Why Crops Produced The Way They Did in 2003 - Ability to Handle Drought and Heat Stress.

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Introduction:

Drought and heat stress are the two most important stresses limiting crop productivity around the world. In the short growing season of the Canadian prairie, temperature and moisture deficit increases gradually during the growing season and crops frequently suffer from these stresses. However, temporal and spatial variations in stresses are always observed. Crops, being stationary to a location adopt strategies to avoid or tolerate stresses in the field (Ludlow and Muchow, 1990). Crops often vary in the strategies they adopt. Crop diversity in the Canadian Prairie has increased due to increased awareness of sustainable cropping systems. Therefore, it is important to understand different strategies used by crops to avoid drought and heat stress.

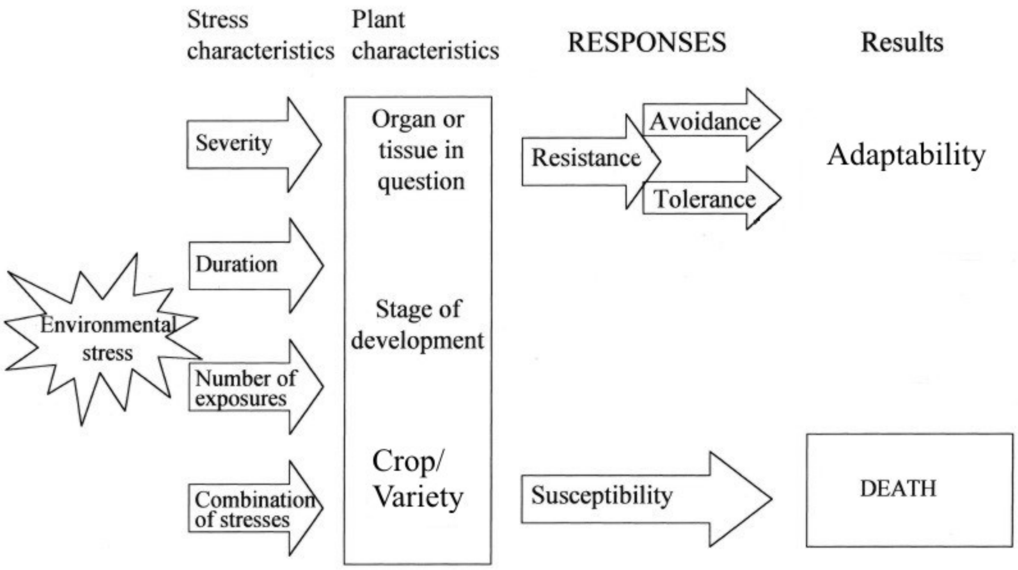


Figure 1. Plant response to environment stress depends on the interaction between stress factors and plant factors.

Crop yield is an integrated response to the growing season environment from seeding to harvest. Therefore, assessing the effect of stress on crop depends on interactions between factors associated with stresses and factors associated with crops (Figure 1). While severity, duration, number of exposures and presence of other stresses are important from a stress perspective, plant response to stress depends on the physiological processes affected, sensitivity of the tissue or organ, developmental stage of the crop and type of the crop and/or variety subjected to the stress. In general, flowering is the most sensitive stage and any stress during that period can reduce yield significantly. Similarly, a moderate stress may slow down photosynthesis but may continue to fill the sink (seed) by retranslocating stored photosynthates. A crop is adopted to a region if the strategies adopted to avoid or tolerate predominant stresses prevailing in the region are effective.

Drought Stress:

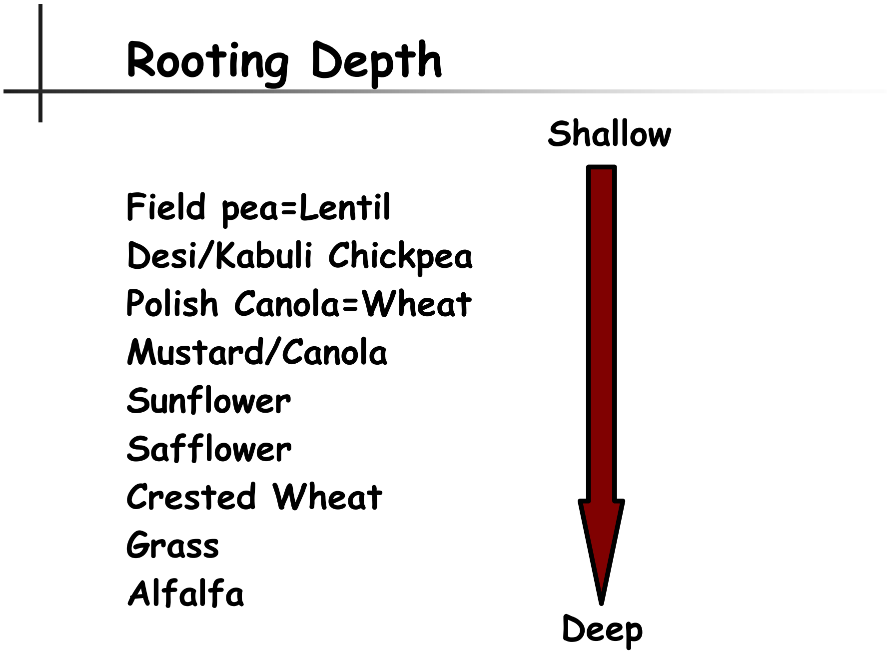
Drought stress occurs when a plant is not able to replenish the water lost by transpiration. When stress disturbs processes in the highly integrated system of plants, a variety of control mechanisms are initiated to adjust other processes to maintain functional balance (Subbarao et al., 1995). Drought tolerance of plants is determined by a large number of physiological and morphological traits. The potential value of a trait depends on the crop and the nature of drought (i.e., intermittent vs. terminal drought) (Ludlow and Muchow, 1990). Drought tolerance traits involve either conserving tissue water content or maintaining the productivity over a range of tissue water content in a water-limiting condition. Overall, drought response strategies adopted within alternate pulse and oilseed crops vary significantly (Turner et al., 2001).

Drought Tolerance Traits:

1. **Root System:** Plants depend on their root systems to absorb water from the soil reserve. Rooting depth, root length density and root hydraulic conductivity are the important traits that vary among crops species.

Rooting depth varies among crops grown on the prairie (Figure 2). Under rainfed conditions a deeper root system provides stability to crop yield (Ludlow and Muchow, 1990). Rooting depth varies with growing environment, nutrient availability, soil temperature, availability of water at depth, soil texture, and tillage practices. Annual crops usually reach their maximum rooting depth around anthesis, while perennial crops (eg. alfalfa) reach their deepest rooting depth after two growing seasons. It is difficult to accurately predict rooting depth of a crop at any particular period. However, we can compare rooting depths of different crops based on observations in the field. Field pea/lentils are shallow rooted crops and alfalfa is a deep rooted crop. Approximate rooting depths for crops under Canadian prairie conditions are 0.80 m for field pea/lentil, 1.00 to 1.20m for chickpea, 1.20m for Polish canola and wheat, 1.40 m for mustard and Argentine canola, 1.80m for sunflower, 2.00m for safflower/crested wheat grass and 3.00m for alfalfa. Root length density is the length of roots present in a unit volume of soil profile. Minimum root length density is needed in each soil layer for efficient extraction of water and nutrients. Among crops grown on the prairie, canola and field pea are dicots and have a tap root system, while wheat is a monocot and has a fibrous root system. Comparison of root length density of the above crops indicated that canola and field pea had 60 to 75 % root length in the top 2 ft compared to wheat (Angadi et al., 1999). Below 2 ft, field pea root length decreased at a faster rate, while root length of canola was 100% of wheat at 1.00m depth. These observations indicate that major root length density differences in crops are observed at lower depths. Shallow rooting crops (field pea) have lower root length at depth compared to deep rooting crops (canola), thus becoming less efficient in extracting water from depth.

Root hydraulic conductivity indicates the amount of water extracted per unit length of root. Species with lower root hydraulic conductivity are reported to conserve moisture under rainfed conditions and utilize it later during the grain filling period. Pulses and wheat are reported to have this conservation strategy. Sunflower, on the other hand, relies on its strong root system and high hydraulic conductivity to extract more water from soil to meet the water demand of the crop. This strategy may work if there is lot of water at depth and rainfall is expected at regular intervals.



Rooting Depth

Shallow

Field pea=Lentil
Desi/Kabuli Chickpea
Polish Canola=Wheat
Mustard/Canola
Sunflower
Safflower
Crested Wheat
Grass
Alfalfa

Deep

Figure 2. Rooting depth ranking of crops grown on the Canadian prairie.

2. **Stomatal Regulation:** A major portion of the water extracted by the root system is lost to the atmosphere while the leaf takes in CO_2 during photosynthesis. Stomata, leaf openings, play a major role in this exchange. Since, photosynthesis is the only process for converting solar energy into seed grains, water loss is an unavoidable evil. However, some crops are efficient in regulating stomatal opening so that water loss during middle of the day (most water demanding period) is reduced. Cow pea is a good example of stomatal regulation, while crops like sunflower rely less on stomatal regulation.

3. **Osmotic adjustment:** When water is limiting, many crops accumulate salt in leaf cells and maintain leaf turgor. This helps in maintaining green leaf area, biomass retranslocation, and maintaining better grain to dry matter ratio. Wheat, due to its strong osmotic adjustment, maintains tissue turgor over a range of tissue water potentials and is considered well adapted to the semiarid areas of Canadian prairie (Entz and Fowler, 1990). In general, canola and mustard are poor in osmotic adjustment, but mustard maintains greater turgor potential under high water deficit than canola and thereby greater dry matter and seed yield. Osmotic adjustment in different pulse crops varies significantly (Subbarao et al., 1995).

4. **Leaf Movement:** Solar radiation is the major source of energy for water evaporation (transpiration) from the leaf. Some crops, during moisture stress, adopt leaf movement strategies to reduce radiation load. These include wilting (eg. sunflower), rolling (eg. wheat) and folding (eg. pulses). Similar to stomatal regulation, use of leaf movement strategy in the middle of the day when radiation load is maximum, reduces water loss from plants.

5. **Morphological Adjustment:** Crop leaf area and water use increase gradually during the growing season, peak around the reproductive period and then decline (Figure 3. continuous line). If plants are subjected to water stress early in the season, they will initiate their first line of defense of reducing leaf area and thereby seasonal water use (Figure 3. red dotted line). This is a very efficient strategy in reducing seasonal water use. However, it is a conservative approach and the plant could fail to utilize optimum growing conditions that may prevail later in the season. On the other hand if stress prevails later in the growing season, plants try to reduce their leaf area and water use by shedding lower leaves. Duration of crop growth affects the seasonal pattern of water use. Longer season crops like corn reach their peak water demand at a later date compared to early season crops.

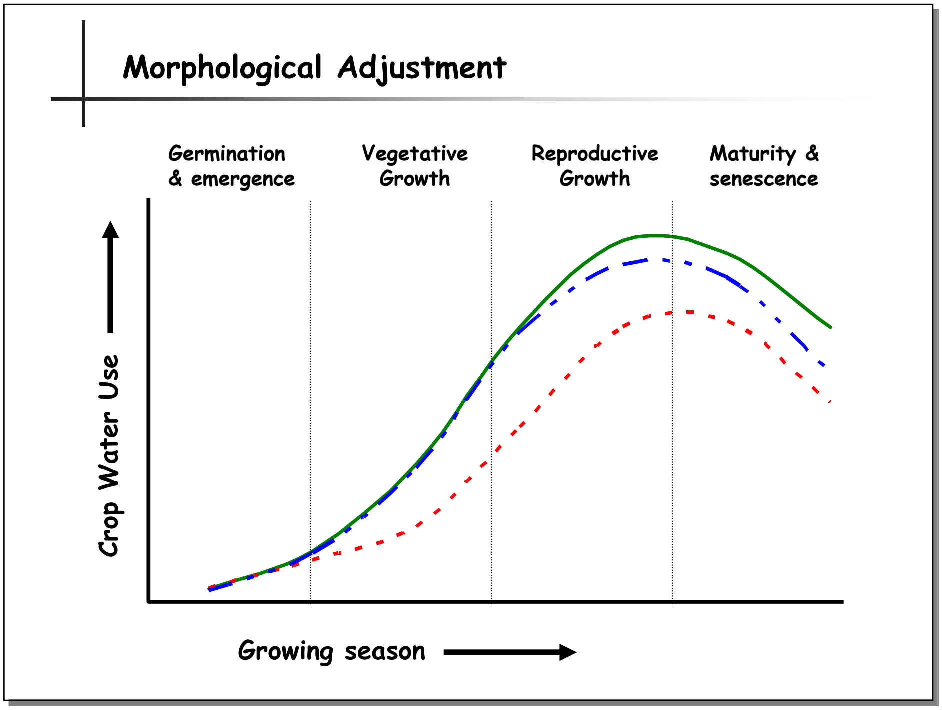


Figure 3. Seasonal pattern of water use by crops (solid line) and effect of early season stress (dotted line) and late season stress (broken line with two dots) on that water use pattern.

6. **Retranslocation of Pre-anthesis Photosynthates:** Typically most crops produce more photosynthates early in the season than their vegetative growth needs. The extra photosynthates along with some of the extra mobile nutrients (eg. N) absorbed are preserved in storage organs like stems, leaves and roots. Later during the grain filling period, especially when plants are stressed, these food materials are retranslocated to the grain. This is a good drought tolerance strategy in most crops under most conditions. However, if the retranslocation is excessive in crops like sunflower and corn, weak stems cannot support the heavier head/cob leading to lodging problems.

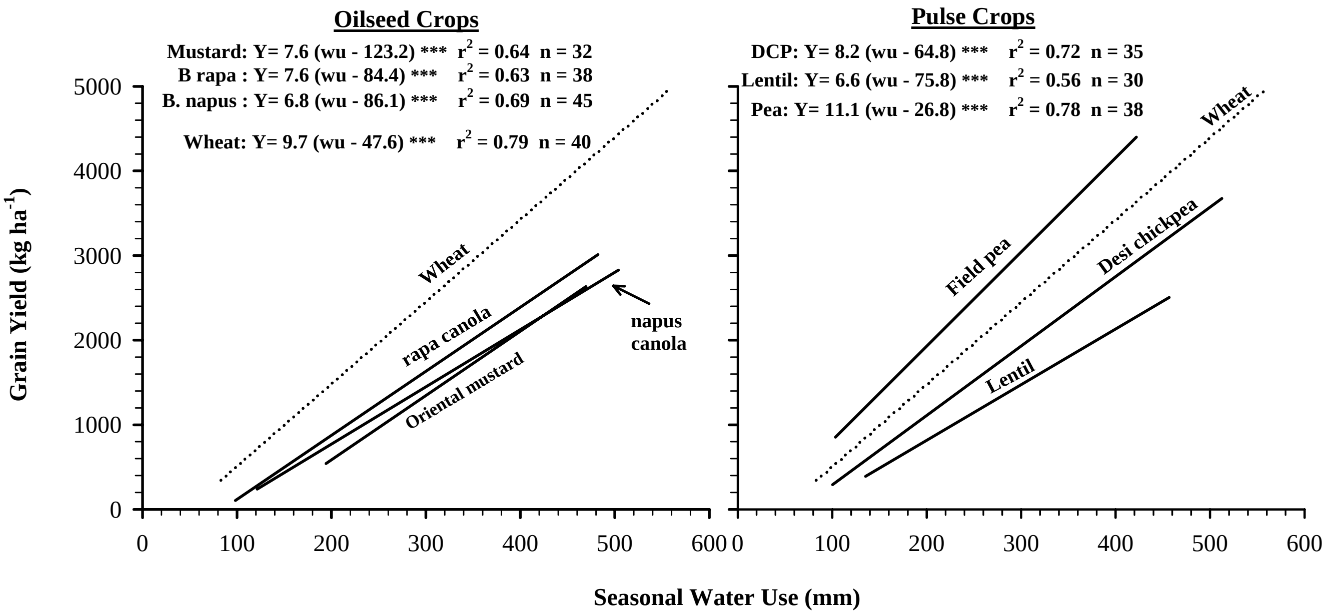


Figure 4. Relationship between seed yield and water use (defined as soil water extraction plus rainfall received between seeding and harvest) for different pulse and oilseed crops in comparison to wheat at Swift Current (ASngadi et al. 1998).

7. **Water Use and Seed Yield Relationship:** Seed yield of all crops increases linearly with an increase in water use. However, some crops are more efficient than others. In a study conducted at Swift Current, Saskatchewan field pea produced the greatest seed yield response per unit increase in water use, (11.1 kg ha^{-1} seed for each mm increase in water use) (Figure. 4) (Angadi et al., 1999). This was significantly higher than all other crops except wheat. As a group, Brassica oilseeds had the lowest water use efficiency. Mild water stress is essential for initiating seed filling in indeterminate crops like pulses. This was especially true for lentil, which failed to switch from the vegetative phase to the reproductive phase at higher water availability. Some of the lowest grain to dry matter ratio for pulses recorded in this experiment were observed under irrigated conditions. Therefore, the final relationship between seed yield and water use was weak in some of the pulse crops. The need for mild stress to initiate grain filling in pulse crops makes it ideally suited for semiarid regions as well as for stubble cropping.

Heat Stress:

High temperature stress is the second most important abiotic stress affecting plant productivity around the world. Temperature variation in both time and space exists. The yield losses due to high temperature are large and are often combined with losses from other environmental stresses. Compared to drought stress, heat stress is more complicated and can strike the crops at very short notice. High heat stress directly affects seed yield by reducing flowering, fertilization, and seed formation. By increasing the rate of plant development, warmer temperatures also reduce the length of the growing period, thereby reducing the yield potential. The direct effects of high temperature stress depend on the crop species and its adaptability.

Heat Tolerance Traits:

1. **Leaf Cooling by Water Extraction:** Increased water extraction in response to high temperature increases transpiration. Transpiration helps in converting heat energy into latent energy. Thus, plant tissue remains cooler than air temperature. However, different crops have different threshold temperatures up to which leaf cooling works.

2. **Maintaining Leaf Area:** Some crops maintain leaf area even under heat stress. This helps in plant recovery at later stages. This also helps plants to recover from heat injury by producing more flowers/pods during the recovery process.

3. **Reducing Radiation Load:** Similar to drought stress strategy, plants use this strategy to reduce heat load.

4. **Heat stress and Growth Stage:** Plant response to heat stress depends on its developmental stage. The reproductive stage is the most susceptible stage for temperature stress in most crops in which temperature response has been studied (Paulsen 1994). In a study comparing canola and mustard heat susceptibility, we observed 7 days of 35 °C day time temperature reduced seed yield by almost half (Angadi et al., 2000). Recovery from heat stress was better in mustard compared to canola. Flowering was the most sensitive stage for heat damage (Figure 5).

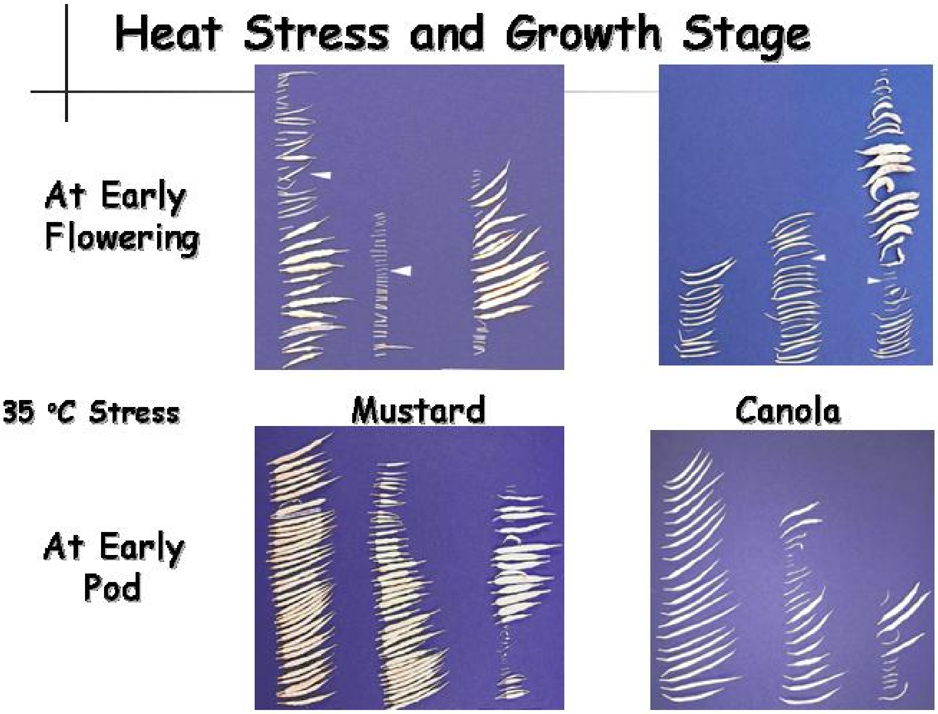


Figure. 5. Effect of heat stress on fertile pod formation on the main stem in canola and mustard at early flowering (top) and early pod development stage (bottom), respectively (Angadi et al., 2000). Pods from lower 1/3rd (left), middle 1/3rd (middle) and top 1/3rd (right) are arranged separately for clarity. Arrows in the top pictures indicate beginning and end of stress period.

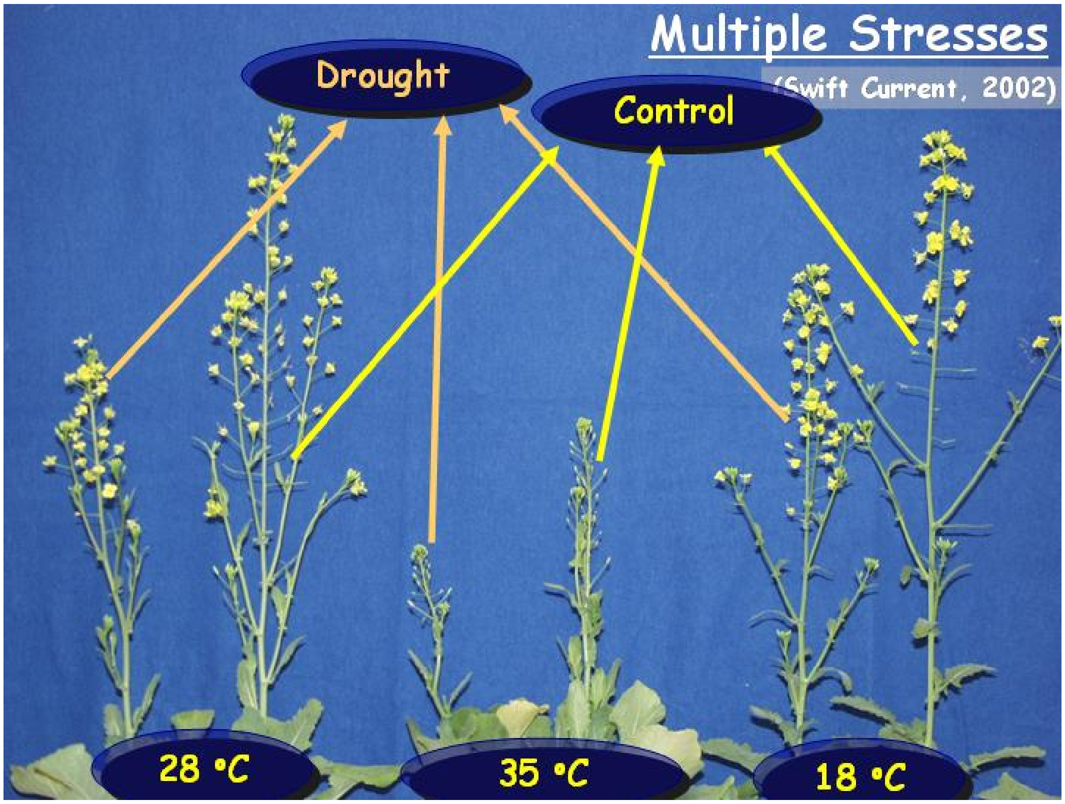


Figure. 6. Effect of heat and water stress on canola at bud formation stage (Gan et al., 2004).

Multiple Stresses: Heat and Drought Stress:

High temperature stress and water stress frequently occur simultaneously in many crop production regions of the world. Various stresses in crop can be synergetic or antagonistic, with one stress increasing the severity of the overall stress in some cases, while one stress factor can also reduce the severity of overall stress in other cases. A study was conducted to understand the response of canola and mustard to temperature and drought stress (Figure 6). Seed yield decreased gradually as the daytime temperature increased from 20 °C to 28 and 35 °C. A short period of water stress had a smaller effect on yield reduction, but seed yield recovery from branches was greater in absence of water stress. Thus, availability of water reduced heat stress effect.

Summary:

Drought and heat stress prevailed in many parts of Manitoba during 2003 growing season. Crops responded differently to these stresses. In areas where the soil moisture reserve was high, the crops produced exceptionally high yields and no effect of heat stress was observed. In some areas crops with deep and efficient root systems (eg. Sunflower) failed to produce good yields. An effort to understand the above responses from analyzing morphological and physiological responses of important crops indicated the following. When stresses occurred in the field, crops had an established root system and there was moisture available at depth in many cases. Many crops used that water judiciously for yield formation. However, less sensitive crops like sunflower could not benefit from this situation. Crops also initiated other stress responses like osmotic adjustment, stomatal regulation, leaf movement. Stress prioritized seed filling over new growth. There was good retranslocation of stored photosynthate. Established root systems, availability of water, leaf movement strategy, helped in reducing the heat stress. In addition, by the time heat stress occurred plants had already initiated flowering and sink formation helped maintain yield. Better grain to dry matter ratio also contributed to good yield.

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