The water footprint of Arabica and Robusta coffee bean production in South America

The consequences of climate change on the feasibility of the South American continent for coffee production

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Abstract

Climatic changes such as rising temperatures and changing precipitation patterns have had a global influence for the past number of decades. These changes also relate to agricultural production. With the influence of these climatic changes of the past decades, the production of the Arabica and Robusta coffee bean in South America is also at risk. Higher temperatures and changing precipitation patterns lead to uncertainties regarding water usage. The water footprint is used to determine the ratio between rainwater and irrigation water for crop production. To see how climatic changes over the past number of decades have already influenced blue water usage, a regression analysis was performed using climatic data by the IPCC combined with an index for calculating blue water usage by Arabica and Robusta coffee beans. With the current climatic changes, the ratio between blue and green water will shift to blue water as more ground- and surface water is required to irrigate coffee beans in order to sustain production. This can lead to issues of water scarcity and to overcome this, the production of these crops on the South American mainland may need to shift to other regions on higher altitudes and local farmers may need to differentiate and grow different kinds of crops more suitable to the adapted climate. However, moving coffee bean production elsewhere can have serious socio-economic and ecological consequences. Farmers differentiating to other types of agricultural production can lead to a loss of jobs. Moreover, issues of water scarcity can lead to higher food prices contributing to the threat of loss of local food security.

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1. Introduction

1.1 Background

For the past decades, the issue of climate change has been prevalent worldwide as among other things global temperatures are rising and precipitation is becoming more unpredictable (IPCC, 2021). The consequences of climate change on sustainable water resource management are becoming increasingly prevalent worldwide and are naturally also relevant for agricultural production. These climatic changes have implications for agricultural practice on a global scale, especially for crops that are historically heavily reliant on rainwater (Ovalle-Rivera *et al*., 2015). One example of such a crop is the coffee bean (Ovalle-Rivera *et al*., 2015). The coffee market is rather substantial, with over 166 million 60kg bags consumed worldwide in the year 2019/2020 alone (*International Coffee Organization*, 2021) Therefore it is necessary to look at the consequences of climatic changes on coffee production, especially in areas where coffee production takes up a large part of their export. South American countries together are responsible for about 46% of the world's total coffee production, with Brazil being the largest exporter (Szenthe, 2019). These large exports of coffee beans make the aforementioned areas heavily reliant on this sector. Especially countries that are historically large exporters, as is the case with Brazil which was already the largest coffee producer in the world in 1850 (Bethell, 1989). In figure 1, below, all current global top coffee producing countries can be seen.

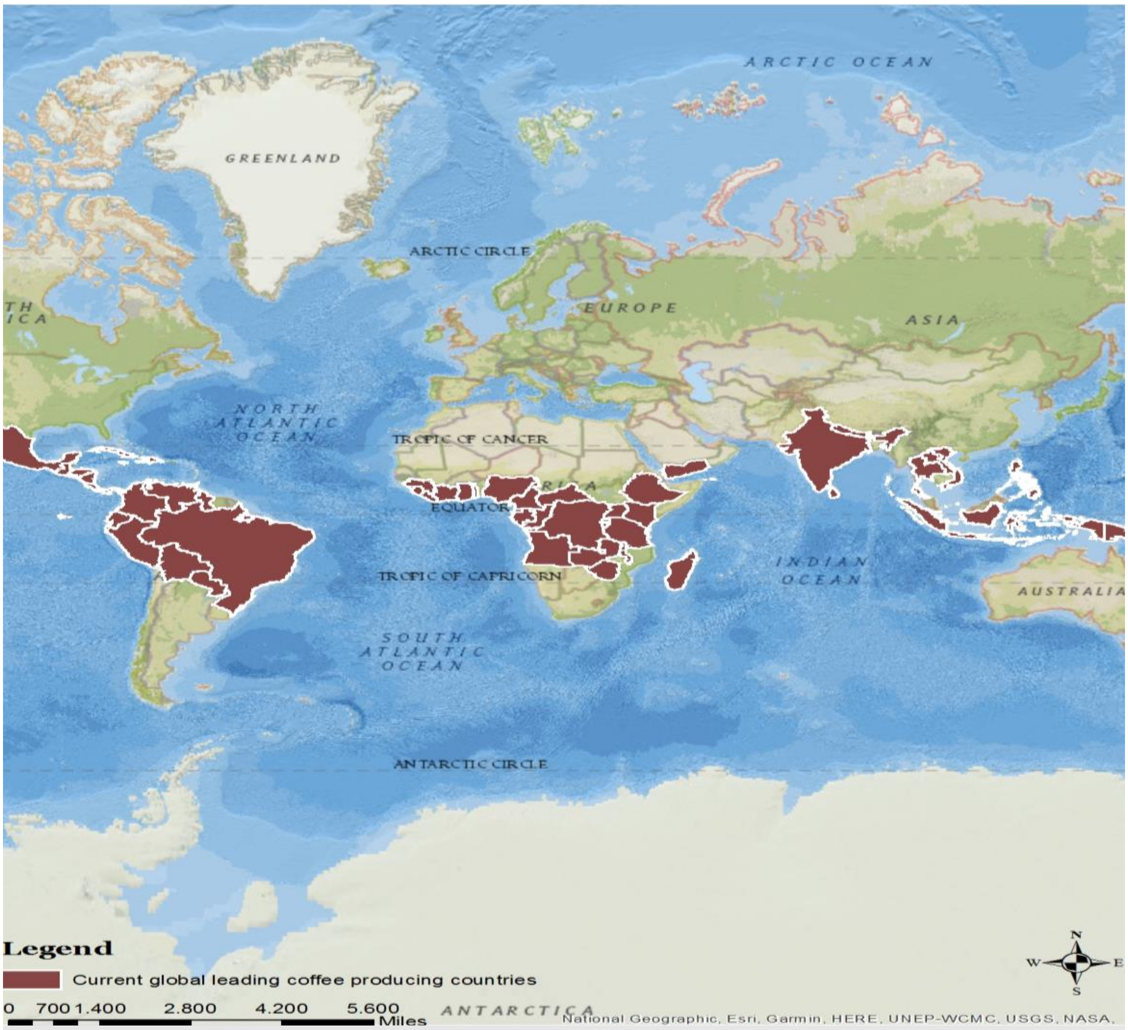

Figure 1: Current top coffee producing countries (made by author with GIS)

Since climatic changes include among others also changing precipitation patterns and rising global temperatures (IPCC, 2021) it is necessary to see how these changes relate to agricultural production. Also, to see to what extent these climatic differences can over time influence the production of crops that are for a large part reliant on rainwater, such as coffee. Since coffee production is a major export product for South American countries (Szenthe, 2019), and as these are historically climatically very well adapted to the production of coffee beans, this thesis will zoom in on this continent specifically to research sustainable water resource management in this context. The two most prevalent coffee bean species grown in South America are Arabica and Robusta (canephora) (Davis *et al.*, 2006). Between both kinds, ecological growing conditions differ greatly. Arabica coffee beans, for example, grow in shaded environments whereas Robusta (or canephora) beans grow in sunny environments (Davis *et al.*, 2006). Robusta is often deemed of lesser quality and taste than Arabica coffee beans (Lashermes *et al.*, 1999). The Robusta coffee bean however is better adapted to changing climatic conditions as its tolerance for less or more precipitation and higher or lower temperatures is much greater than the tolerance of the Arabica coffee bean. (Haggar and Schepp, 2012). This could make Robusta more suitable for growth under new climatic conditions as a result of climate change. To estimate how the suitability of both coffee bean types fits into the context of climate change, and how this relates to issues of irrigation and water scarcity, the concept of the water footprint will be used to estimate these changes. The water footprint can be used to estimate the amount of water that is required to produce one unit of a crop (Hoekstra *et al.*, 2011). To expand on this, the concepts of blue and green water will be used to describe how the ratio between rainwater and irrigation water for the growth of coffee beans will be used. In this context, blue water relates to water used for irrigation whereas green water relates to precipitation. As precipitation patterns might change and temperatures may rise, the crop of coffee being heavily reliant on rainwater can become more reliant on the usage of blue water derived from the ground- and surface water. This could be an issue as problems of water scarcity arise in South American countries. (Murtinho *et al.*, 2013). These differences in blue water usage can have climatic impacts, but they also might lead to situations where coffee production in these regions will not be economically feasible in the future. Discussed in this research will be whether this is or will be the case and whether it would make sense for farmers to differentiate. Also, it might be of interest to see to which regions on a global scale, production might migrate to more suitable regions for coffee production as the demand for coffee remains still or even increases.

1.2 Research problem

The research will aim to see how changes in the ratio of green and blue water in the water footprint of the production of Arabica and Robusta coffee beans in South America are affected by climatic changes such as different precipitation patterns and rising temperatures in order to make predictions for the economic feasibility of agricultural production of coffee in South American regions, to make statements about possible local water scarcity issues and accordingly make policy recommendations for making agricultural adaptations, possibly moving production elsewhere or supporting agricultural differentiation.

To research this topic the central question to be asked will be:

‘What is the influence of increasing global temperatures and changing precipitation patterns as a result of climate change on the water footprint for local coffee production in South American countries?’

Secondary questions that arise from this central question are:

- How do climatic changes influence the availability of green water (rainwater) for coffee bean production?
- To what extent does the ratio between blue and green water change?
- Will sustainable coffee production in South America be feasible as the water footprint ratio changes?
- Would it be more economical to move production elsewhere globally and differentiate locally?

1.3 Structure

The structure of the thesis is as follows. The first chapter contains an introduction in which the topic is introduced. The background of the study will be discussed, as well as the research problem in which the main research question and sub-questions are posed. The second chapter of the research includes the theoretical framework in which a literature review is described as well as a conceptual model which puts the review in a visual perspective. In the third chapter, the methodology of the research is explained. The fourth chapter contains the results of the research. The final chapter of this thesis contains a discussion on methods and results.

2. Theoretical framework

2.1 Literature review

Over the past decades, global climate systems have changed immensely. Global and local temperatures have risen and precipitation has in certain areas declined and in other areas, it has risen and has become more unpredictable (IPCC, 2021). These changes undoubtedly have their effects on agricultural crop production. These effects are especially prevalent in crops that are highly reliant on precipitation and sensitive to temperature changes. Therefore it is necessary to see how these climatic changes influence coffee production as this crop is reliant on certain temperatures and precipitation absolutes and patterns. Precipitation patterns have changed and absolute precipitation has also been known to decrease in South American regions (IPCC, 2021). Therefore, coffee bean crop production could require a substantially larger quantity of irrigation water in order to sustain a sufficient coffee bean production. We know that, historically, coffee already has a large water footprint (Mekonnen *et al*., 2011). What we can also derive from past research is that these climatic changes are already influencing coffee production (Ovalle-Rivera *et al*., 2015). To see whether the rising temperatures and different precipitation patterns can lead to an increase in demand for surface- and groundwater to compensate for the loss of (efficient use of) green water to still be able to produce coffee in these areas, this project will offer insight on these issues. In other words, we will see whether and how the water footprint with the ratio of blue and green water, changes for the production of coffee in changing climatic conditions. To investigate how differing precipitation and higher global temperatures influence the different types of water for coffee production, the concept of the water footprint will be used (Hoekstra *et al*., 2011). Using the water footprint we can see how the ratio between blue and green water changes (Chapagain *et al*., 2012).

The crop that is central to this agricultural issue, is the coffee bean. The coffee bean has certain properties that are directly influenced by climatic conditions. The coffee bean consists of two main parts. This involves the outer layer of the bean called the pericarp and the seed inside. This layer, the pericarp, consists of the exocarp, mesocarp and endocarp (Eira *et al*., 2006). The exocarp is the peel of the seed. This outer layer is green during the initial growth stages and later becomes yellow or red. The mesocarp is also referred to as the pulp as this is a layer of material that is stiff at first and becomes softer with maturation (Eira *et al*., 2006). The endocarp is the outer layer of the coffee bean. Within the endocarp, the seed is found. The seed consists of the silver skin and the endosperm. The silver skin is a thin outer layer of the endosperm. The endosperm is the most important part of the seed as it is the part that mostly remains for coffee production (Eira *et al*., 2006). Below, figure 2 shows the physiology of the coffee bean.

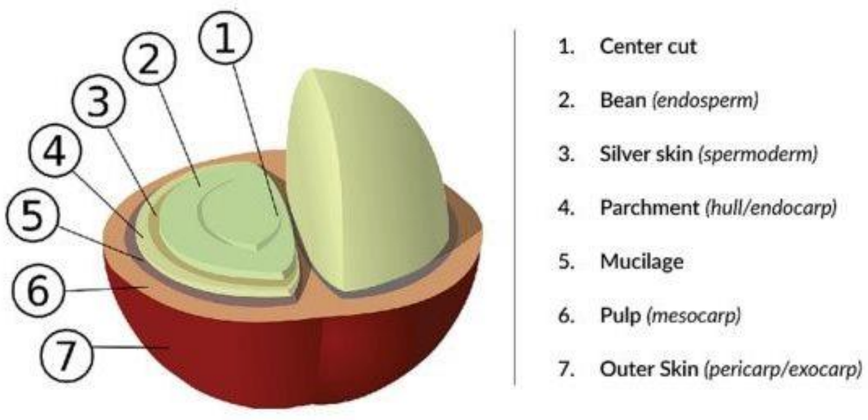

Figure 2: Physiology of the coffee bean (derived from coffeecrossroads.com)

Overall the bean is egg-shaped and has a hard external region and a soft internal region in the seed. The flowering of the beans does not happen simultaneously and can take up to two or three days. After flowering, the growth of the bean can stagnate up to sixty days depending on climatic conditions such as when the period with high rainfall starts. With Arabica seeds it can then take up to 250 days to mature whereas for Robusta beans it can take up to 350 days. As mentioned before, rather significant differences exist between coffee species Arabica and Robusta (Davis *et al.*, 2006). Rainfall ratios for example differ among species (see table 1). Arabica is better suited to large quantities of rainwater than Robusta. However, both species do require a dry period in order for the flowering to take place. Moreover, the required rainfall also depends on factors such as cloud cover, soil conditions, humidity, and agricultural techniques (DaMatta *et al.*, 2007). High air humidity is required for both species of coffee bean to grow although Arabica beans can grow under slightly less humid conditions than Robusta (DaMatta *et al.*, 2007). Regarding required soil conditions, these can also vary greatly due to other circumstances. For instance, large dry periods can lead to increased root development making both Arabica and Robusta coffee bean plants more sustainable for periods of drought as more green water can be taken up by the roots in the soil (DaMatta *et al.*, 2007). In South American coffee-producing regions, the dry period can last up to six months. However, future climate projections indicate that dry periods can increase by one or two months within the next fifty years in South American regions, meaning the dry period will be too long for a sufficient crop yield regardless of the larger root availability (Ovalle-Rivera *et al.*, 2015).

In order to overcome these difficulties with changing climatic factors, more blue water could be required for coffee production. This project will aim to offer insights on whether the possibly increasing need for blue water can have a negative influence on the already existing water scarcity in South America and mainly the Andes region (Murtinho *et al.*, 2013). The concept of Water scarcity is defined as 'The ratio of the total blue water footprint in a catchment to the blue water availability, whereby the latter equals natural runoff in the catchment minus the flow that needs to be maintained in support of local ecosystems and communities (Hoekstra *et al.*, 2011). This concept needs to be taken into account to complete the equation on whether coffee production in South American countries will be sustainable in the future. Research shows that already we can see that by 2050 water stress can pose severe problems in the South American region as well (Vorosmarty, 2000).

Even though many different climate models have predicted alternative scenarios for climatic changes in the future, many models indicate that climate change will eradicate 50% of all coffee plantations worldwide (Bunn *et al.*, 2015). In figure 3 below, we can see how current coffee-producing areas are already becoming substantially less feasible for coffee production by 2050, whereas some smaller areas are becoming more suitable for coffee production.

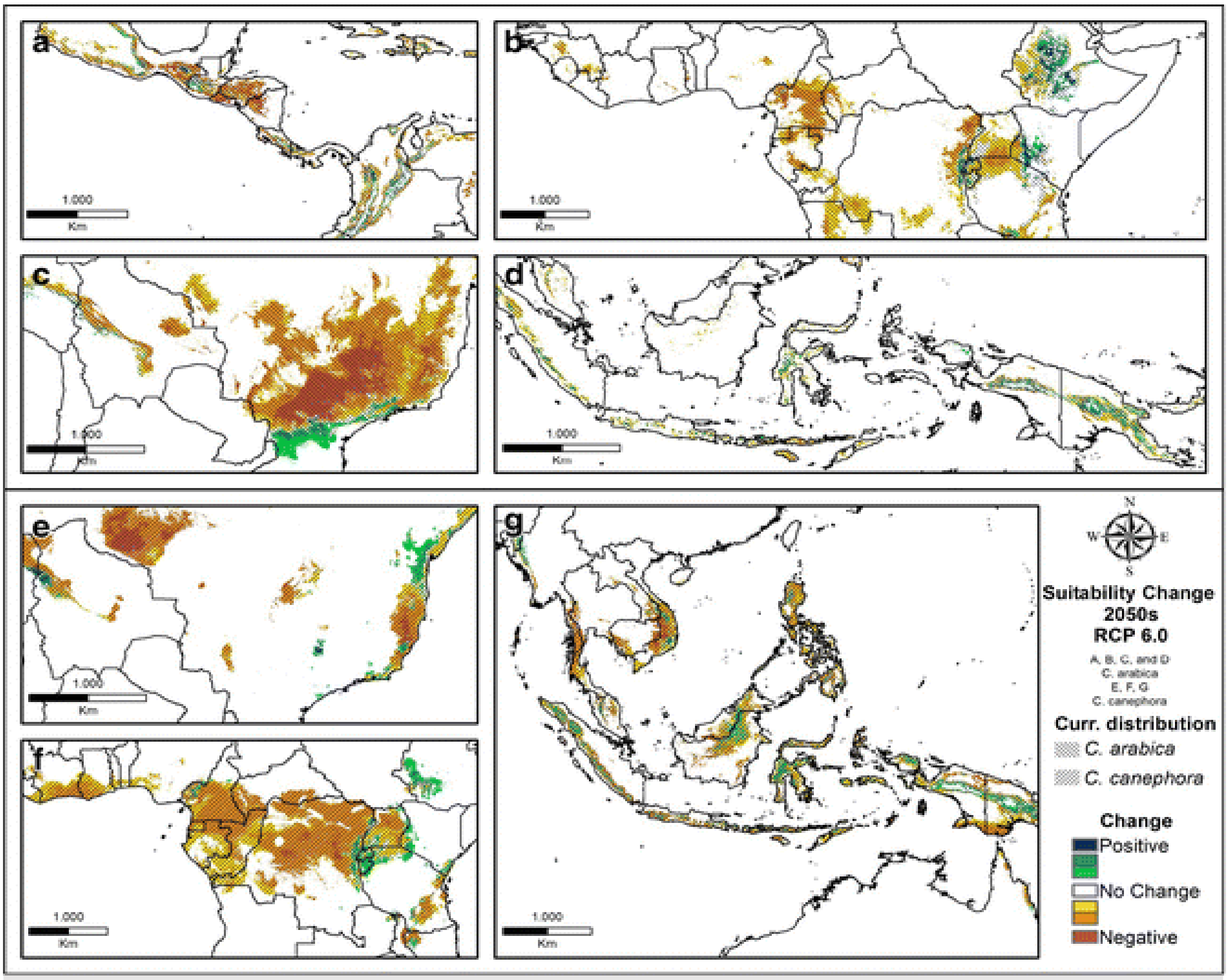

Figure 3: Suitability changes by the 2050s in the RCP 6.0 scenario; A-D: Arabica, E-G: Robusta. Hatching indicates the current suitability distribution; Warm colors represent areas with negative climate change impacts and cold colors positive changes (Bunn *et al.*, 2015)

Possible solutions to combat the increasing demand for ground- and surface water for coffee production in these countries might simply be using different agricultural processes to make the use of blue water more efficient, such as soil mulching and drip irrigation (Nouri *et al.*, 2019). However, an increase in the use of blue water is still likely (Schmitz *et al.*, 2013). The shift from green to blue water for coffee production could have serious consequences. For one, it can create local water stress for individual consumption (Schmitz *et al.*, 2013). Also, as water becomes a more scarce good for agricultural production, the water price may rise. This increase in price can lead to high prices for coffee and lead to coffee becoming a more luxury product that not anyone can afford. Furthermore, high prices for agricultural production as a result of the higher water price in general, can lead to high food prices and can locally threaten food security (Schmitz *et al.*, 2013).

A more extreme measure to combat issues with coffee production under changing climatic conditions, could be to move production elsewhere on a global scale and differentiating locally. For example, due to climatic changes certain areas in Brazil have become increasingly suited for the production of maize, soybean and sugarcane (Schlindwein *et al.*, 2021). Therefore, local farmers may decide to invest in producing crops such as these rather than coffee beans. However, not only climatic changes drive differentiation of agricultural production. Population growth also influences the demand for agricultural products in South America. (Schlindwein *et al.*, 2021). This population growth leads to an increase in demand for agricultural products for food security which leads to more intensive farming for food production in certain areas. This could also be a factor that pushes out coffee production locally. With these environmental and social impacts on coffee production, it will mainly be the smaller farmers at first that suffer the consequences. This is also because of the simple fact that small farms make up the largest part of global coffee production. Even though most farms make up less than ten 10 hectares per farm, these types of farms do make up a large labor market of over 100 million people (Rice, 2003). Small coffee producers do have a small margin and as climatic difficulties are increasing, farmers have already started shifting production to other crops such as coca. Coca can grow under a very wide array of climatic circumstances and is, therefore, an option to combat the loss of suitability of land for coffee production. However, coca production is much less intensive than coffee production and has therefore already eradicated many jobs (Rice, 2003). Large industrial sites, however, have means to shift their production to for example Robusta beans as they are better suited to climatic changes (Rice, 2003). At the rate at which climatic changes are currently taking place it could however mean that in the future, even producing coffee with Robusta beans is no longer possible. However, for some regions, climatic changes can even lead to new opportunities as some areas actually become a better fit for producing coffee (Ovalle-Rivera *et al.*, 2015). Asian countries such as Vietnam produced almost no coffee before and during the 1990s but are now top producing countries globally. In South America, areas of higher latitude generally seem to become better suited to coffee production as climatic changes take place (Zullo *et al.*, 2011). Also, areas of higher altitude seem to become a better fit for producing coffee as high altitudes often involve cooler temperatures which battle the effect of increasing temperatures as a result of climate change. Below in figure 4 is shown in which regions coffee production will be less feasible and which regions will become more suitable for coffee production as a result of climate change based on projections on altitudinal apr (Ovalle-Rivera *et al.*, 2015). However, moving coffee production elsewhere could threaten local ecosystems (Läderach *et al.*, 2013).

Figure 4: Future suitability of coffee producing regions on the South American continent

2.2 Conceptual model

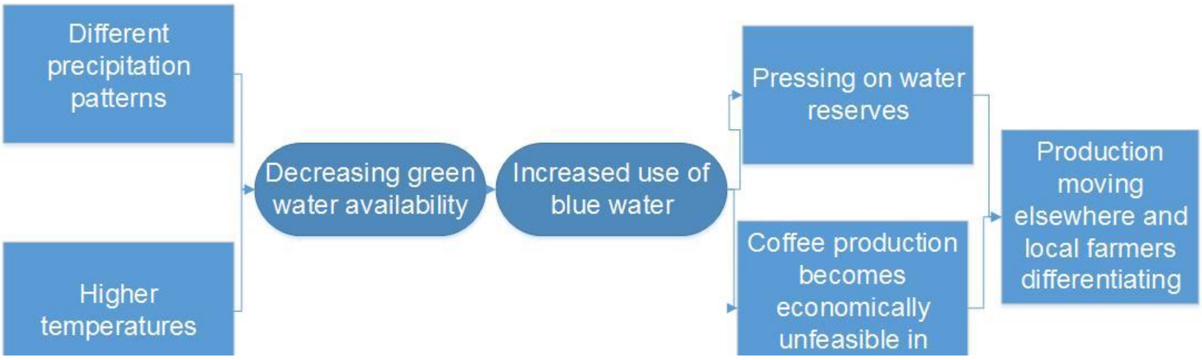

Figure 5: Conceptual Model

In the conceptual model above in figure 5, we can see that the expectation is for changing precipitation patterns, combined with higher temperatures to lead to a decreased availability of green water. This is the expectation as precipitation is likely to decrease in certain areas in South America and as temperatures rise the evapotranspiration also rises (Schmitz *et al.*, 2013). The decrease in a green water supply will lead to increased use of surface- and groundwater (blue water) to compensate for the loss of green precipitation water in order to still be able to produce a sufficient coffee bean crop yield. This increased use of blue water will then result in increasing water scarcity issues locally and also will eventually have economic consequences as production might become less feasible economically. This then leads to possibly moving production coffee production elsewhere in the world where climatic conditions (possibly through climate change) are more favorable for coffee production. This then also means local farmers in South America might need to differentiate and grow different crops.

2. Methodology

To answer the research questions, secondary data analysis is performed using secondary quantitative data. To determine how climatic changes over the past decades have influenced the water footprint of coffee production, a linear regression analysis is performed using secondary data on climatic properties. The dataset that is used is from the IPCC (Intergovernmental Panel on Climate Change). This dataset is from the IPCC Data Distribution Center and involves data on absolute temperatures and precipitation (measured in millimeters per year) in 10-year periods from 1901 to 1990 for all longitudes and latitudes. This is used to see the changes in absolute temperatures and precipitation over time. Besides this, data from IPCC simulations involving data from 2010-2199 is used to estimate whether blue water usage will increase in the future as a result of projected shifts in temperature and precipitation. Because of the longitude/latitude system in the data, we can specify the dataset to South American countries only to make the data fit the analysis. In this dataset, the longitude/latitude grid data have 2 decimals making it possible to choose the so-called four most extreme points of latitude and longitude on the South American continent to filter the relevant spatial data within these points so that we have data for the mainland of the continent. Below, in figure 6, the extreme points of the South American mainland that were used, are indicated. The dataset provided by the IPCC contains spatial data of only the mainland of South America which helps alleviate any possible bias that could have arisen from the fact that data from above water bodies would be used, which would of course pose some problems of bias as agricultural production is not possible in such areas.

Figure 6: The extreme points of the South American mainland

This dataset is accessible and was downloaded online in different file types and used for analysis. Regarding ethical considerations, the data is derived only from secondary sources and contains no personal information as it contains climatic data. The most important consideration to take into account is the proper referencing of the data sources.

Ideally, another dataset would be used which contains data on the ratio of rain and irrigation water that is used over a long period of time for coffee production on South American coffee plantations. Unfortunately, these data are not available. To solve this issue, an index is created to estimate the ratio of blue and green water over time.

Optimum precipitation -

Actual precipitation - = Indicator for blue water usage

Crop Evapotranspiration

The optimum rainfall and total annual precipitation data for the production of Arabica and Robusta coffee is used. Table 1, containing these data, can be seen below. The annual rainfall, which is derived from the IPCC dataset, will then be deducted from the optimum rainfall. The number that arrives from this can be seen as water shortage which then can be used to estimate the amount of blue water that is used to irrigate and compensate for the shortage. In table 1 below, the optimal and absolute conditions for growing Arabica and Robusta coffee beans can be seen. These data were used to estimate blue water usage by using the optimum precipitation for both Arabica and Robusta coffee beans, deducting the actual precipitation derived from IPCC climate data and minus the crop evapotranspiration which was derived from the Penman equation which can be seen below (Valiantzas, 2006).

	Arabica				Robusta			
	Optimal		Absolute		Optimal		Absolute	
	Min.	*Max.*	*Min.*	*Max.*	*Min.*	*Max.*	*Min.*	*Max.*
Temperature	14	28	10	34	20	30	12	36
Rainfall	1,400	2,400	750	4,200	1,700	3,000	900	4,000
Soil pH	5.5	7	4.3	8.4	5	6.3	4	8

Table 1: Optimal and absolute conditions for growing Robusta and Arabica coffee beans (Haggar and Schepp, 2012)

Estimating crop evapotranspiration

To estimate crop evaporation, a simplified Penman equation was used. This equation can be used to estimate evaporation based on other climatic data (Valiantzas, 2006). Firstly, the input variables required for this equation involve, among others, T (air temperature). This was derived from the IPCC dataset mentioned above. All formulas below are derived from Valiantzas (2006). Ra was calculated as follows (Valiantzas, 2006):

$$R_A = 37.59 d_r [\omega_S \sin(\phi) \sin(\delta) + \sin(\omega_S) \cos(\phi) \cos(\delta)]$$

Rs (extraterrestrial irradiation) can then be calculated using the Ra variable (Valiantzas, 2006).

$$R_S = R_A \cdot \left(0.5 + 0.25 \cdot \frac{n}{N}\right),$$

N is calculated by the formula below. To calculate N, i (month in the year, where 6 means june for example) and ϕ (latitude in radians) are required. For latitude, the extreme latitudinal points of the continent were used. These two values for N were then used to calculate an average value for N. For i, for each time period, 1 to 12 were used to determine the average N (sunshine hours). (Valiantzas, 2006)

$$N \approx 4\phi \sin(0.53i - 1.65) + 12,$$

Other required variables include RH (relative humidity), Tmax (maximum temperature), Tmin (minimum temperature). These variables are derived from the IPCC dataset. Remaining variables include α (albedo) for which the grassland average of 0.23 was used (Valiantzas, 2006). For au the constant 0.5 was entered and for u (wind speed) the global average of 2 m/s was entered (Valiantzas, 2006).

$$E_{\mathrm{PEN}} \approx 0.051(1-\alpha)R_{\mathrm{S}}\sqrt{T+9.5}$$
$$-\,0.188(T+13)\left(\frac{R_{\mathrm{S}}}{R_{\mathrm{A}}}-0.194\right)\left(1-0.00014(0.7T_{\max}+0.3T_{\min}+46)^2\sqrt{\frac{RH}{100}}\right)$$
$$+0.049(T_{\max}+16.3)\left(1-\frac{RH}{100}\right)(a_{\mathrm{U}}+0.536u)$$

The equation below shows the simplified Penman equation that was eventually used for all time periods to estimate evaporation. The formula was used for all time periods for every month of the year and the average of this was used to estimate the evapotranspiration as the IPCC dataset also only contains annual data. Below, table 2 containing the average evaporation in millimeters per day can be seen for each time period.

PERIOD	*CROP EVAPOTRANSPIRATION (MM/DAY)*
1900-1910	*1,98*
1911-1920	*1,96*
1921-1930	*2,01*
1931-1940	*2,46*
1941-1950	*2,67*
1951-1960	*2,71*
1961-1970	*2,89*
1971-1980	*2,88*
1981-1990	*2,91*
1990-2000	*2,96*

Table 2: The average crop evaporation by time period in millimeters per day for the average of the extreme latitudinal points of the South American continent

Using this estimation of average crop evaporation combined with precipitation data gives us an estimate of the shortage of water in order to successfully grow coffee beans. This gives an indication of the amount of blue water which is then used to overcome this shortage by irrigation methods. There are limitations to this method, as there are more factors influencing the amount of water that is used, such as soil conditions. However, it should function as an indication.

The aforementioned datasets were combined into one excel file with a comprehensive overview of all relevant data. The variables in the combined dataset were transferred into an

SPSS file to perform a linear regression analysis. Two separate regression analyses were performed to show if and which connections exist between the different variables to conclude whether higher temperatures and different precipitation patterns indeed lead to a shifted blue to green water ratio in coffee production. These analyses were done separately for the Arabica coffee bean and the Robusta coffee bean as both beans differ in regard to precipitation and temperature tolerance.

3. Results

3.1 Coffea Arabica

In order to see whether the climatic changes, such as rising global temperatures and changing precipitation patterns, that have been progressing for the past number of decades have had an influence on the water footprint of Robusta and Arabica coffee bean production, a multiple regression analysis was performed to recognize these relationships. Table 3 shows the results of the multiple linear regression analysis. In this case, dependent variables include precipitation data from 1900 to 2000, 2010 t0 2199 and temperature data from 1900 to 2000 and 2010-2199. The independent variable that was used, is the estimated blue water usage for irrigation for the production of Arabica coffee beans. Table 3 shows that from the quantitative analysis (a multiple linear regression) we can see that the t-values for the temperature data in the 1910-1950 are generally lower than the critical value of 1.96 with a 95 percent confidence level. This means that we can not reject the null hypothesis of there being no linear relationship between the temperatures and the estimated usage of blue water for Arabica coffee bean production. This means that for these time periods, there is not necessarily a strong relationship between the differences in temperature as a result of climate change and increased stress on water resources by using blue water for irrigation. Regarding the temperature data from the period of 1951 until 2000, all the t-values do exceed the critical value of 1.96. Therefore, we may reject the null hypothesis of there being no linear relationship between these temperatures and the usage of blue water for Arabica coffee bean production. We can say that, based on these data, temperature changes from 1950 onwards do correlate with an increase in blue water usage for crop irrigation. These results do comply with the theoretical and conceptual model as increasingly with time, global warming leads to an increase in blue water use. The time periods past 2010 up to 2199 all show a significant relationship with an increase in blue water usage as all t-values exceed the critical value of 1.96 and we can therefore reject the null hypothesis of there being no relationship between temperatures from 2010 to 2199 and the usage of blue water for Arabica coffee bean production. We can therefore state that the blue water usage will increase with the temperature changes that are projected by the IPCC. This complies with the academic literature as the expectations are that blue water usage will increase in agricultural production as a result of climate change (Schmitz *et al.*, 2013).

The precipitation data presents a vaguer picture. Although from the 1950's onwards, almost all t-values exceed the 1.96 critical value and for these values we can therefore reject the null hypothesis of no linear relationship between the precipitation data and the blue water use for the production of the Arabica coffee bean. For the periods between 2010 and 2199 we can see only significant results as the related t-values are all higher than 1.96. We may reject the null hypothesis of no relationship between precipitation values from 2010 to 2199 and blue water usage. Therefore, we can say that based on these data, blue water usage will likely increase as changes in precipitation happen in the future up to at least 2199.

Model 1 (Arabica) Variable	*β*	*t-value*
Constant	-2852,512	-1,481
Temperatures 1900-1910	6,125	0,319
Temperatures 1911-1920	49,673	2,173
Temperatures 1921-1930	40,263	1,826
Temperatures 1931-1940	9,127	0,126
Temperatures 1941-1950	8,173	1,817
Temperatures 1951-1960	12,347	1,973
Temperatures 1961-1970	10,872	2,291
Temperatures 1971-1980	9,175	1,952
Temperatures 1981-1990	87,482	-4,082
Temperatures 1991-2000	31,065	2,961
Temperatures 2010-2039	21,137	3,852
Temperatures 2040-2069	7,827	2,257
Temperatures 2070-2099	9,273	-2,971
Temperatures 2180-2199	4,291	-3,183
Precipitation 1900-1910	-0,092	-0,467
Precipitation 1911-1920	-1,254	-1,982
Precipitation 1921-1930	1,067	2,352
Precipitation 1931-1940	1,873	-1,901
Precipitation 1941-1950	-1,411	2,617
Precipitation 1951-1960	3,903	-1,087
Precipitation 1961-1970	-1,857	-2,061
Precipitation 1971-1980	-3,771	1,840
Precipitation 1981-1990	3,502	-3,144
Precipitation 1991-2000	1,562	1,985
Precipitation 2010-2039	2,193	-2,198
Precipitation 2040-2069	5,287	-2,320
Precipitation 2070-2099	2,281	3,238
Precipitation 2180-2199	12,189	-3,201

Table 3: The effect of temperatures and precipitation on blue water usage for irrigation of Arabica coffee beans: results of the multiple linear regression analysis

3.2 Coffea Canephora (Robusta)

For the second multiple linear regression analysis, the independent variable that was used was the blue water usage for Robusta coffee bean production. In table 4 we can see that regarding the temperature variables, the temperatures from 1900-1960 generally do not exceed the critical value of 1.96 (apart from the temperatures 1911-1920). For these variables, we can not reject the null hypothesis of there being no linear relationship between the temperature data and the blue water usage for the Robusta coffee bean. From the temperature variables from 1961 onwards, the t-values indicate a significant result and therefore we may reject the null hypothesis of no linear relationship. Similarly to the Arabica coffee bean, we can therefore see a correlation between temperature increase and the increased use of blue water for irrigation. This complies with the expectation as laid out in the literature review and the conceptual framework. For the temperatures from 2010 to 2199 we can also see significant results. All t-values exceed the critical t-value of 1.96 with a 95 percent confidence level. We can therefore say that we can reject the null hypothesis of there being no relationship between blue water usage and the production of Robusta coffee beans. From this we can conclude that, based on these data, the usage of blue water will increase for the production of Robusta coffee beans as temperatures are correctly projected to rise.

The precipitation overall shows a less strong relationship with the blue water use for Robusta coffee bean production. The t-values corresponding with the precipitation data do not give a clear picture as they are only partly and seemingly randomly significant. The less clear relationship can be explained by the Robusta coffee bean growing properties as this bean has a substantially larger tolerance for precipitation variability than the Arabica coffee bean (Haggar and Schepp, 2012). However, for the projected precipitation data by the IPCC for 2010 onwards to 2199, we can see a significant relationship between blue water usage for Robusta coffee bean production and precipitation projections. All t-values from 2010 onwards show a t-value that exceeds the 1.96 critical t-value with a 95 percent confidence level. We can therefore, based on these data, say that in the future there can be a relationship between increasing blue water usage for Robusta coffee bean production and projected precipitation absolutes.

	Variable	*B*	*t-value*
Model 1 (Robusta)	*Constant*	2589,575	1,937
	Temperatures 1900-1910	0,819	0,089
	Temperatures 1911-1920	32,162	2,019
	Temperatures 1921-1930	21,872	1,356
	Temperatures 1931-1940	19,001	0,772
	Temperatures 1941-1950	10,245	0,378
	Temperatures 1951-1960	12,390	2,081
	Temperatures 1961-1970	0,871	-4,610
	Temperatures 1971-1980	-65,19	-2,249
	Temperatures 1981-1990	-49,267	-2,946
	Temperatures 1991-2000	-0,371	-2,394
	Temperatures 2010-2039	11,762	-2,541
	Temperatures 2040-2069	28,928	-2,981
	Temperatures 2070-2099	21,381	-2,775
	Temperatures 2180-2199	1,293	2,105
	Precipitation 1900-1910	0,982	2,871
	Precipitation 1911-1920	-0,862	-1,289
	Precipitation 1921-1930	-0,183	-0,129
	Precipitation 1931-1940	0,198	0,401
	Precipitation 1941-1950	1,297	2,918
	Precipitation 1951-1960	0,210	1,302
	Precipitation 1961-1970	-4,732	-1,707
	Precipitation 1971-1980	-0,219	-4,912
	Precipitation 1981-1990	4,718	-2,464
	Precipitation 1991-2000	0,013	2,027
	Precipitation 2010-2039	3,128	3,298
	Precipitation 2040-2069	2,721	-2,423
	Precipitation 2070-2099	4,228	-3,381
	Precipitation 2180-2199	1,053	4,913

Table 4: The effect of temperatures and precipitation on blue water usage for irrigation of Robusta coffee beans: results of the multiple linear regression analysis

4. Conclusion

The main research question of this thesis is: What is the influence of increasing global temperatures and changing precipitation patterns as a result of climate change on the water footprint for local coffee production in South American countries?'

To answer this question, there has been looked at how climate changed has affected temperatures and precipitation patterns in South America. We can conclude that also on the mainland of the South American continent, absolute temperatures have risen and precipitation patterns have become increasingly unpredictable, and locally less precipitation or more precipitation has fallen (IPCC, 2021). As past research results have shown, climatic changes have already greatly influenced coffee production in certain areas (Ovalle-Rivera *et al.*, 2015). Also, predictions are that by 2050, up to 50 percent of coffee plantations will not be feasible anymore (Bunn *et al.*, 2015). Therefore the expectation was that the data to be analyzed will show similar results so that the ratio between blue and water used for coffee crop production will shift towards blue water as less rainwater is available for the bean growth and more blue water will be required for irrigation. The regression analysis has shown how that in more recent years, indeed rising temperatures and different precipitation patterns have led to an increase of blue water use for irrigation of both Arabica and Robusta coffee beans. We can therefore say that the ratio between the use of green and blue water for coffee production is shifting towards blue water slowly but steadily. The analysis has also shown that when future climatic predictions prove to be accurate, the increase in blue water usage will remain relevant for both Arabica and Robusta coffee beans. However, for the analysis optimum data for growing coffee beans has been used instead of absolutes. Robusta coffee beans naturally have a larger tolerance for an in- or decrease in precipitation and Arabica coffee beans also show a certain tolerance larger than the optimum conditions in which the beans can grow. Both coffee bean types can therefore likely still grow in their current environments. However, a larger amount of irrigation water will have to be used nevertheless as the coffee beans will be of lesser quality in cases where the optimum growing conditions are not met. (Haggar and Schepp, 2012). Quality standards will remain of great importance as the global coffee market is highly competitive (Kilian *et al.*, 2004). To guarantee these quality standards, irrigation methods will be needed to be used in order to sustain local coffee production. If this becomes economically unfeasible, or for reasons of water stress can no longer be sustained, this could mean that the areas on the South American continent that produce coffee today, could in the future be less feasible for coffee production. In this case, in the future, it could be more feasible for the local farmers to differentiate and grow different types of crops. The production of Robusta and Arabica coffee bean could then possibly be moved to other areas globally which become more suitable due to the same effects of climate change. The production of coffee could move up to higher altitudes. Local farmers could grow other crops such as maize or coca (Schlindwein *et al.*, 2021). This however has a large socio-economic impact as it does cost a lot of local jobs. Issues of water scarcity also pose a problem as a result of climatic changes on agricultural production in general. Water becoming more scarce can mean an increase in water prices which can lead to increased food prices. This could be threatening to food security in the future (Schmitz *et al.*, 2013).

Further research should be done to determine which areas in the future could be a better solution to grow coffee beans in order to alleviate problems of water scarcity due to the increased usage of blue water in South American coffee-growing regions.

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