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The Economic Values of Coffea Arabica Biodiversity in Ethiopia

Tadesse Woldemariam Gole[1]* and Aseffa Seyoum[2]

[1]Environment and Coffee Forest Forum, Addis Ababa, Ethiopia

[2]College of Development Studies, Addis Ababa University, Ethiopia

ABSTRACT

Ethiopia possesses the most important and diversified genepool of *Coffea arabica* in wild populations, traditional landraces and cultivated varieties. The availability of high genetic diversity is fundamental for any crop improvement program for use by the plant breeders. This study presents economic valuation of *Coffea arabica* in terms of pest and disease resistance, increased productivity /yield, drought tolerance or climate change resilience, low caffeine content and higher cup quality.

The wild *Coffea arabica* embedded in the natural forest has a wide range of benefits, including cultivated coffee genetic enhancement, provision of ecological services as well as an intrinsic value. This economic assessment estimated the values of *Coffea arabica* biodiversity in term of coffee genetic enhancement for increased yield, increased pest and disease resistance, low caffeine, high cup quality, drought and climate change resilience, and GHG reduction using indirect market-based of revealed preference techniques.

Our assessment revealed enormous potential of Ethiopia's Arabica coffee biodiversity to improve and sustainably produce coffee globally and in the country. If Ethiopia exploits its coffee genetic resources potential for coffee production in the country, it gets an additional benefit of USD 2.37-5.84 billion per year. Besides, if coffee producing countries use the genetic resources in Ethiopia to solve their coffee production problems, there is a potential economic benefit of USD7.6-8.1 billion per year. If users of these genetic resources are willing to pay 5% of their gain in economic benefit from the accessed Ethiopian coffee genetic resources to Ethiopia, the country can get additional income of about USD380-403 million per year.

***Corresponding author**
Tadesse Woldemariam Gole, 1Environment and Coffee Forest Forum, Addis Ababa, Ethiopia.

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Introduction

Background

Coffee is the most popular soft drink in the world and is the second most exported commodity after oil, employing over 100 million people worldwide [1-3]. There are over 120 species of coffee (*genus Coffea*). However, there are only two species of economic importance: Arabica coffee (*Coffea arabica*) and Robusta coffee (*Coffea canephora*). Ethiopia is the center of origin and genetic diversity of Arabica coffee.

The spread of coffee all over the world was based on seeds from a single tree or a few trees introduced to Yemen. Thus, cultivated coffee varieties have a very narrow genetic base. The best hope for crop improvement lies in the progenitors or wild relatives of the cultivated plants that harbor rich genetic resources for tolerance against abiotic (drought, cold, heat, salt, solar radiation), and biotic (pathogens, parasites, competitors) stresses [4,5]. In this regard, the Ethiopian Arabica coffee genepool represents the most important and diversified genepool of the species in the world.

Ethiopia possesses all categories of the genepool for *C. arabica*, including wild, traditional landraces and cultivated varieties [6]. Sylvain [7] witnessed the existence of a great variation among the wild coffee plants in Ethiopia. In efforts to collect coffee genetic resources and document their use in breeding programs, researchers have collected a total of around 11,691 Arabica coffee germplasm accessions from different coffee growing areas throughout Ethiopia. The collections are conserved *ex situ* in field gene banks at Jimma Agricultural Research Center and its sub-centers (5,960 accessions) and in Choche (5,731 accessions), Jimma zone of Oromia state, Ethiopia [8]. The collection at Choche is mainly for conservation and is managed by the Ethiopian Biodiversity Institute.

Diversity in the Wild Population

The wild populations of *C. arabica* in the montane rainforests are the most important genetic pool of the crop. Tesfaye [9] reported. Reported high genetic variability within and between different wild populations in Ethiopia. He further noted that wild coffee plants are genetically distinct and more diverse among themselves when compared to the cultivated varieties grown in Ethiopia and around the world.

The presence of high genetic variation in natural coffee populations in the forest and semi-forest systems can partly be attributed to the presence of wide ecological variation, ranging from 1000 m to 1800 m or even up to 2000 m in altitude, with highly dissected and rolling topography. The average temperature and rainfall also vary with a similar magnitude.

The availability of high genetic diversity is fundamental for any crop improvement program for use by the plant breeders. In the absence of genetic diversity, any improvement endeavor is time consuming, expensive and with little success. Similar with other crop species, the conservation of coffee genetic resources plays a significant role for the economic potential, ecosystem conservation and survival capacity of the species. Coffee breeding programs have been striving to identify disease tolerance, drought resistance, and low caffeine varieties. Therefore, a diverse coffee gene pool is of paramount importance for breeding. Particularly, cross breeding of cultivars and wild genetic material leads to above average results in yield due to heterosis effects or hybrid vigor [10,11]. For instance, Ameha and Belachew [12], have reported a heterosis effect of 36% to 60% in hybrids of indigenous wild genotypes in Ethiopia. Similarly, an average heterosis effect of 30% was observed in hybrids two varies when compared with the best parent [10]. In this regard, the Ethiopian wild coffee populations provide highly diverse genetic material for future coffee breeding and selection.

Diversity in Cultivated Coffee

Surveys in main coffee growing regions of the country show that there is a high diversity among coffee landraces. In garden coffee systems and other cultivated coffee production systems, farmers choose the coffee types of their preferences and often grow more than one landrace in the same area. Some farmers plant up to five landraces in their garden. Each has its own advantages. Some are high yielding; some have good aroma and flavor and some are resistant to diseases. A total of 130 landraces known by local names in different localities have been recorded in the areas covered by the various surveys [13,14]. The list is not complete since many coffee growing areas have not yet been surveyed.

Threats on Coffee Biodiversity

Scholars identified that loss of habitat, shifting to other cash crops, and climate change are among the major drivers of change that pose threat on the coffee biodiversity in Ethiopia. Particularly, the wild populations of Arabica coffee are threatened by deforestation- or habitat loss since the montane rainforests with the wild population are cleared and converted to agricultural land for food crops production. This leads to loss of the most diverse coffee genepool, i.e., the wild coffee genetic resources, as well as associated diversity of plant and animal species, and the ecosystem level diversity [8,15-20].

The shifting to other cash crops is the main threat to loss of the coffee genetic diversity in traditional landraces or cultivated coffee. With volatility of coffee price, farmers are shifting their coffee farms to other cash crops like Khat (*Catha edulis*). Climate change is the other driver of change that pose threat to both the wild populations and the cultivated landraces of coffee biodiversity. Recent study revealed that about 40-60% of the current coffee growing areas will no more be suitable by the end of this century due to climate change [17,19].

Conservation of the coffee genes both in the wild and forests managed for coffee production in Ethiopia is crucial for sustainability of the coffee industry, through improvements of the cultivated coffee worldwide. Findings of our joint research project (CoCE) with the Center for Development Research (ZEF) of the University of Bonn revealed that management of the coffee forests for conservation and sustainable use of coffee biodiversity has much higher economic return in the long-term than intensive management for coffee production or conversion to other land uses [21,22]. Findings of the CoCE project research estimated that the net present value of coffee genetic resources to be around of 1.5 and 0.5 billion US$ at discount rates of 5% and 10% respectively [23]. The valuation, however, considered only breeding for three types of enhanced cultivars: increased pest and disease resistance, low caffeine contents and increased yields.

ECFF has been conducting different research activities jointly with different partners, including recent works on climate change and resilience potential with the Royal Botanic Gardens, Kew and the University of Oxford from UK. Based on the current state of knowledge, climate change emerges to be a serious threat. It also worsens other agronomic problems like pests and diseases. It is, therefore, highly important to re-assess the economic values of the coffee biodiversity in Ethiopia and design appropriate mechanisms for conservation and sustainable use.

Objective of the Study

The immediate goal of this study is to assess and update the economic values of coffee forest and *Coffea arabica* biodiversity in Ethiopia. The long-term goal is to develop management guidelines or manuals for sustainable use and conservation of coffee biodiversity in the context of climate change and other drivers of change. Previous assessment of economic value of *Coffea arabica* was done for three breeding functions only. The threats associated with these have also changed because emerging threats of climate change.

The specific objective of this study is therefore to re-assess the economic values of Ethiopian coffee biodiversity for more breeding functions, and conservation of forest habitat for some ecosystem services. Hence, the study presents economic valuation of *Coffea arabica* in terms of pest and disease resistance, increased coffee productivity or yield, drought tolerance or climate change resilience, low caffeine content and higher cup quality. The study also estimates the ecosystem services benefits of the coffee forests, mainly GHG emission reduction, and protection of species and ecosystem diversity (that can be sources of food and medicine) benefits.

Methodology

The economic value of *Coffea arabica* biodiversity can be estimated at different levels of biological organization: genetic diversity (the variety of genetic information), diversity of species and ecosystem diversity of the natural system [24,25]. The most diverse *Coffea arabica* genetic resource is found in the moist Afromontane forest in Ethiopia. This diverse genetic resource of *Coffea arabica* embedded in the natural forest has a wide range of benefits related coffee genetic enhancement, provision of ecological services as well as an intrinsic value. Key ecosystem services of coffee endowed natural forest include: production function (food, raw material, genetic resources etc.), regulatory function (gas and climate regulation such as reduction of CO2, land coverage change), habitat function (such as serving as refugia for *Coffea arabica* genetic resource and other biodiversity), and information function (science and education) [26-28]. Nonetheless, quantifying all the benefits require conducting various empirical case studies which is not within the scope of this assignment. Our focus with this economic assessment is to look at the economic benefits of *Coffea arabica* genetic resources and genetic diversity in coffee breeding for enhanced cultivars, and its ecosystem service of coffee forest in term of climate change mitigation.

The economic values of biodiversity are not typically revealed by markets since all its use benefits are not directly traded in the markets. Goods and services with limited commercial values that are not traded tend to be undervalued. Though market fails to capture economic and social benefits of biodiversity, economic valuation remains vital tool for informed decision making. For instance, to allocate resources between the conservation of genetic resources and other efforts [29]. This study is mainly to reveal the importance of *Coffea arabica* biodiversity and its coffee forest ecosystem by identifying and monetizing selected functions of the ecosystem. By doing so, this study contributes to awareness creation for economic and social policy making and to advocacy for investment in promoting sustainable conservation and utilization of *Coffea arabica* biodiversity and the coffee forest ecosystem. Through the economic value estimation exercise, the study demonstrates possible economic loss if public and private sectors failed to invest in conservation of the coffee forest ecosystem.

Economics valuation provides monetaryvalues that human attach to resources based on their choice of preferences. Considering the different economic values of *Coffea arabica* biodiversity in the context of a total economic value framework is important to have overall understanding of benefits of the resource [30]. The total economic value consists of use and non-use values of biodiversity. The use values (direct and indirect uses) comprising benefits that individual or societies derive from goods and services supplied by the biodiversity including produces, natural amenity, and socio-cultural values associated with their attributes. Non-use values are the significance individuals or societies attach to biodiversity to ensure that it exists or will be passed on to future generations, regardless of whether or not it is used. The traits demanded by societies, such as resistance to plant pests and diseases, and quality attributes preferred by consumers, also change frequently in response to environmental stress and economic changes. In this study the focuses on the use values. These use values of *Coffea arabica* biodiversity is estimated in term of benefits in coffee genetic enhancement for increased yield, increase pest and disease resistance, low caffeine, high cup quality, drought and climate change resilience, and GHG reduction using indirect market-based of revealed preference techniques.

The benefit of coffee biodiversity in terms of yield gains from new coffee varieties involve multiple factors such as management practices in addition to yield trait of genetic resources. Decoupling productivity gain from yield enhancement trait of coffee genetic resources and that of management practices, such as diseases and pest resistance, is challenging and context specific. In this study we treated the yield gain benefits of coffee biodiversity in terms of yield increment from breeding for yield enhancement while the diseases and pest resistance benefits are gauged in term of avoided yield loss. The yield increment from breeding for yield enhancement is estimated based on marginal changes in productivity *Arabica coffee* per unit of area valued at current market. The benefit of Arabica coffee biodiversity as a source of coffee genetic enhancement for pest and disease resistance is estimated based on extent of prevented yield damage and avoided cost of agrochemicals.

The low caffeine contents benefit of *Coffea arabica* biodiversity is estimated based on costs that coffee industrials, otherwise, incur for decaffeination process. Alternatively, it could be estimated based of price difference between low caffeine coffee and regular coffee, considering the total volume of low caffeine coffee consumed globally. Nevertheless, the low caffeine may not necessarily fetch a higher price as compared to regular coffee. The drought tolerance or climate change resilience of *Coffea arabica* biodiversity is assessed based on estimated yield impact of climate change on coffee production. A cup quality benefit of *Coffea arabica* biodiversity is estimated based on farm gate value of good coffee over the average quality coffee. Additionally, ecosystem services benefits of the coffee forests estimated in this study include emission reduction due to avoided deforestation and carbon sequestration due to restoration of coffee forests and agro-forests. The carbon sequestration benefit of natural *Coffea arabica* ecosystems is estimated based on findings of prior studies for national REDD+ program design.
Table 1 presents the ecosystem functions and valuation techniques.

Table 1: presents the ecosystem functions and valuation techniques

Identified economic benefits	Economic benefits estimation techniques
• Increased yields	• Based on yield data generated from on-farm adaptation trails using secondary sources
• Increased pest and disease resistance	• Based on cost avoidance of chemical application
• Low caffeine contents	• Based on cost of decaffeination -empirical studies
• Increased drought tolerance or climate change resilience	• Based on value of production damage that could be prevented
• Cup taste quality	• Based on value of mild Arabica coffee obtained from secondary data sources
• Climate change mitigation (GHG emission reduction and removal)	• Based on emission reduction due to avoided deforestation, as well as sequestration due to degraded forests restoration.

Results and Discussion

Productivity or Yield Benefits

Coffea arabica is the dominant coffee type in global production and trade. It makes about 60% of the total global coffee production, and about 70% of the global coffee traded value. Nevertheless, the total production, productivity, and quality of *Coffea arabica* are under growing challenge due to increasing climate change and climate change induced disease and pest. In the face of these growing challenges, *Coffea arabica* biodiversity is a vital resource of germplasms to develop climate resilient, high yielding, and disease resistant varieties. *Coffea arabica* biodiversity stock remain key source of germplasm for, among others, good yield and quality breeding programs [31]. In this study, the economic value of *Coffea arabica* germplasm is measured as yield gain that can be achieved through breeding and developing high yielding cultivated varieties.

Yield benefit is one of the important traits. *Coffea arabica* biodiversity consist of a mixture of genotypes with different degrees of expression of a number of traits of interest [32]. Prior studies revealed that coffee yield varies across countries depending on, among other things, the use of improved varieties and application of inputs. Globally, the national average for major producers like Brazil and Vietnam varies from1.91 tons/ha to2.61 tons/ha, respectively. Currently, Ethiopia's coffee production is 470,221.00 tons per year. Researchers in Ethiopia have released 42 coffee varieties through selection, which produce 1.2 to 2.6 tons/ha on research plots, and 0.7 to 2.3 tons/ha on farm adaptation trial plots. As Ethiopia is the genetic powerhouse of *Coffea arabica*, there is huge potential to increase farm level yield even higher, with further research. The current national average is 0.7 tons/ha, much lower than the potential, and can easily gain some production potential of the released varieties within few years. The national target within 5 years, as indicated in the draft coffee sector strategy of Ethiopia is 1.2 tons/ha (Berhanu Tsegaye, ECTA, personal communication).

A national yield benefit of *Coffea arabica* biodiversity is estimated considering a total area of 1million ha under coffee production, taking the yield gap of 0.5tons/ha between current average productivity and national average productivity targeted in the draft strategy, and average commercial price of Arabica coffee in 2018 which was2.93 USD per kg. Up on 100 percent adoption rate of high yielding cultivars, the national yield benefit of *Coffea arabica* biodiversity is estimated to be about **1.465 billion USD per year**.

According to the draft strategy, the government has plan to double coffee production by 2030. Assuming coffee price remains more or less the same, and taking productivity of 0.7 tons per ha, the yield gain benefits of *Coffea arabica* germplasms will show significant increase and reach about 2.29 million tons by 2030. Previous study estimated that the global value of increased yield benefit of enhanced coffee cultivars (in net present value over 30 years) is about 2.240 Billion USD at 5% discount rate assuming 30% application rate. Economic value of Coffea arabica's yield trait benefits increase with the increase in productivity, price of coffee or area under coffee production [23]. With the increasing trend of coffee productivity, the national and global yield benefit of coffee is expected to rise over time. Therefore, Ethiopia has to design economic and social policies that can promote research, and payment for ecosystem services to tap the benefit and in turn ensure sustainable conservation of the *Coffea arabica* biodiversity.

Disease Resistance

Pest and disease are among the main challenges in coffee production. For instance, Bellachew [31] noted that coffee leaf rust is a wide spread coffee production problem in Africa, India and the rest of South-East Asia [33]. Another study reported that coffee leaf rust, one of the major diseases of Arabica coffee, can cause yield losses of up to 35% and have a polyetic epidemiological impact on subsequent years [33]. Estimate of loss varies, and ranges 30-50% in Central American countries depending on the planting system and year, plant age, crop management, and cultivar [34]. A recent studies show that coffee leaf rust and berry borer are among growing challenge in many coffee producing countries of Asia, and central and Latin American [35]. For instance, in Columbia, coffee leaf rust caused significant crop damage and yields dropped by one third (from 934 kg/ha to 614 kg/ha) in 2008/09 compared to the three-year average [36].

Similarly, coffee berry disease (CBD) is becoming another big threat to Arabica coffee production in Africa and Latin America, particularly in highlands of Eastern and Central Africa [31]. The disease has been recorded to cause up to 80% yield loss, but on susceptible cultivar under favorable environment, 100% loss may occur (Etana 2020) [37]. The *Coffea arabica* biodiversity serves as a source of breeding inputs for disease resistant varieties to halt yield loss as a result of emerging coffee berry disease, and to retain stable coffee production and supply for the global market. Estimated annual coffee yield losses caused by CWD are about 7.4%, 1.6% and 2.6% in Uganda, Ethiopia and Tanzania, respectively (Komlan et al. 2003). Komlan et al (2003) reported that with the average infestation rates of 5.64% and 6.36%, the total production losses amounted to 2.60% and 3.18%, respectively. In East Africa, heavy infestation of as high as 96% has been experienced.

The smallholder farmers face limited access to and prohibitive cost of fungicides. Yet, application of fungicides is the most important method to control coffee leaf rust disease for Arabica coffee. Production of disease resistant coffee cultivars exempts farmers from the use of pesticides, reducing production costs and risks of environmental contamination, whereas the yield potential is comparable to that of the best cultivars According to a study in India the cost of chemical application to control coffee leaf rust, including cost of purchase of chemicals and labour cost of chemical spray is about 100USD to 157.25USD per ha [32,38]. On the other hand, *Coffea arabica* genotypes from Ethiopia have demonstrated resistance to coffee leaf rust, coffee berry disease, as well as resistance to *Meloidogyne incognita* [39,40]. In the absence of genetic diversity, however, breeding for high yield, disease tolerance, drought resistance, and low caffeine varieties can be time consuming, expensive and it may result in little success. Therefore, the pest and disease resistance benefits of coffee genetic resources can be estimated based on either net benefit yield loss saved or pesticide or insecticide cost avoided as a result due to development of pest and disease resistance varieties. Beside genetics, coffee-micobiome association may also play importance roles in disease resistance [41]. In this analysis, however, we have only considered the genetic potential, since the biological control function of microorganism as associated with coffee is not yet quantified to enable valuation.

Taking the pesticide and fungicide cost of **100** USD to 157.25 USD per ha estimated in India (pesticide and fungicide use in Ethiopia in negligible), and total area under *Coffea arabica* production in Ethiopia, national disease resistance benefit of *Coffea arabica* biodiversity is estimated to be **100 to 157 million USD per year**. At global level considering a 6.372 million ha (about 60% of the total 10.62 million ha of global coffee area), based on the pesticide and fungicide cost, the global diseases resistance benefit of *Coffea arabica* is estimated to be about **0.6 to1 billion USD per year**.

Low Caffeine Benefits

There are significant differences in the caffeine content among coffee cultivars. Arabica coffee beans contain 1% - 1.5% caffeine, while for the Robusta variety these values vary between 1.7% and 4.0%. The low caffeine content of *Coffea arabica* drives to high demand among consumers around the world. The development of low-caffeine or caffeine-free cultivars would be of enormous economic potential. In many countries, low-caffeine coffee products are now an established part of the manufacturers' range. Seven to 10 million bags of green coffee are used annually for the costly process of decaffeination [42]. For instance, in the United States, 'decaffeinated' is generally taken to mean that the caffeine content has been reduced by 97% of the original content. This can be done as either a mixture of regular coffee and decaffeinated coffee or blends of coffees with a naturally low caffeine content, or through the decaffeination process [43].

Decaffeinated coffee was developed in Europe, but achieved its first broad market in the United States during the 1950s. It is estimated that the consumption of decaffeinated coffee various across countries from 7% in Germany, France and Italy to 13% in United States and 16% in Spain [43]. Decaffeinated coffee is accounting for 8%– 9% of mainstream sales and about 20% of sales of specialty coffee [43]. It is estimated that decaffeinated coffee currently accounts for around 10% of the global coffee consumption [43]. Its market share is forecasted to grow by 7.4% from 2020 to 2027.

The naturally low caffeine coffee will also avoid potential negative environmental impact of industrial decaffeinating process such as extra water and energy use, and emission. *Coffea arabica* germplasm of Ethiopia has been reported to have almost zero caffeine content by Brazilian research on coffee germplam collected from Ethiopia [44]. The cost of industrial process for decaffeination from green coffee beans ranges from 0.50USD per kg to 0.65USD per kg, for the cheapest process using methyl chloride, to about double that for the more expensive methods [43].

Considering that export constitutes around 72% of the 10.4 million tons of global total coffee production, and taking into account that *Coffea arabica* makes about 60% of the global coffee production, and the market for decaffeinated coffee to be about 10% of coffee consumption worldwide, we have estimated that the share of decaffeinated *Coffea arabica* in the global market is about 0.45million tons [43,44]. Considering the decaffeination cost of 0.50 USD per kg to 0.65 USD per kg, the global benefit of low-caffeine or naturally decaffeinated *Coffea arabica* is estimated to range from **225 million to 292 million per year**.

Today, coffee extracts are increasingly being used in food and beverages industry to add flavor, energy and natraceutical properties. In this valuation, we have not considered economic values of coffee extracts in food, beverages, and pharmaceuticals, since disaggregated information is lacking and attempt may compound the valuation.

Cup Taste Quality

In today's changing preference of coffee consumers, its biological diversity serves as the source of desired traits to satisfy the evolving tastes and preferences. Scholars noted that coffee cup taste quality depends on varieties and management activities along the value chain from production to consumption [45]. For instance, at exporter or importer level, coffee quality is gauged based on bean size, lack of defects, regularity of provisioning, tonnage available, and physical characteristics. At consumer level, coffee quality includes taste and flavor, effects on health and alertness, geographical origin, environmental and sociological aspects such as organic coffee, fair trade, etc [45]. In this study cup taste quality refers to coffee quality that can be improved through genetic breeding such as physical quality (bean size and evenness in size, beans shape beans visual appearance etc.), and organoleptic quality [45]. The organoleptic quality includes chemical compounds such as sugars, lipids, proteins, chlorogenic acids, and methylxanthinesm that commonly determined based on consumers preference, and trained assessors.

There is high diversity in Ethiopia to achieve much higher quality that fetches higher prices than commercial grade. Hence, we estimated the cup taste quality value of *Coffea arabica* genetic resources based on quality specialty coffee, since specialty coffee differs from regular or commercial coffee primarily for its high quality. Ethiopian specialty coffee is sold at average price of 7.17 USD per Kg. The price of commercial grade coffee ranges between 1.85 to 2.204 USD per kg. Global average for Arabica coffee was 2.93 USD/kg, and that of mild Arabica was around 3.21 USD per kg in 2018. Currently specialty coffee is estimated to comprise about 5% -10% of total coffee market volume. This sector has the most growth potential because of changing consumer habits including growing demand for more ethically sourced products [46]. Our estimate, however, is based on the price of mild Arabica.

Based on estimates that export constitutes around 72% of the 10.4 million tons of global total coffee production, the fact *Coffea arabica* makes about 60% of the global coffee production, and a gain 0.28USD/kg due to improved quality, producing countries can gain about 1.26 billion USD per year from export. Hence, the global value for improving cup taste quality of *Coffea arabica* biodiversity is estimated to be **1.26 billion USD per year**.

The national cup taste quality benefit of *Coffea arabica* is estimated to be **65.8 million USD per year**, considering that Ethiopia exports about 50% of its total coffee production (about 470,221 tons in 2018) per year. It was also estimated that the specialty coffee (reputable quality coffee passing through the union marketing system) was about 10% of the total volume of Ethiopia coffee export, which has currently reached about 12%. The national target is to reach 25% over the next 10 years (Dr. Adugna Debela, ECTA, personal communication) [47].

Climate Resilience / Drought Tolerance Benefit

Climatic variability has always been the main factor responsible for the fluctuation of quantity and quality of coffee produced in the world. Climate change, as a result of global warming, is expected to change where and how coffee may be produced in future. It will affect millions of producers and other participants involved in coffee value chain. Climate change induced drought is estimated to lead to loss of 30% area suitable for coffee production around the world, over the coming decades.

On the other hand, scholars noted that *Coffea arabica* gemplasms are promising to develop varieties for drought tolerance [48]. Having a wide ecological range and gradients in rainfall and temperature, Ethiopia offers opportunities to select drought tolerant varieties. The basic assumption considered in assessing the economic value of drought tolerance are: average global productivity of 0.98 tons/ha; about 6.372 million ha of *Coffea arabica* production area; estimated loss of about 30% the current coffee production area due to climate change; and global average price of Arabica coffee in 2018 of 2.93 USD/kg. Accordingly, the drought tolerance or climate change resilience benefit of Arabica coffee genetic resource is estimated to be 5.5**billion USD in total, or 3.95 billion USD in export earnings**. The national loss for Ethiopia, if 30% is unsuitable, at national average yield of 0.7 ton/ha, is equivalent US$ 615.3 million. Since 50% is exported, this equivalent to loss of US$ 307.65 million in export earnings. Socio-economic damage is huge, considering the millions of families that depending on coffee for their livelihoods.

Climate Change Mitigation and Ecosystem Services Benefits

The climate change mitigation benefit of the coffee forests is GHG emission reduction and provisions of ecosystem services that enhance production. Coffee is a shade loving plant. In Ethiopia, over 80% coffee is produced under shades of trees, of at least 50% canopy cover [16,49]. Total coffee production area is around 1 million ha. Besides, the forest areas falling within the ecological range of coffee in Ethiopia covers around 4.97 million ha. These systems store high carbon stock of up to 600 tonsCO_{2e}/ha in above ground and below ground biomass.

Deforestation rate in coffee area is 1%, which is about 49,700 ha forest loss or 29.8 million tons of CO_2 equivalent [49,50]. If measures are taken to reduce deforestation, and if it is possible to reduce by half, we can also reduce emission by 14.9 million CO_2 equivalent, and at the average price of 5 USD per ton of CO_{2e}, the value of emission reduction can be up to 74.55 million USD/year. The management cost is about 2 USD/ha for natural forest [51]. For the whole coffee forest, it can be up to **9.94 million USD per year**. Hence, the net gain from potential trading of carbon credits from emission reduction of coffee forests is 64.61 million USD/year.

In addition, maintaining forest/ shade trees also has other ecosystem services including pollination and pest control. Forests harbor insect pollinators and Arabica coffee is 30% cross pollinated. Hence, pollination services contribute 30% of the coffee yield. Further, studies have confirmed that Ethiopian coffee agroforestry/ forest is the most bio-diverse in bird species [52]. Birds are important for pest control in coffee production systems. A study in Costa Rica showed that the pest-control service of forest birds has prevented US$75–US$310 per ha/year loss [53]. Taking the 800,000 ha of coffee production area with more than 50% canopy cover, the pest control service is estimated to be US$60-248 million per year.

Additional ecosystem services of the coffee forests and agro-forests are quite broad. The notable ones include soil and water conservation, nutrient cycling and soil fertility enhancement through soil-micro-biota association and habitat for many species of organizations [15, 54-59]. Most of these services are difficult for valuation in monetary terms, and attempt on inadequate information can lead to overestimation or compounding other estimates, and therefore, not considered in this assessment.

Realizing Economic Benefits of the *Coffea arabica* Biodiversity

Most of the economic benefits of *Coffea arabica* biodiversity estimated in this study have not been realized. Ethiopia needs to explore options to realize the considerable economic benefits of *Coffea arabica* biodiversity. First, to create demand for Ethiopia's unique *Coffea arabica* produces and coffee genetic biodiversity, the country needs to invest in coffee research to characterize and identify potential benefits. In addition, the country needs to undertake more development research and extension services to realize national benefits such as the **yield increment, and disease resistant benefits.**

Secondly, Ethiopia needs to design and implement suitable certification schemes for shade and forest coffee to realize the **cup taste quality** and **low caffeine** characters. Some researchers argue that coffee certification programs may create an incentive for producers to accelerate forest degradation to expand their coffee-growing areas in the surrounding natural forest. Nevertheless, some empirical studies reported that the sustainability certification of forest coffee areas slightly increased in forest density [60]. The study emphasized that shade and forest coffee certification criteria need to strengthen regulations that protect the surrounding environment.

Thirdly, Ethiopia should also do more to realize ecosystem services benefits of *Coffea arabica* biodiversity by sourcing payment for ecosystem (PES) from within country and globally. The PES could be used mainly to realize benefits related to ecosystem services such as climate change mitigation and climate resilience. Ethiopia has enabling policy environment for PES including the environmental protection policies and proclamations, the forest policy and proclamations, the REDD+ strategy, the Climate Resilient Green Economy strategy and other related sector policies that underline the need to involve local communities in conservation and utilization of natural resources.

Maintaining viable ex-situ collection of *Coffea arabica* genetic resources is expensive. To avoid future risks, it is appropriate for coffee producer nations to finance *in-situ* conservation of *Coffea arabica* biodiversity under the framework of UN Convention on Biodiversity (CBD) which Ethiopia is party to. The CBD addresses many aspects of conservation and use of biodiversity, including sustainable use of genetic resources and the fair and equitable sharing of benefits derived from this use. Moreover, the Convention reaffirmed the sovereign rights of countries over their natural resources, and noted that the authority to determine access to genetic resources rests with national governments and is subject to national laws.

Fourthly, Ethiopia needs to explore options to realize **global economic benefits of conservation of *Coffea arabica* genetic resources** including the access and benefit sharing (ABS) mechanisms of the Nagoya Protocol. Under the Access and benefit sharing mechanisms of the Nagoya Protocol, provider of genetic resources receives fair and equitable benefits on products developed from utilization of genetic resources in Research and Development as per negotiated and agreed Mutual Agreement Terms (MATs).

Nevertheless, developing countries like Ethiopia have limited capacity to negotiate the mutual agreement terms, and to enforce the agreements, which remains to be a challenge in realizing the benefits under access and benefit sharing (ABS) provisions of Nagoya protocol. This has been observed in the case of *Teff* germplasm in the past. In April 2005, a Dutch company called Health and Performance Food International (HPFI) signed ABS agreement with the Ethiopia Biodiversity Institute (EBI) and the Ethiopian Institute of Agricultural Research (EIAR) to develop non-traditional teff-based food and beverage products. According to the agreement, HPFI agreed to pay a mix of license fees, royalties and a share of profits to the Ethiopian Government over ten years period from the time the agreement starts being implemented. But, the company failed to honour its agreement and only paid a small amount as an upfront towards the beginning of the implementation of the agreement. The company even went to the extent of getting breeder's right on teff. Due to the bad experience the county has there is always a concern about possible bio piracy.

On the other hand, international research organizations have made some progresses regarding genetic material transfer for research purposes. For example, CATIE, which holds major Arabica coffee germplasm collections outside of Ethiopia started to use the FAO's Standard Material Transfer Agreement (SMTA) for the exchange of germplasm with the designation of its collections to FAO. About 44.3% of the entire collection were wild and semi-domesticated genotypes obtained from Ethiopia (primary center of origin) and secondary center of diversity, Yemen [11]. Therefore, Ethiopia need to explore option to enhance its capacity to negotiate the Mutual Agreement Terms (MAT), as well as effectively enforce the policy, legal, and institutional frameworks as well as implementation guideline to realize the economic benefits of *Coffea arabica* genetic resources to fight biopiracy while engaging in the Access and benefit sharing [61-72].

Conclusion and Recommendations

Conclusion

Our assessment revealed enormous potential of Ethiopia's Arabica coffee biodiversity to improve and sustainably produce coffee globally and in the country. If Ethiopia exploits its coffee genetic resources potential for coffee production in the country, it gets an additional benefit of USD 2.37-5.84 billion per year (see Table 2 below). Besides, if coffee producing countries use coffee genetic resources in Ethiopia to solve their coffee production problems, there is a potential economic benefit of USD7.6-8.1 billion per year. If users of these genetic resources are willing to pay 5% of their gain in economic benefit from the accessed Ethiopian coffee genetic resources to Ethiopia, the country can get additional income of about USD380-403 million per year.

Table 2: Summary of National and Global Economic Value of *Coffea arabica* Biodiversity

No	Attributes of *Coffea arabica* biodiversity	National Value Ethiopia (million UD$)		Global value (millions of US$)	
		Low	High	Low	High
1	Yield increment benefit	1,465.00	4,688.00		
2	Disease resistance	100.00	157.00	600.00	1,000.00
3	Low caffeine			225.00	292.00
4	Cup taste quality	65.80	65.80	1,260.00	1,260.00
5	Climate resilience	615.30	615.30	5,500.00	5,500.00
6	Ethiopian coffee forests Ecosystem service- Climate change mitigation	64.61	64.61		
7	Pest control of forest birds	60.00	248.00		
Total		2,370.71	5,838.71	7,585.00	8,052.00

The potential revenue from access of coffee genetic resource alone is around 50% of the coffee export revenue that Ethiopia receives at the movement. Even though there is a globally agreed protocol on access to genetic resources and sharing of the benefits from exploitation with the country that provided the genetic material, it is not yet operationalized, and there is no institutional framework to facilitate or oversee its implementation.

The economic valuation presented in this study is not without limitations. For instance, although the *Coffea arabica* biodiversity has a wide range of non-economic benefits, current economic valuation has focused only on the use values, as presented in the methodology section for practical reason. Since the interest of this valuation is to estimate overall benefits of the *Coffea arabica* biodiversity, we didn't do the cost benefit analysis. Thus, the valuation has not considered the production costs related to agronomic practices, and costs of developing new desirable varieties using the existing genetic diversity of coffee in Ethiopia, which significantly reduce the estimated value. Nevertheless, results of the economic, conclusion and recommendation presented in this report remains valid.

Recommendations

The availability and use of the largely untapped gene pools of *Coffea arabica* biodiversity embedded in the coffee forest of Ethiopia remains critical in the future of coffee improvement in terms of quality, yield, and bio-physical stresses tolerance. Exploitation of coffee biodiversity in Ethiopia nationally, as well as in global coffee industry requires appropriate investments in science, institutional frameworks development and resource management. To this end, we recommend the following:

Strengthen Research, and Capacity Building

Strengthen national research capacity on characterization of coffee germplasm collection, conservation of coffee genetic resources and breeding new coffee varieties that overcome emerging challenges of sustainable coffee production. More specifically, it is noted that Ethiopia has not yet characterized most of its coffee genetic resources. The country needs to conduct the genomic finger printing, as a pre-condition to promote access and benefit sharing. There is a need to conduct assessment of national research capacity (institutional, technical and human resources) to characterize coffee germplasms and their potential for use in breeding programs to develop coffee varieties that are high yielding, good quality and tolerant to different environmental and biological stresses. Government should work on having a well-equipped national coffee breeding programs that can develop varieties for different agro-ecologies and agronomic problems.

Mobilize Resources

National and international mobilization of financial resources is crucial to strengthen capacities in human resources and technology/infrastructure for impactful research, development and dissemination. Nationally, it is important to develop a system that enables resources mobilization from coffee related business. Globally, dissemination of information about the importance of coffee biodiversity for world coffee industry, gaps in capacity and policy frameworks to exploit this potential and the need to collaborate with donors and coffee producing countries that can benefit from the coffee biodiversity resources in Ethiopia.

Support Ex-Situ and In-Situ Conservation

Support for field gene banks of *Coffea arabica* genetic resources, characterizing and making core collections, and identifying germplasms that differ in qualities and characteristics to develop different varieties with required traits. Further, conducting collection of coffee germplasm from all possible ecological ranges, ecosystems and production system and establish additional field gene banks primarily designated for research, is equally important, in a race against climate change and land use change that are threatening coffee and its natural habitats. This involves conservation of the wild population *in situ* in the forest, cultivated land races *in situ* on farm, and vulnerable population in increasingly unsuitable areas *ex situ* in field gene banks close to the natural ecological range. *In situ* conservation approaches may include establishment of UNESCO biosphere reserves like the Yayu Coffee Forest BR, or community forest reserves with clearly designated strict conservation areas.

Promote Partnerships

It appears important to establish scientific collaboration platform to facilitate exchange of information and production technologies with scientists and, expertise in coffee producing countries. Strengthen coffee sector development intervention by strengthening extension services of the sector, and collaboration with other relevant sectors (agriculture, environment, forest) and development partners (donors and NGOs) is also strongly recommended. Extension services on coffee development should be provided by well trained development agents. Coffee production involves multiple sectors and institutions, for which partnership and collaboration is important for success;

Policy Enforcement

Ethiopia has already various policies in place to realize the economic values of *Coffea arabica* biodiversity. Yet, implementation of national policies needs to support the coffee sector. Policies need to support re-investment of benefits generated from coffee. Establishment of global and national mechanisms of law enforcement for sharing coffee and other crop genetic resources that also ensures sharing of the benefits with the provider countries of the genetic resource is vital. This includes strong enforcement of checkpoints at entry to avoid genetic pollution, and exit points to fight biopiracy. Promotion of market segmentation policies, and registration of branding mechanisms can help generate more revenue from the supply chain of coffee.

Awareness Creation and Technology Transfer

To realize benefits of the economic values of Ethiopia's Arabica coffee biodiversity, relevant institutions and other actors should create awareness among world coffee industry, the national and international policy makers, the coffee industry actors, donors and the research community. It is also important to promote technology transfer and adoption of improved varieties to realize the benefits of *Coffea arabica* biodiversity.

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