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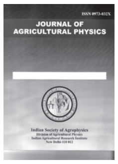

Research Article

Assessing Weather and Moisture Stress using Moisture Stress Index/ Indices

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ABSTRACT

Indexing of moisture stresses in food production system is the priority area to be dealt with utmost care and systematic planning. Since food security is statistically linked with weather and moisture stresses, quantification of weather variables to the production efficiency and weather led moisture stresses are therefore pre-requisite for policy planning. Evaluation of reduction of production, quality assessment and physical deterioration are some of the possible attributes to address the problem. Analysed data showed pan evaporation in mango orchards varied between 2.0 to 17.0 mm day^{-1}. The Progressive changes in soil moisture content towards the end of maturity cum harvesting were observed; moisture stresses were recorded in mango. Energy component in the form of incoming solar radiation at phenology (BBCH scale) based analysis showed variability from 9.9 to 14.3 mm day^{-1}. A range of 803.7 to 1014.6°Cd, 5055.7 to 8686.3°Cdh and 8512.6 to 12364.7°Cdh thermal heat accumulation, heliothermal and photothermal units were recorded across BBCH scales. The problem of moisture stresses were also found in other fruit tree orchards and food crops as well. Analysis of vast data indicated the role of scientific analysis and thereby future source of action for rapid estimation, contingency planning and implementation protocol to address the problem of moisture stresses.

Key words: Moisture stress, Indexing, Weather, Food production system, Subtropical region

Introduction

Moisture stress is the key factor in any robust food production system. Moisture stresses during critical phenophases led to aberration in flowering, fruit setting and developmental stages. This forcibly resulting low production, fruit maturity, early immature ripening and fruit drop may hamper production efficiency in orchards and led to loss of revenue to the growers. Similar is the case of other food production system wherein moisture stresses leads to low productivity. Thus, quantification of *in-situ* and within-growing season of crops/trees are pre-requisite for obtaining stress-free production level. Invisible moisture stress in field is very critical for supporting the life cycle of crops and thereby assessment of soil-crop-tree-forest and other agri-horti-silvi-pastoral system is the need of the hour for long-term survivability of production economics (Adak *et al.,* 2020a; Adak *et al.,* 2022). Narasimhan and Srinivasan (2005) recommended the applicability of soil moisture deficit index and evapotranspiration deficit index for stress monitoring *vis-à-vis* crop productivity. Sehgal *et al.* (2011) emphasized on the crop phenology metrics through satellite derived data and crop stress monitoring. Carrão *et al.* (2016) suggested the use of empirical standardized soil moisture index to predict soil moisture variability and crop productivity like in soybean, wheat and Maize. Sheokand *et al.* (2019) suggested to use of nuclear technique (GM counter) to predict water status in medicinal plants *vis-à-vis* irrigation

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scheduling; ofcourse decrease in mass attenuation coefficients indicated decrease in moisture content in leaves. Arya *et al.* (2019) critically analyzed the latent heat flux, sensible heat flux and ground heat flux in wheat and maize during dough to maturity in order to quantify the heat stress activity under subtropical condition.Based on soil (metric potential, moisture content) and plant indicators (stomatal conductance, maximum daily branch shrinkage and midday stem water potential), Blanco e*t al.* (2018) recommended that midday stem water potential > metric potential>maximum daily branch shrinkage> stomatal conductance> moisture content is the best order for water stress indicator for cherry trees on a sandy loam texture.Moisture is significantly correlated to several soil factors to sustain the best possible outputs. Liu *et al.* (2020) recommended the use of visible and near-infrared spectroscopy with chemometrics to predict 17 soil physical and chemical properties *viz.,* bulk density, pH, soil organic matter, total Nitrogen and other properties. Culumber *et al.* (2019) found that tree-rows with trefoil alleyways improved the nutrient cycling (nutrients, microbial biomass, enzymes etc) in orchard soil. Assi *et al.* (2019) recommended the use of soil aggregate based pedostructure to estimate water relations (field capacity, permanent wilting point and available water etc) in clay loam, silt loam, silty clay loam and loamy fine sand.

The problem of moisture stress is elevated by the weather and climate led aberrations. Several factors dominant on the process of stress development and consequent impacts, outcomes may always be in negative trend. Thus, in order to identify the stress, robust techniques should be applied to quantify the actual amount of moisture present and exactness of moisture stress. Indexes were used to quantify the moisture stress in vast ecologies and also to eliminate the possible minute variables contributing to the on-going discussion on moisture stress *vis-à-vis* production efficiencies. Babu *et al.* (2021) scientifically analyzed the stresses in fruit orchards and suggested for scientific management practices also to mitigate the stress impacts. Zarco-Tejada *et al.* (2013) are in opinion of using normalized photochemical reflectance index with chlorophyll and canopy structure to predict water stress in vineyard grown on fine sandy loam. Sperry and Love (2015) nicely suggested for using hydraulic supply-loss theory and the physics behind the whole water relation scenario in trees to survive in climate led drought. The question remains how root and their system responses and functions under stress condition. For this purpose, recently, Suseela *et al.* (2020) described that the composition of heteropolymers are strategically varied across fine root orders in trees under drought condition without harming the tissue protection. Apart from physiological aspects, even, airborne hyperspectral imagery was successfully used to estimate production efficiency in Citrus (Ye *et al.,* 2008). It has also been recorded that hyperspectral imagery may suitably be used for precision irrigation strategy (Zovko *et al.,* 2017). Osco *et al.* (2019) expressed that artificial neural networking can significantly and scientifically predicts early stages of water stress in lettuce plants with the hyperspectral data set. Recently, scientists also demonstrated that eddy covariance technique being suitably applied to estimate the water use efficiency in Citrus orchards (Peddinti *et al.,* 2020).

Materials and Methods

Field experimentations were conducted in the fruit orchards of ICAR-CISH, Lucknow over decades. Approximately one thousand soil moisture data was generated from the orchard soils at root zone depths. Data collected from tree basin in soil depth of 0 to 60 cm was also incorporated. Log transformed values were developed and presented. Pictorial presentation of moist orchard soils and stressed soil was incorporated. Day to day meteorological data (maximum and minimum temperatures, pan evaporation, wind speed, rainfall, bright sunshine hours and relative humidity) was accessed from the Agrometeorological Observatory situated within the orchard ecosystem. Pan evaporation data were graphically presented to indicate the variability. Stress situation was created before flowering by applying no irrigation. Standard water application was followed at the time of fruit set to development in case of mango. Changes in the incoming solar radiation and BBCH scale based agroclimatic analysis were also estimated. The detailed equation for calculation and estimation of thermal indices was followed as per Adak *et al.* (2016). Phenology based data were incorporated and the information of mango phenology using BBCH scale was scientifically generated and followed as per Rajan *et al.* (2011). Role of soil moisture index was incorporated across food production system. Application of spectral, hyperspectral, thermal imaging techniques to identify the moisture stress on soil and tree/crops was also incorporated.

Result and Discussions

Soil moisture cum phenology vis-à-vis productivity

The soil moisture content determines the dryness and moistness in soil. Under stress condition, soil moisture responses differently to the trees whereas wetness implies continuous flow of sap through xylem. Fig. 1 depicts the stressed and moistness condition in mango orchard. Analysis of the deviation of moisture content indicated that at the initial level, deviation is less; as soil starts drying under evapotranspiration, the deviation fluctuates and more fluctuations were recorded at later stages indicating the role of atmospheric demands cum evaporation *vis-à-vis* transpiration (Fig. 3). The logarithmic distribution showed 1 to 4% variations with greater magnitude of distribution across scales (Fig. 4). The phenology was significantly correlated with the weather-soil-tree continuum and yield variations were found as a function of moisture stresses in mango orchards (Fig. 2). The Scattered distribution

Fig. 1. Mango orchards soils with dryness and wetness

Fig. 2. Mango fruit yields with differential soil moisture content

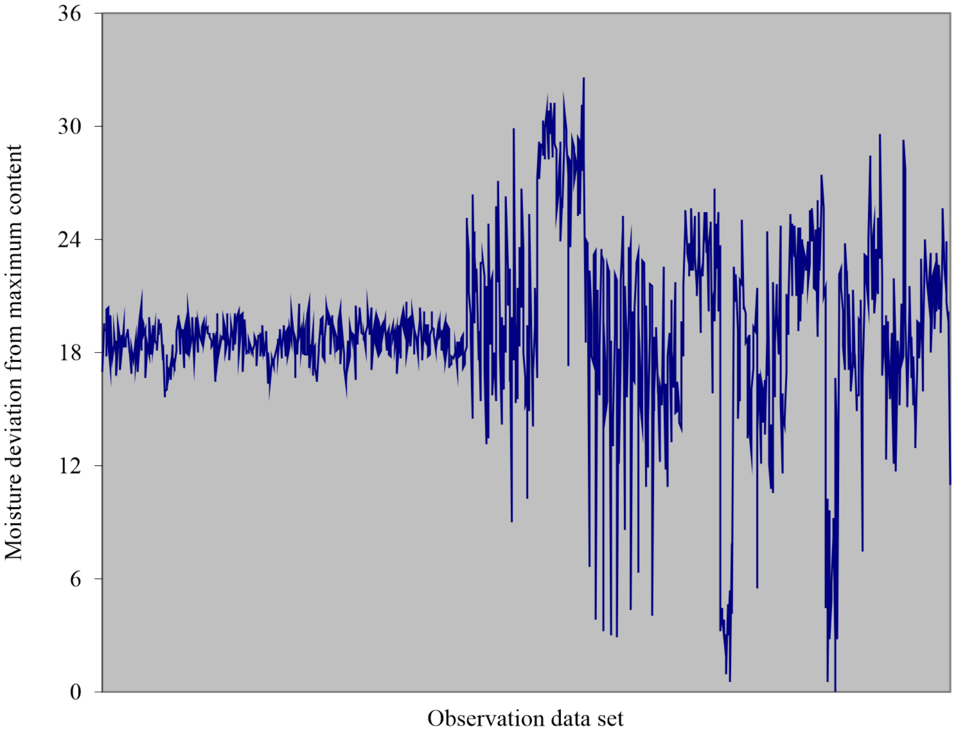

Fig. 3. Deviated moisture contents from the maximum recorded soil moisture

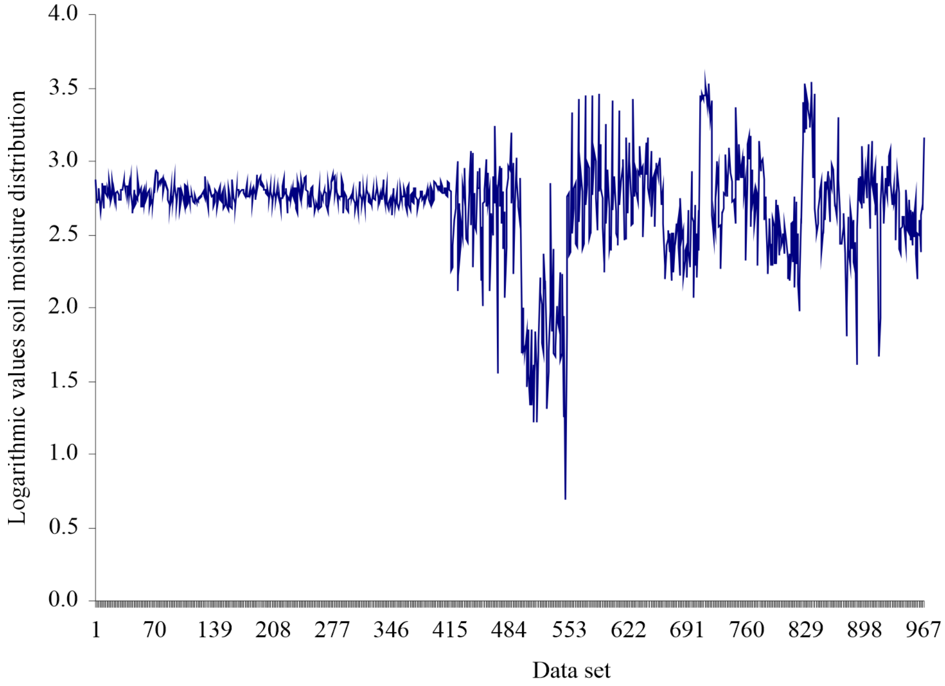

Fig. 4. Logarithmic distribution of orchard soil moisture

showed variability among the evaporation in the orchards contributing towards moisture stress. The agroclimatic analysis (energy components; indices etc) and study on mango phenology revealed that the inflorescence emergence started during January first week and continued up to March 1st week in Northern India (Table 1). The BBCH scale was applied to evaluate the phenophase occurrence in

Table 1. Thermal indices and energy component (Ra)

BBCH scale	SMW	Months	GDD (°Cd)	HTU (°Cdh)	PTU (°Cdh)	Ra (mm/day)
510	3rd -5th	Jan-Feb I	807.1	5055.7	8512.6	9.9
511	6th-7th	Feb I-II	803.7	6122.0	8864.9	11.0
513	7th	Feb II	805.9	5556.6	8953.6	11.3
514	8th	Feb III	833.6	7563.8	9402.2	11.8
515	8th-9th	Feb IV-March	845.3	7642.7	9610.0	12.0
517	9th	end of Feb-March I	857.0	7721.6	9817.8	12.3
610	9th-11th	March I- III	882.2	7268.8	10271.6	12.8
613	10th-11th	March II-III	894.8	7042.4	10498.5	13.1
615	10th -12th	March II-IV	912.5	7129.2	10794.4	13.3
617	11th-12th	March III-IV	925.7	7560.7	11035.3	13.6
619	13th	end of March	1014.6	8686.3	12364.7	14.3

different standard meteorological week (SMW); 510 stage (3rd -5th SMW-Jan-Feb I), 511(6th -7th SMW; Feb I-II), 513(7th SMW; Feb II), 514(8th SMW; Feb III), 515 (8th -9th SWM; Feb IV-March), 517 (9th SWM; end of Feb-March I). The thermal heat accumulation (GDD) at each stage was estimated and found to be varied between 807.1-857.0°Cd (Table 1). Further, the Heliothermal (HTU) and Photothermal units (PTU) were found to be ranged between 5055.7-7721.6°Cdh and 8512.6-9817.8°Cdh. The first flowering (610 BBCH scale) stared at 9th-11th (SMW; March I- III week). The flowering and fruit set stages (613-10th -11th, March II-III; 615-10th -12th , March II-IV; 615-10th -12th , March II-IV; 617-11th-12th March III-IV; and 619-13th, end of March) had a range of 882.2-1014.6°Cd, 7268.8-8686.3°Cdh and 10271.6-12364.7°Cdh respectively. The energy component in the form of incoming shortwave radiation (Ra) and its dynamics over the mango season were estimated. A range of 8.9 to 16.6 mm day^{-1} Ra was recorded during the entire season and month's wise energy component was presented graphically (Fig. 6). During the fruit developmental stages and maturity to harvest (April-June), a range of 15.3-16.6 mm day^{-1} was estimated. During the vegetative phase (September to December), 13.9-9.0 mm day^{-1} while in the next reproductive phase (inflorescence emergence to fruit set) 9.5-13.4 mm day^{-1} Ra was recorded. All these dynamics were found to be associated with the weather dynamics and changes in phenological stages *vis-à-vis* productivity. Adak *et al.* (2020b) critically evaluated the yield variations because of soil health conditions in orchards.

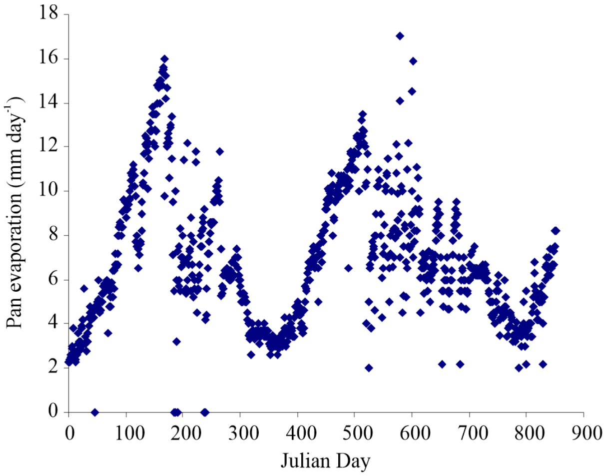

Fig. 5. Distribution of pan evaporation (mm day^{-1}) in orchards (n = 851)

Quantification of moisture stresses through indices and remote sensing applications

Soil moisture supports the life cycle of the crops grown on it. Tree water status supports the metabolisms and life cycle to grow and survive even under harsh climatic situation. Stresses if any developed at any point of time, needs to be identified and put on knowledge based network system so that early and time bound action is taken. Trees can withstand in flooding also by regulating its in-house mechanisms but succumb to death under severe stress

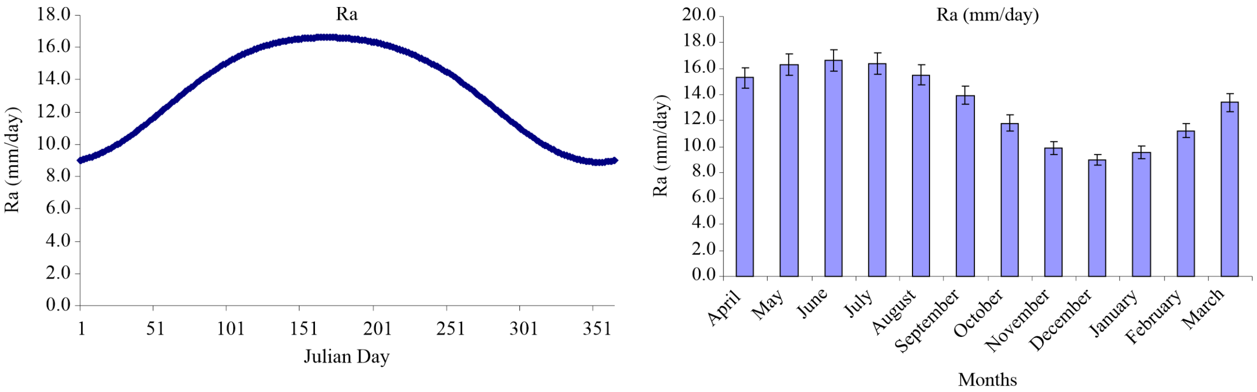

Fig. 6. Dynamics of Ra during the vegetative and reproductive cycles in Dashehari mango

condition. Acute syndrome of trees, either fruit or forest or timber trees shown at the end of stresses makes it impossible to rectify the ecosystem. Thus, ecosystem restoration through viable option like use of remote sensing application to quantify the water stress *vis-à-vis* stresses either in soil or in tree or standing crops parts are crucial. Image processing over vast region of plantations or orchards or within orchard several trees, temperature and moisture stresses can be quantified and reported to take precise decision. All these efforts were time bound and result oriented to achieve sustainable production efficiencies. Table 2 inferred the moisture stresses prediction using robust technologies. Albergel *et al.* (2012) accomplished the ground based soil moisture data set for using in hydrological and crop planning

Table 2. Moisture stress prediction and associated scientific outcomes using robust technologies

References	Country	Soil	Crop	Technology	Activity
Adak *et al.* (2015)	India	Sandy loam	Mango	Fertigation technology	Evapotranspiration based analysis in mango and greater water use efficiency in different fertigation regimes.
Pradhan *et al.* (2016)	India	Sandy loam	Soybean	Reference and actual ET based soil moisture prediction	Soil moisture predicted to avoid moisture stress and improve water use efficiency.
Dzikiti *et al.* (2010)	South Africa	Clayey loam	Satsuma mandarin trees	Spectral and hyperspectral remote sensing	Spectral, hyperspectral and physiological data indicated tree water status for moisture stress prediction.
Quebrajo *et al.* (2018)	Spain	Clayey and sandy	Sugar beet	Thermal imaging and soil remote sensing for irrigation	Thermal imaging detected higher levels of water stress and resulted in reduction of sugar content and fresh root mass.
Padhi *et al.* (2012)	Australia	Clay soil	Cotton	Infrared thermography to predict soil water stress	Thermography may be successfully applied to quantify soil water deficit in cotton using stomatal conductance index.
Virlet *et al.* (2014)	France	Local soil	Apple	Airborne thermal imaging	Vegetation index- temperature scatter-plot and Water deficit index was precisely used to detect the water stress.

purposes. Yang *et al.* (2017) recommended application of modified soil water deficit index for water resource and draught monitoring management; ofcourse other indexes *viz.*, soil moisture deficit index, soil water deficit and atmospheric water deficit indices can also be used. De La Rosa *et al.* (2015) nicely described water stress indicators for precise irrigation use in nectarine trees. Even under disease stressed environments, soil moisture content and water uptake is impacted in trees as observed by Kadyampakeni and Morgan (2017).The spectral data set can provide accurate and precise information on the level of stressed condition situated in soil/field or plants/trees. Krishna *et al.* (2019) applied hyperspectral data set for water related stress evaluation in rice whereas Camino *et al*. (2018) used canopy stress indicator for precision farming. Freeman *et al.* (2019) methodically proved that cloud-based artificial intelligence in combination with small unmanned aircraft system and spectral imaging scientifically provides crop stress information. Das *et al.* (2018) quantified the quality aspects of water stressed condition in 16 rice genotypes; visible and near infrared and shortwave infrared spectroscopy can successfully be used to estimate sucrose, reducing sugars and total sugars. Lamour *et al.* (2020) using approx. 3.95 lakhs data sets from flowering to harvest, developed temporal variability in banana vigour to support precision decisions. Effective crop stress monitoring in Kauri Trees via hyperspectral signatures was also in use (Meiforth *et al.*, 2020). Henceforth, stress related symptoms in soil and tree or plants should be quantified in advance so that proper monitoring of production system can achieved at its full potential range.

Estimation of weather led moisture stresses and associated problems

The weather led stress is complex in nature and season bound moisture and temperature stress is often difficult to predict. Such system existed even in standing crops and fruiting trees and required to watering the trees for better results. Physiological responses are different in such a situation wherein plant/tree responses in a different ways to acclimate in present/existing weather condition. Table 3 showed sensitive response to climate change associated moisture stresses. Leaves, its functionality, water relations between soil to plant and within tree system, evaporation, transpiration, root functionality; phenolic compounds etc. are all together different from stressed situation to a well watered condition. Oxidative stress responses and cell sap flow data gives an insight into the stress mechanisms. More often alternate drying and wetting of soil had impacts on the hydraulic architectures of soil and tree and alters nutrient dynamics too. Dodd *et al.* (2008) estimated the xylem ABA concentration through sap flow data from roots in differential soil moisture regimes. Blackwell *et al.* (2009) described the rate of re-wetting and drying on the phosphorus transformation in soil. Even, iron deficiency leads to oxidative stresses in genotypes of quince and pear (Donnini *et al.,* 2011). Ladda *et al.* (2010) critically analysed the soil moisture and rainfall impacts on the productivity of maize and black gram in a vertisol. Deficit irrigation and partial root zone drying are the scientific advancement towards water conservation *vis-à-vis* production. Such regimes do impacts on the physiological attributes in trees. Improvement in water use efficiency of lemon involving partial root-zone drying regimes was recorded by Pérez-Pérez *et al.* (2012). Early detection to water stress is the most important factor for sustainability of food ecosystem. Summy *et al.* (2015) recommended use of midday leaf water potential, canopy temperature depression, relative water content, chlorophyll fluorescence and relative stress injury are useful for developing moisture stress in chickpea genotypes. Ahumada-Orellana *et al.* (2019) determined the threshold value of water stress in olive >0.18 mol m^{-2} s^{-1} (Stomatal conductance) and > -2.0 MPa (stem water potential). Indexes were used to detect the water stress through meteorological dynamics and canopy structures *vis-à-vis* spectral signatures. Liu *et al.* (2011) expressed serious concern for systematic retrieval of soil moisture data through microwave remote sensing and also suggested for developing soil moisture dataset for future modelling and planning. Halwatura *et al.* (2017) critically examined soil moisture related droughts through indices like standardized precipitation index and reconnaissance drought index. Wider applicability of indices is therefore required to retrieve big data set *vis-à-vis* sustainability module development. Economics is

Table 3. Climate change led moisture stresses and associated responses

References	Country	Crop/tree	Responses
Pauwa and Ramasamy (2020)	African	Agriculture	Projection for 2050 indicated that per capita resource availability index will be declined due to climate change.
Dhakar *et al.* (2013)	India	Pearl millet, sorghum, pulses, maize and groundnut	Use of trend adjusted vegetation condition index for early detection of crop water stress and policy planning.
Rathod *et al*. (2013)	India	Pearl millet, sunflower, pigeon pea, chickpea etc.	Contingency crop planning for *kharif* season based on rainfall analysis and *Rabi* season on residual soil moisture was developed for Maharashtra.
Mangus *et al.* (2016)	USA	Corn in greenhouse	Soil moisture variability in corn was effectively predicted using crop water stress index via thermal infrared imagery.
Zunzunegui *et al.* (2010)	Morocco	Argan tree	Higher (28.11 to 71.3 kg tree^{-1}) and lower (2.97 to 1.95 kg tree$^{-1)}$ fruit production in better and harsh climatic condition with oil production of 28.2 to 35.4 and 0.9 to 4.4 kg ha^{-1} respectively. Better climatic management and maintenance is needed to conserve.
Améglio *et al.* (2002)	France	Walnut and peach	Scientific ways attributed for restoration of branch hydraulic conductivity in walnut and peach trees was identified and insights for water regulation were conceptualized.

significantly dependent on the agricultural production and given the situation of moisture stress; there is every possibility of economic loss. Therefore, quantification of loss in terms of existing market value and other socio-edaphic based indices needed for contingency planning. Intercropping of spices or vegetables grown in interspaces of fruit orchards with minimal watering is also an option to coup of harsh situation. In this context, based on existing cropping patterns and markets values, Mandal *et al.* (2015) stated that economic loss in high rainfall year was 1.81 times greater than normal rainfall years whereas 3.81 times greater as compared to draught years. Under severe moisture stress condition, the loss is enormous. The situation needs to be controlled and future projections on the availability of resources should be kept in mind for robust policy planning.

Conclusions

Soil moisture is the key player in the soil mediated dynamics cum crop response. Stress developed may be required for flowering in fruit crop like mango but at fruit set and developmental stages poses risk of bearing capacity. Likewise, moisture stresses of crops at critical stages are correlated with the production cum economics. The dynamics changes in thermal heat accumulation (803.7 to 1014.6 °Cd), heliothermal (5055.7 to 8686.3°Cdh) and photothermal (8512.6 to 12364.7°Cdh) indices at critical phenological stages (BBCH scale wise) was observed. Greater soil moisture deviations along with higher pan evaporation were indicative of moisture stress existence in orchards. Therefore quantification of moisture stress through indices and remote sensing tools are crucial for food production system. Further, mechanisms for quantifying exactness of stresses *in-situ* should be developed for precise management of orchards and crop for food security. Use of thermal imagery and canopy temperature based indexes in different mango germplasms and other fruit crops cum annual crops should be given priority in tropical and subtropical areas for efficient utilization of scientific knowledge for stress studies and effective mitigation to coup up the stress for continuum food supply.

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