3	Minimum distance to mean	99.823	96.616	88.100	99.564	96.618	0.879
4	Parallepiped	97.889	98.411	81.285	93.502	86.175	0.810
5	Spectral angle mapper	56.442	68.869	58.431	62.421	49.118	0.432

Table 4.3. Statistical summary comparing observed LAI with Image derived LAI values for wheat crop grown moisture stress condition

SL No	Classification methods	Observed mean LAI	Predicted mean LAI	R^2	ME%	RMSE	MBE
1	Maximum likelihood	1.930	1.744	0.624	58.4	0.431	0.187
2	Mahalanobis	1.930	1.263	0.344	-16.6	0.721	0.667
3	Minimum distance to mean	1.930	1.542	0.556	31.0	0.555	0.389
4	Parallepiped	1.930	1.593	0.530	45.9	0.492	0.338
5	Spectral angle mapper	1.930	0.525	0.180	-39.69	1.489	1.405

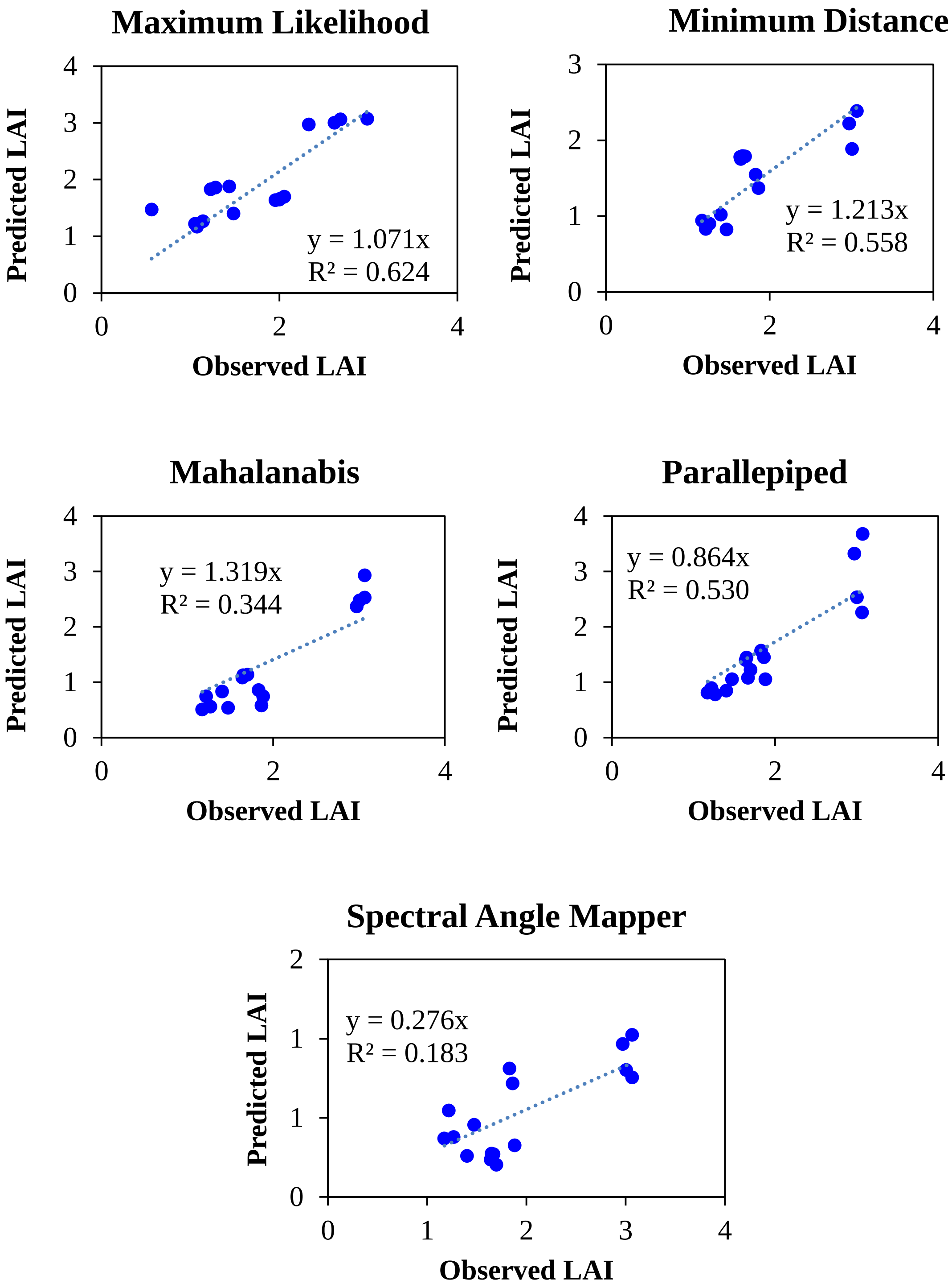

Fig 4.23 Relation between observed LAI and calculated LAI from thermal image analysis

5. DISCUSSION

Infrared radiation is emitted by any object which has a temperature more than the absolute zero (-273^{o}C). Thermal radiation is a type of radiation emitted by a body due to the difference in the energy absorbed and transmitted by the body. It can be explained by Stefen Boltzmann's law that governs the heat transfer in the form of radiation. The normal thermal camera detects the infrared energy emitted by an object, converts this into temperature values and ultimately displays the thermal image which comprises of the temperature distribution. Infrared thermography using thermal camera is a non-contact and non-invasive temperature quantifying technique. In this technique due to non-contact with the object the surface temperature of the object of interest is not altered and it is capable of measuring and presenting real time distribution of temperature. The application of thermal imaging in agriculture has become important tool as it has already been used in military, human health care and in other preventive and predictive services.

Crop Canopy temperature is determined by the rate of transpiration from the crop, especially leaf. During the leaf transpiration a considerable amount of energy is utilized to convert water in its liquid form to gaseous form (vapour). This energy in turn is utilized when water evaporates from the leaves; this in turn lowers the leaf temperature and results in cooling (Jones *et al*., 2009). Many studies have shown that leaf temperature is negatively correlated with grain yield (Pradhan *et al*., 2014). The main advantage of using thermal camera is that it covers huge area with higher precision. Thermal camera consider into account more than thousand instantaneous temperature measurements at a time. Hence this study was undertaken to characterise the effects of moisture stress in wheat using thermal imaging.

In this study wheat crop condition was characterised using thermometry and crop biophysical parameters. For this wheat crop was grown under four different moisture stress conditions for two years and various crop biophysical, meteorological, and soil parameters were collected systematically.

5.1 Crop moisture stress response

Water is an important for crop growth processes and crop needs a huge quantity of water for its growth and development as 50-90% of fresh weight of plant is water (Lambers *et al.*, 2008). Whenever there is deficiency in water availability plants and plant organs which do not have sufficient sclerenchyma loose its strength and wilt (Ehlers and Goss, 2003). Water is becoming an important factor for wheat production in India due to increased cropping intensity. In India wheat is grown during the cooler period (winter season) where there is less water loss from the soil surface.

Moisture stress, an important environmental stress, that negatively affects the crop growth and development, finally it limits crop production (Shao *et al.*, 2009). Moisture stress limits productivity of wheat crop by decreasing the photosynthetic processes at the canopy, leaf or choloroplast level. The response of the wheat crop plants to moisture stress is controlled by the duration and intensity of the stress. Under moisture stress condition as characterised in this study the stomatal characteristics were affected which in turn resulted in the decrease in biomass. Wheat crop when grown under moisture stress tend to have lesser stomatal conductance, thus helping to conserve water and maintain sufficient leaf water status but in the mean while reduces internal leaf CO_2 concentration and photosynthesis. Thus the intensity of moisture stress during vegetative stage reduced the biomass and yield. This is because yield loses are dependent on the crop growth stages that were affected by the moisture stress. These changes in turn indirectly affected the photosynthetic rate and ultimately result in less assimilate product. In wheat crop the grain yield is correlated with biomass and also with harvest index.

Plant response to moisture stress is characterised basically by the growth analysis. Among the different growth parameters leaf area is an important physiological determinant of crop yield. The possible cause of reduction in leaf area index is due to the changes in the plant water status which in turn restricts the cell enlargement, stunts the growth (Tardieu, 2013) and decreases the photosynthetic activity of leaves (Huseynova, 2012). Increased leaf senescence rate due to the decrease in water status of the crop under moisture stress might be one of reason for the decrease in LAI. The results of the present study are in line with observations of Acevedo *et al*., 2002, that water stress during the vegetative growth stage caused reduction in LAI of wheat. Similar observations were observed for wheat crop under moisture stress conditions by Victor *et al.,* 2015. Crop photosynthetic rate expresses the rate of dry matter accumulation that provides useful information about the nature and intensity of stress effect on wheat crop growth. In the present study, water stress markedly reduced the crop growth and decreased shoot biomass these are often associated with the decrease in their photosynthetic rate.

When water supplied to a leaf, is stopped a well know effect called 'Iwanov' effect occurs. Due to which a rapid initial opening of the stomata occurs before the long-term closure. Plant CO_2 absorption by photosynthesis is controlled by leaf stomata and also by loss of water by transpiration. Hence observations on decrease in stomatal conductance under moisture shows that the stomatal conductance is affected under moisture stress of the crop. Stomatal opening regulates photosynthesis by affecting the intercellular CO_2 concentration and in turn it affects other biochemical processes of the chloroplast. The opening of the stomatal is in turn is regulated by the intensity of light and also by the water status of the guard cells.

Reduced photosynthetic rate as observed in our study under moisture stress may be due to stomatal closure. A complete account on the stomatal functioning during moisture stress condition is given by (Frquhar and Sharkey, 1982). The observations on stomatal conductance are in general agreement with those of Siddique *et al.,* 1999, who reported that moisture stress led to noticeable decrease in stomatal conductance. But insignificant relationship between photosynthesis and stomatal conductance implies non-stomatal restrictions on photosynthesis.

In our study significant reduction in LAI is observed under moisture stress. Loss of green leaf area during the reproductive phase of the crop growth is called leaf senescence. During moisture stress plant utilize their resources to survive hence only limited resources are available for the grain development. In addition moisture stress stimulates the senescence associated metabolic changes in the wheat crop. Further, during moisture stress conditions chlorophyll biosynthesis is also inhibited, all these accelerated the leaf senescence. Thylakoid components are also disintegrated during moisture which ultimately leads to leaf senescence.

Estimating soil water content before irrigation is essential to schedule irrigation and also to irrigate the wheat crop with the sufficient moisture content (Laaboudi and Mouhouche, 2012). Studies on wheat have shown that precipitation during the wheat growing period accounted only for 65-95% of the actual water consumed by the crop and 5-35% of the consumed water was obtained from the soil water stored before sowing. In our study plant growth was not affected when soil water content was close to field capacity. In the I4 treatment the soil water content decreased to 15% and leaves ultimately senesced and plant growth was affected drastically. In addition to the depletion of soil moisture content due to plant growth, during the reproductive stages soil water content decreased very quickly due to increased soil evaporation due to increased air temperature. Adequate soil moisture lengthens days to maturity of wheat crop.

In the present study when sufficient irrigation was given to the crop the rate of drying of soil was slow, resulting in soil water to be available for longer period which in turn gives a better crop growth and yield. The effect of sufficient irrigation that conserves water in deeper layer of soil is reported to be useful to crops during grain filling (Li *et al.*, 2005). Less soil moisture content in plots with treatment I2 to I4 indicates extraction of soil water to the maximum possible extent by roots. Depletion of moisture from deeper layers was more under moisture stress treatments that might be due to upward flux of water to the drier layers above due to evaporation pull. Changes in soil moisture are most noticeable upto 75cm and it is reported to change very less beyond 120cm depth (Zhu *et al.,* 1990). Changes in soil temperature are similar to the changes in soil moisture content. In general in tropical region changes in soil temperature do not have significant effect on yield of wheat crop, because the decrease in temperature during winter wheat in tropical region is not as low as observed in temperate regions (Rawson and Bagga, 1979; Li *et al.*, 1999).
Grain number and grain weight are sensitive to moisture stress. Effect of moisture stress on each of these yield components is due to the shortening of the pheno-stages of the crop. According to (Saini and Aspinall, 1982) moisture stress hastens the development of the spike, reduces the spikelet number and thus the number of grains.

5.2 Thermal Indices

Studies have shown that canopy temperature is an indicator of 'crop stress' (Jackson *et al.,* 1981; Idso, 1982; Jackson, 1982). With the recent development in infrared camera, thermal imagers have great opportunities for the observations on the thermal properties of crop canopies and broadened the scope of characterising the crop condition (Boissard et al., 1990; Jones, 1999b). Indices like Crop Water Stress Index', CWSI, calculated based on the canopy temperature (Tc) and a 'non-water stressed baseline' temperature for an analogous but well-watered crop (Tnws) is often used to characterise the crop condition. Similarly index like IG, which was developed in an attempt to increase the applicability of infrared assessment of crop stress indices by using either dry (Qiu *et al.,* 1996) or dry and wet (Jones *et al*., 1997; Jones 1999a) reference temperatures. The advantage of this methodology is that it is based on reference surfaces, hence it permits a proper scaling of the leaf or canopy temperature measurements with the existing environmental conditions.

In general Water Stress Indices (Jones, 1999a) are based on the assumption that the radiative and boundary-layer mass transfer characteristics of the models and the real leaves are the same. Similarly, it ignores the variations due to the relative orientations to the sun and thus ignores the changes in the radiation absorption. Even small differences in solar radiation absorption can significantly alter the energy balance (Jones, 1999a). Hence in this study we have used wetted or petroleum jelly-covered leaves. By doing so the problem of equivalent radiative properties is minimised.

Previous studies have used infrared thermometers, in the thermal studies of plant canopies, these studies measure an average temperature over a single target area. The single pointed target area can unintentionally contain soil, stem or sky in the sensed area which might result in consequential errors while estimating the canopy temperature. In addition, the infrared thermometry makes use of the average canopy temperature, but this might be made up of a wide range of leaf temperatures, with senesced leaves having much higher temperatures than the normal leaves. By using thermal imagers, we can select an area of interest from each image that does not include sky, soil, or other non-leaf components. Thus it is possible to select proper leaves as desired.

Thermal infrared imaging and infrared thermometer (IRT), are the two approaches used to measure the canopy or leaf temperature, they allow us to estimate the range of evaporative cooling that occurs in a crop canopy. By using these techniques crop water balance can be remotely sensed. In our study these two techniques were used to determine the three thermal indices namely CWSI, IG and I3. Between these two approaches thermal indices calculated by infrared imaging using thermal camera gave significant differences among the moisture stress treatments. This is because thermal infrared imaging by using an infrared camera offer several benefits compared to the thermometer based temperature sensors. The main advantage of using thermal camera is the spatial resolution and their ability to sample larger area at one go. Infrared cameras used in the present study have arrays of 640 × 420 sensor elements, which mean about 2,68,800 discrete temperature readings are recorded in a single image. Thus accurate measurements of the thermal profile of a wheat canopy are possible within a fraction of the time required to record several replicate readings per plot. This kind of measurement using infrared thermometer is also subjected to error due to varying environmental conditions between measurements. In contrast, the thermal imagery system is a powerful tool as it can capture the temperature differences of plant canopies quite rapidly.

Our study clearly shows the better correlation of CWSI determined by the thermal image under different moisture stress conditions. This is because CWSI is based on the canopy temperature, and of all the environmental weather parameters like VPD, wind speed and light intensity it is highly affected by the air temperature (Wen-zhong *et al.,* 2007).According to Blum, (1998) plants decrease their transpiration as an adaptive mechanism to dehydration under moisture stress and this leads to a decrease in canopy temperature. Under moisture stress condition plants regulate their stomatal activity by closing their stomata to transpire less (Rebetzke *et al.,* 2013), this result in increase in canopy temperature as observed in the present study.

Aerial plot wise canopy temperature determination using the portable thermal camera as followed in this study seems highly reliable and precise for monitoring the crop status in field condition in comparison to leaf based canopy temperature measurement using commercial infrared thermometers (Wang *et al.,* 2013). This is because the thermal camera captures the crop canopies of many plants in a plot and this helps to minimize the error due to sampling in comparison to the spot measurements using the infrared thermometers (Kashiwagi *et al.,* 2008). Another advantage is the simultaneous measurement of the whole crop canopy area by the camera and the related inbuilt software that helps to quantify the range and mean canopy temperature. While measuring the water requirement of a smaller canopy it might be small and hence result in a cooler canopy. Another advantage of this study is the opportunity to image a large number of plots in a field trial at a time, in one go, This allows the comparison of variances in canopy temperature in different cultivars as shown rice (Jones *et al.*, 2009) and also to capture the variations within a huge crop field in one go as required in precision agriculture. By using this highly promising and throughput imaging technique it is possible to monitor the crop condition in a large-scale without any error due to varying environmental conditions that occurs between measurements using infra-red thermometers (Berger *et al.,* 2010).

5.3 Estimation of LAI from Thermal image analysis

Leaf Area Index (LAI) is an important parameter to characterise the canopy structure especially during crop stress condition. LAI is generally considered as one side area of leaves per unit area of soil. Many methods are available for characterising the LAI (Campbell & Norman, 1989). There are direct measurement methods like harvesting the plants and determining the leaf area using scanners or by using manual measurements (Casa and Jones, 2005). But these direct measurements are destructive and labour intensive. Hence indirect methods based on inclined point quadrat method canopy reflectance, satellite or field imagery using the spectral reflectance differences allometric method and non-contact methods – terrestrial methods like based on the radiation transmission and gap fraction theory, methods based on clumping and overlapping effect within plant canopy, spectroradiometer, airborne optical remote sensors, multi-spectral remote sensors and satellite based spectral remote sensing are applied. Due to the advancement in the manufacturing of the infrared camera accompanied by the concomitant reduction in the cost of these cameras the application thermal imaging in varied fields which were never attempted before has been made possible. But the fast and easy applicability of this technique in field has great potential in agriculture. Till now, thermal imagery is mostly related to the leaf temperature determination and estimation of leaf temperature based thermal indices but our study has clearly demonstrated the application of the thermal imaging to determine the LAI of the wheat crop.

The present study showed that thermal imagery is able to characterise the differences in the canopy and soil temperature under moisture stress condition. A bimodal distribution of the frequency distribution of the temperature recorded by the thermal image showed the intensities of the pixels clustered into two significantly separated peaks. This served as a benchmark and the frequency distribution of the temperature of the wheat plot clearly showed the differences in temperature between crop and soil. Hence the application of thermal imagery to characterise the LAI was explored in this study.

Image classification assigns pixels of an image to classes. Image classification of thermal image is likely to assemble pixels with identical temperature values into two classes of our interest leaves and soil only. For this we have followed supervised classification using ENVI software. By following this supervised image classification technique we have grouped or classified an unknown pixel by comparing it with a pixel whose identity was already assigned by the image analyst (Campbell and Wynne, 2011). During these two year of study, five different supervised image classification techniques namely maximum likelihood method, minimum distance method, mahalanobis method, parallepiped method and spectral angle mapper method were used for classifying the image (as it was given by Mather and Koch, 2010; Lillesand *et al.,* 2014) into two classes (leaves and soil) and there after leaf area index was predicted form the above mentioned method. The classification accuracy of two different classes was also obtained which includes producer's accuracy, user's accuracy, overall accuracy and kappa coefficient for all the image classification method (Foody 2002, Keuchel *et al.* 2003, Maxwell *et al*. 2004). Performance of these image classification techniques in predicting the leaf area index of crop grown under different moisture stress treatment was also determined by calculating the modelling efficiency, RMSE value and also by estimating their mean biased error (MBE). The result showed that the maximum likelihood method is performing the best as compare to other classification methods and spectral angle mapper showed least performance. Maximum likelihood method has provided an overall accuracy of 98.76% while, spectral angle mapper was found to be least accurate with lowest overall accuracy of about 49.11%. On cloe observation it was found that existence of larger unclassified portion in the classified image was a possible reason for this lower overall accuracy and least kappa coefficient value by the spectral angle mapper method as compared to other classification method. The possible reason for larger unclassified area in the classified thermal image by spectral angle mapper method may be due to its higher insensitivity of illumination variation in the field condition (Lillesand, *et al.*, 2014). It is mostly suitable for greenhouse condition (Leinonen, 2004) where the illumination variation is very less. Since, maximum likelihood method is the parametric image classification technique it works on the assumption that the spectral data of different classes in the raw image were following normal distribution or Gaussian distribution (Lillesand, *et al.*, 2014). It not only takes mean and standard deviation of each classes into account but also calculates mean vector and covariance matrix for each training classes, hence gives greater overall classification accuracy and higher value of kappa coefficient as compare to other methods of image classification of wheat crop grown under different moisture deficient situation (Lillesand and Kiefer, 2014). It was also noticed that the size of the land cover type (crop and soil) that has been classified by maximum likelihood method, mahalanobis method and the minimum distance method were more or less similar or statistically at par but when the leaf area index was estimated by all this three classification method, it was found that maximum likelihood method showed higher R^2 value (0.624) as compare to minimum distance method (0.558) or mahalanobis method (0.344). Lower predicting efficiency of LAI by mahalanobis method compares to minimum distance method and maximum likelihood method may be due to its poor agreement between the land cover map with the reference data. Although minimum distance method has produced lesser overall accuracy (96.61%) and kappa coefficient (0.87) as compare to mahalanobis method, it showed better agreement in predicting LAI. Comparative better performance by minimum distance method is due to its simplicity in discriminating function which uses only mean of the training class as a statistical information (Fujimura and Tsubaki 1985). It has also been reported that the influence or effect of mixed pixel in the raw image which could accommodate a number of classes in a single pixel was very less when image classification was performed by the minimum distance method as compare to mahalanobis method (Ishida and Inamura 2002). But when compared with maximum likelihood method, minimum distance method performed poor. Minimum distance algorithm lets the analyst specify a distance or threshold from the class mean beyond which a pixel will not be assigned to a category even though it is nearest to the class mean of that category (Lillesand, *et al.*, 2014). This may be a possible reason for lower overall accuracy as compared to maximum likelihood method. Like maximum likelihood method, mahalanobis method considers covariance of a particular class and it also assumes that the data is normally distributed. However, due to large values in the covariance matrix for a particular class mahalanobis algorithm tends to over classify a particular class, also it is much slower than minimum distance method due to its strong dependence on data set which is normally distributed (Al-Ahamadi and Hames, 2009). These are some of the reasons which may be supportive in answering the inefficiency of mahalanobis method for its poor prediction of LAI as compare to minimum distance method which showed lower overall classification accuracy as compare to mahalanobis method. Parellepiped method of image classification also showed more or less similar performance in predicting LAI from the classified image with a value of R^2 = 0.53 as compare to minimum distance method with R^2= 0.55. Like spectral angle mapper method, parallepiped method showed some unclassified portion in the classified image, but the portion of the image area that was registered itself for unclassified area is quite small as compare to spectral angle mapper. As a result of this, it gave quite a high value of overall accuracy (86.17%) and kappa coefficient (0.81) as compare to spectral angle mapper method. Also the predicting ability of LAI by parallepiped method is much higher as compared to spectral angle mapper method but it was much less than that of maximum likelihood method. Parallepiped algorithm was seen to be more efficient in classifying remotely sensed data. Unfortunately, because some parallepipeds overlaps, it is possible that an unknown candidate pixel might satisfy the criteria of more than one class. In such case it is usually assigned to the first class for which it meets the criteria which might be a reason for getting a smaller portion of unclassified area in the classified image (Lillesand, *et al.,* 2014).

6. SUMMARY AND CONCLUSIONS

Agricultural production at present is based on the growth and yield of a few important cultivated crop species. In view of the predicted effects of global warming, there is depletion in the availability of water for irrigation. Wheat crop during the year 2014-15, with a production of around 89 MT, showed a decline in its rate of production by 7.51%. This reduction its production was mainly attributed to the moisture and temperature stress during the early stages of its growth. Wheat yields within the major growing states have huge differences because of irrigation availability, soil health, and technology. Wheat yields in irrigated regions of northern India are above 4.5 tons per hectare, on the other hand yields in central and western regions are less (2.4-2.8 tons per hectare). Hence monitoring the moisture stress condition of the crop is essential to improve the crop yield. Although different techniques are available for estimating the crop status under moisture stress condition, availability of a technique that is reliable, reproducible and accurate is necessary. With the advancement in the image processing technique and the availability of thermal imaging cameras an attempt was made in this study with the following objectives: (i) Characterization of crop condition using thermometry and crop biophysical parameters under different moisture stress conditions in wheat and (ii) To estimate the crop stress index based on thermal image and correlate with biophysical parameter

To achieve these objectives field experiments were conducted on wheat (var. HD 2967) under four levels of moisture stress conditions in the experimental form of Indian Agricultural Research Institute, New Delhi, during *rabi* seasons of 2014-15 and 2015-16. In the first objective, crop condition was monitored using thermal imaging camera, Infra-Red Thermometry, in addition different biochemical, biophysical and plant physiological parameters were measured from wheat crops grown under different moisture stress conditions. Daily meteorological data on maximum and minimum temperatures, rainfall, relative humidity, wind speed, bright sunshine hours, and pan evaporation for the crop growth period were obtained from the nearby IARI agro-meteorological observatory. In the second objective Crop Water Stress Index based on Thermal Image and Infra-Red Thermometer was estimated and compared with the observed crop parameters. In addition image analysis techniques were done by supervised classification using different methods of image classification. The image processing based Leaf Area Index was derived for each method. The derived LAI were then compared with the observed data and accuracy assessment were done.

The salient findings of the study are described below:

- Differences in weather parameters (rainfall and maximum temperature) was observed during both the cropping seasons of the study
- Crop biophysical parameters were significantly related to different irrigation treatments and weather related parameters. Observations on leaf Photosynthesis, stomatal conductance and transpiration showed significant decrease due to moisture stress treatments
- Among the different biophysical parameters tested in this study, LAI, NDVI showed typical response pattern for the moisture stress treatments in both the season
- Under the severe moisture stress treatment (I4) maximum value of LAI was achieved 4-5 days earlier than the ambient condition (in both the years of the study)
- Soil moisture content was found to be higher for I1 and least for I4 during both the years of the study. However soil temperature was higher in I4 and lower in I1 during both the years of the study
- In 2015-16, volumetric soil moisture content was below PWP under extreme moisture stress treatments i.e., I3 & I4 but similar effect was observed only in I4 treatment during 2014-15 Higher soil moisture content was observed in 2014-15 than in 2015-16, was due to heavy rain during the cropping season of 2014-15
- Canopy temperature was found to be very much correlated with soil moisture availability and air temperature during both the cropping season and it was highest for stressed condition and least for non-stressed condition. Higher canopy temperature was observed during 2015-16 due to prevalence of higher (around 10° C) maximum temperature and lower rain in 2015-16 compared to 2014-15
- Yield and its attributes showed good correlation with moisture stress treatments. However year 2014-15 showed lower yield and its

attributes due to the occurrence of heavy rain during grain filling stage followed by crop lodging

- Bimodal thresholding histogram of temperature distribution in thermal image of the wheat plot, showed the presence of at least two separate classes and temperature distribution at CRI stage. As crop grows this bimodal distribution pattern is progressively vanished as it can be seen at Tillering stage
- But crop under I4 moisture treatment condition show bimodal pattern due to appearance of soil area which proves poor canopy coverage under moisture stress condition
- Thermal image based indices like CWSI-TI, IG-TI and I3-TSI show distinct pattern of distribution according to the stress level for both the season than the IRT based indices
- Correlation between image based indices and crop biophysical parameter showed significant result for both the season. IRT based indices like CWSI and IG also showed significant correlation with biophysical parameter but not so perfect as compare to image based indices
- Leaf Are Index for crop was calculated by Image classification using ENVI under five supervised classification methods (Maximum likelihood, Minimum distance, Parallepiped, Mahalanobis, Spectral angle mapper (SAM))
- All the methods except Spectral Angle Mapper showed better overall accuracy and kappa coefficient value
- Correlation with thermal image based predicted LAI and observed LAI showed satisfactory result for maximum likelihood method and least for SAM. Similarly compared to all the methods tested in this study maximum likelihood method showed the highest Modelling efficiency
- Thus the present study clearly showed that thermal image analysis could be applied as a non-destructive, rapid, less erroneous technique to characterise the crop canopy temperature and also estimate the LAI of the wheat crop grown under moisture stress conditions.

Thermal image analysis of wheat crop grown under moisture stress conditions

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ABSTRACT

In view of the global climate change and burgeoning population there is a greater constraint on the availability of water for agriculture. Wheat crop growth and yield are much affected by the availability of water during the growing season. Experiments were conducted during the year 2014-15 and 2015-16, to characterize the effects of moisture stress on wheat crop using thermal image analysis. The goal of the study is to apply the principles of infrared thermometry and image analysis to characterise the changes in growth and yield of wheat crop raised under moisture stress condition. Wheat cultivar HD 2967 was grown in the research fields of Indian Agricultural Research Institute, New Delhi under four different levels of moisture stress. Periodic observations on biophysical parameters and thermal imagery were made. Three thermal indices namely CWSI, IG and I3 were estimated based on the canopy temperature measured through thermal image and infrared thermometer (IRT). Results showed that the thermal image based indices were more consistent than IRT based indices. This is because the thermal camera captures the crop canopies of many plants in a plot and thus helps to minimize the error due to sampling in comparison to the spot measurements made using the infrared thermometers. In addition the thermal indices calculated by the thermal images correlated significantly with the crop canopy based parameters like NDVI and LAI.

As a further application of this technology, an attempt was made to estimate the Leaf Area Index (LAI) of the wheat crop grown under different moisture stress conditions using Thermal Image Analysis. Thermal Images were analysed with five different supervised image classification techniques namely Maximum likelihood, Mahalanobis, Minimum distance to mean, Parallepiped and Spectral angle mapper methods using ENVI - image analysis software. Results showed that the best estimation of LAI was possible using Maximum likelihood method, due to its higher overall classification accuracy and Kappa coefficient. This is further supported by the statistical analysis based on the observed LAI. In general Maximum likelihood method estimated the wheat crop LAI from the thermal image meaningfully with high R^2 value of around 0.624 and low values of RMSE and MBE. Thus the present study clearly showed that thermal image analysis could be applied as a non-destructive, rapid, less erroneous technique to characterise the crop canopy temperature and also estimate the LAI of the wheat crop grown under moisture stress conditions.

आर्द्र तनाव परिस्थिति में उगाये गए गेहूं का थर्मल बिम्ब विश्लेषण

सारांश

वैश्विक जलवायु परिवर्तन तथा तेज़ी से बढ़ती हुई जनसंख्या के कारण कृषि के लिए उपलब्ध जल में आए दिन भारी कमी होने वाली है। उपयुक्त मौसम में पानी की कमी के कारण गेहूं में वृद्धि, विकास तथा उत्पादन पर काफी असर पड़ता है। 2014-15 तथा 2015-16 में गेहूं पर आर्द्र तनाव के प्रभाव को विश्लेषित करने के लिए थर्मल बिम्ब विश्लेषण का उपयोग कर प्रयोग किए गए। प्रयोग का उद्देश्य इंफ्रारेड थर्मोमेटेरी के सिद्धांतों का इस्तेमाल कर बिम्ब विश्लेषण द्वारा आर्द्र तनाव परिस्थिति में गेहूं की वृद्धि तथा उत्पादन का अध्ययन करना था। इसके लिए गेहूं की किस्म HD 2976 को भारतीय कृषि अनुसंधान संस्थान के अनुसंधान प्रक्षेत्र में 4 अलग अलग आर्द्र तनाव परिस्थितियों मे उगाया गया। जैवभौतिकी तथा थर्मल बिम्ब का सामयिक अवलोकन किया गया। तीन उष्ण सूचकांकों (CWSI, IG तथा I3) का आकलन थर्मल बिम्ब तथा इंफ्रारेड थर्मोमीटर द्वारा कैनोपी तापमान को मापकर किया गया। परिणाम से पता चला कि थर्मल बिम्ब पर आधारित सूचकांक IRT पर आधारित सूचकांकों की तुलना में ज्यादा संगत थे। ऐसा इसलिए हुआ क्योंकि थर्मल कैमरा किसी क्षेत्र के काफी संख्या में पौधों के कैनोपी के बिम्ब को लेता है तथा इस प्रकार सैम्प्लिंग के द्वारा उत्पन्न हुई त्रुटि को कम करता है, जबकि इंफ्रारेड थर्मोमीटर किसी एक ही स्थान को मापता है। इसके अलावा थर्मल बिम्ब के आधार पर लिए गए थर्मल सूचकांक पौधों के कैनोपी संबन्धित पारामीटर (NDVI तथा LAI) से काफी संगत में पाये गए।

इस तकनीक की एक और उपयोगिता को इंगित करने के लिए अलग-अलग आर्द्र तनाव परिस्थितियों में गेहूं में LAI को थर्मल बिम्ब विश्लेषण द्वारा आकलित करने का प्रयास किया गया। थर्मल बिंबों को 5 अलग-अलग संचालित बिम्ब वर्गीकरण विधियों यथा- मैक्सिमम लाईक्लिहूड, महलानोबिस, मिनिमम डिस्टन्स टू मीन, परलेपिपेड तथा स्पेक्ट्रल एंगल मैपर का प्रयोग ENVI बिम्ब विश्लेषण सॉफ्टवेयर के माध्यम से किया गया। परिणाम से पता चला कि मैक्सिमम लाईक्लिहूड विधि द्वारा सर्वोत्तम LAI का आकलन हो सकता है क्योंकि इसकी वर्गीकरण यथार्थता तथा कप्पा गुणक काफी ज्यादा हैं। इसको आगे सांख्यिकी विश्लेषण द्वारा भी समर्थित किया गया जो कि LAI पर आधारित था। सामान्य तौर पर मैक्सिमम लाईक्लिहूड तकनीक द्वारा गेहूं के LAI का आकलन थर्मल बिम्ब द्वारा सार्थक रूप से अधिक R2 मान (0.624) तथा कम RMSE तथा MBE मान के साथ हुआ। अतः वर्तमान अध्ययन दर्शाता है कि थर्मल बिम्ब विश्लेषण का उपयोग एक बिना विनाशकारी, तेज़, कम त्रुटिपूर्ण विधि के रूप में फसल कैनोपी तापमान को विवरित करने के लिए तथा गेहूं में LAI का आकलन आर्द्र तनाव परिस्थिति में करने के लिए किया जा सकता है।

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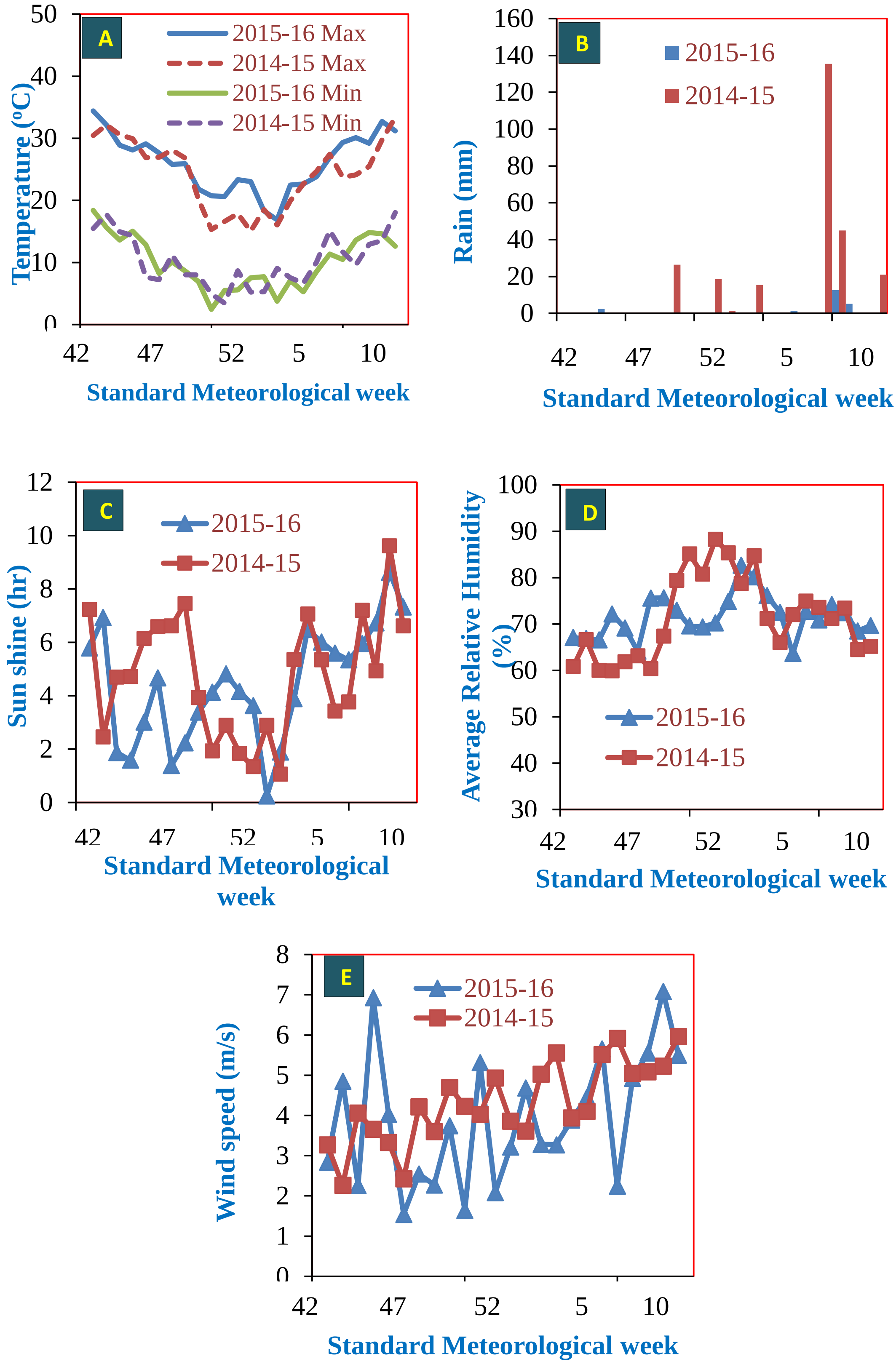


Fig 4.1 Weekly meteorological parameters measured at IARI observatory during 2014-15 & 2015-16 *rabi* crop seasons. (A) Weekly min & max temperature, (B) Total rainfall, (C) Weekly sunshine hours (D) Average Relative Humidity % (E) wind speed (m/s)

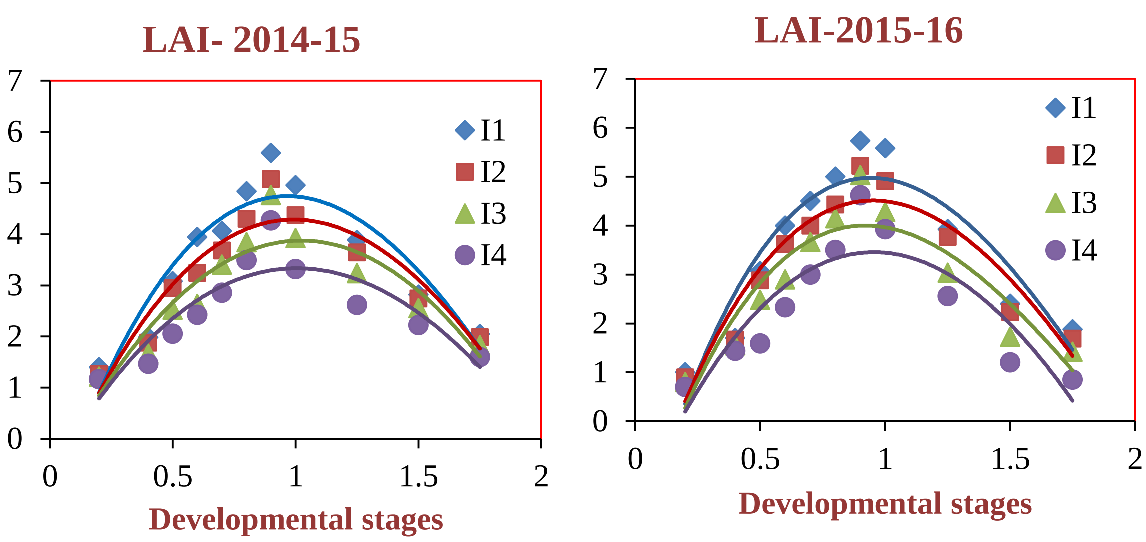


Fig. 4.2 Changes in LAI profile of wheat crop grown under different moisture stress conditions

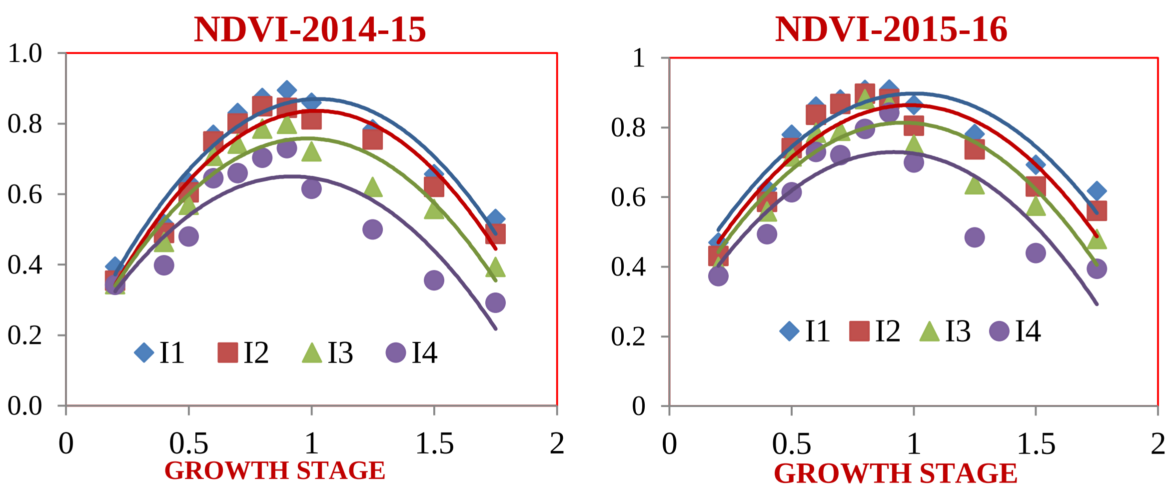


Fig. 4.3 Changes in NDVI during different irrigation conditions of sowing wheat crop

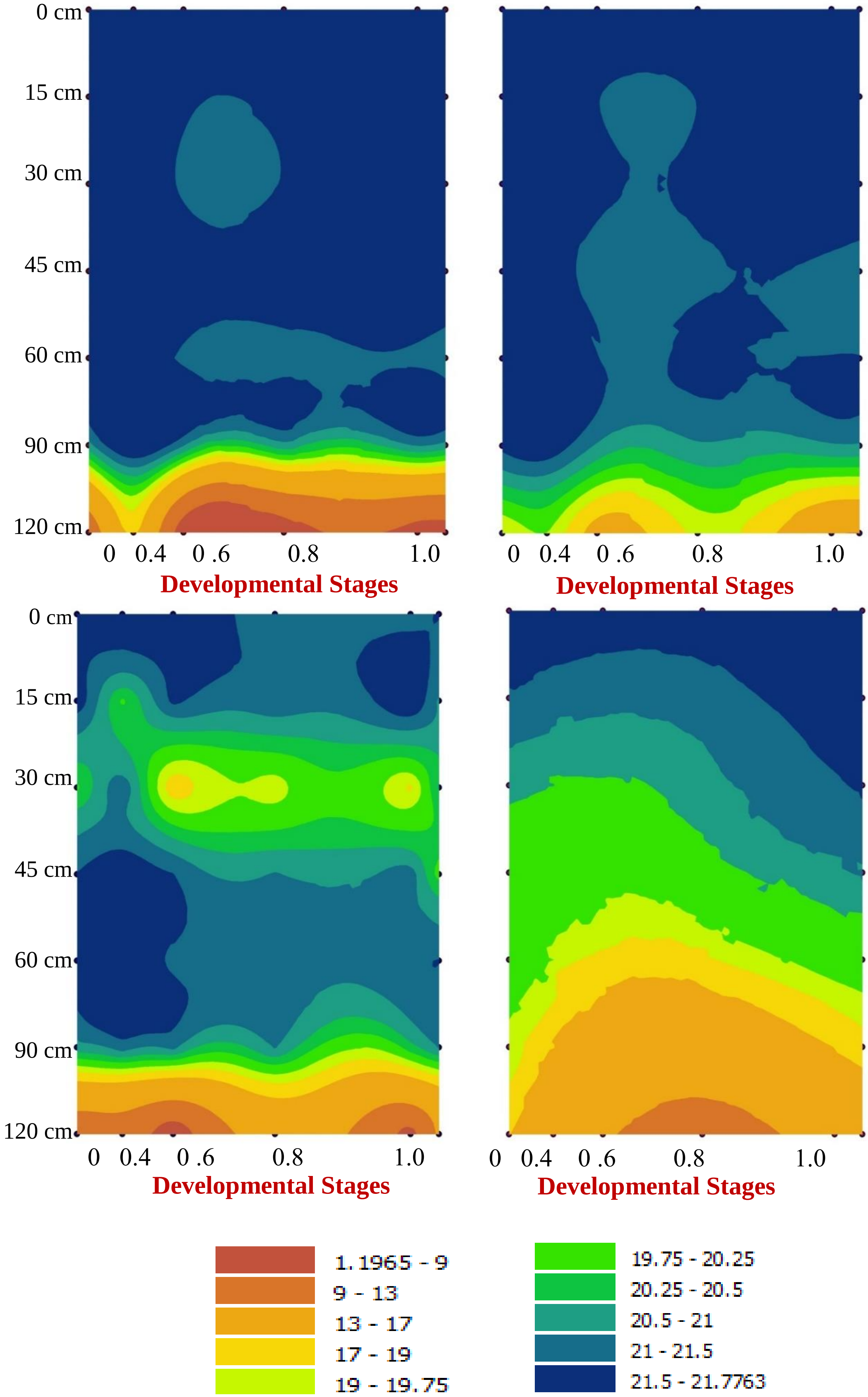


Fig. 4.4. Volumetric soil moisture depth wise 2014-15

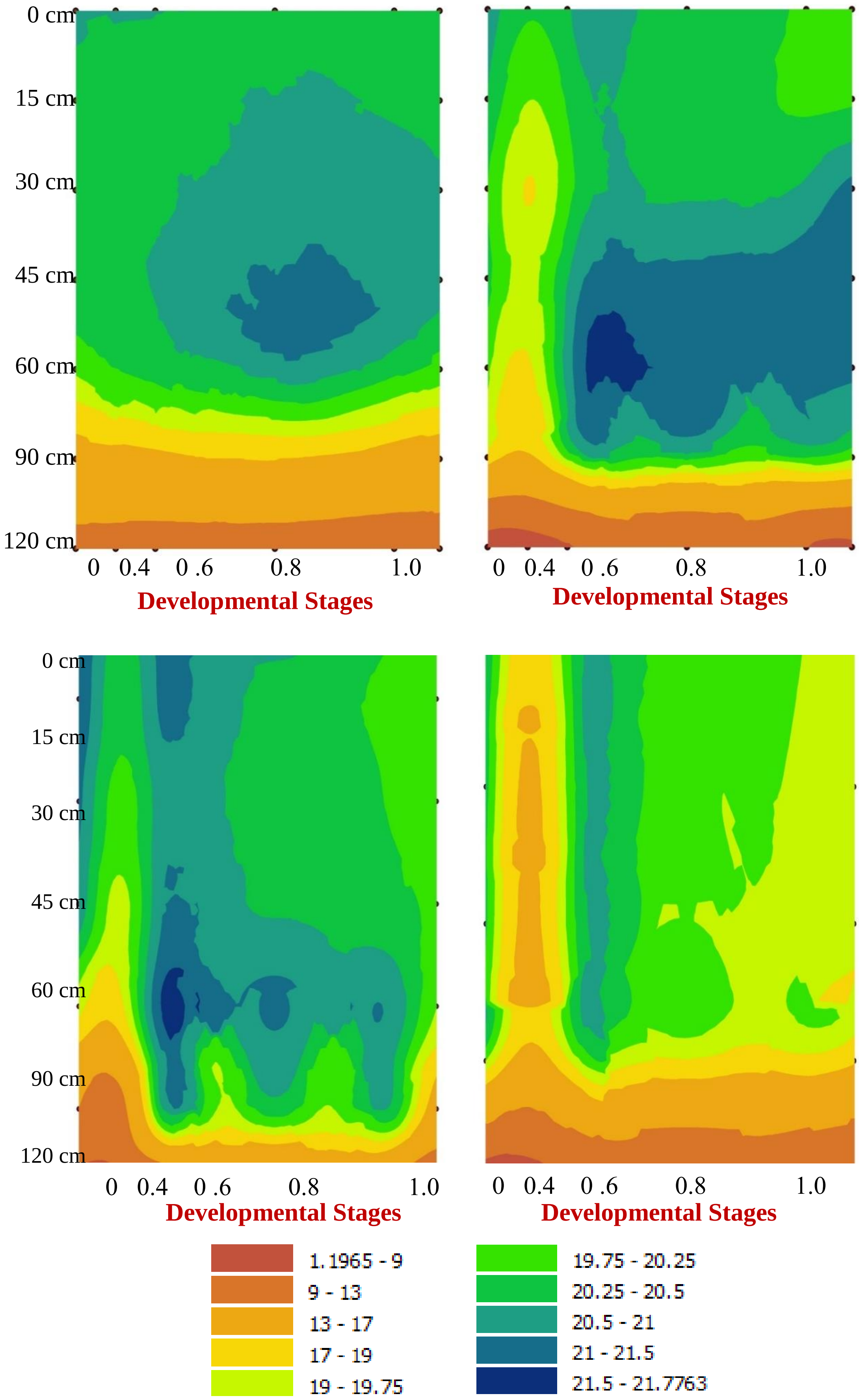
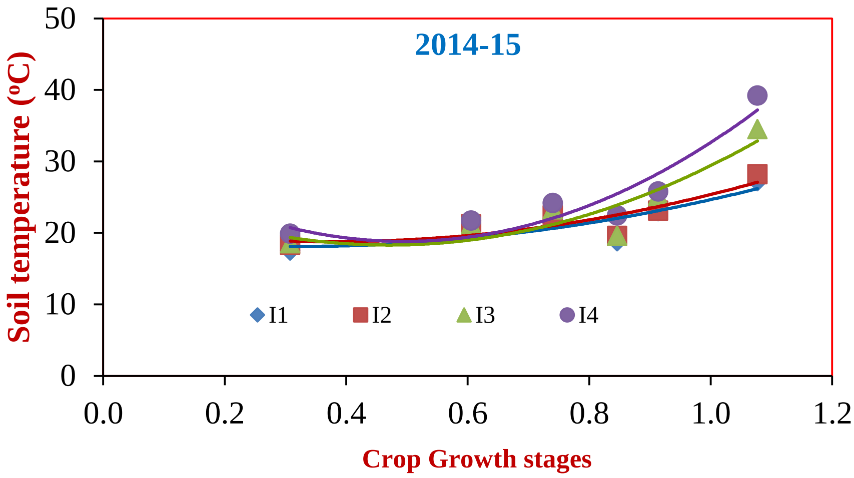


Fig. 4.5 Volumetric soil moisture content depth wise 2015-16



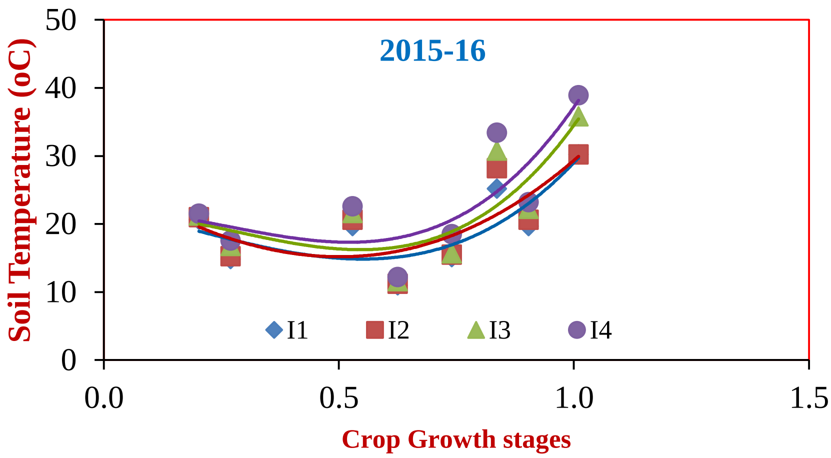
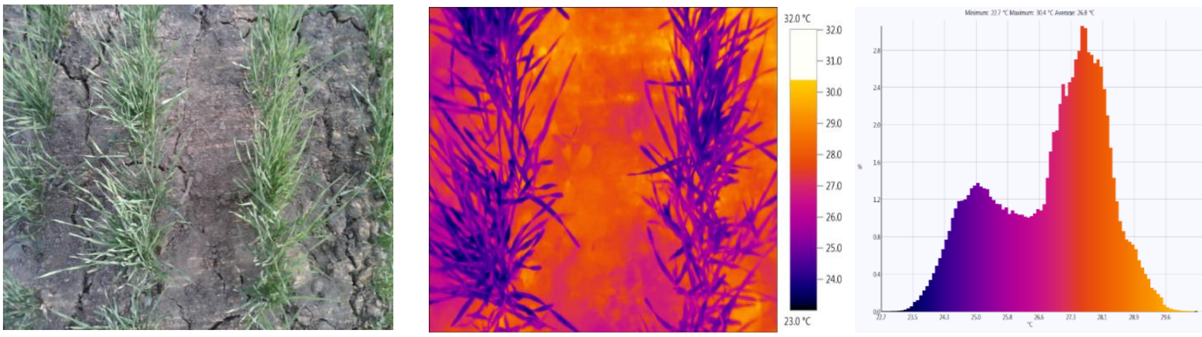


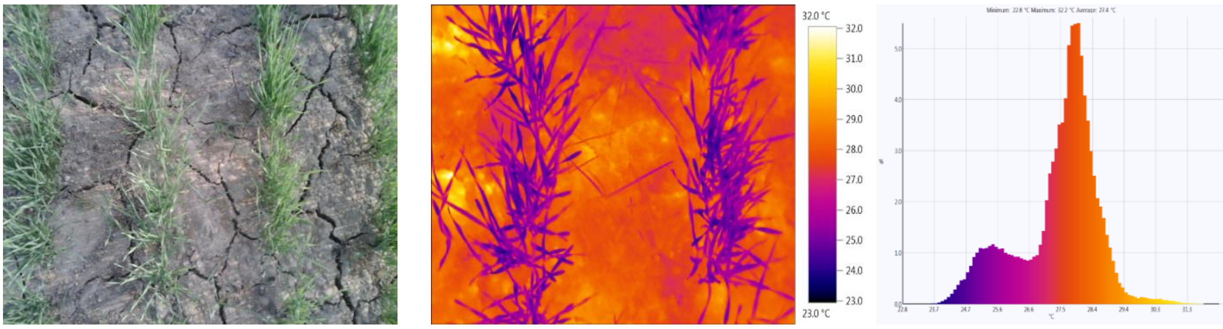
Fig. 4.6 Changes in soil temperature during different irrigation conditions of sowing wheat crop

Optical Image | **Thermal Image** | **Frequency distribution of the temperature**

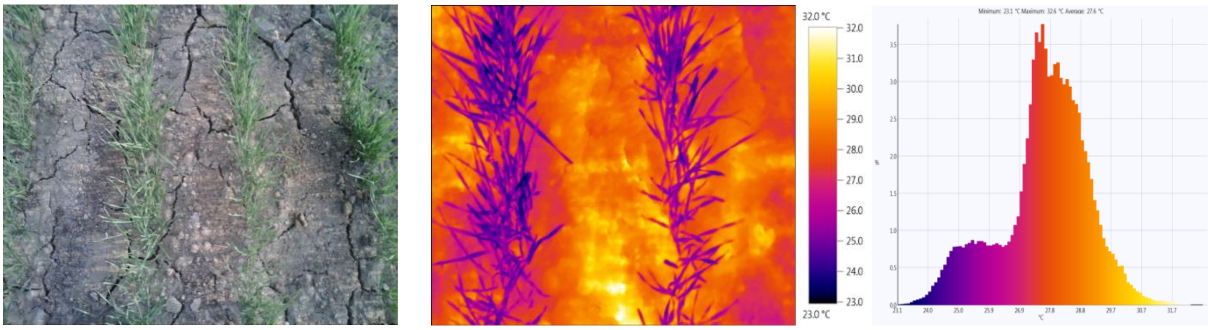
I1



I2



I3



I4

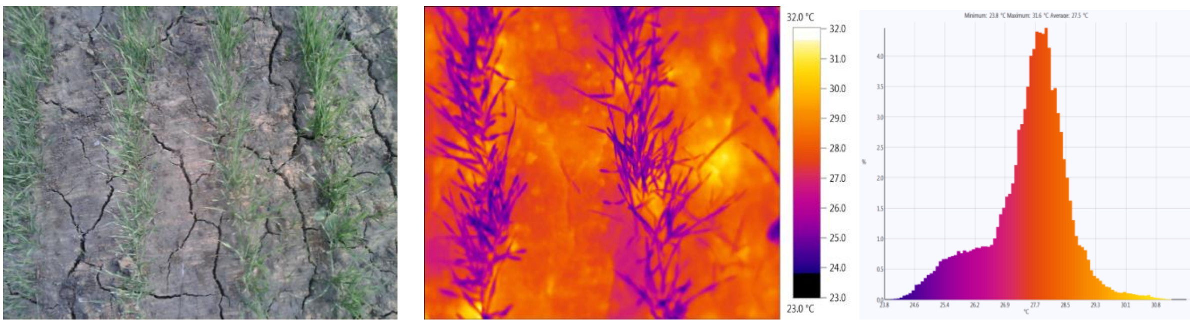


Fig. 4.7 Digital & Thermal image of wheat at CRI stage

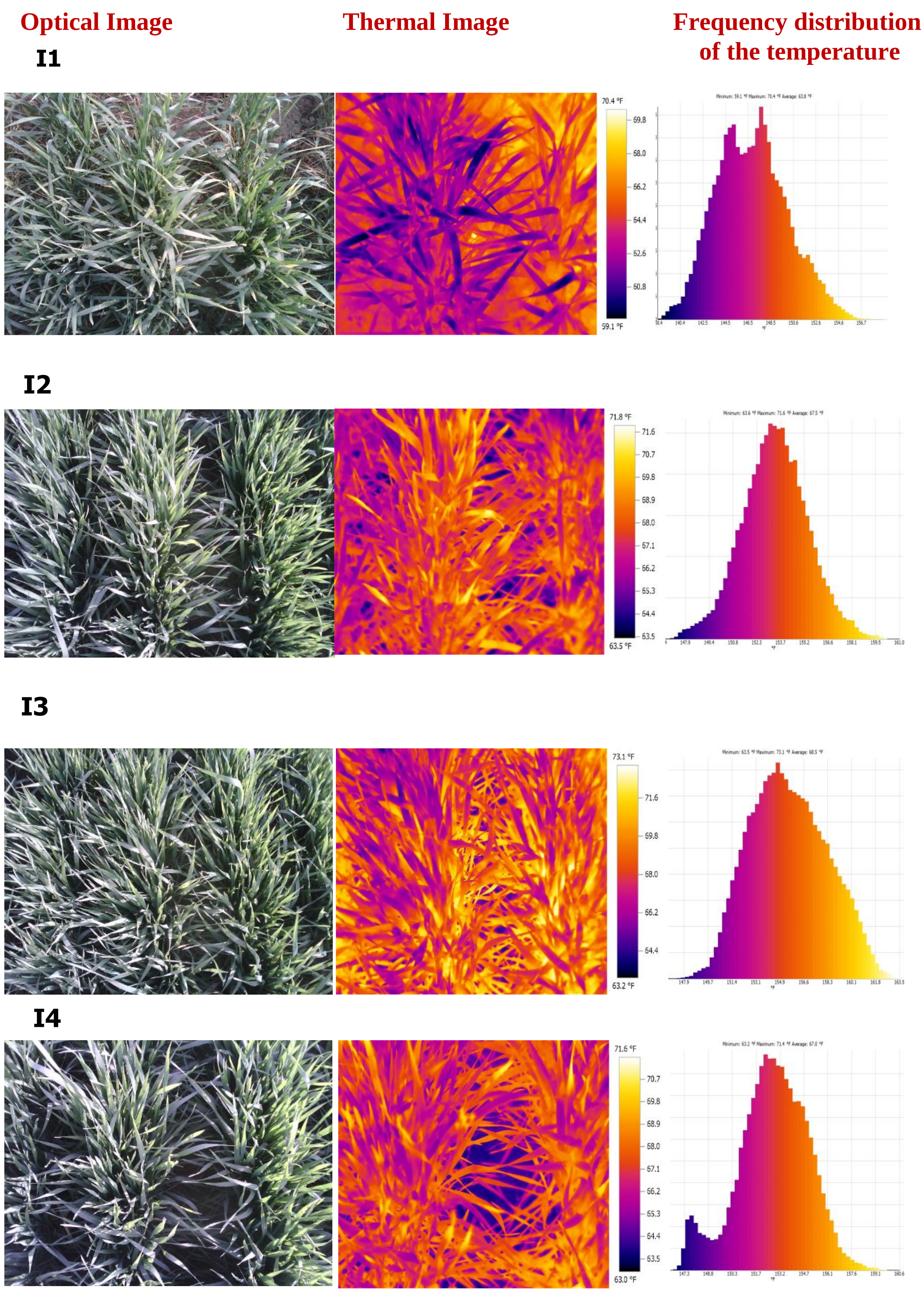


Fig. 4.8 Digital &Thermal image of wheat at Tillering stage

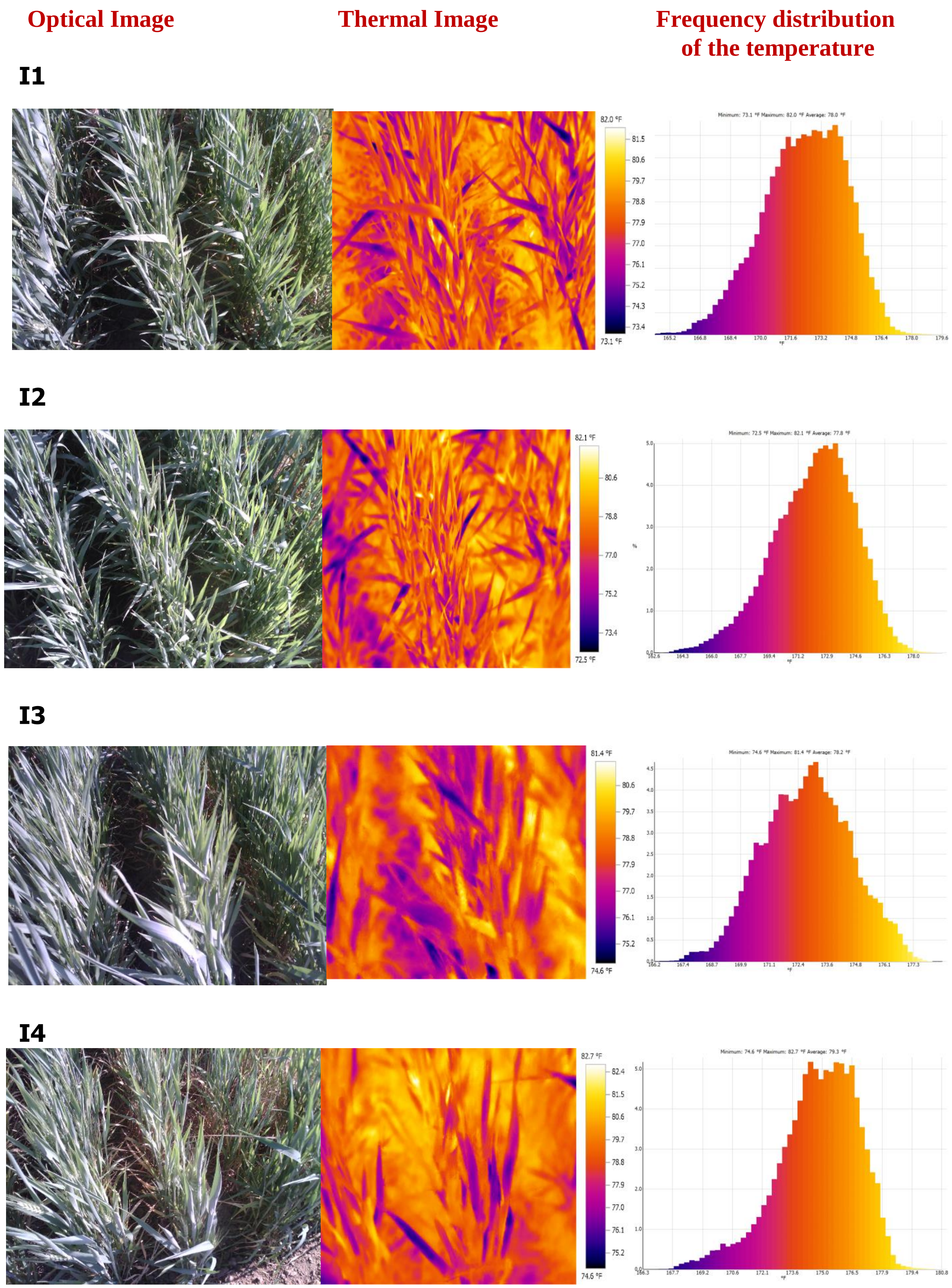
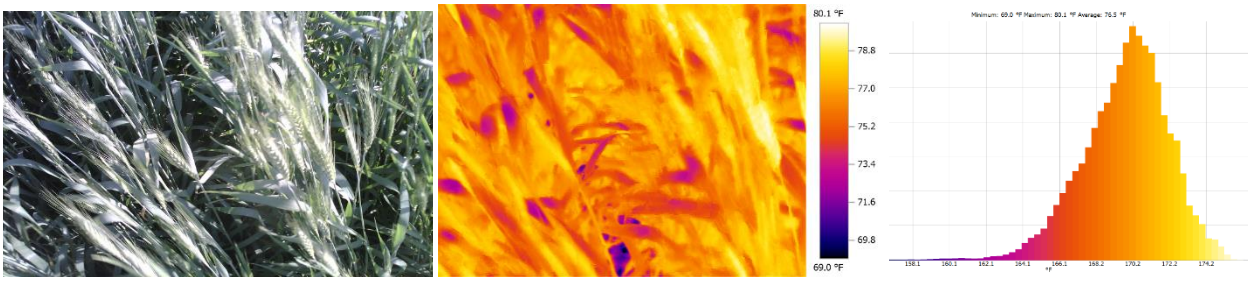


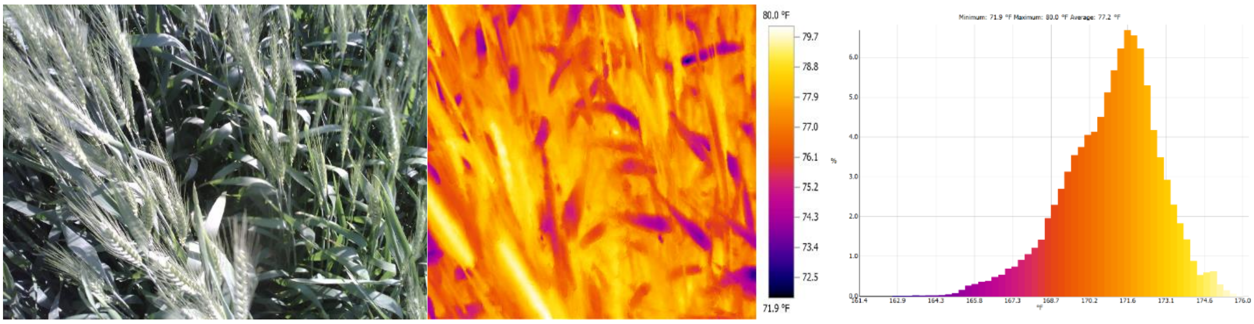
Fig. 4.9 Digital &Thermal image of wheat at Booting stage

Optical Image **Thermal Image** **Frequency distribution of the temperature**

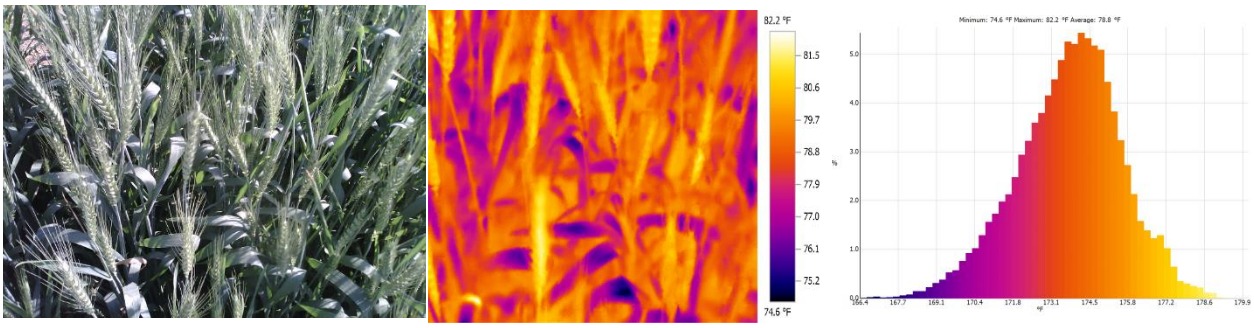
I1



I2



I3



I4

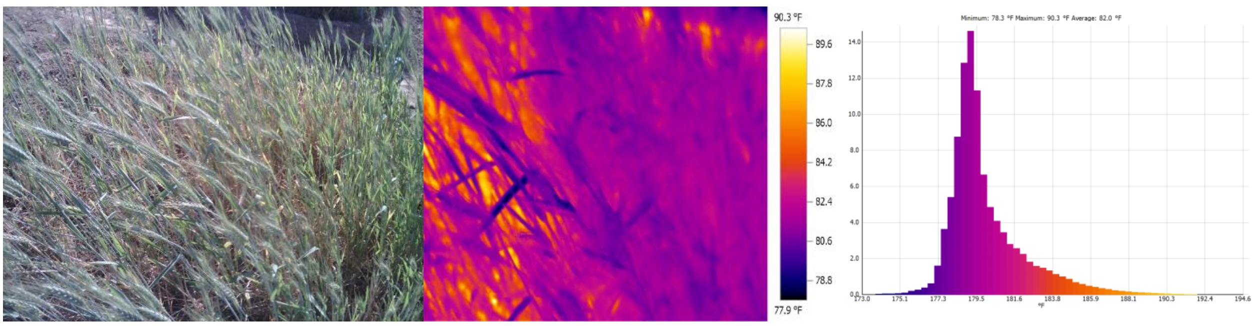
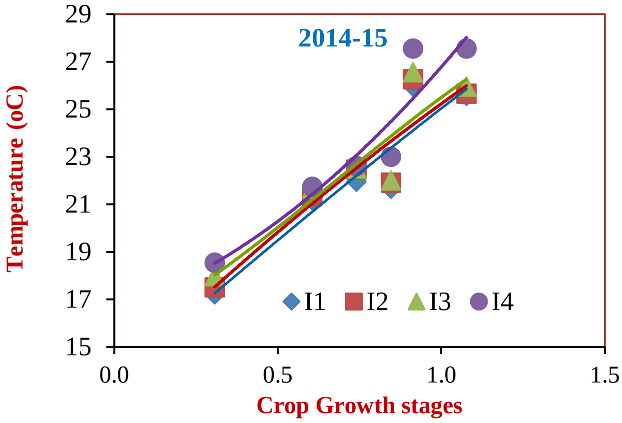


Fig. 4.10 Digital & Thermal image of wheat at Anthesis stage



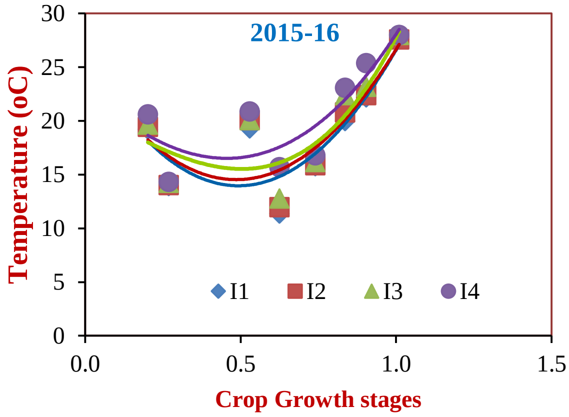
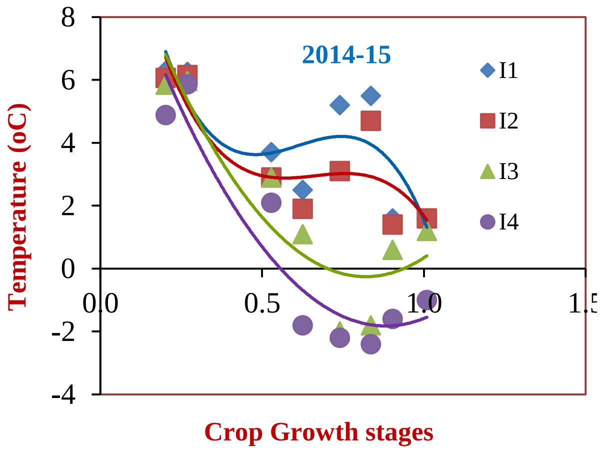


Fig. 4.11 Changes in Crop canopy temperature during different irrigation conditions of sowing wheat crop



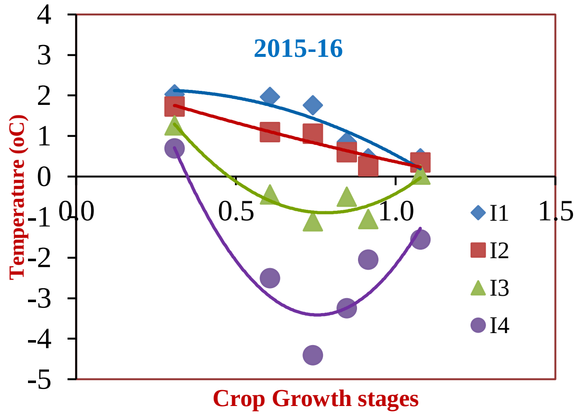


Fig. 4.12 Changes in Crop Canopy temperature Depression (CTD) during different irrigation conditions of sowing wheat crop

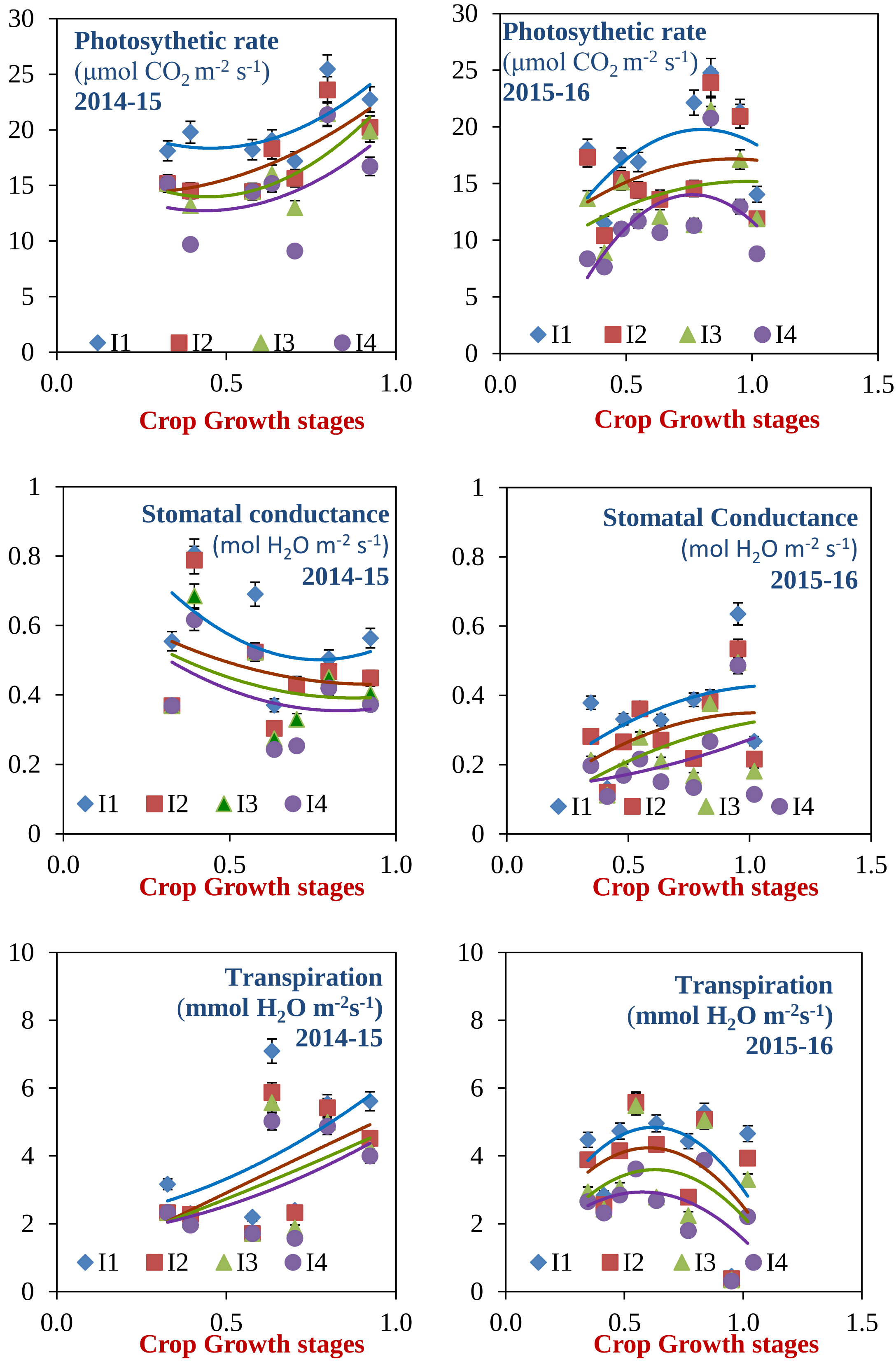


Fig. 4.13 Photosynthesis rate, stomatal conductance and transpiration rate under different irrigation condition

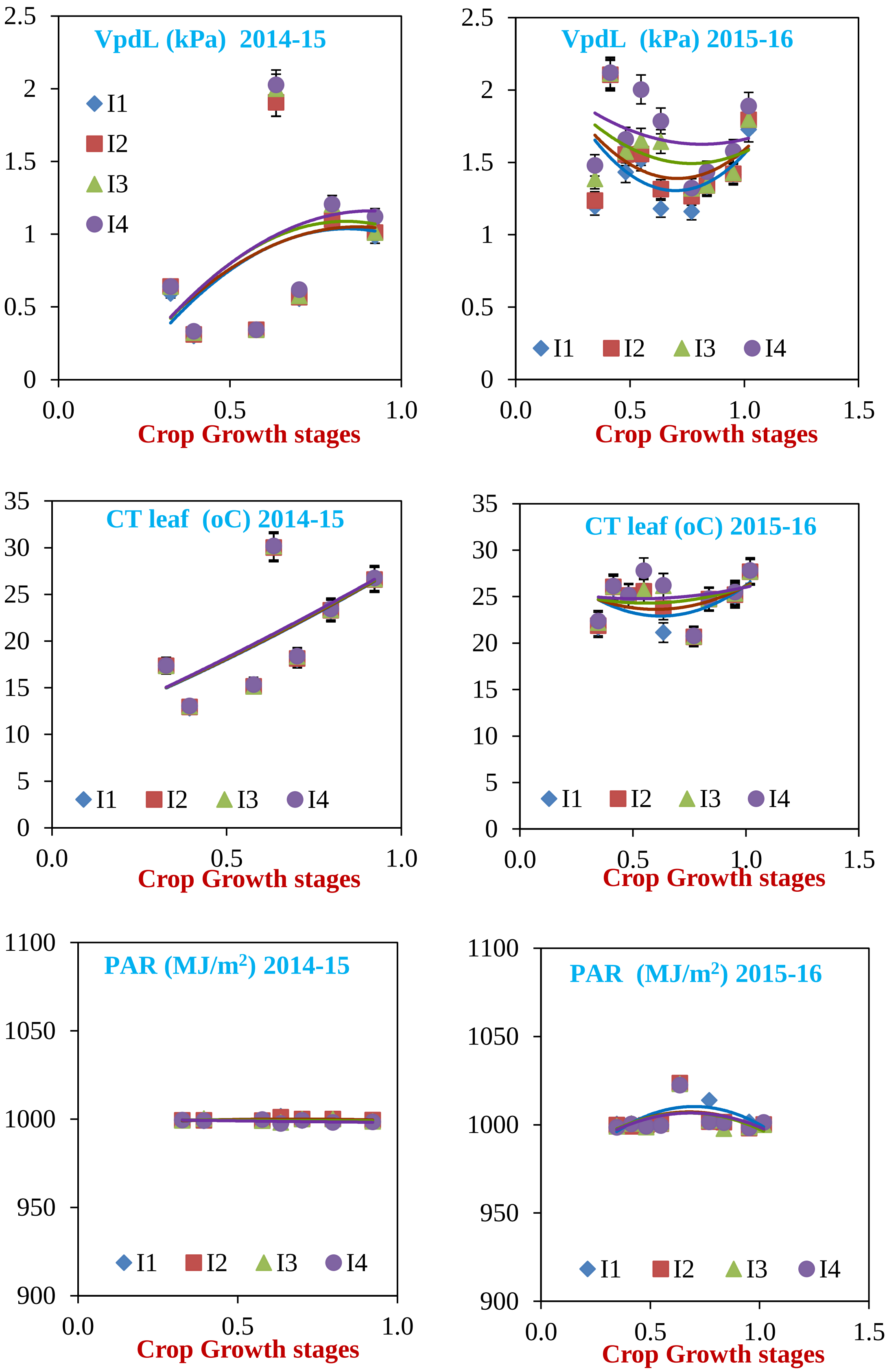


Fig. 4.14 Leaf temperature, VPD of leaf and PAR value under different irrigation treatment

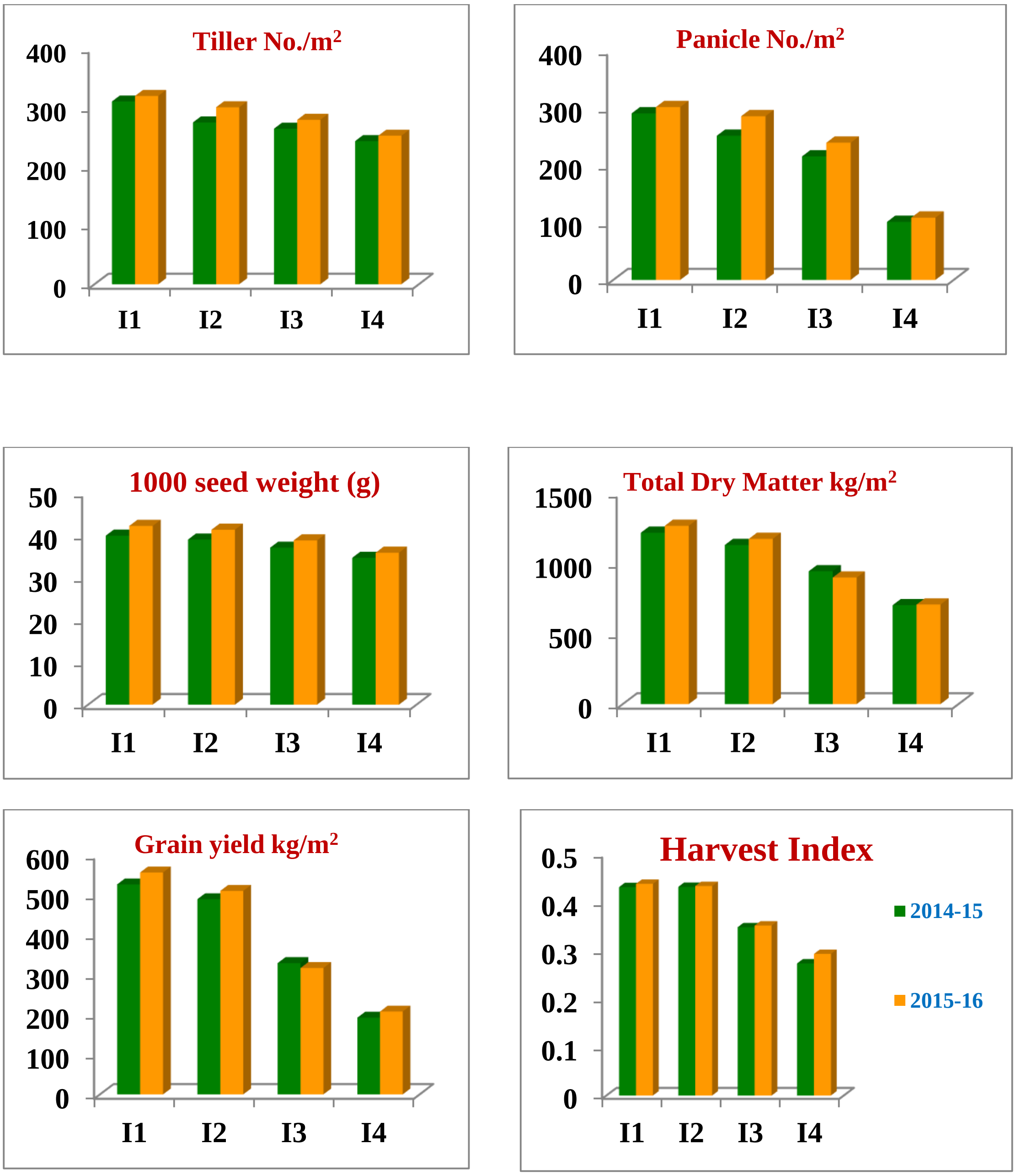


Fig. 4.15 Grain Yield anf biomass for both the year of study

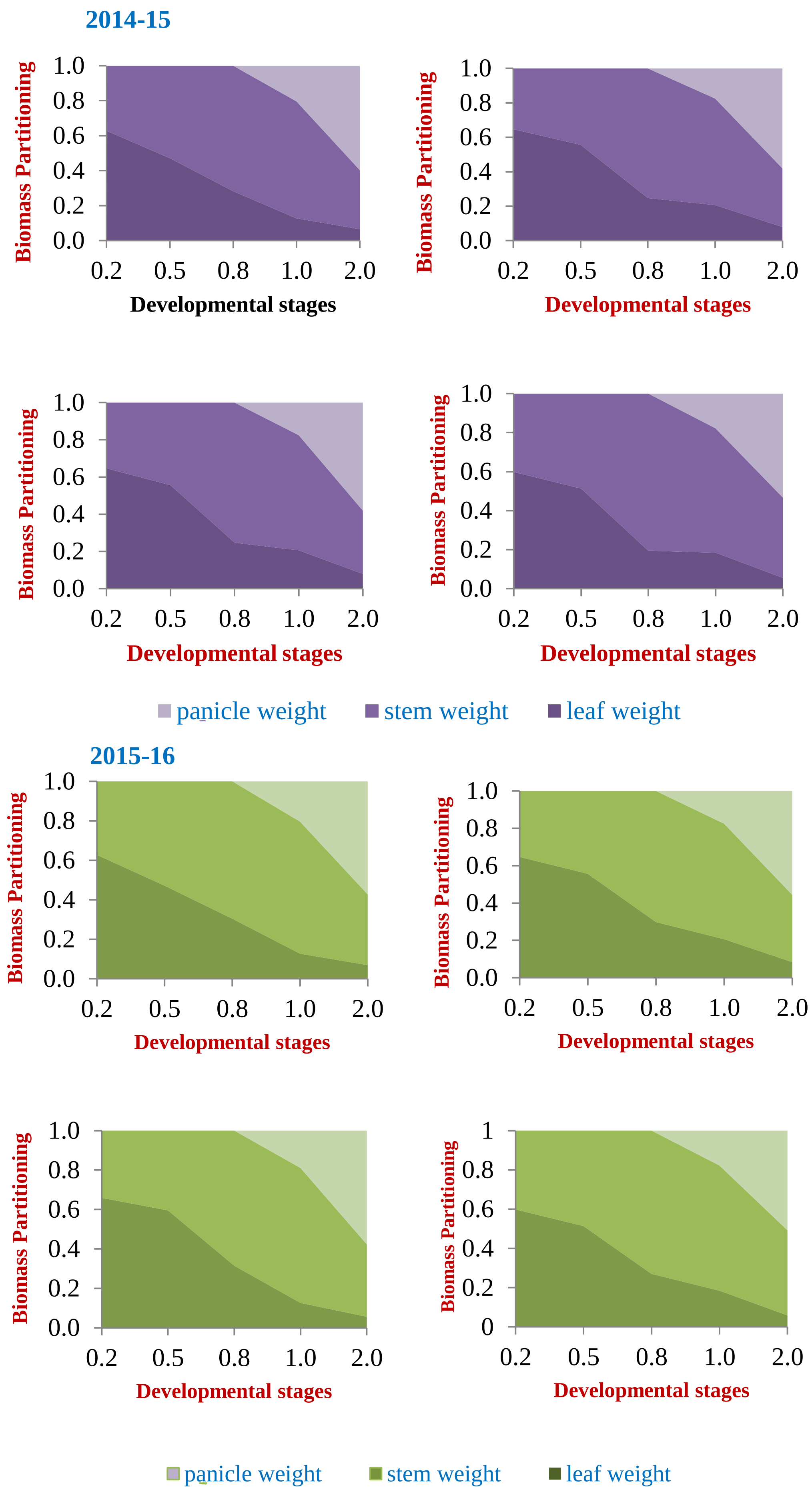


Fig. 4.16 Biomass partitioning under different developmental stages

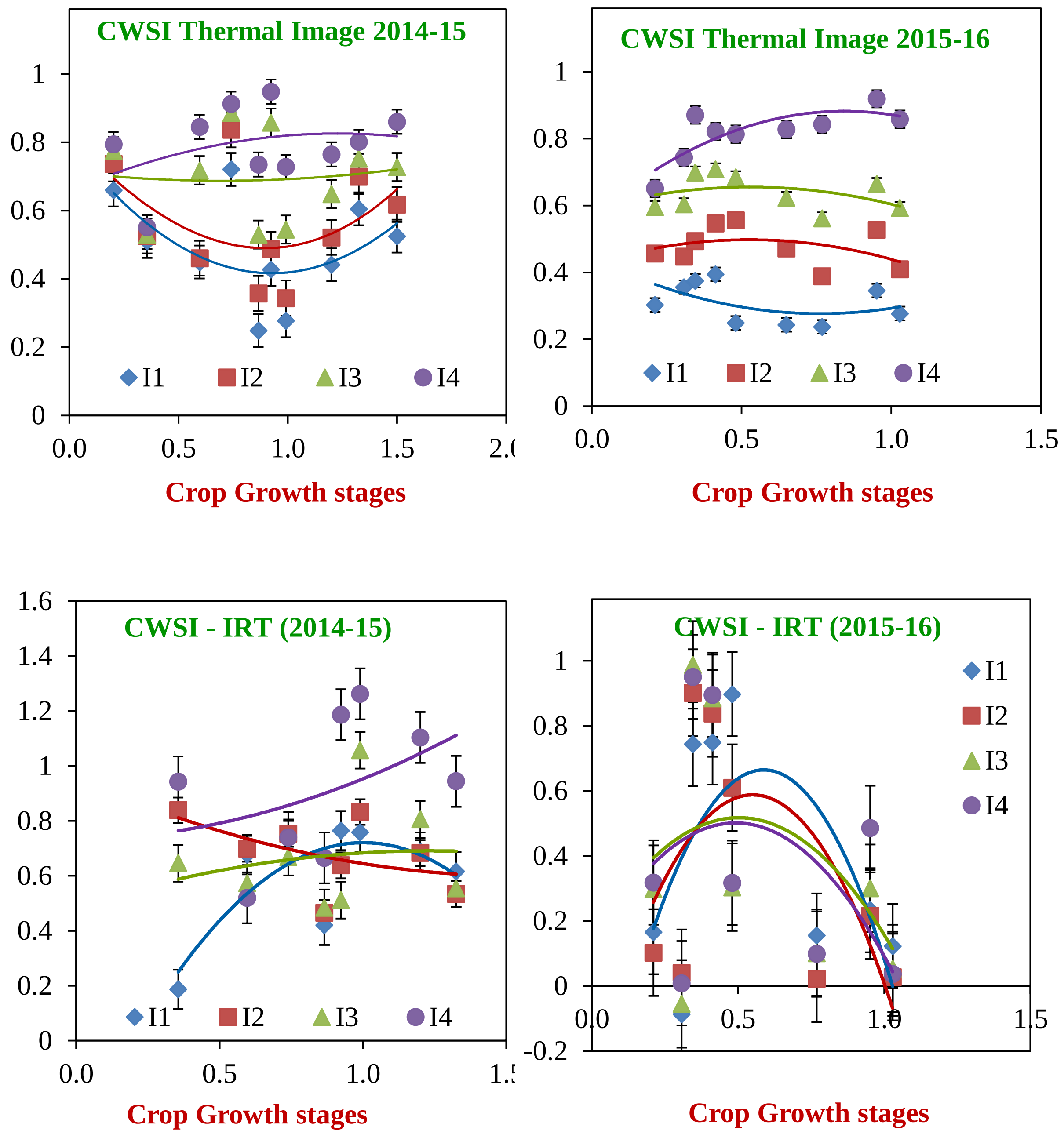


Fig. 4.17 Thermal Stress Index 1 - Crop Water Stress Index by Thermal Image (TI) and Infrared thermometry (IRT)

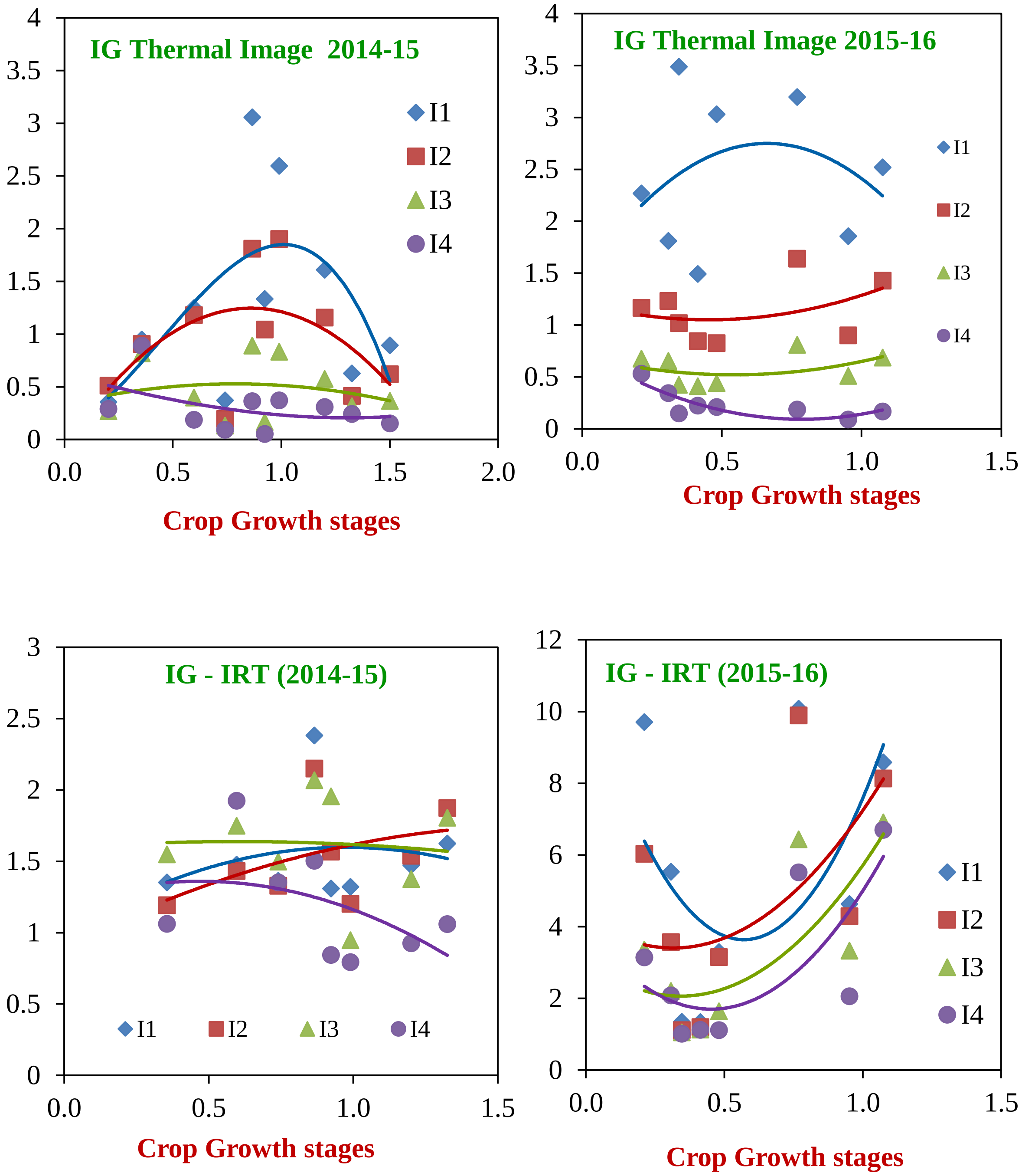


Fig . 4.18 Thermal Index IG - by Thermal Image (TI) and Infrared thermometry (IRT)

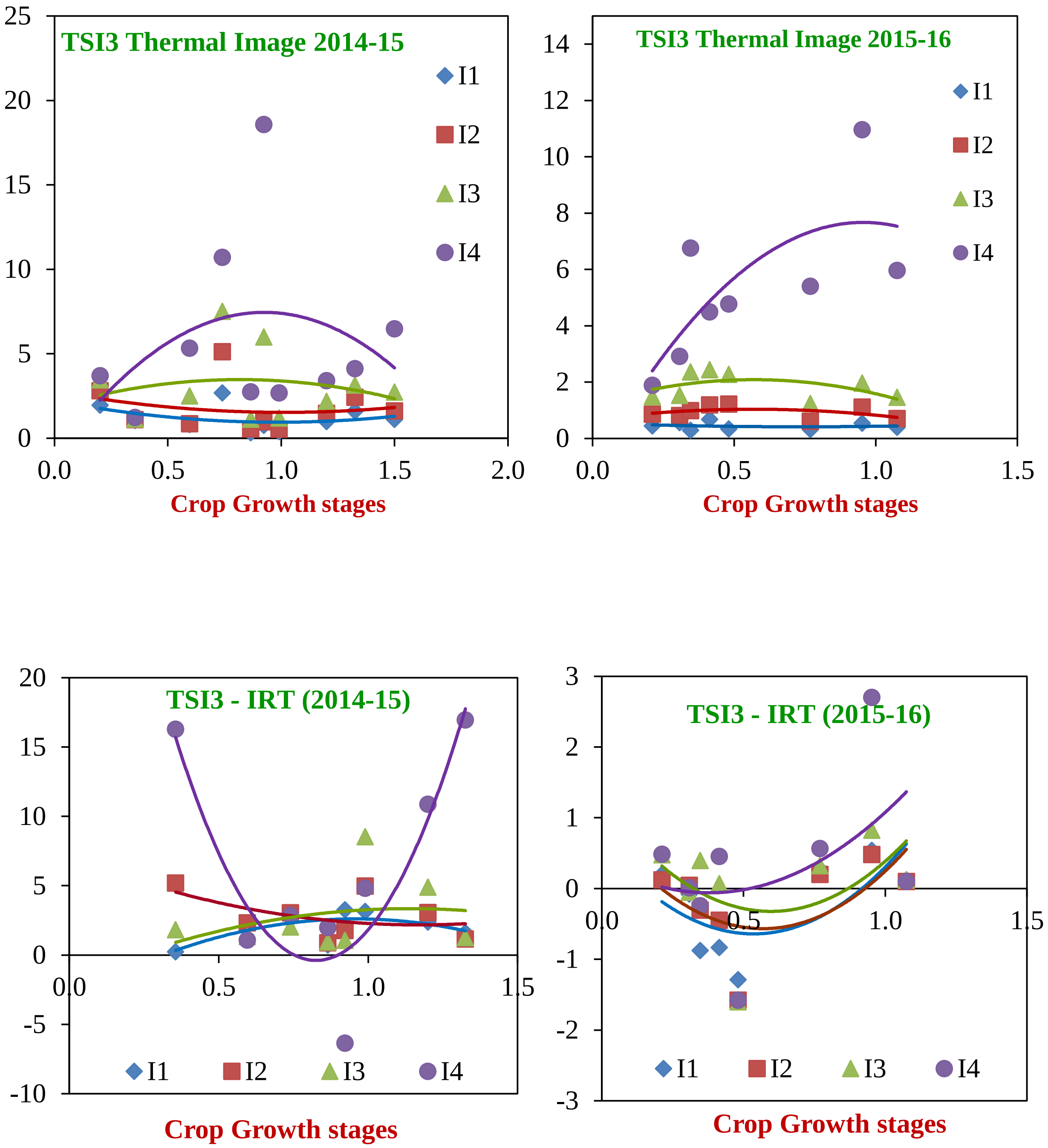
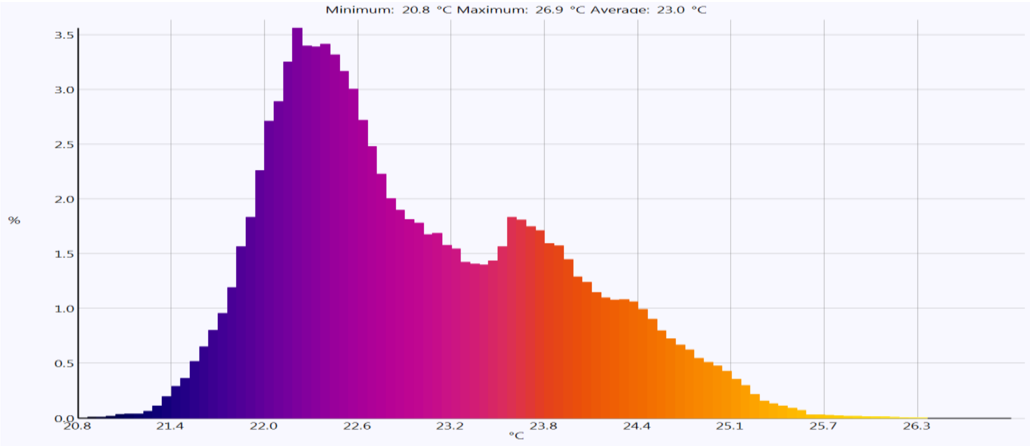
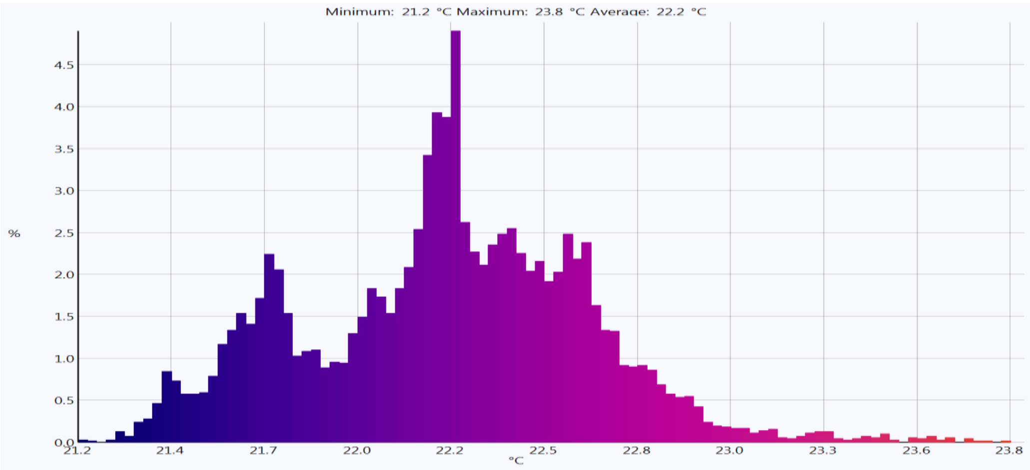


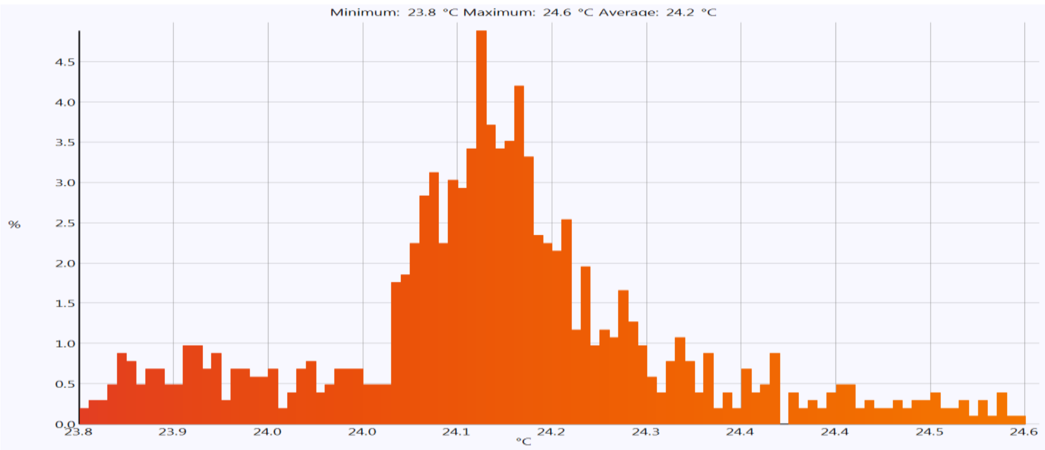
Fig. 4.19 Thermal stress Index 3 (TSI3) – by TI and IRT



A - Whole Image



B - Leaf only



C- Soil only

Fig. 4.20 Temperature distribution for a (A) whole thermal image (B) Leaf only (C) Soil only of wheat field

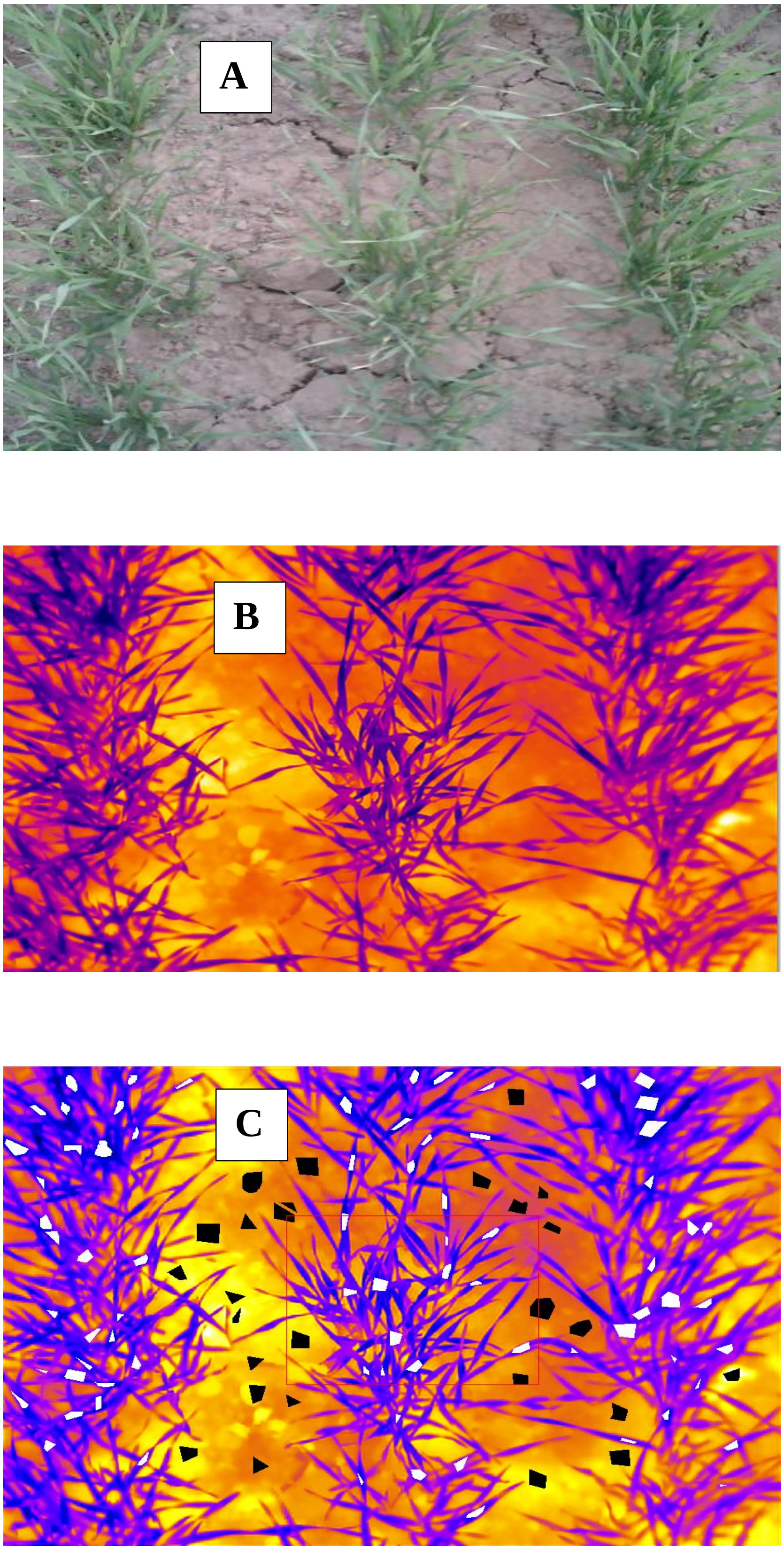


Fig. 4.21 Thermal Image analysis: (a) Optical Image (b) Thermal Image (c) Image showing the selection of Region of Interest ☐ Leaf and ■ Soil

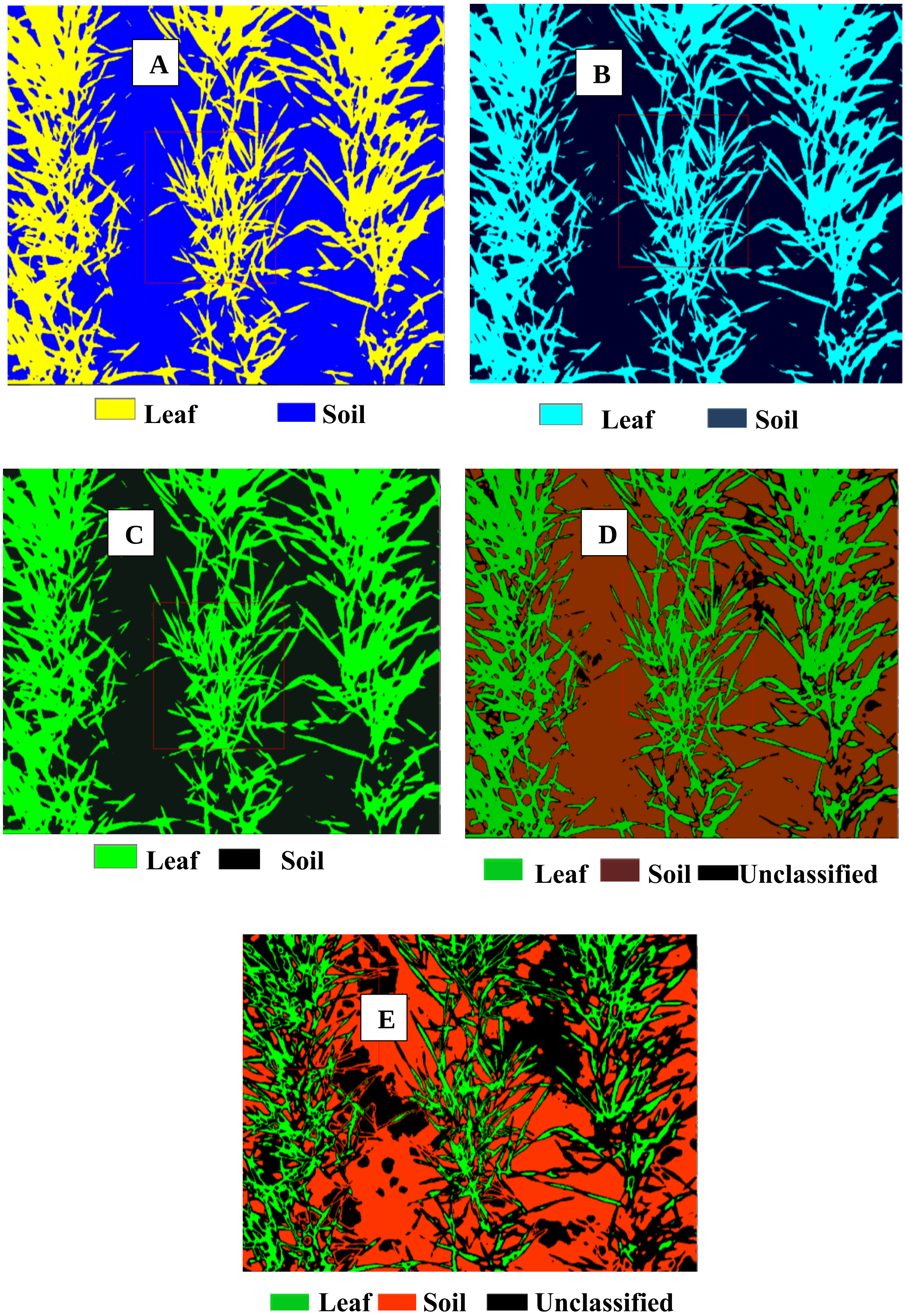


Fig. 4.22 Image classification by different techniques (A) Maximum Likelihood (B) Mahalanobis method (C) Minimum distance method (D) Parallelepiped method (E) Spectral angle mapper method