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Review

Drought and heat tolerance in coffee: a review

Cheserek J.J.* and Gichimu B.M

Coffee Research Foundation, P.O. Box 4 – 00232, Ruiru, Kenya

Abstract

Climatic variability is the main factor responsible for the fluctuations in the coffee yield in the world. The relationships between the climatic parameters and the agricultural production are quite complex, because environmental factors affect the growth and the development of plants under different forms during the phenological phases of the coffee crop. Such environmental factors include reduced rainfall and high temperatures both of which majorly contribute to drought. This paper briefly reviews some of the important aspects of drought and heat tolerance in coffee. It highlights the impacts of draught and high temperatures in coffee production, tolerance mechanisms, necessary interventions, selection challenges and current advances towards development of drought and heat tolerant coffee cultivars.

Keywords: Coffee, Water Stress, High Temperatures, Tolerance Mechanisms.

INTRODUCTION

Among some 90 species of the genus *Coffea*, *C. arabica* L. (Arabica coffee) and *C. canephora* Pierre (Robusta coffee) economically dominate the world coffee trade, being responsible for about 99% of world bean production (Da Matta and Ramalho, 2006). Arabica coffee accounts for more than 62% of the world coffee production (Dias et al., 2007) and 90% of the world coffee market (Worku and Astatkie, 2010). Robusta coffee accounts for the rest. Compared with Arabica, Robusta coffee generally appears to be more vigorous, productive and robust, but the quality of the beverage derived from its beans is considerably inferior to that from Arabica (Coste, 1992; Da Matta and Ramalho 2006).

Drought is an environmental factor that causes water deficit or water stress in plants (Pinheiro et al., 2005). Overall, drought and unfavourable temperatures are the major climatic limitations for coffee production (Da Matta and Ramalho 2006). These limitations are expected to become increasingly important in several coffee growing regions due to the recognized changes in global climate and also because coffee cultivation has spread towards marginal lands, where water shortage and unfavourable temperatures constitute major constraints to coffee yield (Da Matta and Ramalho 2006; Kimemia, 2010). The global warming caused by increase of greenhouse gas emissions (carbon dioxide and methane) in the atmosphere is causing wide changes in atmospheric events resulting to climate change. These include, shifting of optimal growing zones, changes in rainfall (amount and distribution), and changes in dynamics of crop diseases and pests, loss of agricultural land due to either rising sea levels and/or desertification (Kimemia, 2010). The combined effects of this phenomenon have critical impacts on coffee production.

Many reviews focusing on the morphology and physiology of both Arabica and Robusta coffee with respect to drought and extreme temperatures (Barros et al., 1999; Carr, 2001; Maestri et al., 2001; DaMatta and Rena, 2001, 2002; DaMatta, 2004 and DaMatta and Ramalho, 2006) have been published. The present review is mainly focused on impact of draught and high temperatures on coffee production and necessary interventions related to crop improvement. It therefore highlights some morphological and physiological traits/mechanisms which are important in selecting drought and heat tolerant coffee genotypes. It further focuses on selection challenges and current advances towards development of tolerant genotypes.

*Corresponding Author E-mail: cheserekjerono@yahoo.com

Impacts of drought and high temperatures on coffee production

Coffee is indigenous to African regions characterized by abundantly distributed rainfall and atmospheric humidity frequently approaching saturation (Pinheiro et al., 2005).

For this reason, coffee probably evolved as 'water-spender' species (DaMatta and Rena, 2001). Coffee is therefore a highly environmentally-dependent crop and an increase of a few degrees of average temperature and/or short periods of drought in coffee-growing regions can substantially decrease yields of quality coffees. Taking into account the global warming phenomena, severe reductions of adequate coffee growing areas are to be expected (DaMatta and Ramalho, 2006) thus sustainability of coffee productivity and quality may become more difficult to maintain. Experts warn that temperature may rise up to 5.8°C in the tropical area by the end of the 21st century (Camargo, 2009). In Kenya, climate change has rendered a significant proportion of traditional coffee growing zone less suitable for coffee production. This has caused shifting from optimal to sub-optimal and marginal growing zones, resulting in changes in crop yields and quality. In Uganda, severe impacts of climate change on coffee production are expected as temperature rise by 2ºC in the next few decades (Kimemia, 2010). In Brazil, Robusta coffee is currently largely cultivated in regions where water availability constitutes the major environmental constraint affecting crop production (Pinheiro et al., 2005).

Extreme temperatures, depending on their intensity, duration and speed of imposition, impair cell metabolic processes (e.g. photosynthesis), growth and survival of plants, as well as their economic exploitation (DaMatta and Ramalho, 2006). In fact, temperature may limit the successful economic exploitation of the coffee crop, in part because coffee growth is particularly affected by both high and low temperatures (Barros et al., 1997; Silva et al., 2004). The optimum mean annual temperature range for Arabica coffee is 18-21ºC (DaMatta and Ramalho, 2006). Above 23ºC, development and ripening of fruits are accelerated, often leading to loss of quality (Camargo, 2009). Continuous exposure to temperatures as high as 30ºC could result in not only depressed growth but also in abnormalities such as yellowing of leaves and growth of tumors at the base of the stem (DaMatta and Ramalho, 2006). A relatively high temperature during blossoming, especially if associated with a prolonged dry season, may cause abortion of flowers (Camargo, 2009). In addition, large variations in temperature also increase bean defects, modify bean biochemical composition and the final quality of the beverage (Carr, 2001; Silva et al., 2005). For Robusta coffee, the optimum annual mean temperature ranges from 22 to 30ºC (DaMatta and Ramalho, 2006). Robusta coffee can be grown between sea level and 800 m, whereas Arabica coffee grows best at higher altitudes and is often grown in hilly areas, as in Colombia and Central America (Baker and Haggar 2007). In Kenya, the main coffee growing areas ranges from low to high altitude (1200 m to over 1700 m above sea level) (Kimemia, 2010; Gichimu 2012).

Drought and heat tolerance mechanisms

For cultivated plants, tolerance to drought is generally considered as the potential for a particular species or variety to yield more in comparison to others under limited soil water conditions (Pinheiro, 2004). A complementary approach to improve plant performance for drought-prone regions involves the identification and selection of traits that contribute to drought tolerance. A partial list of potentially important traits might include water-extraction efficiency, water-use efficiency (WUE), hydraulic conductance, osmotic and elastic adjustments, and modulation of leaf area. Most of these traits are complex and their control and molecular basis is not well understood (Da Matta, 2004). However, species/varieties more tolerant to drought generally differ morphologically and/or physiologically with mechanisms that allow them to produce comparable yield under limited water supply (Da Matta, 2004). Examples include maximization in water uptake by growing deep roots and/or minimization of water loss by way of an effective stomatal closure and reduced leaf area thus improving plant water status and turgor maintenance (Kufa and Burkhardt, 2011; Kramer and Boyer, 1995). Turgor maintenance, which provides the potential for keeping physiological activity for extended periods of drought, may be achieved through an osmotic adjustment and/or changes in cell wall elasticity (Kramer and Boyer, 1995; Turner 1997).

Like many plant species, coffee displays a diversity of acclimation mechanisms to avoid and endure drought and heat stresses (as well as the oxidative stress usually promoted by them), developed within the genetic bounds of the plant/species (Da Matta and Ramalho, 2006; Worku and Astatkie, 2010). When working with potted plants, Pinheiro et al., (2005) found out that plant water stress develops more slowly in the drought-tolerant than in the drought-sensitive clones. Morphological traits such as leaf area and root mass to leaf area ratio were not associated with that response. Instead, the much deeper root system of the tolerant clones enabled them to gain greater access to water towards the bottom of the pots and, therefore, to maintain a more favourable internal water status longer than in drought-sensitive clones. Root characteristics and growth play a crucial role in maintaining the water supply to the plant, and drought adapted plants are often characterized by deep and vigorous root systems (Blum, 2005). However, Burkhardt et al., (2006) observed coffee plants with extensive root system but vulnerable to drought due to their hydraulic system and stomatal behavior.

Physiological evaluations of some of the coffee clones perceived to be drought tolerant suggested that keeping an adequate water status, maintenance of leaf area (Da Matta et al., 2003; Pinheiro et al., 2005), and steep leaf inclinations (Pinheiro and DaMatta, unpublished results), are of utmost importance. Biochemical traits such as improved tolerance of oxidative stress (Lima et al., 2002; Pinheiro et al., 2004) and ability to maintain assimilate export (Praxedes et al., 2005) are also considered important. Drought-tolerant coffee genotypes are able to maintain higher tissue water potential and water use efficiency than drought-sensitive ones under water-deficit conditions (DaMatta, 2004; Dias et al., 2007). Such differences are even more evident in the field, where the development of the root system is much less restricted (Da Matta et al., 2003). When comparing the yields of drought-tolerant and drought-sensitive clones, Da Matta et al., (2003) found that the better crop yield of the drought-tolerant clone was associated with maintenance of leaf area and higher tissue water potentials, as a consequence of smaller stomatal conductance, which would result in less carbon isotope discrimination. Combining traits associated with a favourable water status and suitable biochemical characteristics, which enable some degree of tissue tolerance to desiccation, should improve coffee yields over a range of drought conditions**.** However, most of these traits do not appear to be well developed in drought-tolerant clones which favour survival over productivity under drought conditions.

Different species of coffee (e.g. Arabica and Robusta) may also differ in morphological and/or physiological mechanisms that allow them to produce considerably well under limited water supply (Da Matta, 2004). Arabica coffee genotypes have been found to differ in drought adaptation mechanisms such as stomata control and soil water extraction efficiency (DaMatta and Ramalho, 2006), plant water use and biomass allocation to the stems and leaves (Dias et al., 2007) and tissue water potential (DaMatta, 2004). On the other hand, studies on Robusta coffee showed deeper root system (Pinheiro et al., 2005) and larger root dry mass in drought tolerant clones than in drought sensitive ones (DaMatta and Ramalho, 2006). Further, Lima et al. (2002) proposed that drought tolerance in Robusta coffee might, at least in part, be associated with enhanced activity of antioxidant enzymes although Pinheiro et al., (2004) did not corroborate these findings. The efficiency of all these mechanisms will determine the ability to cope with such environmental conditions, thus setting limits to species/genotypes distribution.

Necessary interventions and selection challenges

Researchers are being challenged to be better prepared by breeding varieties that will cope with the impacts of drought or high temperatures (Motha, 2008) and repackage and promote climate change mitigation strategies (Smith et al., 2008; Kimemia, 2010). Identification of coffee genotypes that could withstand drought spells with acceptable yields should be the first requirement for a successful breeding programme for drought tolerance. Considering the fast changing climate, drought tolerant genotypes must also have good combining abilities for yield, diseases and quality. Under low-input conditions typical of many farming systems of drought-prone regions, cultivars with better yield stability under drought stress, or better able to survive drought episodes, may be of greater value than cultivars with high yield potential selected for improved environments. However, despite all the efforts applied towards understanding drought tolerance in coffee, there is no consistent information about the causes of the differences in drought tolerance in coffee. According to Blum (2005) the conceptual framework of what actually constitutes a viable target for selection in respect to drought tolerance is not always clear. For Arabica coffee, additional challenge is that of low genetic variation available within the genome and its close relatives forcing the breeders to look further afield.

Current advances

In some countries, research on developing drought tolerant coffee varieties for climate change adaptation has started. In Brazil plant breeders have registered considerable success in selecting some promising Robusta clones with relatively high bean yields and low year-to-year variation of bean production under rain-fed conditions. The selection has been largely empirical as al., information about how coffee responds physiologically to drying soil is still unclear (Pinheiro et al., 2005; Da Matta and Ramalho 2006). In Kenya and Uganda, basic research is ongoing whereby coffee genotypes are being subjected to drought and heat stress by denying them sufficient water in a greenhouse to detect and select those that are tolerant. The genotypes will then be tried in hot and dry areas. Some Arabica coffee genotypes that are known to have some drought tolerance attributes include Tanganyika Drought resistant genotypes DR I and DR II (Trench, unpublished), and Indian cultivar Sln 9 (D'Souza 2009). Such genotypes could be exploited in future drought tolerance breeding programmes.

CONCLUSION

This review enabled better understanding of the different ways in which coffee adapts to drought and heat tolerance. It further highlighted some morphological and physiological traits which are important in selecting drought and heat tolerant coffee genotypes. These facts will guide the ongoing and future trials on heat and drought tolerance in coffee.

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