IDENTIFICATION OF SUITABLE TEA GROWING AREAS IN MALAWI UNDER CLIMATE CHANGE SCENARIOS

CALI, COLOMBIA; NOVEMBER 2017

UTZ IN PARTNERSHIP WITH CIAT
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SUMMARY

Malawi is one of the most vulnerable countries of the world to climate change. Its people still face extreme poverty and climate hazards may strongly weaken the food security. Climatic change could potentially reduce the growth rate and quality of the tea plant by altering the distribution of temperature and precipitation. As tea production contributes significant shares to foreign export earnings and rural employment such effects would have negative consequences for the entire country.

Objectives

This study is intended to bring attention the risks of being idle in front of potential climate impacts. We hypothesized potential hazards for tea production for the country and their relative importance for the different tea regions. This way our study may serve to prioritize adaptive action or investment alternatives between regions. But, this study is not a certain look into the future and should not be interpreted down to plot level. The results of the models showed high uncertainty of projections for tea production in the future. Precipitation is defining for tea cultivation but global climate model projections disagree about the direction of change for these variables. We considered the climatic range currently occupied by tea in Malawi, but not a possible expansion of this range by novel technologies or technology transfer from other countries. Adoption of adaptive agricultural practices may result in alternative developments of the tea sector in Malawi in the future.

Approach

In this study we discussed projected long term climate change impact projections for tea production of Malawi. We developed a gradient of climate change impacts and assessed projected risks to tea production in Malawi from global climate models (GCM). Suitability types for tea production in Malawi were defined by RandomForest (RF) classification of a combination of spatial climate data from WorldClim and a database of occurrences of tea production. Malawian experts evaluated and verified tea occurrence data for model input and confirmed the validity of the resulting model for current conditions. The validated models were then extrapolated on climate data for the periods 2020 to 2049 and 2040 to 2069 in an intermediate emissions scenario for 19 GCMs. We conducted two kinds of analysis, one in which all available variables were used, and one were variables were separated into temperature, precipitation, evapotranspiration and soil variables. In our analysis we focused on the three most important districts Mulanje, Thyolo and Nkhata Bay but also considered potential areas for expansion.

Key findings

Nkhata bay was found to be most at risk from climate change. The GCM projections for temperature and evapotranspiration suggested unsuitable conditions in the future, as well as some precipitation projections. Climate change will likely result in increased potential evapotranspiration so that precipitation needs will increase. Of the GCMs used in this analysis some models projected reductions in precipitation to levels that would be unsuitable for tea, even when considering equal temperatures. Already, stakeholders reported that the area is productive only with irrigation, and that with very high temperatures productivity may be low despite these measures.

The climate change impacts in the Thyolo area will likely depend on the altitude. Low lying areas were found to be at high risk from climate change. Lower lying areas will be threatened by increasing temperatures even though most GCMS agreed that precipitation will remain at suitable levels. The projected increase in potential evapotranspiration will result in a reduction of the potential area to the higher slopes of Thyolo.
The Mulanje district was projected to face an uncertain climate future. While it will most likely remain suitable, the projected conditions will be unlike current conditions. By the 2050ies evapotranspiration levels will on average reach levels at the margin of currently suitable levels. While climate in Mulanje showed a tendency to migrate in altitude, soils suitability could be a potentially limiting factor to such an extension of area. Thus, the area will be suitable for tea production, but the combination of climate variables should be considered a novel climate distinct from current conditions.

Stakeholders in Malawi pointed out that within Malawi in proximity to mountainous ranges suitable conditions for tea may be found. We were able to confirm that at the Northern border with Tanzania suitable area can be found. Nevertheless, the suitable area in the North was projected to be affected by similar trends as the Nkhata bay area. Suitable temperatures and potential evapotranspiration were found to show a migration to higher altitudes as climate change progresses. Precipitation was found to be likely favorable but some scenarios showed that conditions in the future may be marginal.

The combined projections for the two coffee species Arabica and Robusta closely resembled the potential distribution of tea under both current and future conditions. Coffee was found to be more affected by climate change as suitable area will likely disappear by the 2050s so that it can't be considered a good diversification option for tea producers.

**Outlook**

In the last section we present considerations for the promotion of a climate smart tea sector in Malawi. The development of portfolios of appropriate action that are tailored for different groups of actors is recommended. Climate information services at temporal scales of differing length will be required to support a planned anticipatory adaptation process. The long term projections presented in this study should be complemented with seasonal forecasts and analysis of near term trends. Ecosystem based measures at landscape, novel germplasm and adequate shade management promise high benefits for adaptation but will require collective action and a long lead time. Therefore, such measures should be complemented by promoting the development of good agricultural practices into climate smart practices for tea that respond to site specific hazards at farm scale. We hope that this report is only the starting point towards a climate smart tea sector in Malawi.

**Key words:** Climate Change, Impacts, Malawi, Random Forest, Tea, Suitability
This report contains a study on the impacts of climate change on tea production in Malawi. In essence, this study is a comparison of the spatial distribution of climate variables in scenarios derived from climate models. It is intended to bring attention the risks of denying climate impacts. It can be used to hypothesize potential hazards for tea production for the country and their relative importance for the different tea regions. This way it may serve to prioritize adaptive action or investment alternatives between regions. But, this study is not a certain look into the future and should not be interpreted down to plot level. To design locally appropriate climate smart practices local knowledge needs to be taken into account and regarded in the context of local climate trends and perceptions. There will not be a single solution to confront the changes. We recommend to develop portfolios of potential practices from which stakeholders choose cost effective options.

We first reviewed available literature about the relationship between climate and tea production. Then we used a decision tree based learning method to describe the spatial distribution under current and several scenarios of future climate conditions. We considered the climatic range currently occupied by tea in Malawi, but not a possible expansion of this range by novel technologies or technology transfer from other countries. Adoption of adaptive agricultural practices (e.g. novel varieties, irrigation, or shading) may result in alternative developments of the distribution of tea in the future. The results in this study should therefore be interpreted with care and within appropriate context.

An important ecological factor for the production of tea is an adequate distribution of precipitation throughout the year. Long term projections of climate change, however, exhibit a high degree of uncertainty about the distribution of precipitation. In addition, it is important to emphasize the difference between long term mean changes as considered here, and unusual climate variability. For marginal smallholder farmers often a single failed crop from an event such as extended drought may be more important than the prospect of viability averaged over decades. This study should therefore be complemented with additional work about climate trends and perceptions to reduce the uncertainty of our projections.

From our experience stakeholders tend to perceive the impacts of climate change as a local phenomenon. Therefore, when communicating about our results it should be emphasized that climate change is a global phenomenon that also affects other regions and competitors. Perhaps the nature and degree of impacts may be less (or more) severe elsewhere, but the change itself may result in maladapted production methods unless it is confronted. Acknowledgement of the issue and action, even if this incurs cost, will likely be the better investment than denial.

Last, global climate change has to be separated from the potential effects of local ecosystem degradation. In many respects the local effects of deforestation, water overuse and soil erosion resemble those of global trends. In this study the effects of local land use were not taken into account. Protection or degradation of local ecosystems may increase or reduce the resilience of tea production for the entire landscape. Stakeholders should therefore consider that sustainable landscapes could be a means to improve the resilience of the system.
3 INTRODUCTION

Malawi is one of the most vulnerable countries of the world to climate change since climate hazards strongly weaken the food security of the country with a society still facing extreme poverty (Asfaw et al., 2014; “World Food Programme,” 2017). The agricultural sector is of great importance to the economy, and highly vulnerable to projected climatic changes, especially due to the precipitation heterogeneity (Nkomwa et al., 2014; Stringer et al., 2010). Climatic change therefore creates a major risk for the food security of the country as well as the reduction of poverty. Economic losses have been reported by drought events and on average reduced the GDP by 1 percent every year (World Bank, 2016). Most impacted by the effects of climate change are smallholders. Nevertheless, it can be noted that the effects are variable across the country and their different climatic and agro-ecological zones (Asfaw et al., 2014). Climatic change affects seasonal patterns and with it changes thresholds for plant survival and other agro-ecological factors such as new immigration of pests, diseases and weeds, as well as changes in the wind conditions. Production of the tea plant has to be adapted to these changing factors. In addition, the development of the tea plant in these new conditions has to be observed in order to understand the adaptability of the plant (Selena Ahmed et al., 2014).

Adaptation to climate change in agriculture refers to a change of cultivation practices as a result of observed or projected changes in the climatic environment of the production system. This change may either be spontaneous (e.g. migration during harsh drought) or planned (e.g. adopting a drought tolerant variety) (Füssel, 2007). The stronger the impacts from climate change will be, the stronger the benefit from adaptation. Effective adaptive action therefore need to take into account the severity of climatic changes. A gradient of climate impacts is defined by the ratio of current climatic heterogeneity and the degree of climatic changes (Vermeulen et al., 2013).

The degree of impact versus the feasible coping range is therefore an important determinant of the adaptation strategy. At locations where changed climatic variability is minor compared to historic climatic variability the available coping range of the system may be sufficient. Incremental adaptations may be implemented by transferring adequate existing technological solutions (Vermeulen et al., 2013), such as changed pest and disease control. With increasing degree of climate impacts, systemic adaptation measures will have to be developed in joint public-private efforts that expand the climatic range in which tea can be produced economically (e.g. novel varieties). Finally, when climate change causes frequent events that make adaptation uneconomical when comparing with the benefits from alternative crops a transformation out of the system has to be considered.

Thus, a forward looking adaptation approach to sustainable tea production will enable stakeholders to avoid catastrophic impacts and to develop hazard specific responses. The effective design of response strategies will first evaluate the degree of the climate change impact and then identify hazards to the system from analysis of practitioner’s knowledge, data analysis and climate simulations (Campbell et al., 2016).

This work presents an evaluation of the degree of climate change impacts on tea production in Malawi. First, we differentiated climate zones suitable for tea using variables that described the agro-ecological suitability for tea production and evaluated adaptation needs based on the projected differences between current and 2050s climate. The impact gradient interprets how climate change was projected to affect the tea production areas of Malawi. We differentiated 4 different degrees of impact: Cope referred to suitable tea production areas where the classification remains identical form current to future impacts. Adjustment sites are suitable tea areas but switch from one climatic zone to another in the future. At transformation sites the climate at current conditions was classified as suitable but in the future the climate shifts and affects the area to not being suitable for the tea production anymore. On the other hand, Opportunity sites were not classified as suitable in the present situation, but due to climatic changes in
future scenarios were projected to become be suitable. Last, as GCM projections differ for several locations no unambiguous degree of impact could be identified. Such locations were termed “systemic resilience” to emphasize the need to prepare for an uncertain future outcome.

3.1 TEA IN MALAWI

Malawi was one of the first countries starting to plant the tea bush in the late 1800s and is currently the third largest tea producer of the African continent (after Kenya and Uganda). The livelihood of an estimated 15,000 smallholders depends on tea (Intergovernmental Group on Tea, 2016). Export of tea is the third most important agricultural product by export value of Malawi (FAO, 2015). However, the climatic conditions of the country are not considered as highly suitable for tea production, therefore, the price of the Malawian tea is low on the global market (Smith, 2016).

The climate in Malawi is best described as a mild tropical climate with a summer rainy season. The winter season from May to September is dry and temperatures can go down to 5°C. The country can be affected by cyclones resulting in dry or wet weather events (Jury and Mwafulirwa, 2002). Malawi has an annual rainfall rate of 750 to 1,600 mm (World Bank, 2016). 80% of the tea is produced within the summer season from December to April. In the winter season only 20% is produced (Tea Research Foundation of Central Africa, 2013).

Tea in Malawi is mostly produced in the districts of Mulanje and Thyolo in the Southern regions of the country as well as in Nkhata Bay in the North (Figure 1) (Tea Research Foundation of Central Africa, 2013).

![Figure 1  Tea production districts of Malawi and gps references of tea production zones.](image-url)
Mulanje and Thyolo districts are the regions of the highest tea production in Malawi. In 2001, 33.6% and 47.6% of the tea production areas of tea estates (without smallholders) were located in these two districts with an average yield of 2,939 kg/ha and 2,041 kg/ha, and 43.9% and 43.2% of the national tea production, respectively. Nkhata Bay plays a minor role in the tea production and produced 5.7% in 2001. Smallholders play a minor role for the total tea production of Malawi with 15.4 % of production area and 7.2% of production quantity (Agar, 2002).

Table 1  Tea production in the Malawian Tea Growing Districts (Agar, 2002)

<table>
<thead>
<tr>
<th>District</th>
<th>Hectares under tea</th>
<th>Average Yield</th>
<th>Production</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ha</td>
<td>%</td>
<td>kg/ha</td>
</tr>
<tr>
<td>Mulanje</td>
<td>6,249</td>
<td>33.6</td>
<td>2,939</td>
</tr>
<tr>
<td>Thyolo</td>
<td>8,864</td>
<td>47.6</td>
<td>2,041</td>
</tr>
<tr>
<td>Nkhata Bay</td>
<td>652</td>
<td>3.5</td>
<td>3,669</td>
</tr>
<tr>
<td>Sub-total, Estates</td>
<td>15,765</td>
<td>84.6</td>
<td>2,465</td>
</tr>
<tr>
<td>Smallholders, All Districts</td>
<td>2,862</td>
<td>15.4</td>
<td>1,049</td>
</tr>
<tr>
<td>Total All Producers</td>
<td>18,627</td>
<td>100</td>
<td>2,247</td>
</tr>
</tbody>
</table>

In the years from 1950 to 2000 Mulanje had an average annual temperature of 22.1°C with an average annual precipitation of 1,663 mm. Nkhata Bay has a slightly higher average annual temperature of 22.9°C and a bit less average annual precipitation with 1,445 mm. Thyolo has a lower average annual temperature with 21.6°C and a lower average annual precipitation of 1,266 mm.

The winter period (starting from May) is characterized by low temperatures and low precipitation rates (Figure 2). The temperature rises in September, while the precipitation rates increment in November. Projected precipitation changes are uncertain, but the temperature will rise by two to three degrees in 2030 and 2050 in the intermediate RCP 6.0 emissions scenario. The climate graph shows that the precipitation and the temperature of the summer term are adequate for tea production (described in the following section), since the average temperature is approximately 22°C and the monthly precipitation rate between 200 and 250mm. However, the winter term is rather dry with a precipitation rate of less than 50mm which is not favorable to the tea production. Nevertheless, the temperature still lies within a range positive to tea production.
Figure 2  Climate of the tea producing districts of Malawi; red represent current values, green and blue the average projections for 2030 and 2050 (RCP 6.0); bars show the average precipitation values for each scenario as well as its uncertainty range (error bars); temperature is shown as lines with its range (minimum and maximum) as dashed lines.

3.2 TEA AND CLIMATE

Tea (*Camellia sinensis*) and its varieties can grow in different climates in order to develop a high quality and harvest rate. The growth of the tea plant is highest when having warm and long days with a high humidity and a rainfall in the night (Carr, 1972).

The growth rate of tea is affected by changes of precipitation, both deficits and surplus of rain may impact the plant. Therefore, the distribution of the precipitation is of higher importance to the plant than the total annual rainfall (S. Ahmed et al., 2014; Bhagat et al., 2010; Carr, 1972). 150 mm precipitation per month is beneficial for the plant development, equaling an annual precipitation rate of 1,800 mm. However, the required precipitation rate is strongly tied to other factors such as the overall climate, the soil and the plant. Nevertheless, it can be assumed that an annual precipitation rate of less than 1,150 mm can’t be considered as beneficial for the plant development (Carr, 1972).

A daily temperature range between 13°C and 30°C is considered as being favorable to the leaf growth of the plant. Temperatures below or above this range probably reduce the growth of the plant or may harm it (Bhagat et al., 2010). Optimal temperatures for tea growth range between 18°C and 30°C (Carr, 1972), or around 22°C (Wijeratne et al.,
Furthermore, within the adequate temperature rate and with stable environmental conditions the tea growth was found to be linear to the temperature (Wijeratne et al., 2011).

In addition to precipitation and temperature solar radiation and soil conditions influence tea productivity. Tea grows better during the summer season when days are longer and the longer photoperiod results in higher photosynthetic activity (Bhagat et al., 2010). Poor soil conditions usually require more precipitation than good soil conditions in order to achieve the same productivity. The water holding capacity of the soil is of great importance and is determined by its structure and its physical parameters and its organic matter. Soils with a poor structure and less organic matter do not hold as much water as soils of better quality (Wijeratne et al., 2011) and therefore photosynthesis, growth and survivability of plants may be reduced (Selena Ahmed et al., 2014). Furthermore, the soil temperature affects the growth of the roots (Bhagat et al., 2010). The soil temperature of a depth up to 3 meters should range between 20°C and 25°C for creating optimal growth conditions for the plant (Carr, 1972).

Because of the climatic requirements of the tea plant any change in climatic conditions is likely to have an impact on its cultivation. Projected changes of the precipitation rates in the future suggest a strong variability as well as more frequent extreme climatic events such as heavy rainfalls or droughts and thus implying a high vulnerability of tea production (Selena Ahmed et al., 2014; Asfaw et al., 2014; Nkomwa et al., 2014). Between 1960 and 2006 the Malawian annual temperature increased by 0.9°C (World Bank, 2016). In addition, the number of hot days and nights have increased independent of the season. Between 1960 and 2003 the average annual hot days and nights have grown from 30 to 41 (Resilience Policy Team-Irish Aid., 2015).

Producers have already noted changes in the environmental conditions and have tied these to differences in temperature, winds, and rainfall. In southern parts of Malawi the beginning of rainfall shifted from November to December/January (Resilience Policy Team-Irish Aid., 2015). Additionally, other changes were observed such as declining rainfall trends, warming temperatures, increased frequency of and prolonged dry spells and relatively lower temperatures from October to early December (Nkomwa et al., 2014).

The analysis of the climate conditions of the current situation as well as of future scenarios is indispensable in order to understand the future climate impacts on the tea production and to be able to implement adaptation strategies to counteract these impacts. Therefore, this report analyses the current and future climate conditions and investigates the impacts on tea production areas of Malawi. In the subsequent chapters methods and final outcomes are presented and discussed.
The analysis of suitable zones for tea production in Malawi was based on a combination of spatial climate data and data of the spatial distribution of tea production. We based our analysis on two outputs from a climate classification approach: an agro-climatic zoning and a probabilistic suitability analysis. These two related classifiers were extrapolated on model data for future climate conditions to assess the suitability for tea production. In an iterative process the input data (variables and GPS data) as well as the preliminary outcomes of the modelling techniques were discussed and validated by experts.

4.1 CLIMATE DATA

Current climate data from Worldclim (Hijmans, 2012) was used in order to understand temperature and precipitation patterns for Malawi, as well as climate data projected for the future based on the Representative Concentration Pathway (RCP) 6.0 of the 5th assessment report of the Intergovernmental Panel on Climate Change (IPCC) (Stocker et al., 2013). RCP 6.0 is an intermediate scenario in which radiative forcing continues to increase until the end of the century (Fujino et al., 2006). We used data from 19 GCMs for future projections (Table 2). Of these, we chose three GCMs that represent extreme changes at current tea occurrences for annual mean temperature and annual total precipitation increases. “ncc_noresm1_m” was the GCM with lowest temperature increase and high precipitation increase (“cool-wet”), “giss_e2_h” was the GCM high temperature increase and a reduction in precipitation (“hot-dry”), and “cesm1_cam5” a GCM with average changes (“intermediate”).

Table 2 List of global climate models used to model future climate conditions. GCMs in bold were used to demonstrate climate projection uncertainty.

<table>
<thead>
<tr>
<th>bcc_csm1_1</th>
<th>gfdl_cm3</th>
<th>ipsl_cm5a_lr</th>
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</tr>
<tr>
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<td>csiro_mk3_6_0</td>
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<td>miroc_miroc5</td>
<td>nimir_hadgem2_ao</td>
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<tr>
<td>fio_esm</td>
<td>giss_e2_r</td>
<td>mohc_hadgem2_es</td>
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WorldClim provides data of monthly precipitation, mean monthly minimum and maximum temperatures, and 19 bioclimatic variables derived from these data. The data was interpolated at 0.5°ArcMin (approx. 1km at equator) from historic climate data. Following suggestions of local experts, three more variables (20 to 22) were included which represented the number of consecutive months of precipitation of less than 50mm, of a minimum temperature of 13°C and a maximum temperature of more than 30°C (Table 3).

To include variables that directly model the relationship between water requirements and temperature we added 8 variables that described seasonal patterns of potential evapotranspiration (PET). Based on temperature, precipitation and solar radiation data (Fick and Hijmans, 2017), PET was calculated using the approach of Hargreaves and Samani (Hargreaves and Samani, 1985):

\[
\text{PET} = 0.0023 \times R_a \times (T - t)^{0.5} \times (tm + 17.8) \text{ mm/day}
\]

Where \( R_a \) is the solar radiation, \((T-t)\) is the difference between monthly maximum and monthly minimum mean temperature in °C and \( tm \) is the mean air temperature in °C. The data for the solar radiation were converted from KJ m\(^2\) day\(^{-1}\) to mm/day. This equation has been frequently used for estimating the requirements of crop modelling (Kra
and Ofosu-Anim, 2010; Läderach et al., 2013) since this method doesn’t need as much data input as the more popular alternative for PET calculation from Penman-Monteith (Allen et al., 1998). Based on the calculation it was possible to determine thirteen variables for PET.

As a result 35 bioclimatic variables were used that describe the seasonal characteristics of precipitation and temperature of an average year, with a resolution of 30 arc-seconds (approximately 1km over the equator) (Table 3).

Table 3  Bioclimatic variables used for classification

<table>
<thead>
<tr>
<th>Variable</th>
<th>Variable</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bio 1</td>
<td>Annual mean temperature</td>
</tr>
<tr>
<td>Bio 2</td>
<td>Mean diurnal range (Mean of monthly max temp - min temp)</td>
</tr>
<tr>
<td>Bio 3</td>
<td>Isothermality (bio 2 / bio 7) * 100</td>
</tr>
<tr>
<td>Bio 4</td>
<td>Temperature seasonality (st. dev. * 100)</td>
</tr>
<tr>
<td>Bio 5</td>
<td>Max temperature of warmest month</td>
</tr>
<tr>
<td>Bio 6</td>
<td>Min temperature of coldest month</td>
</tr>
<tr>
<td>Bio 7</td>
<td>Temperature annual range (bio 5 - bio 6)</td>
</tr>
<tr>
<td>Bio 8</td>
<td>Mean temperature of wettest quarter</td>
</tr>
<tr>
<td>Bio 9</td>
<td>Mean temperature of driest quarter</td>
</tr>
<tr>
<td>Bio 10</td>
<td>Mean temperature of warmest quarter</td>
</tr>
<tr>
<td>Bio 11</td>
<td>Mean temperature of coldest quarter</td>
</tr>
<tr>
<td>Bio 21</td>
<td>Number of consecutive months &lt; 13 min. temp</td>
</tr>
<tr>
<td>Bio 22</td>
<td>Number of consecutive months &gt; 30 max. temp</td>
</tr>
<tr>
<td>Bio 12</td>
<td>Annual precipitation</td>
</tr>
<tr>
<td>Bio 14</td>
<td>Precipitation of driest month</td>
</tr>
<tr>
<td>Bio 16</td>
<td>Precipitation of wettest quarter</td>
</tr>
<tr>
<td>Bio 18</td>
<td>Precipitation of warmest quarter</td>
</tr>
<tr>
<td>Bio 20</td>
<td>Number of Consecutive Months &lt; 50 mm precipitation</td>
</tr>
</tbody>
</table>

4.2 GEO-REFERENCES OF TEA PRODUCTION

GPS data was collected of the tea distribution in the tea growing districts of Malawi. In total 182 data points were collected, of which 7 were removed because they were in identical grid cells at 0.5’ resolution. Of the remaining 175 occurrences 75 were located in Thyolo, 65 in Mulanje and 35 in Nkhata Bay. The data was collected by first circling the outline of major tea production areas. In a second step additional points were collected from within these areas
The remaining points of tea occurrences were located within an altitude of 487 to 1,236 m above sea level (mamsl), with the majority of points within 550 and 750 mamsl.

4.3 SUITABLE TEA PRODUCTION AREAS WITH RANDOM FOREST

Random Forest (RF) is an ensemble learning method which is commonly used for image classification. In this technique outcomes of different classification tree models are considered for calculating the response. The final classification vote is the modal vote across the forest ensemble of individual classification trees that were trained on random subsamples of the training sample. This way, the method overcomes the shortcoming of using only one decision tree, since the result of a single tree may be biased. Using multiple decision trees provide a more accurate prediction of classification values and avoids over confidence (Breiman, 2001; Horning, 2010). We used the Random Forest (RF) (Breiman, 2001) classifier in two distinct applications. (1) We initially used it to produce a dissimilarity measure to group occurrence locations into suitability clusters with similar climate characteristics in an unsupervised variation. (2) We used the RF classifier to classify soil and climate data of current and future conditions into the resulting suitability types.

First, to determine distinct suitability zones for tea we used the RF classifier in unsupervised mode (Shi and Horvath, 2006) to calculate dissimilarities based on the bioclimatic variables at tea locations. Clustering was performed using Ward hierarchical clustering using the dissimilarities as input. The number of clusters was determined based on visual inspection of a cluster dendrogram. Description of climate types was based on the difference of within cluster means to the global mean at all locations for selected climate variables. We then trained the RF classifier to recognize the resulting suitable climate zones for tea production areas in Malawi for the current climate and subsequently used this classifier to evaluate the climate in future scenarios of the periods 2020 to 2049 (referred to as 2030) and 2040 to 2069 (referred to as 2050). To do so, the selected variables and the GPS data of the tea presences were joined and were used as an input into the model. In addition, a random background sample set of points within regions of Malawi not known to produce tea was drawn to characterize the general environment at a sampling ration of 1:1 background to occurrence locations. Each RF forest classifier was configured to create 300 decision trees, using all variables available, and to be replicated 25 times (‘forests’). In each repeat a different subset from the presence sample was drawn at the size equaling half the number of case in the smallest subgroup. Such reduction of ecological sampling bias has been shown to improve the capacity of niche based approaches to correctly predict species distributions (Varela et al., 2014).

With this configuration and inputs, the model was extrapolated in two different ways: as a climate type analysis and as a probabilistic suitability score. First, the modal classification of all RF trees was used to determine the distribution of climate classes under current and future climate conditions using all climate variables. Next, we used the percentage of votes by individual trees in the forests to evaluate the model agreement whether a location belongs to one of the suitable classes or the background class. We used this approach to reflect uncertainty in the final model output as follows: we included the suitability classes “mixed” and “limitations”. A grid cell was labeled “mixed” when it was suitable with high certainty but below the 5th percentile of classification confidence, i.e. the agreement of trees across all forests. A grid cell was labelled “limitations” when its most likely class was “unsuitable” but the combined probability to be in one of the suitable classes was higher than the 1st percentile at occurrence locations.

In addition to climate, information of the soil conditions was assessed. The suitability of a site for tea production is not only defined by its climate, but also by soil attributes. To include such information in the suitability zone mapping we developed a soil suitability model from several soil attributes using RF classification. We here focused
on soil attributes that provide resilience against adverse climatic events. The data was provided by the International Soil Reference and Information Center (ISRIC) (Leenaars et al., 2015) of a resolution of 30 arc-seconds. The variables from this source were assembled for a project that assessed the capacity of soils to provide drought resilience for maize production. From the full set of 122 variables a subset of 18 were selected for evaluation by Malawian experts (Table 4).

We implemented a supervised binary classification approach based on the assumption that tea is cultivated at locations with appropriate soils. We used the occurrence location data set as the suitable class, and sampled random background locations in a ratio of 1:1 background to occurrence locations. We trained RF in 25 repeats using random subsamples of this dataset and the soil attributes for training. We then had the RF classifiers evaluate the probability of each grid cell to belong to the suitable or background class. The final map of soil suitability was derived by normalizing the individual classifications from 0 to 1 and averaging the results.

Table 4 Soil Variables for soil classification

<table>
<thead>
<tr>
<th>Variables</th>
<th>Variables</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Bulk density (kg / cubic-m) of the fine earth, at 22.5 cm depth</td>
<td>12 pH (x 10) of soil-water solution, at 22.5 cm depth</td>
</tr>
<tr>
<td>2 Bulk density (kg / cubic-m) of the fine earth, at 150 cm depth</td>
<td>13 pH (x 10) of soil-water solution, at 150 cm depth</td>
</tr>
<tr>
<td>3 Cation exchange capacity (cmolc / kg) of the fine earth, at 22.5 cm depth</td>
<td>14 Sand content (w%) of the fine earth, at 22.5 cm depth</td>
</tr>
<tr>
<td>4 Cation exchange capacity (cmolc / kg) of the fine earth, at 150 cm depth</td>
<td>15 Sand content (w%) of the fine earth, at 150 cm depth</td>
</tr>
<tr>
<td>5 Clay content (w%) of the fine earth, at 22.5 cm depth</td>
<td>16 Available water capacity (v%) of the fine earth, aggregated over the top 30 cm, with field capacity defined at pF 2.3</td>
</tr>
<tr>
<td>6 Clay content (w%) of the fine earth, at 150 cm depth</td>
<td>17 Moisture content (v%) of the fine earth at saturation, aggregated over the top 30 cm</td>
</tr>
<tr>
<td>7 Organic carbon content (g / kg) of the fine earth, at 22.5 cm depth</td>
<td>18 Textural class (USDA) of the fine earth, aggregated over the top 30 cm</td>
</tr>
<tr>
<td>8 Organic carbon content (g / kg) of the fine earth, at 150 cm depth</td>
<td></td>
</tr>
</tbody>
</table>

To better understand the separate effects of temperature, precipitation, evapotranspiration and soils on the suitability projections we carried out additional projections with classifiers trained and extrapolated on the respective sets of variables. This classification was carried out as described for climate variables with subsampling from clustered occurrences to avoid ecological bias. An overview over the different classifications is given in Table 5. The individual classifications were combined into a single suitability score by averaging. Soils suitability was assumed to remain constant over time.

\[
\text{Suitability score} = \frac{(\text{Soil}_\text{Suit} + \text{Temperature}_\text{Suit} + \text{Precipitation}_\text{Suit} + \text{Evapotranspiration}_\text{Suit})}{4}
\]

A minimum suitability score threshold was defined by the lowest value at an occurrence location. Locations below the threshold were assumed to be unsuitable.
We defined a gradient of climate change impacts following the framework described in the introduction. We separated tea areas in Malawi into five different groups: cope (no change of climate zone), adjust (change of climate zone but still suitable for tea), transform (change of climate zone and not suitable for tea anymore), and opportunity (change of climate zone and now suitable for tea). Global climate model uncertainty was reflected by the class “Resilience” which was assigned to areas where less than 11 of the 19 GCMs agreed on the future result.

### 4.4 MODEL VALIDATION

We used three methods to validate our model of the distribution of suitable climates for tea. Foremost, we used focus group and individual discussion with local experts from several stakeholder groups to confirm our projections. Additionally, we compared the model distribution for tea with a coffee as a reference crop. Finally, we used a commonly used metric of prediction performance to assess the discrimination capabilities of our classifier.

The climate change impact model derived from machine learning was validated together with local experts (environmental CSOs, smallholders, and local municipalities). This concept follows the idea of a participatory research methodology (Bergold and Thomas, 2012; Cornwall and Jewkes, 1995; Pain and Kindon, 2007) where research is carried out by including local experts. These local experts take part in the phenomenon of interest of the investigation and provide local knowledge and experience. Including a participatory component into an investigation adds a practical perspective to the scientific approach with the goal that both sides benefit from each perspective (Bergold and Thomas, 2012). Participatory research focuses on the knowledge and condition of the research site and helps connecting problems and processes at different levels and perspectives. Especially marginalized groups can be taken into account with this bottom-up approach (Pain and Kindon, 2007).

This participatory methodology was used for exploring how modeled impact scenarios align with perceived changes of the local experts of the tea community. Studies have already been conducted combining modeling outcomes with local expert knowledge. In particular (DeVries et al., 2016) validated the outcome of the random forest modeling technique by local experts. In (Keane and Reeves, 2012) as well as in the report of (Vargas et al., 2009) local experts were used to validate maps, whereas in (Foody and Boyd, 2013) scientific data was combined with data generated by a participatory GIS (geographic information system) approach.

During the model development phase we engaged twice with local stakeholders. First, we gathered available data and implemented a best practice model. With these results and input data local experts were approached for...
evaluation. In a first step, preliminary findings of a first run of the model were presented in various workshops in Malawi, discussed and evaluated in order to understand if these findings matched the perception of the experts and secondly to improve the findings by enhancing the model inputs. The model was then updated according to recommendations. In a public workshop the updated results were shared and additional feedback was invited. This resulted in a final round of model review. The experts participating in the workshops were several experts of tea estates (Lujeri and EPM), and experts of the Smallholder Association (NSTGA) and two research institutes (TRF and Bvumbwe Research Station). In a second and subsequent step, the preliminary results were presented within a workshop on tea and climate change in Malawi to representatives of key stakeholders, including estate managers, NGO representatives, policy actors and smallholder representatives.

Last, participants in the latter workshop suggested the comparison with coffee distribution maps as a reference distribution. Experts claimed that coffee has climatic requirements similar to tea. Coffee is produced by two related species. Robusta coffee (Coffea canephora var. Robusta) accounts for 30 % of global production (USDA 2012). It is generally more heat tolerant, but is more susceptible to low temperatures than Arabica coffee (Coffea arabica) (Wintgens, 2009). We used climate suitability data from a global assessment of potential climate change impacts on coffee in the same climate scenario as for tea from (Bunn et al., 2015) to compare the modeled climate suitability distributions of tea and coffee.

Additionally the current distribution was validated using the multiclass area under receiver operating characteristic curve (AUC) (Hand and Till, 2001) as implemented in the R package “pROC” (Robin et al., 2011). The AUC assumes values 0 – 1. An AUC of 0.5 indicates that the performance was no better than random sampling, while 1.0 is perfect classification. This definition of the AUC measure can be extended to multiclass problems by averaging all pairwise AUC comparisons to a multiclass AUC (Hand and Till, 2001). We used this measure to evaluate the discrimination of agro-climatic zones by the RF classifier.
5 RESULTS

In this section we first discuss the differences between the tea production zones in Malawi. The following presents the distribution of these climate zones under current and future climate projections. The difference between current and future distribution results in a gradient of impacts. Finally differences are discussed and the validation is presented.

5.1 CLUSTER ANALYSIS

The cluster analysis grouped 175 tea occurrences in three different clusters based on analysis of the cluster dendrogram (Figure 3).

![Dendrogram of agglomerative clustering using RF dissimilarities.](image)

Figure 3 Dendrogram of agglomerative clustering using RF dissimilarities.

The differences of the averaged characteristics of these presences were used to establish the following three different types of suitability for tea production:

- **Type 1** - Warm to hot temperature and high precipitation: characterized by a high average annual temperature and the annual precipitation is very high. High dry season temperatures.
- **Type 2** - Temperature seasonality and high precipitation: characterized by moderate average annual temperatures, a high maximum temperature of the warmest month as well as high diurnal temperature range. The annual precipitation is high with higher precipitation in the driest month than in other zones, additionally, the dry season is defined as short.
- **Type 3** - Cool and dry: characterized by lower average temperatures throughout the year than elsewhere. The annual precipitation is low and the dry season long.

Type 1 climate was for the most part located in the districts Chitipa, Karonga, Mulanje and Nkhata Bay in altitudes between 470 and 2,900 mamsl (with an average of 900 mamsl). The areas of Type 2 were mostly distributed in the
districts Mulanje and Phalombe in altitudes of 550 and 900 maml (with an average of 700 maml). Lastly, Type 3 zones were located in Thyolo of altitudes between 350 and 1,850 maml (with an average of 794 maml) (Figure 4).

All climate types were projected to be affected as climate change progresses. The type 1 area in Nkhata Bay will be substantially reduced and most area will either be strongly limited or “mixed”, meaning that no clear classification was possible. The type 2 area around Mulanje was projected to disappear beyond 2030 and replaced by “mixed” type climate of uncertain characteristics. Type 3 climate will also be reduced in extent and in the future be confined to a smaller area (Figure 4).

We compared the classification results for three GCMs by 2050 that were representative of the range of projected climatic changes. This showed that the classification result for the South was robust for all GCMs: the type 3 climate largely prevails while the type 2 climate will be reduced in extent. Most area will be of a ‘mixed’ class with uncertain properties. However, the Northern Nkhata bay area was projected to face high uncertainty, depending on the future trajectory of climate change. In a worst case scenario the area will not remain suitable, while in a best case scenario the area may remain largely unaffected (Figure 5).
5.2 SUITABILITY ANALYSIS

The previous section of the cluster analysis was based on the majority vote across all classes. In contrast, the probabilistic suitability analysis was based on the number of tree votes that a location belongs to one of the suitable classes for tea on subsets of variables and displays the outcome with results from zero to one. We averaged suitability scores derived from soils, temperature, precipitation and evapotranspiration data. In the model that used all variables, the algorithm accounted for interaction and automatically assigned importance to variables. Here, the different sets of variables were weighed equally and no interactions between temperature and precipitation were considered. High resolution individual suitability score maps for the different sets of variables were placed in the annex.

For future periods we derived the mean probability across all climate scenarios considered. As a suitability threshold the value 0.6 was used, which is the minimum value at occurrence locations. Areas with lower values were determined as not being suitable for tea production. Figure 6 shows the outcome of the classification of the current situation and the future scenarios. Areas of a high suitability for tea were projected in Nkhata Bay, Thyolo and Mulanje. It can be noted that these areas were projected to be reduced for the future scenarios, in Nkhata Bay they vanish completely and are replaced by low suitability areas (Figure 6).
Comparison of the individual projections for selected GCMs for future periods showed that this result is robust for the range of projected climatic changes (Figure 7). In the NCC_NORESM1 scenario which projects precipitation increases and a moderate temperature in Malawi the overall distribution of potential tea growing zones remained similar to the current distribution. Reductions of area may only be seen at the margins. However, in the two GCM scenarios that project a more substantial temperature increase and either constant or reduced precipitation the area in for tea was projected to be reduced. Especially in the Nkhata bay area the models agreed that the area would no longer remain suitable. In the South the tea growing areas were projected to be confined to its core areas.
The development of the underlying individual suitability scores derived from temperature and evapotranspiration variables showed a similar trend as the overall suitability score, while the score from precipitation was in agreement with the agro-climatic zoning classification (Figure 8). The soils suitability was assumed to remain constant. High soils suitability was found in the core tea production areas but also in other regions, e.g., extensive areas North of Nkhata bay and in the Mangochi area (Figure 8a). Temperature suitability for current conditions was found to be highest in the tea areas but also in zones of intermediate altitude. With progressing climatic changes the high suitability zones were projected to migrate progressively towards higher altitudes (Figure 8b). Mean suitability scores for precipitation remained largely similar from current to future conditions (Figure 8c). Precipitation suitability showed high suitability in the tea growing areas and surrounding areas. Little area beyond these regions was found to have adequate suitability scores except the Northern Chitipa region. The suitability score for evapotranspiration under current conditions closely reproduced the current distribution of tea growing areas with some additional area in Chitipa. In the climate change projections the Northern Chitipa and Nkhata bay areas were projected to have inadequate conditions and only Southern Thyolo and Mulanje remained suitable, although on reduced area (Figure 8d).

Comparison of each of these projections for representative GCMs shows that these results were robust for the range of projected climatic changes in Malawi. Temperature projections differed by the degree of migration. Precipitation projections disagreed qualitatively with the GCM that projects and overall increase of precipitation projecting an expansion of area, and on the other hand the GCM that projected reductions of precipitation.
resulting in reduced suitability in the Nkhata bay zone. Evapotranspiration scores were similar for all GCMs, although in the wet scenario Nkhata bay was projected to remain marginally suitable (Annex).

Development of suitability scores for variable sets:
- a) Soils
- b) Temperature
- c) Precipitation
- d) Evapotranspiration from current conditions to 2030 and 2050 in the RCP 6.0 emissions scenario.

Figure 8  Distribution of suitability for tea in Malawi by 2030 and 2050 in the RCP 6.0 scenario for different sets of variables (future time steps represent means for 19 GCMs).

5.3 IMPACT GRADIENT

The impact gradient interprets how climate change was projected to affect the tea production areas of Malawi in the median climate scenario (Figure 9). A great share of the area fell into the category Cope which means that a fair quantity of area will remain suitable in 2030 and 2050. In the four districts in the South (Mulanje, Thyolo, Phalombe and Chiradzulu) an increase of the category Transform was projected between 2030 and 2050 which means a loss of suitable area for the tea production. At the margins of the tea locations extensive area was projected to be in the “systemic resilience” adaptation class. GCM projections showed a high degree of uncertainty in these areas so that no clear impact scenario could be identified.
Figure 9  Gradient of climate change impacts

Figure 10 details the area distribution of the results shown in the previous map for the districts Chitipa, Mulanje, Nkhata Bay and Thyolo. We limited analysis to these districts because most other districts had little or no suitable area for tea or were not of stakeholder interest.

The largest part of Northern Chitipa was unsuitable under current conditions and will remain unsuitable under future conditions as well (Figure 10). However, the region was listed as a potential expansion area for tea by TAML. The gradient of impacts suggested that of the suitable area most will remain suitable. Only incremental adaptation will be necessary on a quarter of currently suitable areas. These areas were located along the low altitudes bordering Karonga district. The high altitudes west of this were projected to require systemic resilience as a main adaptation strategy. Climate projections for this regions were uncertain as to whether the area will remain suitable, or not. Further West in Chitipa where the topography drops again the slopes were projected to become unsuitable.

Currently nearly half of the Nkhata Bay area was found to be suitable (Figure 10). Progressively, most of this area will require substantial adaptation to climate change. In the most likely climate impact scenario, of the suitable area less than half will remain suitable with only incremental adaptation that relies on known hazard management. Most area will face high uncertainty as climate projections disagree about the degree of impact.

Most of Thyolo was found to be suitable under current conditions (Figure 10). Progressively, most of the suitable area will require substantial adaptation to changed climatic conditions. By the 2050s about equal parts of the district
will become unsuitable, require incremental adaptation or face uncertainty. The future unsuitable areas were found mostly along the lower slopes of the district while higher slopes were found to remain suitable.

Under current conditions the entire Mulanje district was found to be suitable for tea production (Figure 10). Only approximately 20% would remain suitable with only incremental changes to production in the climate change scenario.

![Figure 10](image)

**Figure 10** Area distribution of impact gradient for selected districts.

### 5.4 MODEL VALIDATION

We used three approaches to validate our model of the climatic suitability for coffee production: expert validation, comparison with a reference crop, and a quantitative model performance metric.

The experts that were consulted stated that their perceptions coincided with the preliminary findings. However, they suggested certain improvements mostly to the climatic variables of the model. As a result of the first round of validation we added soil data to be included in the model, completed the geo-reference database of tea production locations. Finally, agricultural practices to adapt to climate change were discussed and evaluated.

In the second step, the preliminary results were presented within a workshop on tea and climate change in Malawi to representatives of key stakeholders, including estate managers, NGO representatives, policy actors and smallholder representatives. Stakeholders confirmed the ability of the algorithm to correctly reproduce the current distribution of tea growing areas in Malawi, and also potentially suitable areas in proximity of current production and the extreme North of Malawi. However, representatives of the Tea Association of Malawi and the Tea Research Institute claimed that the model underestimated potentially suitable areas across Malawi, especially highlands in the North and in the districts Nchisi and Dedza. Their claim was based on their observation that areas suitable for coffee may also be suitable for tea production in the country.
Experts in Malawi cited coffee production as a useful indicator to assess the climate suitability for tea. We therefore compared the distribution of suitable climates for tea with the potential distribution of coffee production in a climate change scenario. We identified suitable areas for the highland coffee species Arabica in Chitipa and high areas in Mulanje. Nkhata bay and Thyolo were found to be marginally suitable for Arabica under current climate (Figure 11). In the future area was found to be reduced substantially and confined to high elevations. Nkhata bay and Thyolo would no longer be suitable for Arabica cultivation.

![Figure 11](image1.png)

Figure 11  Climatically suitable areas for Arabica coffee production in Malawi under current (left) and 2050 conditions (right) from (Bunn et al., 2015).

For Robusta coffee production highly suitable areas were identified in Nkhata bay and in lower elevation Chitipa but none in the Southern areas. In future conditions these areas were projected to higher altitudes in Chitipa, but to disappear in Nkhata bay. Some novel areas were projected to become newly suitable in the South (Figure 12).
Figure 12  Climatically suitable areas for Robusta coffee production in Malawi under current (left) and 2050 conditions (right) from (Bunn et al., 2015).

Thus, the combined distribution of suitable areas for Arabica and Robusta coffee does resemble the distribution of tea climate under current and future conditions. The areas that were found suitable for tea were largely identical under current conditions with the areas that were projected to be suitable for coffee. The impacts of climate change on Nkhata bay were similar to the suitability score map derived from the overlay of individual suitability scores but not the cluster analysis. In Northern Chitipa impacts on tea and coffee were somewhat similar with a tendency to migrate in altitude. In the South projections for coffee and tea diverged, with tea projected to remain suitable, but coffee losing suitability.

Finally, the multiclass AUC was .82, where 0.5 would indicate a random classification and 1 a perfect separation. The score of .82 indicates a better than random classification ability. However, the occurrence classes and the background class appeared to be climatically similar so that classification performance is not perfect.
6 DISCUSSION

- The discussion/conclusions are quite short I find. If you would like to focus your work, I would focus on making conclusions clearer, and maybe expanding discussion around recommendations.
- With respect to the suitable areas that TAML was looking for – I see that you included the analysis of the coffee growing regions and also mention the negative outcome in this respect in the discussion. But maybe we could be even clearer about it? I had the feeling I understand it with this background knowledge, but maybe to people like Sangwani it would be too implicit?

Our objective was to develop an actionable assessment of the climate change impacts on tea production in Malawi. We combined state of the art climate impact analysis with expert validation in an iterative process. Validating and incorporating suggestions into the model development served provide more actionable information to stakeholders.

We found that climate change poses a substantial risk to tea production in Malawi. However, currently available global climate projection showed high uncertainty about the future development of precipitation in the region, which is vital information for farmers. Because sufficient precipitation throughout the year is the most important determinant for tea production and GCMs disagree in the direction of projected changes, that is some GCMs projecting increases, other decreases, future projections were equally uncertain about the degree of climate change impacts. The classification model trained on the entire set of variables was therefore ambiguous about the direction of change and suggested that tea growing areas in Malawi will remain suitable as a most likely scenario. This contrasts with results in other studies that found serious decreases of suitability for tea in Kenya (Eitzinger et al., 2011).

We therefore complemented the initial classification model that was based on all variables with four additional classification models that were built on subsets of variables. While the classifier on all variables autonomously assesses the relative importance of variables, the second approach allowed for expert valuation of impacts. Our classification approach assumed the relative importance of variables to be constant over time and did not mechanistically account for the possibility that in the future other variables may become more limiting to production. In the classification approach on all variables precipitation variables were dominant in the assessment because they currently best separated areas with tea occurrences from areas without tea occurrences in Malawi. With increasing temperature this relationship may not hold true.

It has been argued that Malawi will face a “novel” climate that has no current analogous climates (Dahinden et al., 2017). It will therefore be necessary to account for this uncertainty and conduct further research to reduce this uncertainty. As was shown in the analysis of suitability scores the quantity and distribution of rainfall was projected to remain adequate for tea production in future periods. In addition, we assumed soil suitability to remain constant and unaffected over time. However, risks to tea production were projected from temperature increases and changes in evapotranspiration. Future temperatures will be unlike temperatures currently found at tea production locations. For Arabica coffee increased leaf temperatures have been shown to be potentially lethal (Marias et al., 2017). High temperatures have been shown to result in higher leaf turnover and abscission in cocoa (Almeida and Valle, 2007). Such effects could potentially affect the productivity and the management of tea production. In addition, even with sufficient soil water availability Arabica coffee has been shown to close stomata in low humidity conditions (Kaneki et al., 1988). Thus, it appears feasible that supra-optimal temperatures and reduced humidity pose substantial risks for tea production.
The stakeholder workshops for model validation were an effective means to improve the use value of the classification model. Quantitative metrics such as the AUC may be misleading to evaluate model performance (Lobo et al., 2008). Validating models with expert knowledge and expert defined proxies has been argued to increase the value of the information to support decision making processes (Shepherd, 2015). We incorporated variables that experts argued were important determinants of tea production. Some experts had raised concern that our model underestimates the potential for tea area in Malawi, citing positive experiences with coffee and good soils. Our analysis of soil variables showed that according to this metric potentially additional areas could be used for tea production. However, all other analysis support the notion that only Chitipe could be used for expansion of tea under current conditions, but would face similar threats from climate change as existing areas. The comparison with coffee suitability (Bunn et al., 2015) also did not suggest that our tea classifier would underestimate the potential to grow tea in Malawi in future scenarios.

Available climate data and the existing capacity of GCMs to provide robust information about future trajectories of climate change were limiting factors for our analysis. It has been shown that climate change risk for Malawi results from the high climate variability (Stringer et al., 2010). Such effects may substantially harm quality and income from tea production (Selena Ahmed et al., 2014). Such effects therefore may be an important aspect to be considered to fully evaluate the potential impacts of climate change. As GCMs qualitatively disagreed in their projections about future precipitation trajectories this will be a challenging task.

7 CONCLUSIONS

From our analysis we concluded that climate change poses a substantial risk to tea production in Malawi. Stakeholders face high uncertainties from future developments of precipitation and the potential effects of heat and dry stress. The Nkhata bay area was found to be most vulnerable to climate change. Precipitation projections suggested sufficient, though uncertain, water availability. In addition there was high model agreement that temperatures and evapotranspiration may rise beyond sustainable levels in the region. Thyolo and Mulanje were found to be less at risk, even though there will be losses of suitable area in the lower slopes of the region. Facing these more or less drastic changes, it is recommended to adapt strategies to cope with these negative effects on tea production, such as agricultural practices or the use of different tea varieties which adapt to the local climate changes.

Nkhata bay was found to be most at risk from climate change. Under current conditions the area has sufficient precipitation for tea production but temperatures that are higher than in the South, especially during the dry season. The GCM projections for temperature and evapotranspiration suggested unsuitable conditions in the future, as well as some precipitation projections. As temperatures increase the Nkhata Bay area will experience temperatures beyond the levels found elsewhere in Malawi. In addition, this will likely result in increased evapotranspiration so that precipitation needs will increase. Of the GCMs used in this analysis some models projected reductions in precipitation to levels that would be unsuitable for tea, even when considering equal temperatures. Already, stakeholders reported that the area is productive only with irrigation, and that with very high temperatures productivity may be low despite these measures.

The climate change impacts in the Thyolo area will likely depend on the altitude. Low lying areas were found to be at high risk from climate change. Under current conditions precipitation and temperatures were the lowest of all tea growing areas. Currently, the potentially suitable area was found to extend to lower slopes. Such areas will be threatened by increasing temperatures even though most GCMS agreed that precipitation will remain at suitable
levels. The resulting increase in potential evapotranspiration will result in a reduction of the potential area to the higher slopes of Thyolo.

The Mulanje district was projected to face uncertain climate future. While it will most likely remain suitable, the projected conditions will be unlike current conditions. Under current conditions both temperature and precipitation were found to be optimal for tea production in the Mulanje district. Across most climate change projections precipitation levels will remain suitable for tea production. Temperatures, however, will exceed historic levels as early as 2030. By the 2050ies evapotranspiration levels will on average reach levels at the margin of currently suitable levels. While climate in Mulanje showed a tendency to migrate in altitude, soils suitability could be a potentially limiting factor to such an extension of area. Thus, the area will be suitable for tea production, but the combination of climate variables, high precipitation, high temperatures and high evapotranspiration should be considered a novel climate distinct from current conditions.

Stakeholders in Malawi pointed out that within Malawi tea currently does not occupy all potentially suitable areas. Especially in proximity to mountainous ranges suitable conditions may be found. Our approach evaluated the similarity of the state of variables to training samples and should thus be able to identify such areas. Additionally, we used data from a global study on coffee as a proxy to compare our results. As a result, we were able to confirm that at the Northern border with Tanzania suitable area can be found. Other areas appeared to be limited by inadequate soils, temperatures, or precipitation. Nevertheless, the suitable area in the North was projected to be affected by similar trends as the Nkhata bay area. Suitable temperatures and potential evapotranspiration were found to show a migration to higher altitudes as climate change progresses. Precipitation was found to be likely favorable but some scenarios showed that conditions in the future may be marginal. The combined projections for the two coffee species Arabica and Robusta closely resembled the potential distribution of tea under both current and future conditions. Coffee was found to be more affected by climate change as suitable area will likely disappear by the 2050s so that it can't be considered a good diversification option for tea producers.

8 OUTLOOK

This study showed that global climate change will be a substantial challenge for the tea sector in Malawi, but also that in parts of the country tea may remain a viable choice for producers if steps towards efficient adaptation are taken. Development of a climate smart tea sector in Malawi should consider a comprehensive view of climate change impacts and adaptation. Conventionally, adaptation to climate change in agriculture refers to a change of cultivation practices as a result of observed or projected changes in the climatic environment of the production system. A value chain inclusive approach acknowledges that impacts on production may have repercussions beyond farm scale, and that barriers to, and incentives for, adoption of novel practices are often external to farm scale.

An efficient strategy to adapt to climate change will need to be tailored to stakeholder needs and will include climate information services. Adaptation may either be spontaneous (e.g. migration during harsh drought) or planned (e.g. adopting a drought tolerant variety). Adaptation may be re-active to past events, or anticipatory of potential future events. Adaptation may seek to respond to climate variability or changes in long term average conditions. Stakeholders often perceive planned adaptation that seeks to anticipate long term changes a costly intervention that bears a high risk because of the incomplete knowledge about future developments. Without an ordered process, however, damages from climate change will result in economic losses. The process needs to be enabled by providing necessary climate information at various scales to stakeholders.
We recommend that tea stakeholders in Malawi develop a planned adaptation process that meets their needs and ability to act. In this process different stakeholders will design action according to their temporal and spatial involvement. At local scale, actors such as smallholders will likely be preoccupied with avoiding risks from catastrophic yield losses. Their action may be driven by recent experiences and the prospect of repeated occurrence of negative climate events. They would thus seek to minimize their risk on household level in the near term. On the other hand, regional actors would typically be interested in the long term viability of the sector. Such actors may be interested to organize collective efforts with effects over intermediate or long term. Depending on their objectives as a business, adaptive action by private companies would seek to minimize short term supply risk, but may also be interested in the long term viability of their capital.

Just as the ability to act differs among actors, so do climate information needs. As stated above, the long term projections discussed in this report can be used to support projects that seek to achieve climate adaptation at regional scale to secure the long term viability of the sector. Example projects may be the selection and diffusion of improved varieties that are able to tolerate lower humidity, or the protection of forest reserves to secure functioning ecosystem services that provide resilience against extreme events. Smallholder farmers, however, may be more interested to learn how recent hazards have to be contextualized in climatic trends in the immediate and near term. For example, seasonal forecasts would support actors to prepare for excessive drought. Communication about knowledge based expectations for the coming years, e.g. an increase in drought severity, may promote the adoption of cost-effective interventions with immediate effects such as mulching or temporary shade.

In conclusion, the development of portfolios of appropriate action that are tailored for different groups of actors is recommended. Climate information services at temporal scales of differing length will be required to support a planned anticipatory adaptation process. Landscape and other measures with a long term perspective promise high benefits for adaptation but will require collective action. At farm scale good agricultural practices should be promoted and developed into climate smart practices that respond to site specific hazards. We hope that this report is only the starting point towards a climate smart tea sector in Malawi.


Stocker, T. (2013). *Climate change 2013: The physical science basis : Working Group I contribution to the Fifth assessment report of the Intergovernmental Panel on Climate Change / edited by Thomas F. Stocker, Working Group I co-chair, University of Bern [and nine others]*.


Figure 13  Temperature suitability for tea production in Malawi. Data for future periods is the mean across 19 GCMs for the RCP 6.0 scenario.

Figure 14  Temperature suitability for tea production in Malawi in selected GCMs by 2050 the RCP 6.0 scenario
Figure 15  Precipitation suitability for tea production in Malawi. Data for future periods is the mean across 19 GCMs for the RCP 6.0 scenario.

Figure 16  Precipitation suitability for tea production in Malawi in selected GCMs by 2050 the RCP 6.0 scenario
Figure 17 Evapotranspiration suitability for tea production in Malawi. Data for future periods is the mean across 19 GCMs for the RCP 6.0 scenario.

Figure 18 Evapotranspiration suitability for tea production in Malawi in selected GCMs by 2050 the RCP 6.0 scenario
Figure 19  Soils suitability for tea production in Malawi.