IMPACT OF CLIMATE CHANGE ON THE SPATIAL DISTRIBUTION AND PRODUCTIVITY OF *COFFEA ARABICA* L. IN AFRICA: A REVIEW

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ABSTRACT: Coffee is a fundamental export commodity of many African countries. Despite its importance for the national economy of countries, its production and productivity are predicted to be negatively affected by climate change. This review aimed to synthesize the observed and anticipated impacts of climate change on the distribution and productivity of Arabica coffee. To this end, a systematic review of literature was employed. The evidence showed that suitable areas for Arabica coffee cultivation will diminish by 60% by 2050 and vanish at the end of the 21st in Africa if the business as usual scenario continues and interventions are not taken in time. The productivity of coffee has been declining and is predicted to decline substantially (25-60%) by 2050 in Africa. Consequently, the livelihood of smallholder producers and the economy of coffee growing countries are at risk and under a vicious circle of poverty. Furthermore, the African share of the world's Arabica coffee production has been declining with a current share of 12% calling for increasing productivity and ensuring benefit-sharing through securing sustainability and value additions. As climate changes, the currently suitable area for coffee production declines, and shifts to highlands. Consequently, conflicts over land use priorities and deforestation for coffee cultivation will cause the loss of biodiversity. Mainstreaming biodiversity in the coffee production system, interventions for climate change adaptation and mitigation as well as promoting in-situ conservation of the coffee gene pool are important to ensure sustainable utilization of genetic resources.

Keywords: Biodiversity, Climate change, *Coffea arabica*, Conservation.

INTRODUCTION

Coffee is one of the most important global plant genetic resources as it has been playing a significant role in the economy of both producing (DaMatta et al., 2008) and consuming countries (UN, 2018).

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Coffee is produced in more than 80 countries (Ramalho et al., 2013), out of which more than 50 countries have been exporting a substantial amount of their production to the global market (Szenthe, 2019). Globally, coffee supports the livelihoods of more than 25 million people (DaMatta et al., 2008; UN, 2018). *Coffea arabica* L. (Arabica coffee) and *Coffea canephora* Pierre ex A.Froehner (Robusta coffee) are the most widely consumed cash crops (DaMatta et al., 2008) and pharmacologically active beverages (Chen, 2019). Coffee consumption has become a regular part of daily life in the world (UN, 2018). The Arabica coffee is widely consumed and it is by far the dominant bean used in the world (DaMatta et al., 2008), representing about 60% of the total global production in the last five years (USDA, 2019a). In Ethiopia, coffee is an integral part of the socio-cultural value of people in its land of origin. Ethiopian uses coffee for a family gathering, spiritual celebration, marriage ceremony, conflict resolution, during gatherings for farming and mourning.

All global coffee productions are from the equatorial region (coffee belt or coffee-growing zone) of Central and South America, Southeast Asia and Africa (Szenthe, 2019). South America is leading the global market with the largest share of Brazil and Colombia (Iscaro, 2014). Asian countries are also famous for their rich coffee production with earthy and light flavours (Szenthe, 2019).

Africa is the homeland of both Arabica coffee and Robusta coffee (Melke and Fetene, 2014; Bunn et al., 2015; Ovalle-Rivera et al., 2015) and is known for its best coffee flavour and aroma in the world (ICO, 2015; Ovalle-Rivera et al., 2015; UN, 2018). Among other crops, Arabica coffee is a fundamental commodity in Africa (Lemma and Megersa, 2021) and the backbone of Ethiopia's economy (Iscaro, 2014).

Studies show that Arabica coffee is predicted to be significantly affected by climate change (Aerts et al., 2017; Craparo et al., 2015; Hirons et al., 2018). In this regard, Africa is the most vulnerable continent to the negative impacts of global climate change (IPCC, 2014). The temperature of the continent has increased by 0.7^{o}C in the 20th century and is expected to continue warming with a range of 0.2^{o}C (B1 scenario) - 0.5^{o}C (A2 scenario)/ decade during the 21st century (IPCC, 2013). The pattern of rainfall was irregular and erratic in the main coffee-growing countries (Moat et al., 2017). As climate change is predicted to continue in the coming decades, it is expected that the production of Arabica coffee will be altered abundantly in the continent (Davis et al., 2012; Agegnehu et al., 2015; Bunn et al., 2015; Abrha, 2018). Consequently, the livelihood of millions of smallholder producers in the continent, the share of GDP and employment of the producing countries will be highly affected. As a result, the development of the continent and the wellbeing of the human being at large will be subjected to dependency, unless remedial actions are taken in advance.

Despite many research results on coffee (Davis et al., 2012; Bunn et al. 2015; Ovalle-Rivera et al., 2015; Moat et al., 2017), the understanding about the impact of climate change on Arabica coffee is still limited and demanding in Africa (Craparo et al., 2015). Therefore, understanding how and to what extent climate change affects the spatial distribution and productivity of Arabica coffee is important to set adaptation and mitigation strategies for the sector and smallholder producers in the continent (Bro et al., 2019). To this end, this review aimed at compiling and analysing existing information and data on the impact of climate change on the spatial distribution and productivity of Arabica coffee in Africa for influencing decision making processes related to the management of coffee production and its natural ecosystems in the face of changing climate. This review will contribute to the on-going scientific and policy debates on the interplay of coffee, climate change and resilience of stakeholder's livelihoods in developing countries.

METHODS

This review targeted at the major coffee-growing countries in Africa. These countries are mainly situated in the tropics including Burundi, Cameroon, the Democratic Republic of Congo, Ethiopia, Kenya, Madagascar, Malawi, Rwanda, Tanzania and Uganda. They share about 80% of the annual coffee production of Africa (ICO, 2015; UN, 2018; USDA, 2019a).

The data were obtained from different databases and empirical studies to show the impact of climate change on the spatial distribution of coffee production and productivity in the major coffee-growing countries in Africa. The raw data about annual Arabica coffee production and global market share of

Africa by country were accessed from International Coffee Organization (ICO) following an official request.

The search for available literature was carried out systematically. Google scholar, Agora and Science direct have been used as the main database for searching different kinds of literature including books and journal articles. The Boolean searching technique was employed using both "and" and "or" operator with a wide range of keywords such as coffee, coffee production, coffee productivity, coffee and climate, *Coffea arabica*, deforestation, climate change, biodiversity and Africa. Accordingly, a total of 5269 papers (5242 published articles and 27 unpublished) were accessed (Figure 1). All accessed studies were screened by title by raising and answering the basic question for each paper; which is - Does the paper have vital information or evidence to support the objective of this study? Those papers which got a "yes" response were selected for further review. Accordingly, a total of 132 papers were left for abstract review. These selected studies were further screened by their abstract, and papers with having very limited information were screened out. Then, a total of 49 papers were fully reviewed and sufficient data were extracted from all selected studies and synthesized. The data obtained from the different sources were analysed using descriptive statistics.

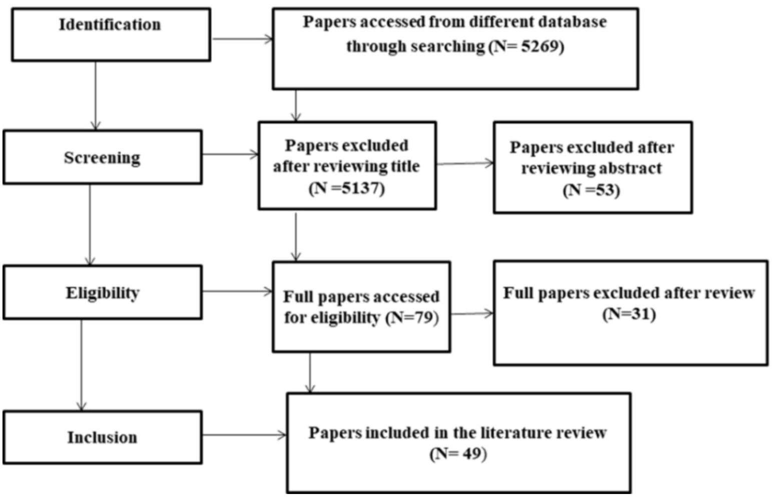

Figure 1. Flow chart of review process and number of literature reviewed adopted from (Pham et al., 2019), N: number of papers.

RESULTS

Current status of coffee production in Africa

The continent of Africa has the highest number of coffee-producing countries in the world (UN, 2018). The International Coffee Organization report indicates that about 25 African countries are producing coffee (ICO, 2015), out of which 10 are producing a significant proportion (about 80% of the continent's production) of Arabica coffee in the last decade (Table 1; Table 2).

Table 1. Arabica coffee Production (1000 x 60-Kilogram Bags) in high producing countries of Africa (2010-2020).

Country	2010/11	2011/12	2012/13	2013/14	2014/15	2015/16	2016/17	2017/18	2018/19	2019/20	Average	Share of the country(%)
Burundi	235	210	235	185	160	240	200	205	200	200	207.0	2.19
Cameroon	90	90	50	50	50	50	50	50	50	50	58.0	0.61
DR Congo	100	90	80	70	70	70	70	75	70	75	77.0	0.82
Ethiopia	6,125	6,320	6,500	6,345	6,475	6,510	6,943	7,050	7,250	7,350	6,686.8	70.89
Kenya	710	750	660	850	750	750	815	715	775	775	755.0	8.00
Madagascar	25	25	25	25	25	25	25	25	30	25	25.5	0.27
Malawi	24	21	25	25	21	23	16	12	11	10	18.8	0.20
Rwanda	317	245	260	250	240	300	230	275	275	300	269.2	2.85
Tanzania	600	365	610	450	600	600	550	600	700	650	572.5	6.07
Uganda	644	875	800	850	750	750	1200	750	800	750	816.9	8.66
Total	8,870	8,991	9,245	9,100	9,141	9,318	10,099	9,757	10,161	10,185	9,486.7	100

Source: USDA, 2019a.

In terms of global Arabica coffee production, the share of African is on average estimated at 12% (Table 1) and this supports the livelihood of more than 25 million smallholder farmers (ICO, 2015; UN, 2018; USDA, 2019a). In Africa, a large number of people depend on coffee growing, processing and marketing for livelihood support (UN, 2018). Coffee contributes to the employment of about five million people in Kenya (ICO, 2019). Besides, coffee contributes significantly to the national economy or GDP of coffee-producing Africa countries (DaMatta et al., 2008). However, the share of Africa in the global market is small and has been declining (ICO, 2015; USDA, 2019a).

Table 2. Average yield and coffee farming area in Africa.

	2010/11		2015/16		2019/20	
Country	**Area(ha)**	**Yield(Kg/ha)**	**Area (ha)**	**Yield(Kg/ha)**	**Area(ha)**	**Yield(Kg/ha)**
Burundi	60,000	281	60,000	258	60,000	200
Cameroon	140,000	220	140,000	214	140,000	130.5
DR Congo	200,000	101	200,000	74	200,000	75
Ethiopia	509,000	800	509,000	837	509,000	866.4
Kenya	160,000	412	160,000	281	160,000	291
Madagascar	200,000	222	200,000	233.7	200,000	86.5
Malawi	3,500	185	3500	184	3,500	184
Rwanda	42,000	500	42,000	429	42,000	429
Tanzania	229,000	216	275,000	170	275,000	273
Uganda	282,284	708	282,000	1,042	282,000	904.26
Others	569,184	-	523,184	-	523,184	-
Africa	2,440,684	408.5	2,440,684	384	2,440,684	368

Source: ICO, 2015; UN, 2018; USDA, 2019a.

Ethiopia, the center of origin for Arabica coffee, is the leading producer and exporter in Africa (Table 2) and ranked fifth in the world (UN, 2018). Out of 6,686,800 of 60-Kilogram bags annual average production (Table 1), Ethiopia exported 55% of total production to the global market. The rest was consumed in the country. The economy of Ethiopia largely depends on the production of Arabica coffee, which accounts for about 30% of total export earnings and 5% of GDP (USDA, 2019b).

In Africa, Uganda is the second-largest exporter of Arabica coffee accounting for 5% of GDP and employ about one million people in the country (Ahmed, 2012). Kenya is also another major producer of Arabica coffee. The Kenyan coffee sector is annually worth about 230 million US dollars in foreign exchange earnings. Tanzania is the fourth producer and exporter of Arabica coffee during the last decade (Table 1). Burundi, Rwanda, the Democratic Republic of Congo, Cameroon, Madagascar and Malawi are among the producer and exporter countries of Arabica coffee in the continent. In these countries, the dependency of smallholder farmers on coffee production has been increasing. The coffee sector contributed to 59% of the earnings of foreign exchange in Burundi (Ovalle-Rivera et al., 2015). In Malawi, the production share of smallholder farmers has increased from 2.6% in 1999 to 15.7% in 2007. In Rwanda, the economy of the nation and livelihood of 500,000 smallholder households which corresponds to 2 million people (i.e. 25% of the total population) depend on Arabica coffee production (Hakorimana and Akcaoz, 2017).

Effects of climate change on spatial distribution of Arabica coffee in Africa

The MaxEnt model prediction indicates that the currently suitable area for coffee cultivation will be reduced by 60% in the mid of 21st century (Davis et al., 2012; Ovalle-Rivera et al., 2015). As a result, Uganda and Tanzania will lose the currently suitable area below 1400 m a.s.l. Madagascar sub-region is predicted to lose its entire Arabica coffee growing area in the low attitudes (<1400 m a.s.l) (Ovalle-Rivera et al., 2015). Zimbabwe is expected to lose about 30,000 to 50,000 ha of currently suitable area for Arabica coffee production by 2050 (Chemura et al., 2015). The current Arabica coffee production areas in some East African countries including Ethiopia, Uganda and Kenya will shift to highlands by the end of 2050 (Bunn et al., 2015; Ovalle-Rivera et al., 2015).

Despite some discrepancies in the efficiency of prediction, if the predicted scenarios of climate change unfold, the suitable area for Arabica coffee production in Africa will diminish from the current 24,406 Km^2 to 7,708 Km^2 in mid of 21st century (Davis et al., 2012; Ovalle-Rivera et al., 2015).

Effects of Climate Change on Productivity of Arabica coffee in Africa

The global demand for Arabica coffee has been increasing (ICO, 2015; UN, 2018). Regardless of the commitment of the producer and other stakeholders to scale up the productivity, the current and future production of Arabica coffee will not satisfy the growing demand of the global market. The average annual production is declining in contrast to the rising demand (UN, 2018) and exhibits decline over the last five decades in Africa (ICO, 2015). The evidence depicts that coffee productivity of the continent has been declining, except in Uganda and Ethiopia (Table 2) and is predicted to decline substantially in the coming decades (Davis et al., 2012; Chemura and Kutywayo, 2015; Gidey et al., 2019; Ngango and Kim, 2019).

It is predicted that some of Arabica coffee-producing countries in Africa lost their total production at the beginning of the 21st century (ICO, 2015). It was showed that Angola had the potential of annual average production of 2.4 million Kg of Arabica coffee at the end of the 20th century. A review of different data showed that Angola has lost its 99% Arabica coffee production in 2003 (ICO, 2015; USDA, 2019a). Zambia had produced 4.73 million kg of Arabica coffee annually at the beginning of the 21st century. However, it has lost its significant production since 2011. Similarly, Zimbabwe had the potential of 5.046 million Kg of average annual Arabica coffee production, which has been largely lost in 2010. The Democratic Republic of Congo and Madagascar had also lost their historical significant global market share (ICO, 2015).

DISCUSSION

Coffee is highly sensitive to temperature and rainfall (DaMatta et al., 2008; Davis et al., 2012; Bunn et al., 2015; Magrach and Ghazoul, 2015). The climate change prediction indicates that the entire continent of Africa will warm in the coming decades with 0.2-0.5°C per decade with erratic rainfall (IPCC, 2013). The previous studies categorize the Arabica coffee growing regions of Africa into two sub-regions: The East African sub-region and the Madagascar sub-region (Ovalle-Rivera et al., 2015). In most parts of Arabica coffee producing countries of the East African sub-region, the annual rainfall is predicted to be reduced in the coming decades (IPCC, 2013). Consequently, substantial size of the currently suitable land area for Arabica coffee cultivation will be reduced (Davis et al., 2012; Ovalle-Rivera et al., 2015) with the narrow optimum temperature range (18 to 22°C) required for its cultivation (DaMatta et al., 2008; Moat et al., 2017) and variable rainfall distribution (Magrach and Ghazoul, 2015).

As the suitable land area continues to decline, farmers will be forced to migrate to the high altitude areas of coffee growing regions for cultivation (Ovalle-Rivera et al., 2015). In the Madagascar sub-region, the range will shift upward from 500-1700 to 700-2000 m a.s.l (Ovalle-Rivera et al., 2015). In the East Africa sub-region, the suitable climate for Arabica coffee production will be shifted upward from 400-2000 m a.s.l to 800-2500 m a.s.l. However, difficulties in high elevation areas including the steep slope, shallow soil depth, too cold temperature and soil of mountainous cultivation challenge the upward migration strategy (Bunn et al., 2015).

Most likely, the projected suitable areas in East Africa sub-region overlap with currently registered and designated biodiversity hotspots (Magrach and Ghazoul, 2015) where originally coffee was found (DaMatta et al., 2008). This leads to land use conflict by putting deforestation on natural forest resources found in high altitudes (Rahn et al., 2013). The expansion of coffee production in this region will have positive feedback both on climate change and the reduction of suitable land areas for coffee production (Davis et al., 2012; Magrach and Ghazoul, 2015). Moreover, this would lead to the loss of 35% of local biodiversity (Magrach and Ghazoul, 2015) including wild Arabica coffee (Davis et al., 2012; Moat et al., 2017). As a result, the current coffee growing and predicated suitable land area will be substantially decreased at the end of the 21st century (Moat et al., 2017; Davis et al., 2012).

Although there are some discrepancies on the projection of suitability of future land area, all studies (Davis et al., 2012; Bunn et al., 2015; Ovalle-Rivera et al., 2015; Moat et al., 2017) confirm that the overall impact of climate change is predicted to be negative in Africa. This affects farmers and all actors in the value chain of coffee marketing (Haggar and Schepp, 2012). Consequently, the livelihoods of about 25 million people who directly or indirectly depend on coffee might be at great risk (UN, 2018). This figure is expected to be doubled by 2050. The national GDP and foreign currency earnings of the countries will also be seriously affected.

As the suitable area continues to decline, the Arabica coffee population is expected to be stressed and reduced (Andrade et al., 2019; Gidey et al., 2019; Justine et al., 2019) with the high risk of extinction at the end of the 21st century. The prediction of previous studies indicated that the unsuitability of the bioclimatic factor for the Arabica coffee population leads to total extinction from its original habitat at the end of this century (Davis et al., 2012). The observed and anticipated evidence pinpoints that the Arabica coffee population is highly vulnerable to extinction at the end of the 21st century (Davis et al., 2012; Moat et al., 2019). The MaxEnt model-based prediction also indicates that the population of wild Arabica coffee will be reduced by 80% by 2088, if precautionary measures are not implemented in advance (Davis et al., 2012; Moat et al., 2019). Even in a managed system, the prevalence of sudden shocks of climate change such as drought, an outbreak of pests and disease causes the mortality of

Arabica coffee soon (Drinnan and Menzel, 1995; Jaramillo et al., 2013; Agegnehu, 2015; Aerts et al., 2017; Moat et al., 2017; Liebig et al., 2018). During the continuous oscillation of drought, the vulnerability of Arabica coffee was reported in different parts of coffee growing regions in Africa (Lemma and Megersa, 2021; Merga and Alemayehu, 2019).

Climate change, among many other factors, hinders the production of Arabica coffee in the continent of Africa (Jaramillo et al., 2011; Davis et al., 2012; Jaramillo et al., 2013; Chemura et al., 2015; Gidey et al., 2019). Humidity, rainfall, and temperature considerably determine coffee production and productivity (DaMatta et al., 2008; Davis et al., 2012; DaMatta et al., 2018). The Arabica coffee needs a less humid atmosphere, comparable to Ethiopian highlands (DaMatta et al., 2008).

Rainfall affects the phenology and consequently the productivity of coffee. The Arabica coffee cultivation requires high rainfall in the range of 1200 to 2000 mm per year (Melke and Fetene, 2014; Bunn et al., 2015). However, excess rainfall during the flowering season alters its flowering. In the main coffee-growing regions of eastern Africa, the rainfall has decreased during the coffee-growing season by 15% in the last 30 years (Moat et al., 2017). Hence, unreliable, erratic and short rainfall season has posed unanticipated challenges on the patterns of cherry ripening in most coffee-growing countries (ICO, 2019).

Arabica coffee is highly sensitive to increasing temperature during blossoming and fructification (Haggar and Schepp, 2012). The optimum temperature of Arabica coffee is 18-22^{o}C (Moat et al., 2017). The average temperature beyond 23°C hinders the growth and ripening of the coffee cherries. Temperature about 28-30°C alters flowering and fruit formation (Drinnan and Menzel, 1995). The continuous exposure to daily temperatures above 30°C leads to the loss of the leaves. Beyond 33°C the survival of the crop might be largely challenged and leads to slaying the crop (Drinnan and Menzel, 1995). If the other factors are constraints, Arabica coffee can gradually survive temperatures as high as 37/30°C (day/night) (DaMatta et al., 2018). However, the yield is not expected. On the other hand, temperature below 18°C depressed the growth of coffee. The enhanced temperature leads to water stress and affects the physiology of Arabica coffee and ultimately limits photosynthesis (Haggar and Schepp, 2012). Productivity is entirely governed by the efficiency of photosynthesis.

The modeling study in Tanzania indicated that temperature rise in +1^{o}C is predicted to reduce productivity of coffee by 25.3% (equivalent 397, 834 ton/year), +3^{o}C reduce by 68.8% (1,081,856 ton/year), +5^{o}C reduce by 96.6% (1,519,001 ton/year) (Haggar and Schepp, 2012). Other studies in the same country also predicted that the productivity of Arabica coffee might decline by 145 Kg/ha by 2060 (Craparo et al., 2015). Furthermore, a study in Ethiopia showed that the productivity of Arabica coffee will be reduced by 4-25% and 20-60% in shading and without shading systems, respectively in the faces of climate change (Gidey et al., 2019). In contrary to projections made so far, the productivity of Ethiopian coffee had shown an increasing trend (0.74 ton/ha in 2015/16 to 0.82 ton/ha in 2029/20) in the last five years (USDA, 2019b). Some scholars argue that enough rainfall and optimum temperature in most coffee-growing areas of the country contributed to the increasing production (USDA, 2019b). Other scholars argued that intensive management practices including shading contributed to sustaining coffee productivity (Moat et al., 2017). The latter group claims that climate change would significantly reduce the productivity of coffee if intensive management is not done in advance.

The prevailing expansion of pests and diseases (Ngango and Kim, 2019) in association with climate change also imposed challenges on Arabica coffee production and productivity in Africa (Hirons et al., 2018). The coffee berry borer (*Hypothenemus hampi* Ferrari) that attacks Arabica coffee (Agegnehu et al., 2015; Liebig et al., 2018) was originally found in the low altitudes (<1400 m a.s.l) of Central Africa. However, this pest had moved upward to the high elevations (>1800 m a.s.l) in east Africa (Agegnehu et al., 2015). As a result of climate change-induced pest and disease expansion (Weldemichael and Teferi, 2019), the current Arabica coffee production areas in Ethiopia, Uganda, Kenya, Rwanda and Burundi are expected to be significantly infested by 2050 (Jaramillo et al., 2011; Agegnehu, et al., 2015). Consequently, the observed and anticipated outbreak of pests and disease would reduce the productivity of coffee in Africa (Hirons et al., 2018).

The interaction of coffee and pollinators is also highly affected by climate change (Imbach et al., 2017). The distribution of pollinators mainly honey bees and butterflies govern the productivity of coffee farming (Ngo et al., 2011). As both pollinators and coffee are sensitive to climate change, the future common/ intersection area is predicted to decline (Abrha, 2018). Ultimately, the productivity of coffee farming is expected to be hindered in Africa. Thus, the livelihood of millions of smallholder coffee producers who substantially depend on coffee production will be challenged and pushed into a vicious circle of poverty (ICO, 2015).

CONCLUSION

Coffee is one of the most important crops in Africa and has a high contribution to the national economy of producer countries. However, the production of Arabica coffee has been affected and predicted to be affected by climate change. The spatial coverage of the currently suitable area for Arabica coffee cultivation will diminish by 60% by 2050 and vanish at the end of the 21st century in Africa. As climate change continues the cultivation of Arabica coffee will move upward to high altitudes. This, in turn, puts pressure on internationally recognized and conserved biodiversity hotspot areas and raises conflicts over land use priorities in some coffee-growing countries in Africa. As a result, deforestation for coffee cultivation will cause local biodiversity loss including wild Arabica coffee from its in-situ conservation area. This also leads to the total extinction of Arabica coffee genetic diversity and population from its original habitat at the end of the 21st century.

Climate change-induced drought, an outbreak of pests and disease caused the mortality of Arabica coffee in the last decades and is predicted to continue in the forthcoming decades. The productivity of coffee has been declining and is predicted to decline substantially (25-60%) by 2050 in Africa. Consequently, the livelihood of smallholder producers and the economy of the growing countries are at risk and under a vicious circle of poverty in Africa.

RECOMMENDATION

An innovative approach in coffee farming to scale up adaptation capacity and mitigation measures would play a significant role to sustain coffee and coffee production. Coffee agroforestry is one of the promising strategies to sustain coffee production and biodiversity conservation in the face of changing climate. In-situ conservation of Arabica coffee gene pool in its natural/original habitat is important to maintain the genetic resource, yield and yield stability across coffee growing regions in the world. Therefore, it is vital to strengthen the in-situ conservation of coffee gene pool to ensure sustainable utilization of genetic resources.

Moreover, despite its recalcitrant nature, biotechnology-based ex-situ conservation has to be integrated as a complementary approach for enhancing the conservation of the diverse gene pools of this important crop. Mainstreaming and integrating biodiversity conservation into the coffee production system and promoting adaptation and mitigation strategies for climate change are important.

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