EFFECT OF HEAT ON POTATO CROPS

What happens when climate change impacts one of the world's most important foods? With a burgeoning global population, food security is one of the most complex problems of our time, and our rapidly warming planet complicates the problem further.

Worldwide, potatoes are the third largest global food crop, cultivated in 158 countries and consumed daily by over a billion people[1]. According to Our World in Data, potatoes produce more food per unit of production area, yet have lower greenhouse gas emissions and use less water per kg, than virtually any other crop.

Potatoes are also low in fat but rich in starch, protein and Vitamin C. As a non-grain food staple, they have an essential role ensuring global food security.

However, potatoes have a key weakness – sensitivity to heat. High temperatures seriously reduce growth and development and can completely stop tuber formation. Heat affects the ability of seed to sprout and the quality and nutritional profile of the tubers formed.

For this reason, Australian exceptionalism aside, most potatoes are cultivated in cooler climes, like Scotland, Ireland, northern America and northern Europe.

However, summer temperature records across the globe are being smashed on a regular basis. As heat is one of the most significant uncontrollable factors affecting potatoes, it is worth examining the impact of climate change and warming on the production, yield and nutritional quality of potatoes.

A COOL CLIMATE PLANT

Potatoes originated in the highlands of the equatorial Andes. Domesticated over 7,000 years ago, they flourished in the cool mountain climate with its constant daylength, strong light intensity and high humidity. Plants reproduced by tubers produced year-round.

One of the keys to cultivating potatoes more widely was adaptation to more variable daylengths. When Andean potatoes were first grown in Europe, they only formed tubers during the last short days of autumn. These were soon followed by freezing temperatures that killed the plants, cutting maturation short and reducing accumulation of nutrients.

Selection of plants that developed tubers under different daylengths has therefore been key to the global success of potatoes. However, as climates warm, potatoes face a new adaptive crisis – becoming more heat tolerant.

Modern European potatoes have a

narrow genetic base. Optimal yield for most commercial potato varieties occurs when average day time temperatures are between 14 to 22˚C. Any hotter and yield falls sharply.

This is largely because the signal to form tubers is highly temperature dependent. Tubers are initiated in response to a protein called SP6A. High temperatures stop production of this protein, so tubers simply don't form, even if the plant is growing well. Current varieties considered 'heat tolerant' likely have either a stronger production of SP6A or are sensitive to low concentrations of this protein.

For example, at 28˚C, yield of Desiree plummets to almost zero and Spunta to ~15%.

This issue is most acute in tropical and sub-tropical zones. In these areas potato production is already constrained by sensitivity to heat. Moreover, cooling through irrigation is not possible in the humid tropics. As a result, climate change is predicted to reduce potato yields by 18 to 32% globally[2].

Heat is not only a problem for local industries growing potatoes for consumption, but for seed growers and exporters. For example, seed maturing at high temperatures is likely to have a reduced period of dormancy. In some varieties heat stress results in strong apical dominance, with only 10-20% of non-apical buds sprouting[3]. For exporters, markets in warmer climates are likely to be impacted as potatoes become more difficult to grow.

Heat stress therefore induces an array of physical, physiological, and biochemical changes that inhibit plant growth and development, ultimately leading to a significant reduction in both yield and quality[4] (Table 1).

Table 1. Summary of heat stress effects on potatoes at different developmental stages. From Singh et al., 2020

Growth stage	Ideal temperature (°C)	Effect of high temperature
Sprouting	16	Increased
Establishment	20 to 25	Early plant growth increased
Shoot growth	Up to 32	Increased vegetative growth
Stolon formation	Up to 25	Reduced at above 25°C
Tuber initiation	15 to 22	Reduced tuber initiation, reduced tuber size
Tuber bulking	14 to 22	Reduced transfer of carbohydrates to tubers, increase secondary tuber formation, increased disorders e.g. russeting, cracking
Harvest	20 to 24	Reduced total yield, size and quality

GROWTH AND DEVELOPMENT

The effects of high temperatures on potato crops depends on variety, development stage, how high and long the heatwave lasts, and whether high temperatures are experienced during the day, night or both.

For example, researchers in South Korea[5] examined the effects of high temperatures at night or during the day, during tuber initiation or tuber bulking (each growth period lasting approximately 3 weeks). Ambient day/night temperatures of approximately 28°C/20°C were increased by approximately 4°C during the day, the night, or around the clock.

Plants appeared unaffected for the first few days, but respiration, photosynthesis and other processes showed significant changes when high temperatures continued for a week or more.

Importantly, the results showed that high temperatures during tuber initiation were the most critical, greatly reducing yield. In contrast, the same conditions

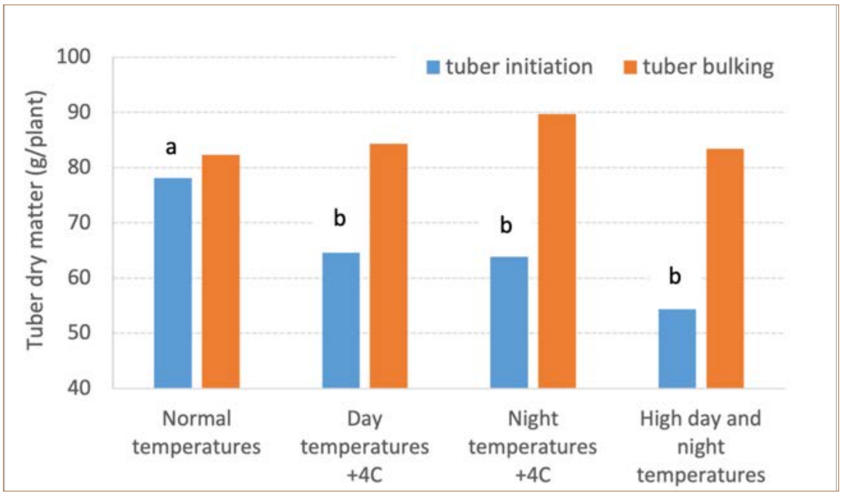

Figure 1. Effect of elevated day temperatures, night temperatures, or both day and night temperatures, occurring during either tuber initiation or tuber bulking, on total yield of potatoes. Derived from Kim and Lee, 2019.

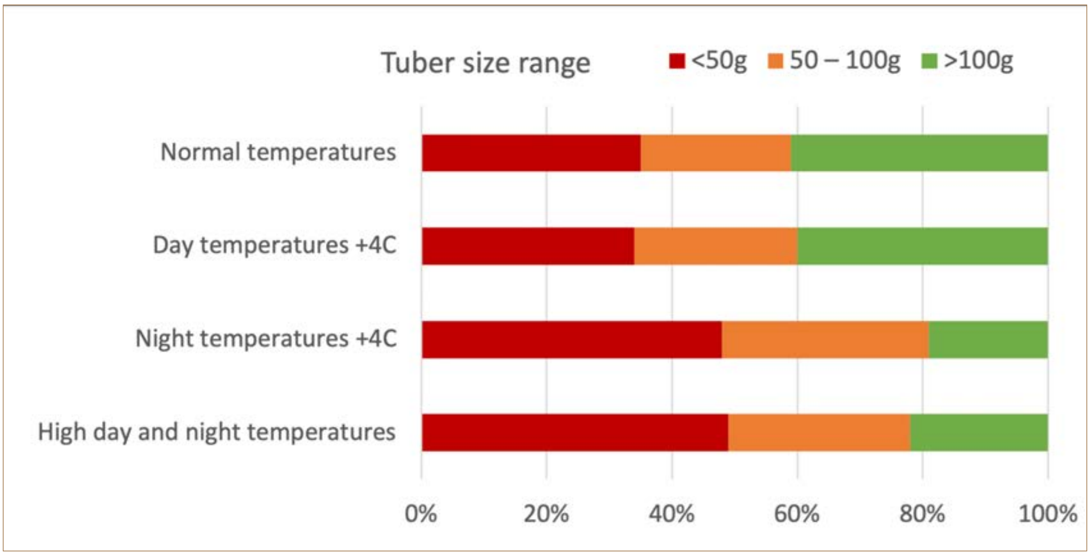

Figure 2. Effect of elevated day temperatures, night temperatures, or both day and night temperatures during tuber initiation on the number of small, medium or large potatoes. Derived from Kim and Lee, 2019.

during tuber bulking had no effect on total yield. (Figure 1).

PHOTOSYNTHESIS

As long as there is adequate soil moisture, day temperatures up to around 30°C actually increase photosynthesis, generating larger leaf canopies.

Unfortunately though, this extra captured carbon does not flow through to the tubers but stays in the foliage[2].

If temperatures go above 30°C photosynthesis also starts to be inhibited. At the same time respiration by the plant increases, effectively sending growth backward[6] .

In the research by Kim and Lee, high night temperatures (up to 24°C) during tuber initiation increased foliage above ground but reduced the number of large size tubers beneath. In this trial, when nights were warm, nearly half of the tubers that developed weighed less than 50g.

As with the effects on yield, high night temperatures had less effect when they occurred during tuber bulking, presumably because the process of filling was already underway.

Considered from the plants point of view, this makes sense. For the potato plant, tubers are a survival mechanism of last resort. Their only purpose is to help the plant survive winter. If the weather is warm and the plant stays healthy, (true) seed is a far more efficient way to guarantee the next generation.

HEAT IN THE ROOT ZONE

While potato plants may be able to cope with a few days of heat stress, longer periods will clearly have greater impact. In part, this is likely to be because of warming of the soil.

Recent (2023) work showed that although exposing the upper parts of the plant to high temperatures reduces tuber size and yield, it is soil temperature which is the most critical[7].

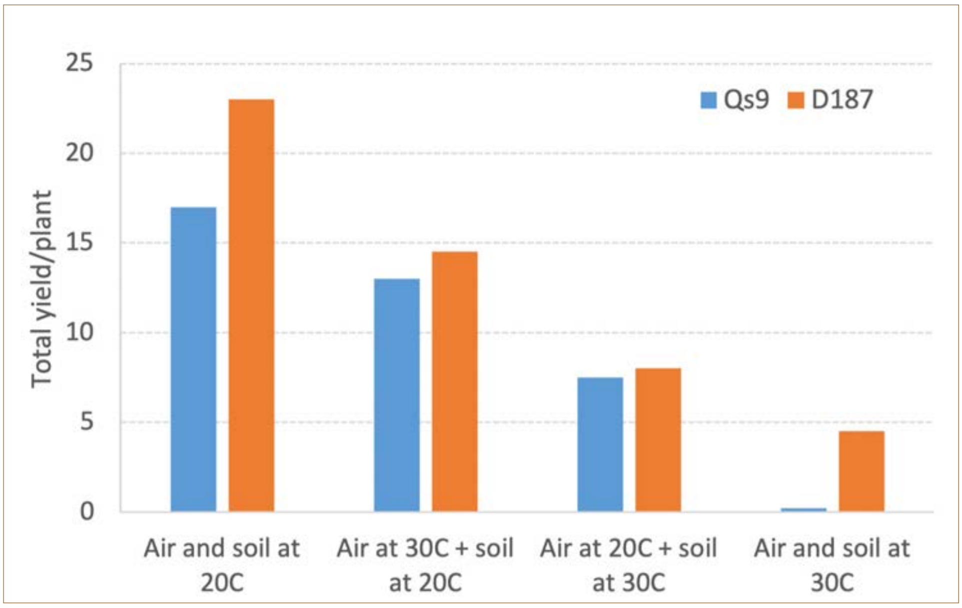

Figure 3. The effects of air and soil temperatures on yield of two different potato varieties (Qs9 and D187). Derived from Kim and Lee, 2019.

Zhou et al investigated plants with air/soil temperature controlled at 20/30°C. Plants still produced reasonable yield if their roots remained at 20°C with air at 30°C. However, when the treatments were reversed, increasing soil temperature to 30°C, the few tubers formed were small and misshapen. If both air and soil were 30°C, yield was minimal or, in the case of one variety, virtually zero (Figure 3).

DISEASES AND DISORDERS

Heat stress induces various physiological disorders in potato tubers, affecting their shape, development, and marketability.

High temperatures close to harvest can induce pre-harvest sprouting, prematurely developing the tuber buds. Skin netting and russeting result from high soil temperatures and affect the appearance and marketability of tubers.

Potatoes exposed to high soil temperatures during development can develop a wide range of physiological disorders, including tuber deformations, translucent end, growth cracks, heat necrosis, internal brown spot, second growth, blackheart, and physiologically old seed tubers[8] .

- Tuber deformations: High temperatures stimulate cell division and reduce the availability of carbohydrates by increasing respiration. Water stress does not in itself cause deformations, but drought exacerbates the deformations caused by high temperatures. The higher the temperatures and the longer the heat wave, the greater the effect.
- Translucent end and jelly end rot: Early-stage high temperatures and water stress may interfere with starch deposition, leading to translucent end / jelly end rot. Pointy bud-end tubers are particularly prone to developing jelly end rot.
- Growth cracks: Rapid shifts from poor to good growing conditions, such as hot, dry weather followed by excessive irrigation or heavy rainfall, can cause growth cracks.
- Heat necrosis: Occurs when slow tuber growth is followed by active growth at high temperatures, resulting in light to dark brown necrotic spots in the vascular tissue. Some varieties are more susceptible than others.
- Internal brown spot: Light brown necrotic spots develop in the tuber flesh during the latter stages of tuber growth due to intense heat or excessive drought. Internal brown spot is associated with an enzymatic disorder and, at times, calcium deficiency.

- Second growth: Temperatures above 30°C prompt increased vegetative growth rather than tuber formation, leading to heat sprouts, chain tubers, or heat runners in susceptible varieties.
- Blackheart: Blackheart occurs when oxygen cannot reach the tuber centre, especially during pre-harvest, transit, or storage. Extended exposure to temperatures above 32°C before harvest is a contributing factor.
- Physiologically old tubers: Heat stress drastically increases physiological age, leading to early sprouting, more stems, and defects in potato formation

NUTRITIONAL QUALITY

Potatoes are a vital source of carbohydrates, vitamins, and minerals. Heat stress can alter the composition of these nutritional elements, affecting the overall nutritive quality of potatoes.

Most studies about heat effects have examined the impact on carbohydrates, which make up about 75% of the potato's dry weight.

Potatoes contain two forms of starch: amylose and amylopectin. Heat stress can not only reduce carbohydrate accumulation by 30% or more, but also affects the balance of different starches. For example, exposure to 35°C reduced the content of amylose in tubers by 36%, but had less impact on amylopectin[1]. Amylose is more resistant to digestion than amylopectin, so heat stressed potatoes could be expected to have higher GI (glycaemic index) values than those grown at normal temperatures.

As carbohydrate metabolism shifts away from starch synthesis, it is replaced by accumulation of sugars, especially at the tuber ends. The result can be undesirable sweetening and, importantly, darkening when fried, a major issue for processed product.

Other effects of heat on nutritional quality are mixed. Potatoes have been bred to have low levels of glykoalkaloids (GA), not exceeding 20mg/100g fresh weight. These are protective compounds produced by the plant, so increase in response to stresses such as drought, insect attack and light exposure.

Research from the 1980s reported elevated GAs in response to high temperatures. However, more recently it was found that soil temperatures of up to 35°C for a week before harvest did not increase GA. This may reflect the extreme low GA values in modern varieties such as Desiree .

In contrast, the anthocyanins that give some varieties their red skin and/or yellow flesh are often reduced by heat stress. Even if warm growing conditions are not severe enough to affect anthocyanin production, red varieties such as Desiree may appear paler than normal. This is due to development of a thicker, rougher skin, which does not allow the anthocyanins to shine through[7] (Figure 4).

Figure 4. Desiree potatoes grown under ambient conditions (left) or with exposure to 33°C soil temperature for one week before harvest (right). From Fogelman et al, 2019.

Growth cracks in tubers (left N. Diplock, right K. Bouchek)

Left to right: Black heart (A. Robinson, NDSU), hollow heart (AHDB), brown centre

Left to right: Secondary growth (AHR), deformed bottle neck (A. Robinson, NDSU), deformed potatoes (A. Robinson, NDSU)

MANAGING HEAT STRESS

Irrigation works as a high temperature mitigation strategy partly because of the power of evaporative cooling, but also because it is the temperature of the roots, not the leaves, which is most important.

As water turns from liquid into gas, it absorbs energy from the environment around it. The more water evaporates, the more heat is pulled from the surface of the leaf or soil.

Of course, if humidity is already high, evaporative cooling can do little to reduce temperature. However, the dry conditions in South Australia make this method highly effective. For example, on a day when it is 35°C and 40% RH, it is theoretically possible to cool plants and soil to 20°C simply through evaporation. Even at 40°C and 45%RH, temperatures can still be kept below the critical limit of 27°C by adding water.

WHERE TO NEXT?

As global climate change intensifies, the issue of heat susceptibility in potato cultivation becomes even more critical. Currently, only a limited number of heat-tolerant potato cultivars are recognised, primarily bred for very specific conditions. This limitation has intensified conventional breeding efforts to find new, tolerant genotypes.

In response to the scarcity of heat-tolerant traits within the cultivated potato gene pool, researchers are exploring the genetics of wild potatoes native to the Americas. These plants are potential sources of valuable resistance genes.

A number of Solanum varieties are known to be heat tolerant, including *S. kurtzianum, S. chacoense, S. stoloniferum and S. demissum* (Figure 5). Genes from *S. demissum* have already been incorporated into modern varieties, providing blight resistance.

Ongoing research in genomics, proteomics, and metabolomics on potato heat response holds promise for enhancing conventional breeding strategies. These molecular approaches provide insights into the genetic and biochemical mechanisms underlying heat tolerance, helping to identify and select desirable traits. *See PotatoLink Issue 10 for more on potato breeding using novel varieties.*

Bioengineering efforts also represent an alternative avenue for developing heat stress-tolerant potatoes. Genetic modification and genome editing technologies (such as CRISPR) may offer targeted solutions by introducing or modifying specific genes associated with heat tolerance.

The combined efforts of conventional breeding, exploration of wild genomes, and advancements in molecular research offer hope for developing heat-tolerant potato varieties.

Potatoes adapted to a changing environment before.

Now, they need to do it again.

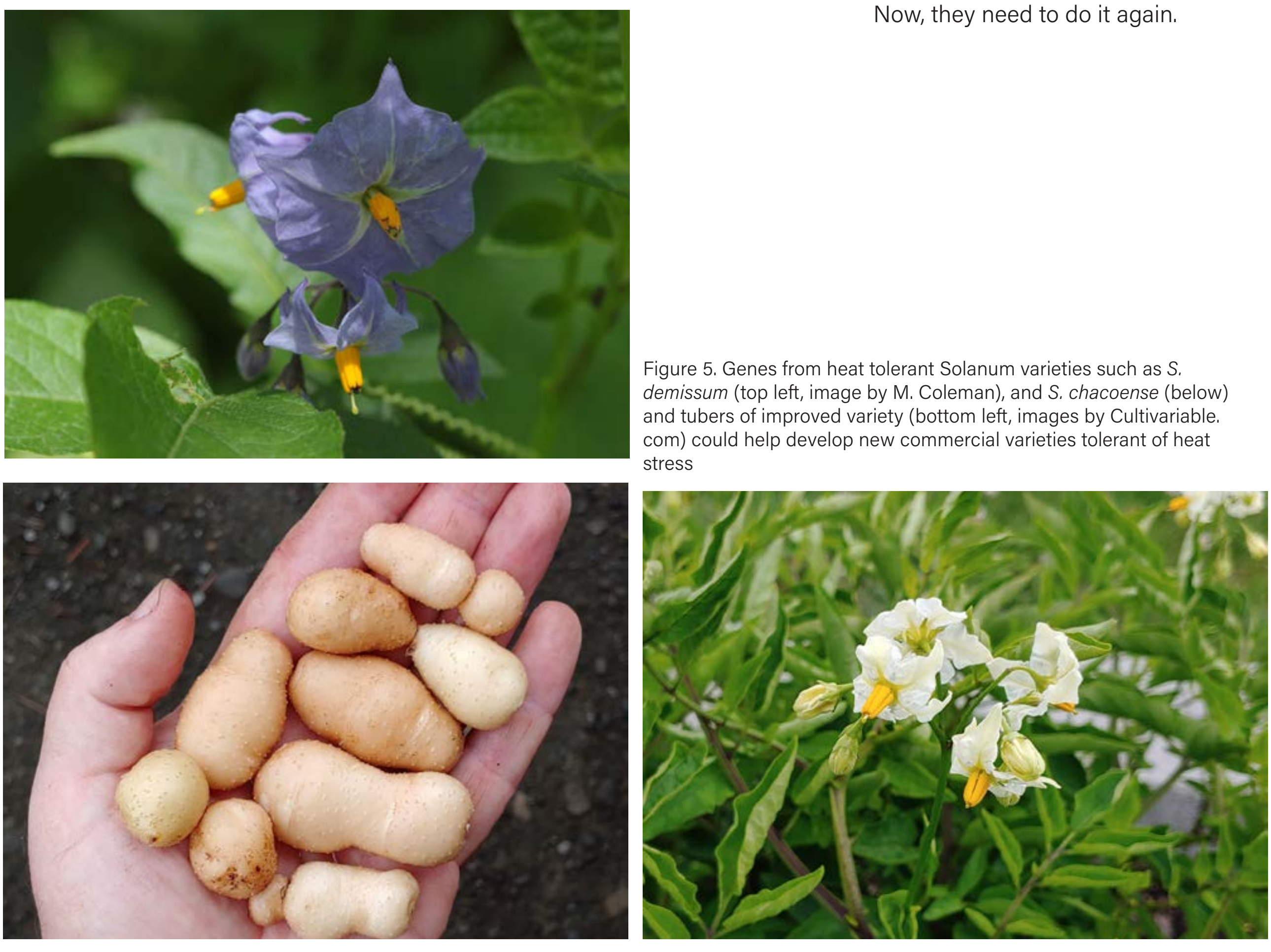

Figure 5. Genes from heat tolerant Solanum varieties such as *S. demissum* (top left, image by M. Coleman), and *S. chacoense* (below) and tubers of improved variety (bottom left, images by Cultivariable.com) could help develop new commercial varieties tolerant of heat stress

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EXPLORE THE TOPIC FURTHER

Webinar: Setting up for summer - preparation for potato growers


Internal discolouration and secondary growth (E. Banks)

GROWING POTATOES IN HIGH TEMPERATURES (>32°C) IN THE SA MALLEE

Conditions in the Soth Australian Mallee can get hot. Around Loxton (a town on the Murray River) temperatures can reach 50°C during summer, with dry soil surface temperatures getting as high as 70°C. It is not unusual to have a five day stretch of 45°C days with warm nights. These warm temperatures can cook roots in the soil, causing significant wilt, and reflectance from the sands can burn the undersides of leaves. Yet, despite these harsh conditions, the Mallee region is a major producer of potatoes.

The key to this is irrigation infrastructure. Applying water to crops and soils helps to cool soils down, create humidity, and reduce reflectance (wet soil, especially sand, reflects less than dry sand).

Applying the right amount of water at the right time can cool soils, raise humidity, and provide the environmental conditions that promote healthy transpiration in plants. The movement of water through the vascular tissue (xylem) removes heat from the plant in a process called evaporative cooling.

However, it is not as simple as flooding a paddock during high heat events and waiting until it blows over. Overwatering can be just as bad as underwatering. Too much water can cause plant stress. If water stays in the soil profile long enough, it can warm up and cause damage to roots. Warm, watery soil is also the perfect environment for fungal and bacterial infections.

Overwatering can also impact the nutrition balance of a plant. Key nutrients such as calcium and magnesium need to balance during these heat events. Just as a person might suffer from cramps due to a lack of magnesium, or nausea from diluting salts in the body when drinking too much water, over watering can dilute nutrients in plants, weakening its defence mechanisms. The use of soil moisture probes is critical to understand the water levels in soil profiles and when irrigation is needed and, importantly, when it is not.

Another major factor to manage during high heat events is plant stress. Heat, wilt, waterlogging, and disease can all impact how a plant will respond. Management prior to and during the high heat events is critical to ensuring plants get through these times. Stressed plants are more susceptible to the negative impacts of high heat events. Forecasting tools can help growers to prepare for the high heat events.

By managing plant stress and nutrition prior to, and during, the high heat event, and applying the right amount of water to encourage transpiration and increase the relative humidity, crops can be successfully managed through these events.