Coffee - Continuous monitoring of stem water potential under drought stress and recovery

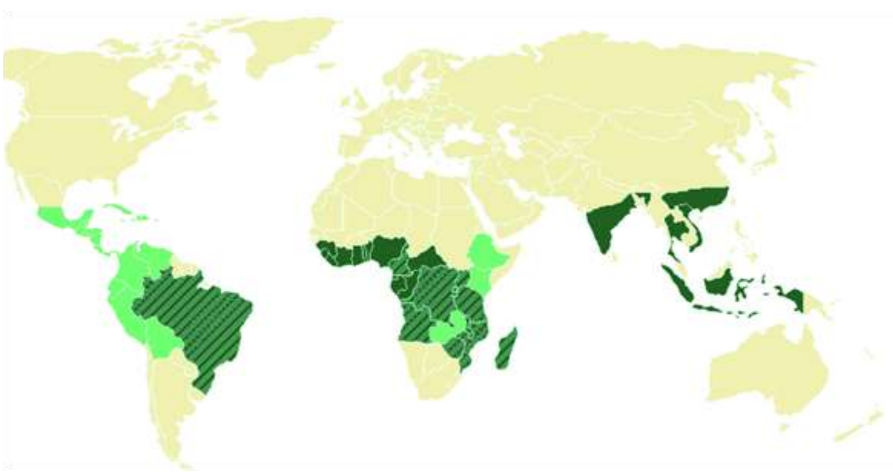
By Alec Downey & Alvaro Arias

Coffee is an internationally important cash crop. It is a globally traded commodity with an estimated market value in excess of $100 billion annually. Coffee is grown in tropical regions across the world and contributes significant revenue to the Latin American, African and Asian economies. Brazil is the world's largest coffee producing country at 29% of global production.

Source: http://www.wikinvest.com/commodity/Coffee

Top 10 Coffee Producing Nations
1. Brazil
2. Vietnam
3. Colombia
4. Indonesia
5. Ethiopia
6. Kenya
7. India
8. Mexico
9. Guatemala
10. Honduras

Coffee Growing Regions



Drawing: *Coffea arabica by Franz Eugen Köhler*

There are more than 20 species within the genus *Coffea* but only two, *C. arabica* and *C. canephora* (commonly known as *C. robusta*) are produced commercially.

Water Relations

Coffee yield is heavily dependent upon achieving the right balance of available soil water to achieve optimum plant water status. "In some marginal regions with no irrigation, coffee yields may decrease as much as 80 % in very dry years" (DaMatta 2006). Conversely, excessive soil moisture results in the imbalance of growth regulators and promoters and a particular hormone responsible for vegetative growth is activated. This drastically reduces the number of flowers. Under such conditions the bush appears healthy, but the productivity suffers (Peasely & Rolfe 2003)

Nevertheless, "drought is considered to be the major environmental stress affecting coffee production" (DaMatta 2004).

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The physiology of plant responses to drought stress is rather complex, showing different modifications following soil drying. The dynamics of soil water depletion, changes in water demand from the atmosphere, as well as plant growth and the phenological state in which water deficit is developed, are sources of the wide variation in plant responses to drought (Medrano et al., 1998). DaMatta (2003) concurs with Medrano et al. that coffee exhibits such multidimensional stress from high solar radiation & temperature when subjected to water stress.

In fact, abiotic stresses such as extreme temperatures, drought, salinity or chemical toxicity represent serious limitations to agriculture, more than halving average yields for major crop species (Bray et al., 2000).
The plant acts as a sophisticated integrator of all the abiotic stresses acting upon it. The integrated effect of which can be measured by the Stem Water Potential **(Ψs).** If Ψs can be continuously monitored on the same piece of plant tissue a record can be logged of the plant water status.

As each abiotic stress is independently regulated the impact of each can be accounted for in the contribution to the overall plant stress. The PSY1 Stem psychrometer was used to monitor Ψs as an integrated variable of all abiotic stresses acting upon a single coffee plant in response to an induced drought stress and recovery experiment.

Methods

A short experiment was conducted to demonstrate the effectiveness of the stem psychrometer to continuously and non-destructively measure the Ψs of a coffee plant. The experiment was conducted in San Rafael de La Union de Tres Ríos Cartago Costa Rica (Latitude N 09° 54’ 33” Longitude W 83° 58’ 53”). At an elevation of 1,345m and an annual rainfall of 2,250 mm distributed over 155 days, there is effectively no distinct seasons rather a constant alternating between heavy rainfall and sunshine. It is these characteristics that aid in bringing the berries to full maturity and make this one of the main coffee growing regions of Costa Rica.

A single mature (approx. 4 years old) commercially producing, coffee plant *Coffea arabica* with a stem size of approx. 10 mm diameter was chosen. The Ψs of the coffee plant was continuously monitored for a period of 45 days. The experiment was conducted in a rain out shelter to prevent unintended rainfall events affecting the drought stress and recovery treatment.

The irrigation set out to simulate the alternating sunny and heavy rainfall conditions favoured by coffee with increasing periods between irrigations so as to induce a drought stress. An irrigation threshold or refill point of -2 MPa was arbitrarily chosen for scheduling of irrigations for the experiment. Irrigations consisted of the application of a visibly saturating volume of water to ensure saturation of the soil volume of the pot as might be expected to occur during a typically heavy rainfall event for this region.

It is recommended that future experiments employ an objective and quantifiable measure of either volumetric soil moisture or soil tension using sensors such as the MP406 soil moisture sensor or the ICTGT3-15 transducer tensiometer.

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Peasely & Rolfe (2003) demonstrated with soil moisture measurements that coffee trees extract between 70% and 93% of their water requirements from the top 300 mm depth of soil. This is even during periods of moisture stress in non-irrigated trees. In order to conserve water and nutrient loss from through drainage in the typically permeable soils upon which coffee is grown, irrigation should be regulated to ensure only the top 300 to 400 mm of the soil profile is replenished with water.

This can be easily achieved using an accurate soil moisture sensor that can measure volumetric soil water content such as the MP406 sensor.

As soil type is not considered a major limiting factor to coffee production soil was sourced locally ensuring it was a permeable media with good drainage which is important to optimum growth as coffee will not tolerate water logging.

A pot size of approx. 0.025 m^3 (or 25 L) that limited the rooting volume to the basic dimensions outlined by Peasley & Rolfe (2003) was chosen. By limiting the soil volume and excluding rainfall or unregulated sources of soil water a rapid drought stress and recovery experiment could be conducted and repeated quickly.

Photo 1.

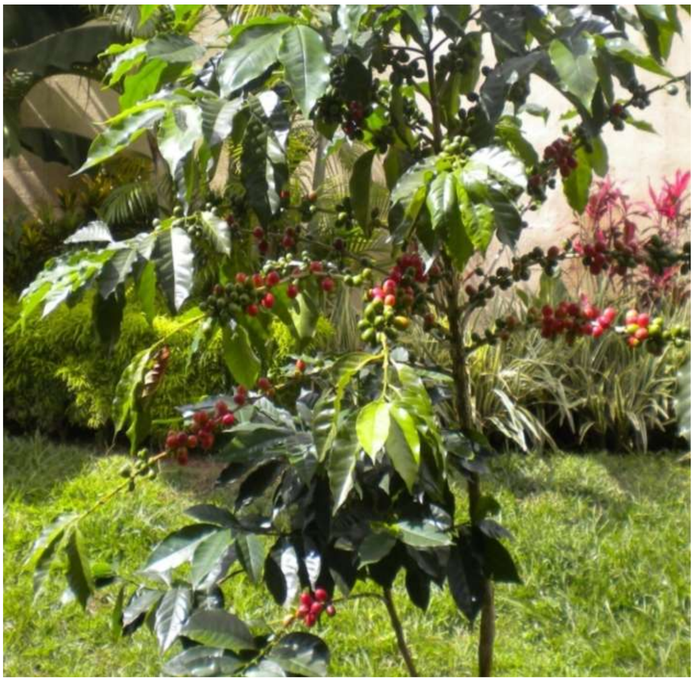

Photo 2.

Photo 1. Coffee plant in 25 L pot

Photo 2. Close up of Coffee fruit during ripening

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Installation

Installation of the PSY1 stem psychrometer on coffee stems is very straightforward. The stem is long and straight with no lower branching obstructions. The stem is lignified and woody with a relatively thin bark and cambium and a clearly defined sap wood or water conducting xylem.

The outer bark is excavated to the sap wood using a single edge razor blade. A straight scraping action is used to expose the sap wood taking care not to gouge the stem with a curved scraping motion that would result in a concave stem face. It is essential to prepare a flat surface to ensure the flat face of the psychrometer chamber can achieve a vapour pressure seal with the sapwood. Failure to achieve the good vapour pressure seal will result in a failed installation.

The excavated site must then be thoroughly washed with distilled water to remove any symplastic or apoplastic fluid or any living tissue. Finally the site must be vigorously dried with a low lint tissue to dry any free water or surface moisture that can condense inside the chamber and prevent a psychrometric wet bulb depression.

Photo. 3

Photo. 4

Photo 3. Exposed sap wood of a coffee stem prepared for installation of the PSY1 stem psychrometer chamber.

Photo 4. PSY1 stem psychrometer chamber clamped to prepared sap wood of the stem.

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Once the psychrometer chamber has been attached it is imperative that it be suitably insulated from external thermal gradients of the surrounding environment. The insulation is designed to act as a dampening buffer to rapid thermal fluctuations. The absolute temperature is not of great significance but rapid increases or decreases in the temperature surrounding the chamber during a measurement cycle must be avoided. The measurement cycle is less than 30 seconds and during this period the ambient temperature must not fluctuate.

The required thermal dampening buffer is typically achieved by using a polyester thermal insulating foam blanket (as used in housing insulation). This provides a lightweight flexible medium that can be wrapped around the chamber. Finally, a reflective shield to reflect incident radiation is required to cover the full installation. A roll of heavy duty aluminium or tin foil provides a convenient and flexible solution.

Photo. 5

Photo. 6

Photo 5. Installed PSY1 stem psychrometer

Photo 6. Fully insulated PSY1 stem psychrometer

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Results

Stem water potential of a single coffee plant was continuously measured at a 30 minute temporal resolution for 45 days throughout the summer growing season from September 10th to October 24th. The data exhibits a diurnal pattern of plant water status characteristic of stress and recovery. As described by Dixon & Johnson (1993), plants routinely undergo water stress even under well watered conditions. This water stress develops when transpiration exceeds absorption of water by the roots. Plants equilibrate with bulk soil water during rehydration which occurs nightly.

Since, diurnal patterns of stress may be common within the operating range of the plant even under well watered conditions, it is then more important to interpret correctly the diurnal patterns of stress. As shown below the continuous diurnal patterns of Ψs show many different patterns of stress and recovery which vary when the plants ability to rehydrate is exceeded.

Coffee Stem Water Potential (Ψs) - 45 day Continuous Measurement

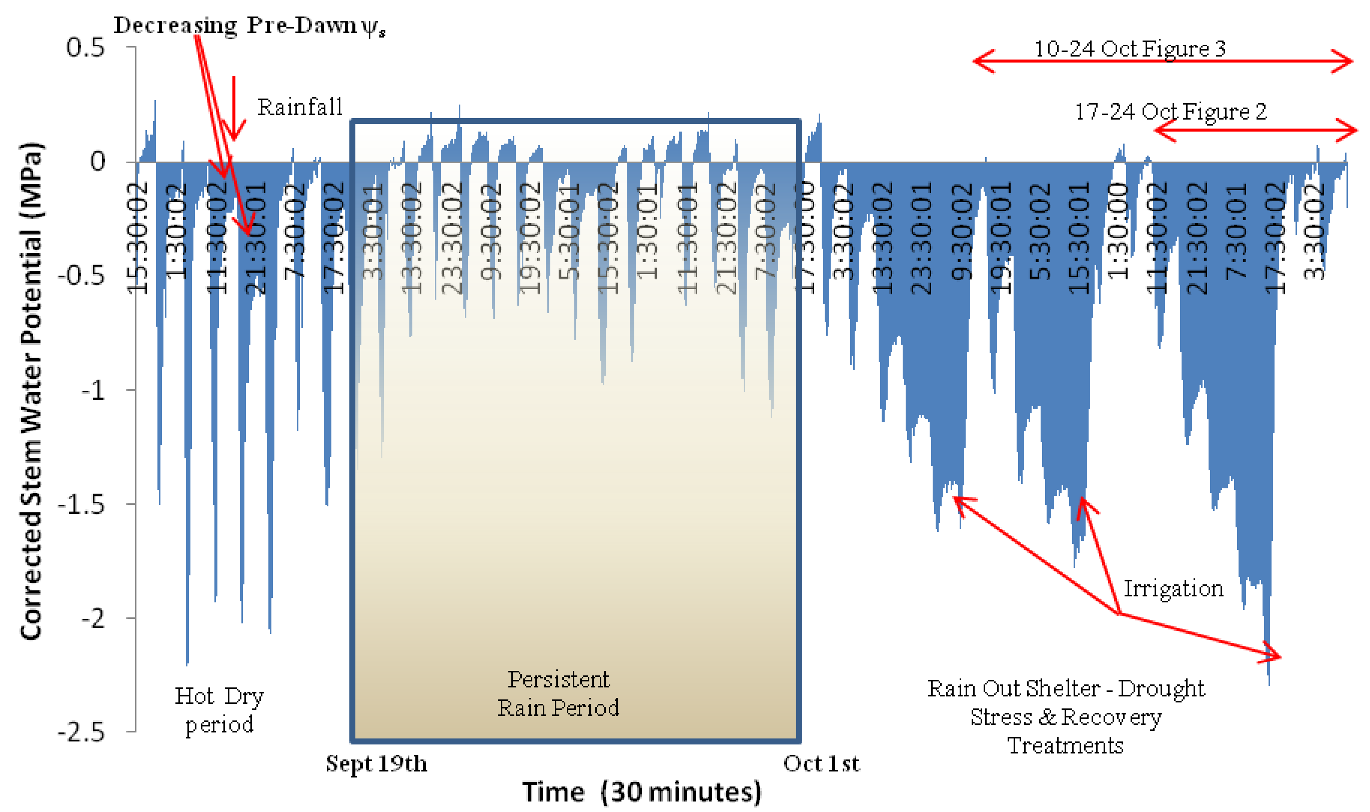

Figure 1. Continuously measured stem water potential of *Coffea arabica* at 30 minute temporal resolution exhibiting characteristic diurnal pattern of plant water status stress and recovery

Stem water potential of the plant was initially monitored under open ambient conditions from September 10th to October 7th during this period the plant was subjected to typical tropical weather conditions such as hot temperatures and high radiation alternating with periods of heavy rainfall. Although the associated weather data is not shown the Ψs data clearly shows this.

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Hot sunny conditions persisted for the first nine days from September 11th to September 15th. This is reflected in the measured Ψs during the period with midday Ψs reaching lows of -2.3 MPa. In the late afternoon of September 15th a rainfall event released the mildly developing water stress which can be seen by the increasing night time or predawn Ψs . Weather remained hot for the following 3 days until a period of persistent rain from September 19th to October 1st. Having established a reliable monitoring of Ψs under hot dry and rainy ambient conditions the coffee plant was moved into a rain-out shelter to impose a drought stress and recovery treatment.

It is important to note an artefact in the data set that is highlighted in the period of rainfall from September 19th to October 1st. Positive Ψs values of up to approx 0.2 MPa are reported at night during this period. Positive water potentials do occur in some plants as a result of root pressure, but are not able to me measured using the psychrometric principle. The cause of these positive values is a result of using a default calibration rather than specifically calibrating the psychrometer chamber prior to deployment.

Positive values of the range 0.1 to 0.2 MPa with an un-calibrated chamber are somewhat expected at the wet end of the spectrum as error increases at the wet end due simply to the limitation of the physics of the principle. If there is no drying force, then there is no Wet Bulb depression and hence, no Ψs measurement. Around 0 MPa, (or wet) the error is an order of magnitude greater than at Ψs of -0.5 MPa or lower (Dixon M.A pers. com 2011). The error can be thought of as logarithmic between -0.1 and -0.5 Mpa because as soon as there is a drying potential on the thermocouples within the chamber to drive thermodynamics the error dissipates rapidly and the accuracy improves. These errors can be further minimised with additional thermal insulation of the chamber so small positives of 0.1 to 0.2 MPa are not of serious concern especially when you see good diurnal rhythms. The offset is also not applicable across the whole data set because the error factor is dissipated very quickly once you generate the drying potential as you extend beyond the very wet, zero Ψs range.

Stress & Recovery

As previously mentioned plants undergo a regular diurnal cycle of stress and recovery in the normal process of growth. The important thing is to identify the development of excessive stress so that it can either be managed or prevented. Figure 2 focuses on the results of the stress and recovery treatment applied in a rainout shelter over a seven day period from October 17th to 24th. Irrigation was applied two days previous in the evening of October 14th resulting in the release of the previous drought treatment from the preceding week by the night of October 16th.

The second day of this drought treatment (October 18th) is well within normal functional range of a coffee plant at -0.81 MPa. However, it is clear that stress is already beginning to build because the night time Ψs failures to reach complete rehydration or zero Ψs equilibrating at -0.32 MPa. The following day midday Ψs reaches -1.24 MPa again well within the functional range of a coffee plant. But, yet again night time Ψs continues to build, this time equilibrating at -0.96 MPa, a decrease in night time Ψs of the previous day of -0.64 MPa.

This trend continues to the 6th day of the drought treatment (October 21st) when the differential between predawn Ψs and the previous midday Ψs was only +0.13 MPa (-1.96 to -1.83) effectively there is no night time recovery or rehydration of the plant resulting in the subsequent midday Ψs declining further to -2.30 MPa before irrigation released the imposed drought stress.

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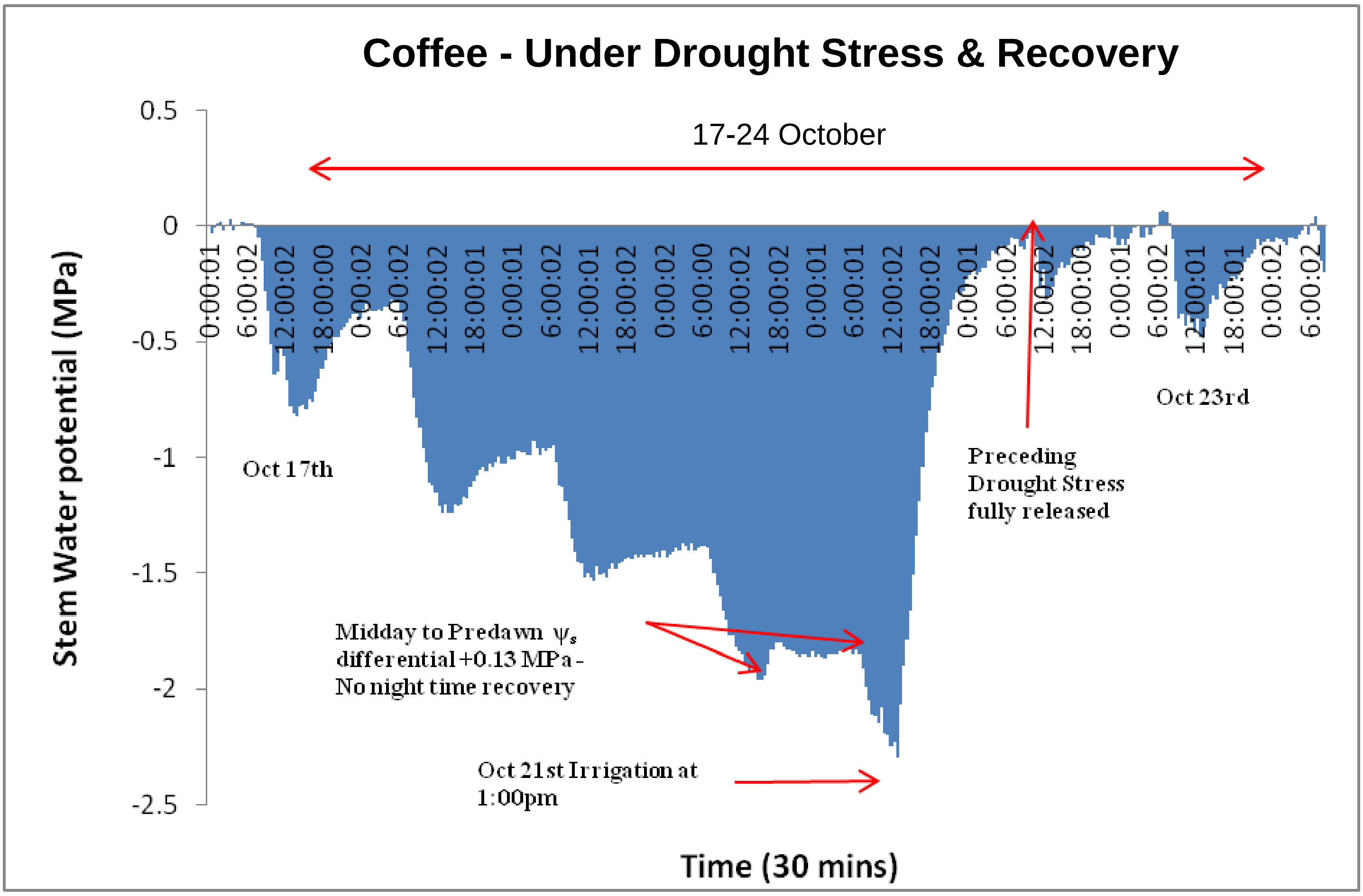

Figure 2. Diurnal stem water potential of Coffea arabica at 30 minute temporal resolution over 7 days drought stress and recovery treatment

Discussion

Akunda & Kumar (1981) showed that for field grown *coffea canephora* (*robusta*) in the south of India, irrigation should be around -2.0 to -1.9 MPa. The data from our drought experiment corresponds with this finding as water stress began to develop at midday Ψs of between -1.2 to -1.5 MPa which was evidenced by the onset of night time Ψs failing to return not only to zero, but to reduce beyond the midday maximum Ψs by less than 50%.

The increase in water stress is clear. Each successive day without water, causes the midday Ψs to decrease, but most importantly so too does the predawn Ψs. Each night exhibiting less and less recovery as soil water availability decreases preventing the plant from rehydrating and achieving a night time recovery.

When irrigation was applied at approx -2.0 to -2.30 MPa water stress was immediately released but built steadily again within days if the drought treatment was reapplied (Figure 3). The water stress almost appears to have a cumulative effect when drought stress and recovery treatments are applied in succession. It is possible that the seeming cumulative nature of the drought stress is related to the multidimensional nature of the effects of water stress on coffee as previously cited by DaMatta (2003).

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Using the detailed information available from continuous monitoring of Ψs using the PSY1 Stem psychrometer this multidimensional stress effect could be examined further. As noted by (Shackle, K. pers. com 2011), the shape and slope of the night time recovery gradients change both in relation to Ψs and successive stress and recovery cycles. Possible causes could be hypothesised that may include; soil moisture content; low night time Vapour Pressure Deficit (VPD); or night time sap flow; however identifying the actual cause of this effect was outside the scope of this study, but it clearly provides an avenue for future research.

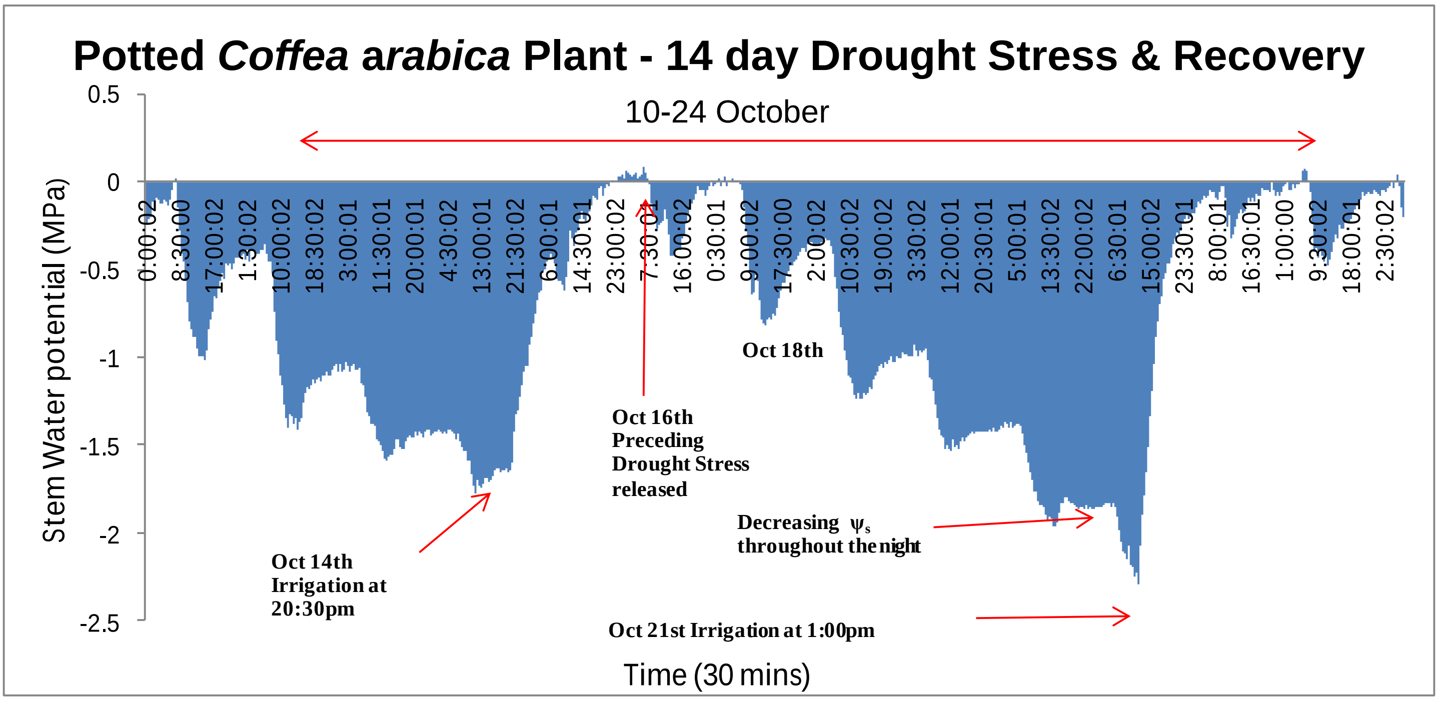

Figure 3. Diurnal stem water potential of Coffea arabica at 30 minute temporal resolution under drought stress and recovery treatment over a 12 day period

The immediate benefit of this research is in demonstrating an advanced tool to aid in the improved irrigation management of coffee.

Current commercial irrigation management practices for coffee as detailed by Carr (2001) rely on manual measurements of individual leaves using a Scholander pressure bomb. First to impose a water stress of -2.5 MPa and then, attempting to maintain that stress for three to four weeks using daily readings each morning. As demonstrated in Figure 3 the pre dawn Ψs is continuously changing and at varying rates of change due to the interrelation of prevailing ambient conditions therefore, relying on a single manual measurement from individual leaves clearly introduces a potential for a substantial error in results. Instead, interpretation of high frequency, continuous and integrated measurements from the same plant using the PSY1 stem psychrometer provide a high level of management information by which to make decisions.

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Traditionally, the coffee tree's fruit does not all ripen at one time. In fact it will have blossoms and berries in various stages of ripening. Only the ripe berries can be picked. The berries cannot be picked when green since they will not ripen once picked. Carr (2001) also detailed the critical importance of imposing a water stress of below -1.2 MPa to stimulate flowering. The identified threshold value was associated with the direction of water movement into and out of the bud. Carr (2001) states that after imposing the threshold stress, irrigation causes a rapid influx of water into the buds which will ensure flowering within 7 to 10 days, but only if buds had experienced Ψs below -1.2 MPa.

Clearly, with flowering so sensitive to water stress, irrigation with more precise monitoring tools at these critical periods provides the opportunity to improve flowering and fruit set and ultimately crop ripening. The ability to so clearly regulate flowering has significant commercial implications such as ensuring flowering occurs at times less likely to be affected by tropical storms; sufficient irrigation water is available to initiate and sustain flowering and berry set; and ultimately to regulate ripening and crop harvest.

It is with this type of precise monitoring and regulation of Ψs that irrigation of coffee trees can be better managed; resulting in more uniform and profuse flowering; higher yields and more uniform ripening and efficient harvesting.

Conclusions

Stem water potential (Ψs) of coffee plants can very easily and accurately be measured using the PSY1 stem psychrometer. The anatomy of the coffee plant is ideally suited to installing the psychrometer and does not exhibit any aggressive wounding around or within the psychrometer chamber. Accurate, reliable and valid data were able to be continuously collected for a period of 45 days in this experiment, measurements could easily have continued for much longer without issue. It is expected that a single installation could remain viable for the duration of the growing season.

The xylem water potentials measured with the PSY1 stem psychrometer corresponded to published data for levels of water stress as measured using a Scholander pressure bomb. However, the advantage of using continuous measurements of stem water potential is the precision upon which irrigation decisions can be made at critical phenological periods such as; flowering and berry set that can significantly impact both yield and quality of the harvested coffee bean.

As highlighted by DaMatta (2006) reviews focusing on the physiology of both *arabica* and *robusta* coffee have been published. However, the majority of drought research conducted on coffee plants has all been conducted in potted plants under controlled greenhouse conditions. It is hoped that through the demonstrated abilities of new field based instrumentation such as the PSY1, more detailed field research can be conducted on coffee trees in field grown, commercial plantations to better understand the impacts of drought. And, ultimately provide commercial producers with protocols for the adoption of the PSY1 for commercial irrigation scheduling of coffee that will produce higher yields and better quality coffee.

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