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El Niño-induced climate stress in fruit crops: physiological responses, yield losses and climate-smart adaptation strategies

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Intricacies of the subject

Perennial fruit crops are especially vulnerable as the fruit bear system is exposed to climatic stresses throughout several phenological stages of the plant. Higher temperatures and moisture deficits break dormancy and chilling accumulation, induce flowering or floral initiation, affect flowering and pollination, impair fertilization and fruit development or kill flowers, and in severe droughts prevent photosynthesis, nutrient uptake and fruit expansion. Pollen sterility, sunburn, premature ripening and deterioration of colour, firmness and sugar–acid balance are other potential effects of heat stress. Excessive rainfall, on the other hand, may cause fruit cracking, leaching of nutrients, root hypoxia and fungal diseases. Production of fruits and vegetables accounts for a significant contribution to food availability, dietary diversity, micronutrient security and rural livelihoods, projected at above 2.1 billion tonnes in 2023 at the level of the globe. Thus, drought and heat-tolerant cultivars and rootstocks, optimized irrigation, mulching and canopy/shade management, and orchard diversification along with phenological prediction and strong early-warning systems are crucial for maintaining productivity and fruit quality as climate variability increases. In addition, integrating climate-smart orchard management practices with locally adapted cultivars can strengthen the resilience of perennial fruit crops and support sustainable fruit production under changing climatic conditions.

Introduction

One of the most important modes of interannual climate variability is El Niño–Southern Oscillation (ENSO), which forms due to the link between the ocean and atmosphere in the tropical Pacific. El Niño occurs when sea-surface temperatures in the central and eastern equatorial Pacific are unusually warm, leading to significant changes in atmospheric circulation and patterns of rainfall and global temperature. Such disturbances can trigger long-term droughts in South and Southeast Asia, Australia and some parts of Africa and boost intense rainfall and flooding in some parts of the Americas and East Africa. This added effect from the strong El Niño 2023–2024, coupled with anthropogenic warming, helped to make 2024 the warmest year on record globally. While scientific evidence so far has not definitively shown the frequency of El Niño events may increase because of climate change, higher

"background temperatures" exacerbate the impact of El Niño-induced heatwaves, droughts, hydrological extremes, and their associated consequences on agriculture.

El Niño-induced temperature stress in fruit crops

El Niño can amplify temperature differences and provide conditions that exacerbate regional heatwaves, in terms of both their severity, length and frequency in the region, especially if they come in conjunction with ongoing climate anthropogenic warming. Strong El Niño phases may lead to over-exposure of fruit crops to relatively high air and canopy temperatures, leading to significant perturbations of carbon metabolism, cellular homeostasis and reproductive development. Photosynthesis is one of the most heat sensitive physiological processes. Excess temperatures above the optimum range lead to decreased stomatal conductance, decreased chlorophyll stability, decreased photosystem II activity and to less Rubisco-mediated carbon fixation. As a result, net carbon assimilation decreases which reduces carbohydrate resources for vegetative growth and for fruit development. High temperature also increases the metabolic activity of mitochondria leading to additional use of carbohydrates for respiration and less carbohydrates for fruit growth. Severe heat stress also causes electrolyte leakage, disruption of the membrane integrity and a decrease in the transport of ions because of the increase in membrane fluidity and lipid peroxidation. Heat-sensitive enzymes are likely to be affected and may change in shape or become non-functional, resulting in changes in protein synthesis, carbohydrate metabolism and hormonal control. Excessive temperature also increase the formation of superoxide radicals and hydrogen peroxide, classified as Reactive Oxygen Species, that injure proteins, lipids, pigments and the nucleic acids. Fruit crop groups vary in their heat sensitivity. Tropical crops, e.g. mango, banana and papaya, have generally higher BASAL thermotolerance, but are sensitive to abortion of flowers, sunburn and damage and retarded fruit development during extreme heat. Subtropical citrus, grape and avocado fruit set and drop may be reduced, while temperate species like apple, pear, peach and cherry are especially sensitive as high winter temperatures inhibit chilling accumulation, which leads to the emergence of dormancy break and synchronization between flowering. Fruit plants will organise their defence system by producing 'heat-shock proteins' (HSPs), which act as molecular chaperones to put stress affected proteins back in shape. Antioxidant enzymes: superoxide dismutase, catalase, ascorbate peroxidase and glutathione reductase detoxify ROS. These defence mechanisms include osmolyte accumulation, together with membrane stabilization and increase in non-enzymatic antioxidants that are critical in a fruit crop determining their ability to withstand thermal stress caused by El Niño.

Drought stress and water scarcity during El Niño events

Altered rainfall and soil moisture availability

El Niño is often associated with the shift in precipitation patterns, leading to below normal rainfall and drought in some of the key fruit-producing areas. Less precipitation coupled with a rise in temperature and increased evapotranspiration result in a quicker reduction in soil-water levels and decreased water availability in the orchard root-zone. These can create seriously seasonal drought stress in rainfed production and lower reservoirs and groundwater supplies or irrigation reliability in irrigated orchards. Prolonged drought can impact productivity both in the current season of production and in

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the subsequent reproductive cycles for perennial fruit crops, due their active root and canopy systems over longer periods of time.

Physiological responses to drought stress

In fruit crops, one of the first reactions to decreasing plant water status is stomatal closure, which is mostly effected by enhanced abscisic acid signalling. Stomatal closure leads to lower transpirational water loss but also to a lower rate of stomatal diffusion of CO2 into leaves that reduces photosynthetic carbon assimilation. During an intense or long drought stress, biochemical constraints intensify as the degradation of chlorophyll, a decrease in Rubisco activity, a decrease in electron transport and oxidative stress further retard photosynthesis. Water scarcity also decreases mass flow and diffusion of mineral nutrients in soil, leading to less uptake of nitrogen, potassium, calcium, magnesium and other essential nutrient elements. As a result, nutrient deficiencies can become more severe with adequate levels of nutrients in the soil. Common adaptive changes in the root system involve compaction, increased root-to-shoot ratio, more lateral root proliferation in the soil layer with adequate moisture and more assimilate allocation to roots that grow deeper in the soil.

Effects on fruit growth and productivity

Flowers and fruits may be shed and the viability of pollen may be lowered, both of which lead to a decrease of such fruit numbers, under drought during flowering and fruit set. Fruit enlargement is restricted by either reduced cell division or reduced cell expansion, resulting in smaller fruit, lower marketability and fresh weight. Water stress can also cause accelerated ripening and render the fruit more susceptible to sunburn and fruit cracking upon rewatering, and change soluble solids, acidity, firmness and peel development. Recurrent drought can also decrease shoot growth, carbohydrate reserves and floral induction, which also affect productivity for the next season. Hence, ensuring proper water status in orchards by applying efficient irrigation systems, mulching, soil moisture conservation and drought-tolerant rootstocks is crucial for the maintenance of fruit production during water shortages in El Niño events.

Impact of El Niño on flowering, fruit set and crop phenology

Alteration of flowering behaviour

Temperature anomalies and balance of rain/sun associated with El Niño can significantly disrupt reproductive phenology of fruit crops. Flowering is very responsive to temperature, soil moisture content, photoperiod and carbohydrate status. The occurrence of these cues may be altered and flower induction thus be delayed, accelerated or even inhibited completely. For perennial fruit crops, these disturbances can also be important because there is frequently a delay of several weeks or even months between the initiation of the floral stage and the first signs of flowering; if stress is encountered during this stage, it could affect subsequent flowering intensity and/or crop load. Extremely high temperature can affect floral differentiation, the length of flowering and an increase in vegetative growth and leaf production instead of reproductive growth. On the other hand, for some tropical fruits moisture stress can increase flower initiation, whereas high moisture deficits can decrease flower production and reproductive potential. Asynchronous flowering, leading to several flowering flushes in one orchard, may also be caused by excessive rains after dry weather.

Effects on pollination, pollen viability and fruit initiation

During flowering higher temperatures can be associated with fewer viable pollens, pollen

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germination and pollen-tube growth. There is the possibility of reduced successful fruit initiation but due to heat stress affecting anther dehiscence, stigma receptivity and/or fertilization. Both very dry weather desiccates floral tissues, and heavy rain can cause pollen to be washed off stigmatic surfaces, and limit the activity of pollinators. Moisture and temperature may also disrupt the transport of carbohydrates and hormonal regulation when fruits are initiated. Flowers and young fruitlets are strong metabolic sinks and thus, if the photosynthetic activity is lowered, or the supply of assimilates is less than required, the flowers are likely to be aborted and fruit drops will occur. Stress also can disrupt the shift from fertilized ovary to fruit development through auxins, gibberellins, cytokinins, ethylene and abscisic acid production in abnormal amounts.

Phenology and seasonal changes

El Niño could affect the onset of bud break, flowering, fruit set, fruit growth, maturity and harvest. Growth and phenological phases of a plant may be accelerated by warmer temperatures for some crops in subtropical and temperate regions of the world; insufficient winter chilling can reduce or delay bud break and flowering in these crops. Such unpredictable changes can affect synchrony of flowering and pollinator activity, variation in fruit maturity and longer harvest schedules. Commercial orchards have to deal with such phenological variability and this introduces difficulties in irrigation, nutrient management, pest control and timing of harvest. Phenology monitoring and weather forecasting help optimize orchard management and reduce climate-related yield losses.

Table 1. Physiological and molecular mechanisms of stress adaptation in fruit crops

Aspect	Scientific explanation	Major consequence
Hormonal imbalance	Heat and drought alter auxin, ABA and ethylene balance, promoting activation of the fruit abscission zone.	Premature fruit drop and reduced fruit retention.
Water stress	Reduced soil moisture lowers stomatal conductance, photosynthesis and fruit-cell expansion.	Smaller fruits, poor fruit development and lower yield.
Nutrient deficiency	Drought limits nutrient uptake and translocation, particularly N, K, Ca and Mg.	Weak fruit growth, poor quality and increased fruit drop.
Oxidative stress	Heat and drought increase reactive oxygen species (ROS), causing membrane and cellular damage.	Reduced photosynthetic efficiency and impaired fruit development.
Fruit size	Limited water and assimilate supply restrict cell division and enlargement.	Reduced fruit weight and marketable size.
Colour development	High temperature disrupts anthocyanin, carotenoid and chlorophyll metabolism.	Uneven colour, sunburn and reduced visual quality.
Sugar accumulation	Stress alters photosynthesis, carbohydrate transport and respiration.	Changes in soluble solids, sweetness and flavour.
Nutritional quality	Severe stress modifies vitamin, phenolic and antioxidant metabolism.	Reduced or altered nutritional value.
Yield reduction	Fruit drop, poor fruit set and restricted growth collectively reduce productivity.	Lower total and marketable yield.

Role of advanced technologies in managing El Niño impacts

In recent years, more advanced technologies are playing an increasing role in mitigating the negative impacts of El Niño on production systems in fruit. Precision horticulture allows for the site-specific management of water,

nutrients and crop stress. Soil moisture sensors powered by IoT technology will give growers real-time resolution about the availability of water in the root zone and alert them early of drought stress. Automated irrigation systems could utilize the information provided by the sensors to irrigate crops based on water needs to save on water usage during dry cycles in the El Niño seasons. Photos taken at a short distance from the tree can also be useful to monitor orchards on a larger scale. Satellite-based drought assessment can clearly show areas of dryness, and vegetation indices, like Normalized Difference Vegetation Index (NDVI) and Enhanced Vegetation Index (EVI), show changes in canopy vigour, chlorophyll status, and plant stress. These tools help to early detect a gradual loss of crop health in large production areas. Currently, artificial intelligence and climate prediction models can combine with weather forecasts, soil conditions, and crop stage to provide a platform for orchard management decisions. These systems may be helpful for predicting irrigation demands, heat stress, incursion of pests, and potential crop losses. Additionally, digital advisory platforms and mobile services can help farmers with timely advice around irrigation management, crop nutrition, and protection and extreme-weather preparedness, enhancing their orchard's resilience and minimizing production risks associated with El Niño.

Future approaches for developing El Niño-resilient fruit production systems

Lessons for future fruit production systems need to shift focus towards being more climate resilient and mitigating negative impacts from heat, drought and rainfall variability events driven by El Niño. Climate-resilient cultivars will be required for continuing productivity in the face of climatic stress and will need to be developed with resistance to drought, heat, stable flowering, and water-use efficiency in mind. Drought-tolerant rootstocks can also help in enhancing root growth, water absorption and physiological stability in fruit crops. The use of plant growth regulators can be useful for the regulation of flowering, fruit retention, and stress resistance, and biostimulants can increase nutrient-use efficiency, antioxidant responses, and abiotic stress resistance. Adding silicon can make the cell wall much stronger, decrease oxidative damage and increase water-use efficiency. Likewise, beneficial microbes such as mycorrhizal fungi and plant growth promoting rhizobacteria have been demonstrated to positively influence the uptake of nutrients, root development and drought stress. The use of climate forecasting in the planning of orchards also needs to be incorporated to assist in irrigation scheduling, planting activities, nutrient management, and taking measures to protect the orchards prior to extreme events occurring. Institutional: policies, climate-smart infrastructure, farmer training, crop insurance, access to reliable climate information. In combination with genetic improvement, biological inputs, digital forecasting, and good policies, they can therefore build up systems of fruit production within which greater resilience and sustainability can be achieved under future conditions of El Niño.

Conclusion

When the variability and intensity of El Niño are high, it can be a huge problem for fruit production because of the risk of heat stress, drought, irregular flowering, early drop, yield loses and quality reduced. A holistic strategy involving knowledge of plant physiology, climate tolerant cultivars, water and nutrient management, and climate smart orchard practices thus needs to be put in place for sustainable fruit production. The implementation of traditional management practices and the use of modern tools like IoT-enabled irrigation systems, remote sensing,

weather predictions, and digital advice can help enhance orchard resilience and minimize production risks during El Niño seasons. Farmers should select drought and heat-tolerant cultivars and rootstock, implement better irrigation water use efficiency (drip, sensors), and use mulching to retain soil moisture. Stress tolerance and fruit retention may be improved with timely nutrition management, biostimulants, beneficial microorganisms and/or appropriate plant growth regulators. Irrigation, nutrition and protection should be managed based on regular monitoring of weather forecasts and crop stress indicators. Additional fruit crop diversification, crop insurance, and climate-advisory and trainings can further mitigate economic risks from future El Niño events.

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