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Adapting to Climate Change: A Sri Lankan perspective

CHAPTER
04

Response of Crops to Heat Stress in a Warming World: Adaptation Measures under Sri Lankan Context

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Abstract

Rising temperatures impose heat stress for a wide variety of crops, negatively influencing their growth and development leading to yield losses. Each crop species has its own thermal thresholds at different growth stages beyond which all these processes get affected. Among different growth stages, reproductive stage has been found to be the most vulnerable to heat stress, and therefore, its influence on yield components is substantial. A comprehensive understanding of crop responses to heat stress has important implications for deciding suitable adaptation measures and for management options. This review provides an account of the influence of heat stress on the above processes giving special emphasis on the thermal thresholds of several crops. Further, conventional as well as potential novel approaches to heat stress adaptation, along with some management options to avert the impacts of high temperature stress in plants have been discussed in this chapter with regard to Sri Lankan context.

Keywords: *Adaptation, crops, heat stress, warming*

Introduction:

Temperature (T) is a critical environmental factor that affects plant growth, development, and yield. Crops require certain basic level of temperature to complete either a given phenophase or the whole lifecycle (Luo, 2011). Cardinal temperatures and lethal temperatures are threshold temperatures that are associated with the crop production processes. Cardinal temperatures include base temperature (T_{base}), optimum temperature (T_{opt}), and ceiling temperature (T_{cel}) of which plant growth and development take place ideally at T_{opt} while at a slower rate from T_{opt} to T_{base} (i.e. sub optimal range) and T_{opt} to T_{cel} (i.e. supra optimal range). Porter and Gawith, (1999) indicated that though the recovery of function is possible from T_{base} to T_{cel} (i.e. within the range of cardinal temperatures) same will not be possible beyond the lethal limits. The rise in temperature even by a single degree beyond these thresholds may impose heat stress on plants (Hasanuzzaman *et al*., 2013).

Abiotic stresses including temperature extremes threaten the productivity and sustainability of many economically important crops worldwide. It is projected to an increase in global mean ambient temperature by 1- 3.4°C due to the global anthropogenic climate change by the end of 21st century (IPCC, 2007). Results of global climate models analysis reveal that tropical and subtropical regions are more prone to heat stress events arise due to global warming than relatively cooler regions of earth. Given the magnitude, direction and frequency of change in temperature thresholds is largely unknown, the effects on exceeding the temperature thresholds on crop yields and their yield components is an active field of study. More importantly the probability of crossing temperature thresholds likely to be even higher in the future, when compared to present temperature regimes (Luo, 2011).

At present heat stress is considered as one of the major limiting factors for crop production worldwide as it substantially effects on a wide variety of economically important crops leading to decreased crop yields. In this chapter we review the basic responses of crop growth, development, and yield with respect to heat stress in a variety of crops. Further, an indication has been given on the thermal thresholds above which crop processes are ceased. Finally, we summarise the effects of heat stress on selected crops under Sri Lankan context while providing current and prospective adaptation measures and management options.

Effects of heat stress

Seed germination and vegetative growth

High temperature effects are apparent at all critical growth stages of a crop starting from seed germination. Poor stand establishment resulted by poor seed germination is expected under elevated temperature as it reduces the germination ability of the seeds (Fahad *et al*., 2016) in many crop species (Burke, 2001; Wahid, 2007). Restricted emergence and elongation of hypocotyls in pea (*Pisum sativum*) in response to heat stress has been found under experimental conditions (Tian *et al*., 2018). Given that, root growth that function under a narrow optimum temperature range, is also reduced due to heat stress (Porter and Gawith, 1999). Other root traits such as root length, root diameter and root numbers may also reduce (Batts *et al*., 1998). Further, heat stress often leads to reduce stem growth and plant height (Simonneau *et al*., 1993; Prasad *et al*., 2006; Wahid, 2007) in many crops with substantial reduction in internodal length such as in sugarcane (Ebrahim *et al*., 1998). Another obvious features that heat stress cause are scorching of the twigs and leaves along with discoloration of fruits and leaves (Vollenweider and

Günthardt-Goerg, 2005) which would ultimately effect on the final quality of the produce.

Developmental processes

Development processes of crops depend basically on two factors; day length/photoperiod and temperature of which the latter act as a major driving force that determine the developmental processes of tropical crops. Thermal duration (i.e. degree days) for a given developmental event is a constant, hence warmer temperatures stimulate developmental events reducing the duration needed to complete a given developmental event.

Floral initiation (rate of panicle initiation) vary under heat stress conditions. For example, duration from panicle initiation to anthesis is reduced under moderate temperature stress; however, the same is increased and panicle development could be ceased under severe temperature stress (Prasad *et al*., 2006). Moreover, failure of fertilization as a result of reduced pollen or ovule function and inhibition of pollen development leading to sterility is another possibility under heat stress conditions (Prasad *et al*., 2000). Heat stress could also leads to shorten the duration of seed filling leading to smaller seed size (Prasad *et al*., 2006), and seed yields. Thus heat stress could result lower yield by reducing grain filling duration in cereals.

Reproductive processes

Reproductive processors are considered highly sensitive to high temperature (Prasad *et al*., 2008; Wahid *et al*., 2012). The most sensitive reproductive events due to high temperature include poor pollen germination and poor pollen tube growth, loss of ovule viability, reduced retention of pollen grain by the stigma, loss of stigma receptivity, impaired fertilization and post fertilization processors (Zinn *et al*., 2010), loss of buds, flowers, fruits and whole seeds and there by substantial reduction in final yield of many crops.

Flowering and fertilization

Flowering is affected by heat stress reducing number of flowers and flower size. In some instances, malformed floral organs (Morrison and Stewart, 2002) are reported resulting loss of flowers along with reduced yields in common beans (*Phaseolus vulgaris*) (Suzuki *et al*., 2001) and mung bean (Tickoo *et al*., 1996). Moreover, boll and flower bud abortion in pea, and brassica is reported at high temperature, which is potentially coupled with limited nutrient and water (Guilioni *et al*., 1997; Young *et al*., 2004). In contrast to high day-time temperatures, cowpea (*Vigna unguiculata*) show susceptibility to high night-time temperatures at early flowering and pod set as a result of anther indehiscence coupled with low pollen viability (Warrag and Hall, 1984). Mature pollens are highly sensitive to heat stress hence demonstrate frequent failures to fertilize under high heat stress conditions (Dupuis and Dumas, 1990).

No pollination or reduced pollination, abscission of flower buds and flowers report in response to heat stress in legumes (Nakano *et al*., 1998). Fertilization may also affected either by inhibiting male (Jain *et al*., 2007) or female (Snider *et al*., 2009) gametophytic development depending on the time of the life cycle, duration of exposure and the severity of the heat stress.

Grain filling and yield

Heat stress lead to substantial yield losses in several important crops including cereals, legumes and vegetables. Heat stress affect the kernel development (Monjardino *et al*., 2005) and kernel quality during grain filling in maize leading to poor final quality in cereals and oil seeds (Wilhelm *et al*., 1999). Reduced individual grain weight as a result of high night temperatures cause declines in substantial grain production in rice (Fahad *et al*., 2016). Moreover, in common beans (Prasad *et al*., 1999), groundnut (Rainey and Griffiths, 2005), cowpea (Hall, 1992) and soybean (Board and Kahlon, 2011) reduced seed filling under heat stress is reported. Obvious reduction in tomato (*Lycopersicum esculentum* Mill.) yield has been reported more likely due to the influence on meiosis, fertilization, and growth of fertilized embryo by the heat stress (Camejo *et al*., 2005). The influence of heat stress on seed filling may exhibit differences depending on crop species.

Threshold temperature of various crops

In agriculture, surface air temperature that usually measured with a thermometer placed 1.5 – 1.8 m above soil is taken into consideration in order to estimate thermal resources and restrictions for cultivated crop plants. However, the temperature of the organs of plants is the most worthwhile parameter to understand the underlying plant processes, which act as a function of temperature. For example, under well-watered condition, leaf temperature could be closer to air temperature as increasing leaf temperature is mitigated through transpiration on the other hand, leaf temperature could substantially be greater when compared to air temperatures when leaf stomata are closed under reduced soil moisture (Drake *et al*., 2017). Similar to leaf temperature, temperature of the soil layer that include the roots also critically affect the root function. Even though soil temperature can be measured at different depths, temperature measured at 10 cm depth is considered to be adequate for agricultural purposes since daily variation is most prominent in superficial soil layer (Ferrante and Mariani, 2018).

In order to understand effect of temperature on crop plants, the knowledge on the actual temperatures to which plant organs expose as well as temperature thresholds under which crop production takes place is vital. A mechanistic understanding on how crop plants operate near temperature thresholds will provide a basis for estimating extreme temperature related risks thereby providing an opportunity to seek for potential adaptation measures in advance (Luo, 2011). The following information reported in past literature provide an indication regarding temperature thresholds and effects that cause under exceeding temperature thresholds on crop growth, development and yield components across a range of crop types (Table 1).

Present distribution and predicted changes of temperature in Sri Lanka

Being a tropical island surrounded by Indian Ocean and presence of a central highland mass, Sri Lanka exhibit a wide variation of temperature across time and space. The mean annual temperature of lowlands of Sri Lanka often exhibits consistent temperatures while it shows decreasing temperatures with increasing elevation towards the central highlands. For example, mean annual temperature of 27˚C at an altitude of 100-150 m drops up to 15˚C at an altitude of about 1800 m at Nuwara Eliya. Especially during the period of January to February diurnal temperature variations in the high elevation areas is wide (Marambe, 2012). It is accepted that in the coastal regions and in the highland diurnal range of temperature could vary between 8°C and 14°C respectively. In general, the warmest period throughout the island is from April to May and the coolest period is from December-January (Bhagat *et al.*, 2016). In contrast during May to September period (during *Yala* season) most of dry zone low land areas experience warm, dry windy conditions.

Table 1: Threshold temperature of some crops at different stages of plant growth and development

	Plant species	Threshold temperature (ºC)	Growth/ process development stage	References
Cereals	Maize (*Zea mays*)	33 - 38	Photosynthesis	(Crafts-Brandner and Salvucci, 2002)
		35	Leaf growth	(Dubey, 1996)
		35	Pollen viability	(Luo, 2011)
	Rice (*Oryza sativa*)	33 for 5 days	Photosynthesis	(Asseng *et al*., 2009)
		33	Biomass /Dry matter production	(Matsushima *et al*., 1982)
		>35	Spikelets sterility	(Yoshida and Hasegawa, 1982)
	Sorghum (*Sorghum bicolor*)	40/30 for 45 days	Photosynthesis	(Djanaguiraman *et al*., 2010)
		> 40	Germination	(Singh and Dhaliwal, 1972)
		26-34	Vegetative growth	(Maiti, 1996)
		36/26	Seed size	(Prasad *et al*., 2006)
Legumes	Ground nut (*Arachis hypogaea*)	31	Pollen viability and seed set	(Vara Prasad *et al*., 2003)
	Common beans (*Phaseolus vulgaris*)	> 30	Flowering	(Konsens *et al*., 1991)
	Mung bean (*Phaseolus aureus*)	28 - 30	Growth	(Poehlman, 1991)
	Soybeans (*Glycine max*)	30.2	Pollen germination	(Boote *et al*., 2005)
		36.1	Pollen tube growth	(Hatfield *et al*., 2008)
		39	Yield production	(Thomas, 2001)

Other crops	Potato (*Solunum tuberosum*)	20	Photosynthesis	(Burton, 1981)
	Tomato (*Lycopersicon esculentum*)	37	Vegetative growth	(Reddy *et al*., 2005)
		28 - 30	Reproductive growth	(Reddy *et al*., 2005)
Plantation Crops	Sugarcane (*Sacharum officinarum*)	35/30	Photosynthesis	(Wahid, 2007)
	Tea (*Camellia sinensis*)	> 35	Shoot growth	(Shoubo, 1989)
	Coconut (*Cocos nucifera*)	> 33	Reproductive growth	(Ranasinghe *et al*., 2015)

Approximately 2.9°C and 2.5°C mean temperature increase is predicted during northeast and southwest monsoon seasons respectively over the base line (1961-1990) by the year 2100 (Eriyagama and Smakhtin, 2010) giving warning signs in advance about incoming threats to crop cultivation. Recent analysis of long term temperature records have shown that the country is warming at a rate of 0.01 – 0.03°C per annum (i.e. increasing of countries mean ambient temperature (Premalal and Punyawardena, 2013) exhibiting a substantial increase in night time temperature compared to that of daytime maximum temperature (Marambe, 2012).

Increasing night time temperature has been noted in many parts of the country over recent decades causing narrow diurnal temperature variations (Marambe, 2012) which could highly impact on root and tuber crop production including potato cultivation in upcountry regions as high night time temperature delay tuber induction, prolong tuber setting, delay onset of rapid tuber growth due to reduced carbohydrate partitioning at early growth (Struik, 2007). Moreover, reduced sugar translocation to fruits leads to increase the sour taste of fruits while reduced palatability of fruits due to increase in the fibre content would also be possibilities that would occur under increased night time temperatures (Marambe, 2012).

Impact of increased temperature on key cultivated crops in Sri Lanka with their current and suggested adaptation measures and management options

Rice:

Rice (*Oryza sativa* L) is the staple food over 20 million Sri Lankans. As the temperature is the driving force for growth and development of rice, the response of rice plants to increase in temperature varies with the duration of exposure to the critical temperature, diurnal temperature variation and physiological status of the plant (Weerakoon *et al*., 2009). Time of the anthesis has been identified as the most sensitive stage in response to increasing temperature (Matsui *et al*., 1999). Spikelet temperatures exceeding 31°C decreased spikelet fertility while complete sterility occurs at 36°C (Weerakoon *et al*., 2008) reducing the productivity of rice in Sri Lanka. December/January and July/August are the periods where anthesis of rice usually occur in major rice growing areas in Sri Lanka. It has been reported that maximum temperature fluctuates between 31-33°C in all growing locations towards end of January while maximum temperature exceeded 35°C in some location in dry zone with fluctuating temperatures exhibiting between 29- 33°C in intermediate zone and wet zone during July – August period

(Weerakoon *et al*., 2009). Thus, the existing evidence provide a clear indication that grain sterility driven by high temperatures would be a critical yield determining factor under the present situation and condition may aggravate with further increase in growth temperature.

Measures have been initiated and already taken in the rice cultivation sector to meet the challenges of increasing temperature. For example, high and low temperature of the rice growing locations have already been identified and appropriate date for the establishment of rice crops has been exactly decided (Rathnayake *et al*., 2016). Further, attention is given on finding the most adaptable varieties for sudden temperature changes have found that variety Bg94-2 is a promising variety for the said purpose (Silva *et al*., 2012). Further efforts have been made to develop short duration varieties that could be fit into short growing season (Harris and Shatheeswaran, 2005). Sri Lanka Department of Agriculture released an ultra-short age rice variety Bg250 that mature in 75-80 days which can cope with shifting season due to irregular fluctuations of temperature and rainfall. Meanwhile the attention has been given on short age traditional varieties such as *Hata Da Vee* (maturing in 70 days) in this regard (Marambe, 2012). Further research needs to be conducted in developing multiple stress tolerance varieties in rice meanwhile making the farmers aware about potential adaptation measures further.

Tea:

Diurnal variation of temperature is greater when compared to annual variation of temperature within tea growing regions of Sri Lanka with February to March recorded as the months with highest diurnal range of the temperatures. The optimum ambient temperature required for growth of tea is considered to be 18-25°C with reduced growth found at air temperature below 13°C and above 30°C (Carr, 1972; Carr and Stephens, 1992).

Assessments carried out during 2002-2004 exploring climate change impact on tea cultivation shows that apart from the tea plantations found at higher elevations (i.e. > 1200 m), majority of the tea plantations in Sri Lanka will be affected due to higher temperatures and dry weather conditions as a result of climate change. Increased ambient temperatures (maximum and minimum) over the last five decades of most of the tea growing regions (except maximum temperature in Nuwara Eliya) provides a sound indication about the direction towards the temperature build taking place (Bhagat *et al*., 2016). In the Report of the Working Group on Climate Change of the FAO Intergovernmental Group on Tea, Bhagat *et al*. (2016) suggested the following as adaptation measures for tea cultivation in Sri Lanka.

As the initial cost incurred with replanting/new planting is very high, it is essential that most suitable regions with lands be identified at regional and plantation level through land suitability classification and used for future planning processes. Through these suitable lands could be retained for tea cultivation while marginal/less productive lands could be diversified into other uses.

Assisting tea growers with high precision weather forecast would enable them to make decision and make their lands ready with regard to facing adverse weather conditions would be a high priority. The growers who are not in a position to make decisions alone should be supported to identify suitable adaptation measures to minimize the potential adverse impacts caused by extreme temperatures.

More importantly providing of financial assistance to tea growers whenever necessary will increase the adoption rates of the strategies to a greater extent.

In the long run, crop improvement will be the best adaptation measure to climate change hence attention given to developing new varieties and graft combination to combat rising temperatures would be highly essential despite the high cost involved in the process.

Among tea growing areas in Sri Lanka, low country regions experience the highest temperature regimes with ambient temperatures above the optimum required for tea hence, further increase in ambient temperatures will negatively effect on the yield as well as the quality of tea. Moreover, it will be highly likely that further increase in temperatures would lead to make the mid elevation tea plantations less productive though the present ambient temperatures that exist is considered conducive. Appropriate stands of low and high shade trees that occupy the vertical space at different height in tea plantations lead to reduces heat and excessive light radiation and thereby ambient temperature around tea bushes and increase RH (Sivapalan, 1993; Mukhopadhyay and Mondal, 2017) hence care given to establish and maintain of shade trees at low elevations and mid country Intermediate Zone having comparatively dry conditions is very important.

Coconut:

The mean annual temperature of 27-30°C is considered as the optimum temperature conditions for growth and yield of coconut (Perera *et al*., 2009; Ranasinghe *et al*., 2015). When compared to vegetative components, reproductive organs of coconut palm are considered highly sensitive to stress including high temperature (Ranasinghe *et al*., 2015). During the reproductive development, number of sensitive stages can be found including three months prior to the opening of the inflorescence during which ovule and pollen formation takes place (Perera *et al.,* 2010). During the first month after inflorescence opening, pollination and button nut formation take place and three months after inflorescence opening number of set fruits is determined. Among above, fruit set is the key yield determining factor which is strongly influenced by high temperature stress in different ways including production of poor quality female flowers and pollen, reduced pollen germination and reduced supply of assimilates to fruits leading to reduced fruit set under heat stress conditions. Moreover, quality of fruits and rate and duration of assimilate production may subject to the intensity of exposure and sensitivity. Empirical studies have revealed that reduced number of female flowers and reduced fruit set leading to poor yield (under temperature stress coupled with water stress) is more prominent in the Dry Zone of Sri Lanka when compared to Intermediate Zone in Sri Lanka (Ranasinghe *et al*., 2015).

The success of fruit set in coconut relies on extent to which pollen germination and pollen tube growth occur under heat stress conditions therefore developing improved coconut varieties with enhanced reproductive heat tolerance will be highly beneficial to the industry in the long run. Results of empirical studies provide evidence that the coconut hybrids; Sri Lankan Green Dwarf × Sri Lanka Tall and Sri Lanka Brown Dwarf × Sri Lanka Tall are the most tolerant hybrids to high temperature stress (Ranasinghe *et al*., 2018).

Incorporation of coconut based agroforestry systems/mixed cropping is found to be highly beneficial as that helps to improve the microclimate of coconut plantations through occupying the vertical as well as ground space by different plants/trees that performs different functions (Ranasinghe *et al*., 2014). Practicing mixed cropping systems have reported reduced air temperatures at canopy level when compared to monoculture systems (Ranasinghe, 2009). Therefore, more attention needs to be given to practice intercrop/agroforestry system as an adaptation measure with a special focus on selection of the correct intercrop/agroforestry system to be practiced.

When the thresholds temperatures given in Table 1 is considered, it is evident that most of the key cultivated crops in Sri Lanka function near their threshold temperature/s beyond which the growth, development and yield is adversely affected. As the frequency of occurring high temperature events has increased especially at dry and intermediate zones during *Yala* season spikelet sterility couple with lower photosynthesis at high temperatures (Table 1) could leads to substantial yield reduction in our staple crop, rice. Similarly, most of the listed crops in the Table 1 will be affected due to either increasing temperature events or due to heat stress.

National Adaptation Plan for Climate Change Impacts in Sri Lanka: 2016 – 2025 have proposed the following strategies to be used for different crop sectors as a measure to adapt to climate change impacts including rising temperature.

Enhance resilience against heat stress could be achieved for other field crops and horticultural crops via developing heat tolerant varieties, enhancing the efficiency of water management and developing the capacity for conducting research on tolerant varieties and enhancing the water efficiency farming practices.

For Export Agriculture Sector (e.g. coffee, cocoa, spices etc.) germplasm improvement for heat stress, **s**creen of existing cultivars for heat tolerance, deep planting at nursery and field level in addition to capacity building for research has been proposed.

Special attention has also been given on this report highlighting the importance of establishment of an efficient climate information and management communication system and improvement of disaster risk preparedness and management plan. The latter to be achieved via developing a system to strengthen the early warning system, preparation of hazard vulnerability maps for all crops and developing guidelines for managing of extreme events in vulnerable areas.

Even though wild fires are not very commonly found in Sri Lanka need of developing a very comprehensive plan for mitigating wild fires has been highlighted as depending on the magnitude and the extent under wildfire could create heat waves which could cause a substantial damage to crops at any given point of the life cycles. Thus identification and preparation of maps related to hazard prone areas, acquire new equipment and training staff to combat uncontrolled wildfires will be essential.

Conclusions and way forward

Many plant processes are a function of temperature. However, rising temperatures exceeding thresholds values for plant growth, development and yield formation cause heat stress, which is a major limiting factor for crop productivity around the world. Among different phases, the reproductive stage is more prone to heat stress, hence crop yields are affected leaving uncertainty for the food security in a warming world.

Heat stress, which affect crop plants at any time in the life cycle is considered as the second most important stress after drought that impose limitations to plant functions. Therefore, a mechanistic understanding on the responses of crops to their supra optimal temperatures at both spatial and temporal scale is required for proposing adaptation strategies to heat stress. Lack of comparative physiological studies on adaptive responses of existing crop cultivars to heat stress is a substantial knowledge gap. Segregation of adaptive responses from acclimation potential of crop plants to heat stress together with understanding of the biochemical and molecular basis of heat tolerance may set the baselines for making agronomic decision such as choosing suitable cultivars for dry and arid regions. Further, reorientation of current varietal improvement and breeding program of the country with the use of more modern breeding techniques including easy to measure physiological parameters for screening against heat and drought stresses is another high priority area that needs immediate attention. Moreover, research on strengthening early warning systems, developing crop specific vulnerability maps and manuals for field practices in farming communities for managing extreme events in vulnerable areas would be beneficial. Since the heat and drought stress occur in combination under the field conditions, understanding how crops response to the combined effects of both stresses and improving crop models to accurately stimulate interactive effects of heat and drought stresses on crop growth, development and yield processes is essential to combat against future warming conditions.

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