Climate risk analysis for adaptation planning in Madagascar's agricultural sector

Potsdam Institute for Climate Impact Research

Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH

On behalf of

Federal Ministry for Economic Cooperation and Development

Climate risk analysis for adaptation planning in Madagascar's agricultural sector

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A report prepared by the Potsdam Institute for Climate Impact Research (PIK) together with the Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH on behalf of the German Federal Ministry for Economic Cooperation and Development (BMZ).

Acknowledgements

This work was commissioned and financed by the PrAda Project by the Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) in Madagascar, which is gratefully acknowledged. A special note of thanks goes to the colleagues from GIZ Madagascar, Lena Klockemann, Emilie Perrousset, Dr. Joost Koks and Lea Doumenjou for providing valuable contributions to the study. We thank them and GIZ Madagascar for providing overall support throughout the study process and assisting in the engagement of Malagasy stakeholders. We would also like to thank the Centre National de Recherche Appliquée au Développement Rural (FOFIFA) for providing access to data, such as for the calibration of the peanut yield model, and the Ministère de l'Agriculture et de l'Elevage (MINAE) for providing production data for the different crops considered. The study also greatly benefited from a workshop held in Antananarivo with stakeholders from the national government, civil society, academia, the private sector, practitioners and development partners. The lively discussions on the study approach and content resulted in insightful recommendations. We are grateful to Yvonne Okumu, who supported the analysis of household-survey data in Madagascar. Furthermore, the authors would like to thank all individuals interviewed for their time and the valuable information they provided.

Authors' contributions

Carla Cronauer, Chiara Sophia Weituschat and Lisa Murken coordinated and edited the overall study, ensuring alignment between the different analysis steps and distilling key results and the conclusion. Carla Cronauer prepared the first draft of the manuscript, supported by Chiara Sophia Weituschat. Sabine Undorf performed the climate analysis in Chapter 2 with contributions by Stephanie Gleixner. Anna Hampf conducted the crop suitability analysis as well as the crop yield analysis in Chapter 3 and 4, with climate data prepared by Stephanie Gleixner. Carla Cronauer prepared the evaluation of the gender dimensions and institutional support requirements for Chapter 4. Chiara Sophia Weituschat and Lisa Murken coordinated and implemented the socio-economic household data collection in Madagascar with significant contributions from Jillian Waid during the design and implementation phases.

Suggested citation

Cronauer, C., Weituschat, C. S., Hampf, A., Undorf, S., Gleixner, S., Waid, J. & Murken, L. (2024). Climate risk analysis for adaptation planning in Madagascar's agricultural sector. A report prepared by the Potsdam Institute for Climate Impact Research (PIK) in cooperation with the Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH in Madagascar on behalf of the German Federal Ministry for Economic Cooperation and Development (BMZ), DOI: 10.48485/pik.2024.005.

Design and Layout: Miguel Faber

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Abstract

KEYWORDS

climate change adaptation

climate impacts

climate risk

agriculture

coffee

vanilla

pepper

peanut

Madagascar

crop modelling

suitability modelling

Madagascar has a high socio-economic dependency on agriculture, a sector which is strongly influenced by weather-related factors and increasingly challenged by the impacts of climate change. Currently, only limited information on climate risks and its impacts is available for the country's agricultural sector. This study aims to provide a comprehensive climate risk analysis including a thorough evaluation of two potential adaptation strategies that can guide local decision-makers on adaptation planning and implementation in Madagascar. The impact assessment consists of several steps, including climate projections based on three emissions scenarios (SSP1-RCP2.6, SSP3-RCP7.0 and SSP5-RCP8.5 scenario), modelling and comparison of future suitability and yield of three widely used crops (coffee, vanilla, pepper) and an assessment of yield changes in peanut production under future climate conditions.

Further, the study outlines gendered challenges and support requirements in national adaptation planning. The simulation results show that Robusta coffee is less sensitive to heat compared to Arabica coffee. The suitable area for Robusta coffee remains almost stable under changing climate conditions, while the suitability of Arabica coffee is projected decrease by 7 % on a national level. Simulation results indicate a slight increase in suitability for vanilla production, particularly in the main growing region Sava, but also in Atsimo Atsinanana, thus safeguarding an important source of income for local farmers and guaranteeing the sustainability of Madagascar´s most valuable export product. Furthermore, climate change is projected to have a rather low impact on the agro-climatic suitability of pepper production. When averaged across Madagascar, the decrease in suitability is less than 1 %, however, there are some noteworthy differences across regions and scenarios.

The results for the process-based peanut modelling show that rising temperature and reduced rainfall amounts are likely to decrease peanut yields across Madagascar. However, elevated atmospheric CO_2 is projected to offset these negative impacts. The study furthermore evaluated the efficiency of two adaptation strategies, namely the use of locally adapted crop varieties and flexible planting dates. The simulation results suggest that the traditional cultivar Kanety is more suited in future climate change scenarios since yields for Kanety are generally higher than those of the improved variety Fleur 11. Interestingly, opting for flexible planting dates as opposed to a fixed planting date does not result in enhanced yields. This result underlines the importance of regional crop calendars to determine optimal sowing dates.

The findings of this study can help to inform national and local adaptation and agricultural development planning and investments in order to strengthen the resilience of the agricultural sector and especially of smallholder farmers against a changing climate in Madagascar.

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List of abbreviations

FIFAMANOR	Fiompiana Fambolena Malagasy Norveziana
FOFIFA	Centre National de Recherche Appliquée au Développement Rural
GDP	Gross domestic product
GIZ	Deutsche Gesellschaft für Internationale Zusammenarbeit
MEDD	Ministère de l’Environnement et du Développement Durable
MINAE	Ministère de l'Agriculture et de l'Elevage
MMEM	Multi-model ensemble median
NAP	National Adaptation Plans
NGO	Non-governmental organisation
RCP	Representative Concentration Pathway
SGG	Seed Grower Groups
SMC	Seed Multiplication Centres
SSP	Shared Socioeconomic Pathway

1. Introduction

This study provides an in-depth analysis of climate risks for selected cropping systems in Madagascar, together with recommendations and an accompanying assessment of selected adaptation strategies. While many countries increasingly recognise the importance of adaptation in a world of changing climate, there is often a lack of guidance on how to operationalise adaptation goals. The agricultural sector is particularly vulnerable to climate change, due to its high dependency on climatic factors. Extreme events and slow-onset events increasingly threaten agricultural production and pose a serious risk to agricultural livelihoods with cascading impacts on food and nutrition security. Low adaptive capacity in the agricultural sector, such as limited access to resources, formal credit or extension services, further increases the sector's vulnerability to climate change. Additionally, when it comes to adapting to climate change, decision-making often happens at the local scale. However, decision-makers often do not have all necessary information about specific climate risks in their area, the potential impacts and the benefits and barriers of different adaptation options. This calls for detailed climate risk analyses as a foundation for risk-informed and economically sound investment decisions at the local level. A better understanding of projected climate impacts on agricultural production, associated climate risks and possible adaptation benefits at both national and regional level is important to guide, incentivise and accelerate public and private-sector investments for climate-resilient agricultural development.

Madagascar faces challenges in adapting to a volatile and changing climate, particularly within its predominantly rainfed agricultural sector. Farmers typically cultivate small plots of land of less than 1 ha[1], allocating the majority of their land to subsistence crop production (Harvey et al., 2014). However, their crop yields remain low, failing to meet the demands of their households and lacking the surplus for commercial purposes. About 33 % of the population is chronically food insecure, making it extremely vulnerable to climatic and non-climatic shocks that further reduce agricultural production and food availability (Fayad, 2023). In its National Adaptation Plan (NAP), Madagascar points out the need for adaptation planning to cope with climate change related risks (MEDD, 2021). Therefore, this study seeks to provide a basis for risk-informed adaptation decisions for the production of coffee, vanilla, pepper and peanuts, by addressing the following questions:

- How are climatic conditions in Madagascar projected to change until the end of the century?
- How will these climatic changes influence agricultural production of coffee, vanilla, pepper and peanuts in Madagascar?
- How appropriate are the two adaptation options of flexible planting dates and selection of locally adapted varieties to address climatic risks in peanut production?
- What are gendered challenges and support requirements for adaptation planning in Madagascar?

The findings can support national and local policy makers, development actors, the private sector, and farmers, to inform long-term resilient land use planning, adaptation planning and investments.

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[1] One hectare (ha) corresponds to 100 are (a).)

Figure 1: Map of Madagascar.

1.1 Study area

Madagascar is an East African island state located in the Indian Ocean (CIA, 2020). The population exceeded 28 million in 2021 with an annual population growth rate of 2.4 % (World Bank, 2021a). The majority of the inhabitants live in the central highlands around the capital Antananarivo and along the eastern coast. Its economy is dominated by the services sector, which contributed 50.4 % to the country’s gross domestic product (GDP) in 2020, followed by the agricultural sector with 24.7 % and the industrial sector with 19.5 % (World Bank, 2020). Rice is by far the most important crop in terms of area harvested, followed by cassava, sweet potatoes and maize (FAOSTAT, 2021). In addition, as of 2021, Madagascar is the world's largest exporter of vanilla and cloves (OEC, 2021). Although services have surpassed the agricultural sector, 74 % of the population is employed in the latter, heavily relying on agriculture to sustain food security and secure livelihoods (World Bank, 2021b). Among the country's agricultural holdings, family farms constitute 99 %. They are responsible for cultivating 95 % of the land and own 97 % of livestock (Sourisseau et al., 2014). Malagasy family farms thus play a decisive role in the country's economy by generating between 1/5 and 1/4 of national GDP and employing nearly 8 out of 10 workers. Finally, these family farms shape, manage and maintain land on a country-wide scale (Sourisseau et al., 2014). However, most of these farms are subsistence-based and rainfed (FAOSTAT, 2021) and are therefore highly vulnerable to the increasing effects of climate change including rising temperatures, reduced water availability through changing precipitation patterns and more extreme weather events, such as droughts, cyclones and floods (Garruchet et al., 2023).

For the analyses in this report, we focus mainly on the six regions Androy and Anosy (south), Atsimo Atsinanana (south-east) and Fitovinany, Vatovavy and Atsinanana (east) (see Figure 1). These regions show a high vulnerability to climate hazards like cyclones (east coast) and droughts (southern regions) (Rakotoarison et al., 2018). Furthermore, they hold significant importance for the cultivation of cash crops like coffee and vanilla, along with other produce grown to ensure food security (Garruchet et al., 2023).

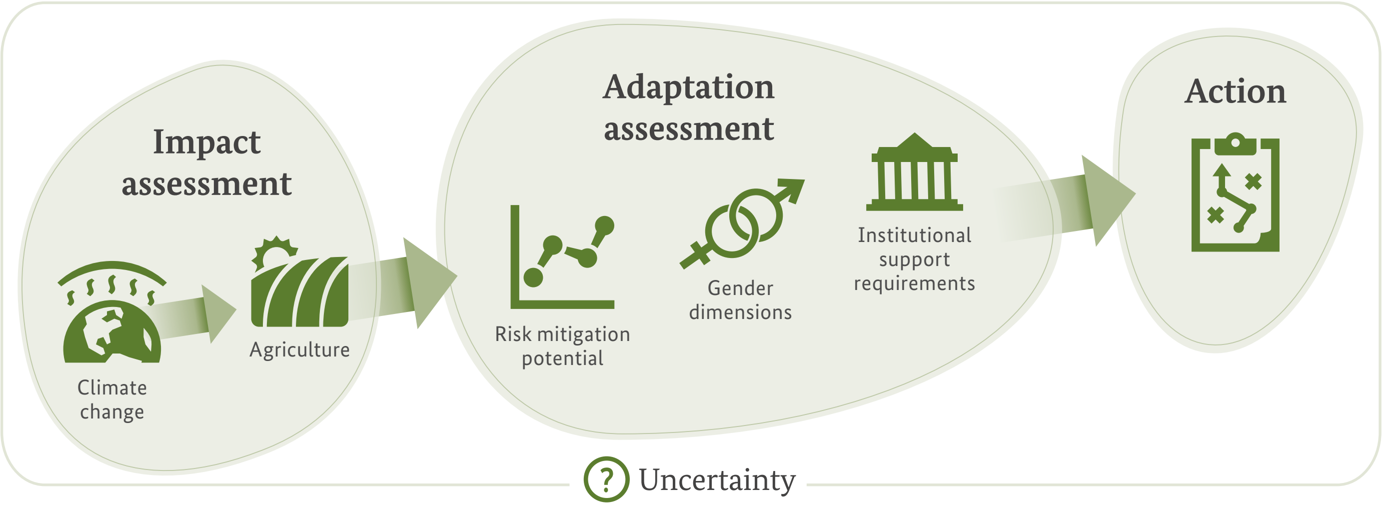

Figure 2: The impact-action chain of the climate risk analysis.

1.2 Study approach

The study presents a comprehensive climate risk analysis to deepen the understanding of current and projected climate risks and their impacts on agriculture as well as possible adaptation benefits at both national and sub-national (local) level. The entire chain from the impact of climate change to taking action is addressed, including analyses of specific adaptation options and support requirements (Figure 2).

The report's primary aim is to improve the evidence base on adaptation, which can help to identify interventions that are appropriate for a given locality. In addition, optimal timing of interventions as well as enabling conditions and barriers to adaptation are studied. Specific crops and adaptation options were selected to narrow down the study focus and provide concrete results to inform long-term climate adaptation planning in the south and east of Madagascar. The selection process of specific crops and adaptation options considered national priorities and feasibility criteria (i.e. compatibility with model analyses and data availability). The process led to the selection of coffee, vanilla, pepper and peanuts for the analysis of climate impacts on agriculture. Moreover, two adaptation options were chosen: the use of locally adapted varieties and flexible planting dates. These two adaptation options were selected due to relatively low implementation costs and limited needs for specialized training. They therefore aim to provide low-threshold access to climate change adaptation. However, those strategies are not meant to provide silver-bullet solutions, but should be interpreted as two possibilities within the wider context of building climate-resilient agri-food systems.

This report is organized as follows: **Chapter 2** gives an overview of the current climatic conditions of the island and how they are likely to change in the project regions in the next decades. **Chapter 3** elaborates the impacts of climate change on the suitability of coffee, vanilla and pepper production and shows the impacts of climate change on peanut yields. **Chapter 4** evaluates the selected adaptation strategies and their potential to buffer climatic risks. The adaptation strategies are further analysed according to their gender benefits and challenges as well as institutional support requirements. **Chapter 5** discusses the results and concludes the report.

2. Changing climatic conditions

To identify future changes in climatic conditions in Madagascar, this chapter analyses several indicators concerning temperature- and precipitation-related variables under three Shared Socioeconomic Pathways (SSPs). These represent different socio-economic developments as well as different pathways of atmospheric greenhouse gas concentrations, the so-called Representative Concentration Pathways (RCPs). The first, SSP1-RCP2.6, represents a low emissions scenario, SSP3-RCP7.0 a medium to high emissions scenario and SSP5-RCP8.5 a high emissions scenario. More information can be found in the Supplementary Information (Section 1) of this report.

The current climatic conditions of Madagascar are presented below (Chapter 2.1). This is followed by an outline of the future climate trends of mean annual and regional climate conditions (Chapter 2.2).

2.1 Current climate

Madagascar experiences two distinct seasons: a hot and rainy season occurring from November to April, and a cooler and dry season lasting from May to October. The sub-equatorial climate on the east coast is influenced by easterly trade winds, resulting locally in the highest and most consistent precipitation within the country, reaching up to 3,700 mm per year. Conversely, the west coast tends to be drier and is prone to significant coastal erosion. The southwest and extreme south are semi-desert environments, receiving less than 800 mm of rainfall annually. Along the coast, average annual temperatures range from 23 °C to 27 °C, while in the central mountains, they vary between 16 °C and 19 °C (CCKP, 2021). Changes in precipitation observed to date are small but tend towards drying rather than wetting. This trend is overlaid by strong interannual (natural) variability in precipitation.

2.2 Climate projections

Climatic changes are projected for the six regions Androy and Anosy (south), Atsimo Atsinanana (south-east) and Fitovinany, Vatovavy and Atsinanana (east) of the country. Information on the methodology of the climate projection can be found in the Supplementary Information (Section 2) of this report. Projected changes in annual mean temperatures for those six regions are shown in Figure 3.

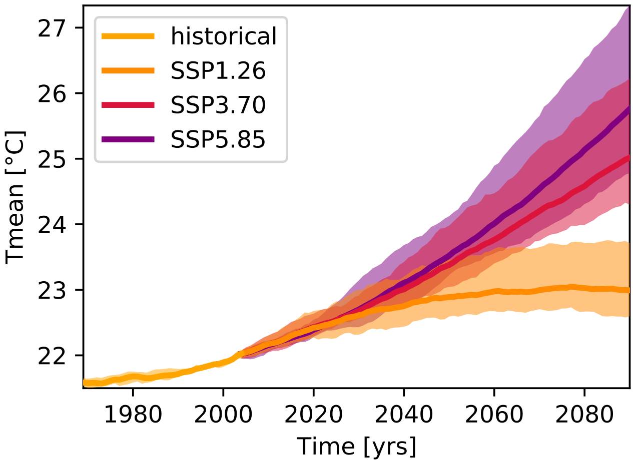

Figure 3: Projected 21-year mean, area-mean temperature change for the six regions Androy, Anosy, Atsimo Atsinanana, Vatovavy, Fitovinany and Atsinanana until 2100 for SSP1-RCP2.6, SSP3-RCP7.0 and SSP5-RCP8.5. The lines represent the multi-model mean value and the shaded areas the full range of the model ensemble.

All climate change scenarios project significant increases in temperature over all regions during the 21st century (Figure 3). This is evident in all analysed scenarios, albeit to different degrees. Under the low emissions scenario SSP1-RCP2.6, the multi-model ensemble mean (MMEM)[2] indicates a projected increase in temperature of around 0.7 °C until 2030 compared to pre-industrial levels and a projected stabilization of mean annual temperatures around 23 °C in the late 21st century. Under SSP3-RCP7.0, the medium to high emissions scenario, temperatures are projected to continually increase throughout the 21st century. By 2030, mean temperature projections show an increase of around 0.8 °C. Until 2050 projected temperature increases already reach 1.5 °C. By the end of the century, mean annual temperatures are projected to be around 25 °C.

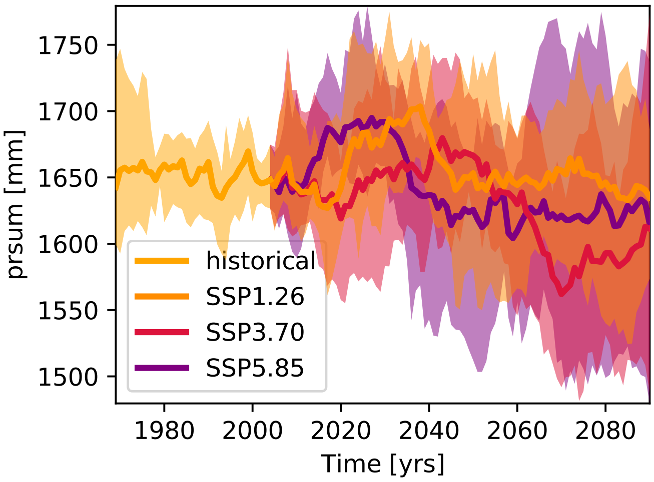

Figure 4: Projected 21-year mean, regional-mean change in precipitation for the six regions Androy, Anosy, Atsimo Atsinanana, Vatovavy, Fitovinany and Atsinanana until 2100 for SSP1-RCP2.6, SSP3-RCP7.0 and SSP5-RCP8.5. The lines represent the multi-model mean value and the shaded areas the full range of the model ensemble.

A steep increase in projected temperature can be observed under the high emissions scenario, SSP5-RCP8.5, resulting in a projected increase of mean annual temperatures of 1.6 °C until 2050, and mean annual temperatures of almost 26 °C by 2100 (Hampf et al., in preparation a). Precipitation trends are much more variable and more uncertain than temperature projections (Figure 4). Nonetheless, a decline in annual precipitation is projected, especially during the period around 2050 (2035–2064) and in medium-to-high and high emissions scenarios (Figure 5). There are also indications that heavy precipitation will be more extreme (Hampf et al., in preparation a).

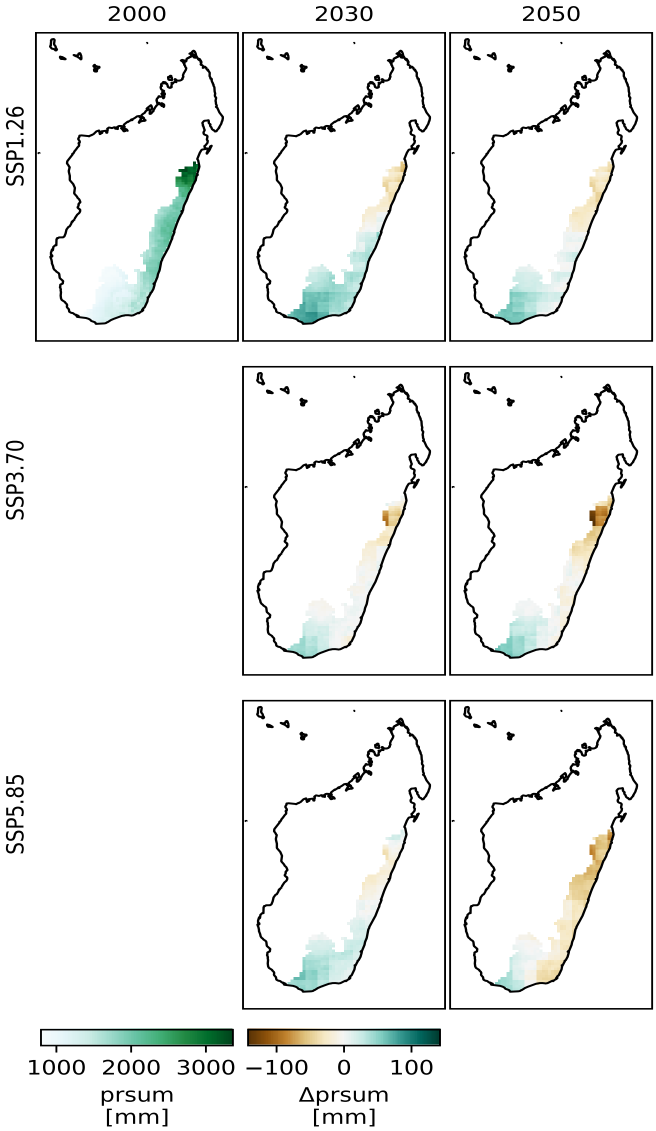

Figure 5: Projected annual-total precipitation for the projection regions within Madagascar for the historical baseline period (1985–2014) (left column), the change between the baseline period and 2030 (2015–2044) (middle column) and between the baseline period and 2050 (2035–2064) (right column). The multi-model mean is shown for the different climate change scenarios (top to bottom rows).

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[2] A MMEM is a method used to create a more robust and reliable estimate of future climate conditions. It involves using multiple different climate models to make predictions and then calculating the average (mean) of those predictions.

3. Climate change impacts on agriculture

About 62 % of Madagascar's population lives in rural areas, where they rely mainly on subsistence agriculture (CIA, 2020). Smallholder farmers are, however, particularly vulnerable to climate shocks due to dependence on rainfed agriculture, limited land area for growing crops and lack of access to resources and finance to prepare for and cope with extreme events (Harvey et al., 2014; Rakotobe et al., 2016). On one hand, crops may respond positively to elevated CO_2 concentrations due to climate change, but on the other hand, increasing variability of rainfall, increasing temperatures and more frequent and intense extreme events like cyclones and droughts can reduce agricultural production (Gachene et al., 2015). Under drier conditions, the proliferation of pests is exacerbated. A notable occurrence in 2021 was the outbreak of migratory locusts, which inflicted damage on over 48,000 ha of land in the south of the country. Additionally, an outbreak of fall armyworms led to crop losses of up to 60 % in severely affected areas (OCHA, 2021). Using a multi-model analysis, Tomalka et al. (2021) found that the proportion of crop land in Madagascar affected by at least one drought per year is projected to increase. While 0.4 % of the national cropland area was affected in 2000, it is projected that this area increases to 1.4 % and 2.6 % by 2080 under RCP2.6 and RCP6.0, respectively.

To make these figures more tangible: 2.6 % of the national crop land corresponds to about 15,000 football fields of crop land being affected by at least one drought per year. Preliminary descriptive results of a representative survey of over 600 farming households conducted in April and May 2023 in the three regions Anosy, Androy and Atsimo Atsinanana, reveal that 61 % of the interviewed farmers perceive weather conditions to have changed compared to the past 10–20 years and 91 % of the respondents have observed more droughts in the last five years than in the past 10–20 years (Weituschat et al., in preparation). Due to the impacts of climate change, a change in suitable crop production area and yields is projected for some crops. In the following sub-chapters, we present the results of a suitability model analysis for coffee, vanilla, and pepper as well as projected climate change impacts on peanut yields. The performance of the suitability model Ecocrop was tested against observed data on harvest area at district level from 2005–2010. During this time Vatovavy and Fitovinany were still one region (Vatovavy-Fitovinany) and thus the results in the following sub-chapters will be presented according to the past administrative division.

3.1 Climate change impacts on coffee production areas

Coffee continues to be one of the most important cash crops grown in Madagascar, despite the fact that the area under cultivation more than halved between 1990 and 2005. From 2005 until now, the area under coffee cultivation has been relatively stable at around 100,000 ha, which corresponds to one sixth of the total permanent crop area in Madagascar. The area only declined again in 2020/2021 due to drought (FAOSTAT, 2023). Figure 6 shows the average harvested areas in ha per district in the period from 2005–2010.

Coffee yields constantly increased from 0.35 t/ha in the 1990s to 0.55 t/ha in 2023 (FAOSTAT, 2023). In Madagascar, Robusta coffee dominates the coffee cultivation landscape, encompassing 95 % of the country's coffee-growing regions (MAEP, 2004). It occupies all areas of the east coast from Sambava to Vangaindrano, including medium-altitude areas up to 800 m (Ifanadiana), and the north-west coast in the Sambirano region. Additionally, it stretches along the north-western coast within the Diana and Sofia regions. Arabica coffee is found in the highlands at altitudes of 1,000–1,500 m, from the Ankaizina region (Bealanana) to south of Fianarantsoa (Ambalavao) (MAEP, 2004).

Suitability modelling can help to identify the regions which are most suitable for growing a certain crop based on temperature, precipitation and soil characteristics. It also supports informed land use planning by showing which regions are likely to be more or less affected by climate change. The objective of the following sub-chapter is to assess the suitability of coffee production in Madagascar for three different time periods: the recent past around the year 2000 (1985–2014), the near-future around 2030 (2015–2044) and the mid-term future around 2050 (2035–2064). To achieve this objective, the EcoCrop model (see Section 3 in the Supplementary Information) was calibrated to coffee cultivars grown in Madagascar and run with past and future climate data for two periods and three climate scenarios (see Chapter 2). Figure 7 shows the modelled suitability of Arabica and Robusta coffee cultivation in Madagascar for the 2000 period, i.e. averaged over 1985–2014.

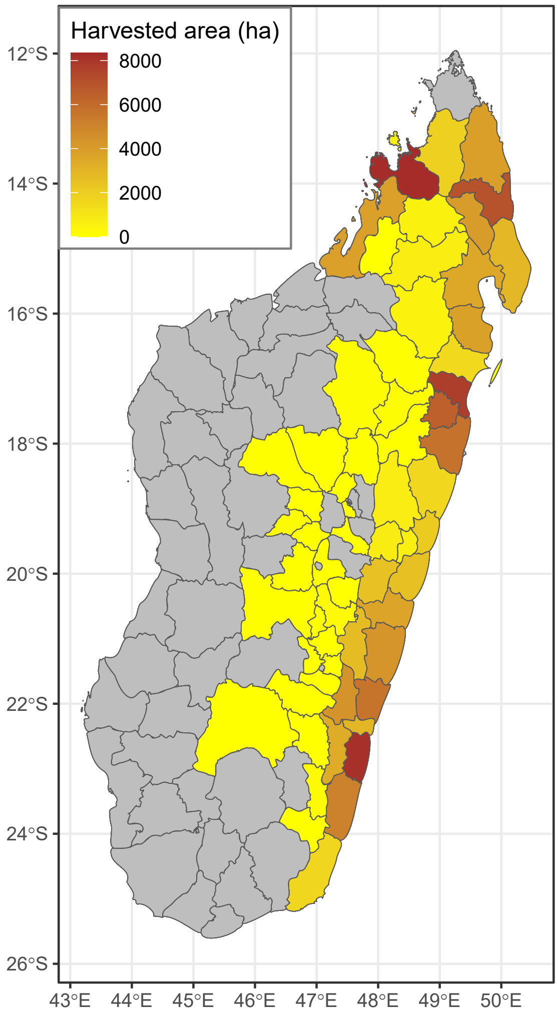

Figure 6: Average harvested coffee areas in ha per district in the period from 2005–2010 (MINAGRI, 2010, 2012).

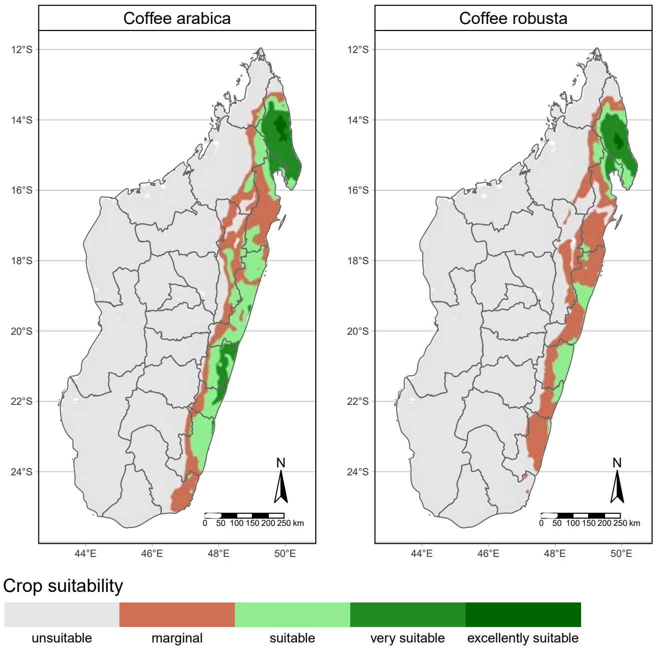

Figure 7: Modelled suitability of coffee Arabica and coffee Robusta in Madagascar for the time period 2000 (1985–2014).

Simulation results show that coffee cultivation in Madagascar under past climate conditions (1985–2014) was suitable on the eastern coast of the country, which corresponds to the humid tropical climate zone and the lowlands, such as the northern part of the Atsimo Atsinanana region, as well as the regions of Vatovavy, Fitovinany and Atsinanana. Excellent environmental conditions for coffee production were only found in the district of Andapa in the Sava region and parts of its neighbouring districts, such as Maroantsetra in the Analanjirofo region and Befandriana in the Sofia region. The highlands, the south and western part of the country were found not to be suitable for coffee production, mainly due to low rainfall and cold temperatures (Hampf et al., in preparation a). This is confirmed by data from MINAGRI (2010, 2012), showing that coffee production in the highlands is only very marginal (Figure 6).

A comparison of the simulated suitability of coffee Arabica production under past and future climate conditions shows that the suitable production areas are likely to decrease by ~7 % in all scenarios, except for the SSP1-RCP2.6 (low emissions) scenario for the near future. However, there are large regional differences. The highest decrease was simulated for the regions of Vatovavy and Fitovinany, followed by the regions of Atsinana and Analanjirofo with reductions of around 30 %. Interestingly, there were also some increases (~10 %) in suitability predicted for the highlands of Madagascar. The differences between the emissions scenarios were rather low (Figure 8). Farmers who grow Arabica coffee should carefully consider to what extent cultivation will still be possible in the future in their region. They may need to switch to other coffee species or crops.

Compared to coffee Arabica, the agro-climatic suitability of coffee Robusta is less impacted by climate change. When averaged across Madagascar, the suitability of coffee Robusta production remains almost stable (<-1 %) under all SSP scenarios and periods. However, again, there are large regional differences. While the east coast of Madagascar is predicted to experience the largest decrease in suitability, this is contrasted by suitability increases in the inland. The largest decrease in agro-climatic suitability was simulated for the regions of Atsinanana, Analanjirofo, Vatovavy and Fitovinany. However, climate change projections also indicate an improvement in the suitability of Robusta coffee in the Vakinakaratra, Itasy, and Analamanga regions. Nevertheless, these regions will not reach the required suitability threshold for the actual cultivation of Robusta coffee within the time period considered (Figure 9, Hampf et al., in preparation b). In summary, even though Robusta cultivation will remain almost unchanged at the national level, at the local level farmers may need to consider whether Robusta cultivation is still sufficiently productive. Switching to different crops or at minimum an adjustment of agricultural practices may be advisable for farmers in regions with decreasing suitability.

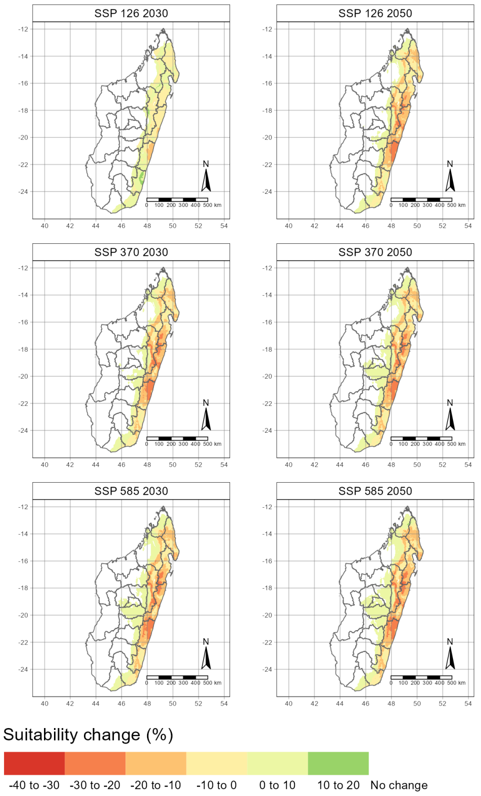

Figure 8: Modelled change in suitability of coffee Arabica in Madagascar for the time periods 2030 (2015–2044) and 2050 (2035–2064) under SSP1-RCP2.6, SSP3-RCP7.0 and SSP5-RCP8.5 scenario.

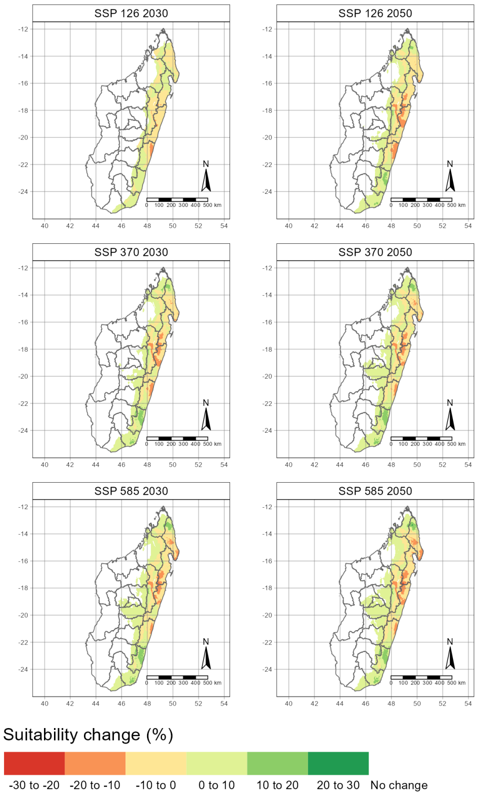

Figure 9: Modelled change in suitability of coffee Robusta in Madagascar for the time periods 2030 (2015–2044) and 2050 (2035–2064) under SSP1-RCP2.6, SSP3-RCP7.0 and SSP5-RCP8.5 scenario.

The results of the coffee suitability analysis confirm and add to those by Bunn et al. (2014). The authors found that climate change is likely to reduce the global area suitable for coffee production by about 50 %. Impacts were found to be highest at low latitudes and low altitudes, which corresponds to the growing conditions in Madagascar. The descriptive results of the representative farm household survey show that in Atsimo Atsinanana, 46 % of the farmers surveyed grow coffee. According to the model results, some parts of the region could experience a potential increase of up to 20 % in land suitable for growing Robusta coffee, while land suitable for growing Arabica coffee could decrease by up to 20 % (Hampf et al., in preparation a). However, the survey also shows that about half (48 %) of all coffee growing households in the two regions of Atsimo Atsinanana and Anosy considered the past coffee growing season to be medium to bad (Weituschat et al., in preparation). Main causes for the loss of crops were reported to be strong winds/storms, problems with rain, pests/insects, problems with soil, diseases, and drought. The results suggest that without adaptation, coffee may not be a reliable source of income in the future. Diversifying coffee farmers' income streams, on the other hand, could cushion the impact of climate change, as well as fluctuations in coffee prices.

3.2 Climate change impacts on vanilla production areas

Madagascar is the largest vanilla producer globally. The orchid was first introduced to Vatomandry on the east coast in 1891, then to the northeastern Sava region (Grisoni & Nany, 2021). Today, 80 % of all global bourbon vanilla supply originates from the Sava region (Hänke, 2020).

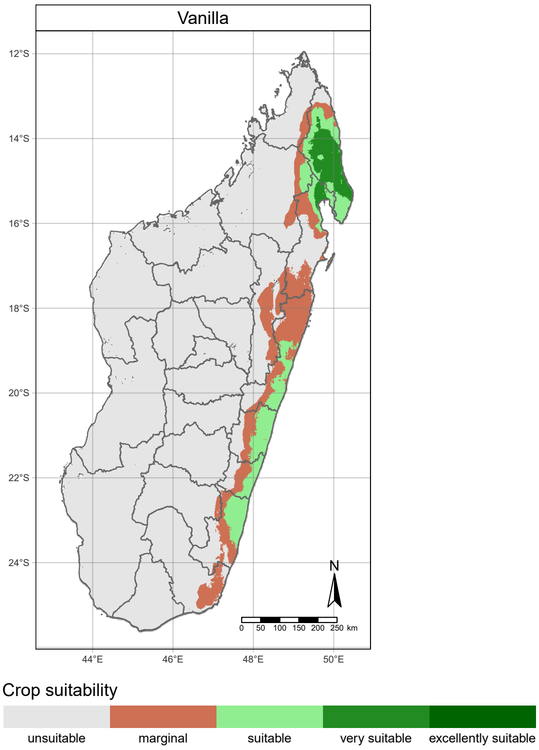

Figure 10: Suitability of vanilla in Madagascar for the time period 2000 (1985–2014).

Figure 10 shows the suitability of vanilla production in Madagascar for the 2000 period, i.e. averaged over 1985–2014. The region of Sava exhibits great potential for cultivating vanilla, followed by the regions Atsinanana, Vatovavy, Fitovinany and Atsimo Atsinanana. However, as for coffee, the highlands as well as the southern and western areas of Madagascar are estimated to be unsuitable for vanilla production due to insufficient rainfall and cool temperatures.

Figure 11 shows the impact of climate change on the agro-climatic suitability of vanilla production in Madagascar, according to different emissions scenarios and time periods. Vanilla is the only crop considered in this report for which an increase in suitability due to climate change is projected. Averaged across Madagascar, this increase is rather low with 0.5–2.5 % compared to the simulated cultivated area for the time period 2000 (1985–2014) and depending on the emissions scenario. There is a clear trend that suitability gains due to climate change are projected to be less pronounced under higher emissions scenarios.

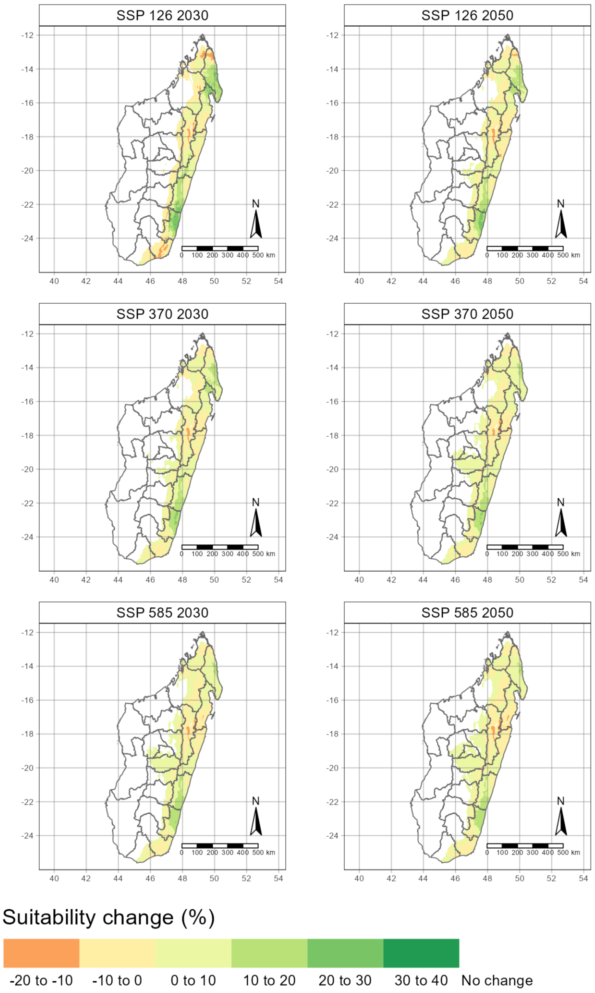

Figure 11: Change in suitability of vanilla production in for the time periods 2030 (2015–2044) and 2050 (2035–2064) under SSP1-RCP2.6, SSP3-RCP7.0 and SSP5-RCP8.5 scenario.

Again, there are noticeable regional differences. The regions of Atsimo Atsinanana and Sava, which were simulated to be suitable and very suitable for vanilla production, respectively, under recent past climate conditions, are likely to see a further increase in suitability. This is an important result, indicating that climatic conditions will allow the cultivation of vanilla in this major production region also in the future (Hampf et al., in preparation a). As vanilla is a significant source of income in Madagascar, expansion of cultivation in suitable regions could bring economic benefits to many farmers and could therefore also be considered as an adaptation to climate change. However, the form of expansion needs to be weighed in terms of sustainability, i.e., whether it is unburned land use types (i.e., old forest, forest fragment, and forest-derived vanilla agroforestry) or burned land use types (i.e., fallow-derived vanilla agroforestry, woody fallow, and herbaceous fallow), for example (Raveloaritiana et al., 2021).

3.3 Climate change impacts on pepper production areas

Pepper is an important cash crop in Madagascar, with an annual national production of around 2,200t (CTHT, 2023). It is mostly produced on the east coast of the island. The results of the suitability modelling for pepper is shown in Figure 12. The figure indicates that conditions for pepper production in the regions Androy, Anosy, Atsimo Atsinanana, Vatovavy, Fitovinany, and Atsinanana were either unsuitable or only marginally suitable under historical climate conditions.

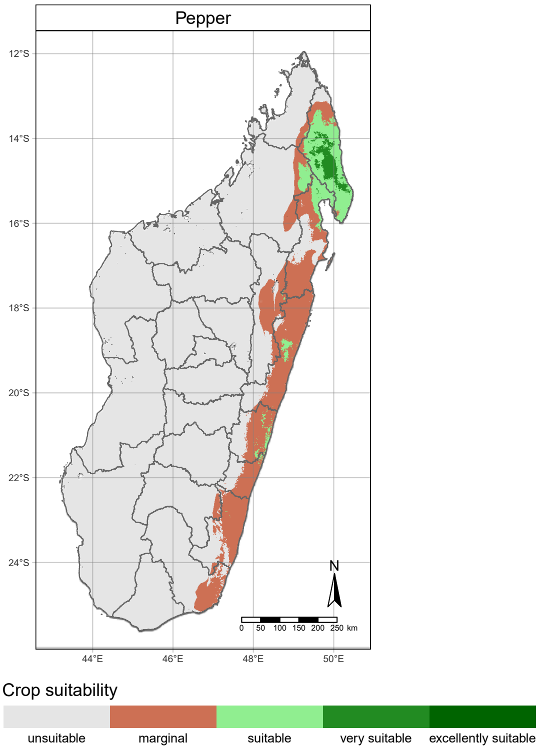

Figure 12: Suitability of pepper in Madagascar for the time period 2000 (1985–2014).

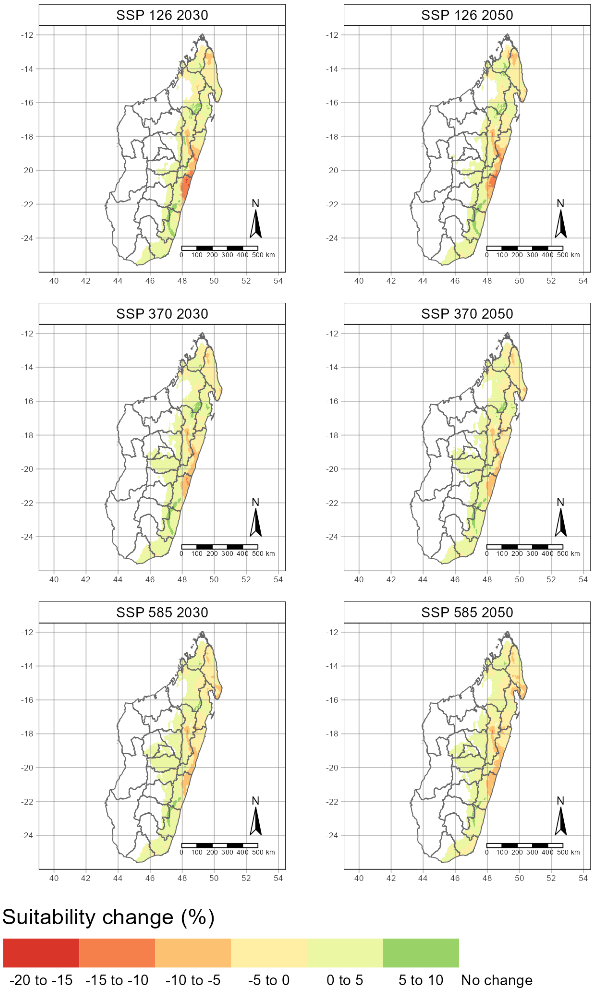

Figure 13: Change in suitability of pepper production in Madagascar for the time periods 2030 (2015–2044) and 2050 (2035–2064) under SSP1-RCP2.6, SSP3-RCP7.0 and SSP5-RCP8.5 scenario.

However, climate change is projected to have a rather low impact on the agro-climatic suitability of pepper production in Madagascar. When averaged across Madagascar, the decrease in suitability is less than 1 %. Nonetheless, there are some noteworthy differences across regions and scenarios. In the SSP1-RCP2.6 emissions scenario, pepper suitability is simulated to decrease by up to 17 % in the regions of Vatovavy, Fitovinany and Atsinanana. This decrease becomes less pronounced in the other emissions scenarios. Other regions, such as Androy, Anosy and Atsimo Atsinanana, which were unsuitable or only marginally suitable under recent past climate conditions, are projected to experience an increase in pepper suitability (Hampf et al., in preparation a). Some parts of Atsimo-Atsinanana could thus become suitable for pepper production under climate change (Figure 13). Supporting the development of pepper cultivation in these areas could help vulnerable farmers adapt to climate change assuming appropriate agricultural practices and marketing conditions can be achieved.

3.4 Climate change impacts on peanut yields

Peanuts have two main uses in Madagascar: consumption of the seeds and production of edible oil. The seeds and paste of peanuts are valued for their flavour, and peanut oil is commonly used for cooking due to its resistance to oxidation during frying. Recently, increasing demand, both domestically and internationally, especially from China, has drawn the attention of local producers and investors (Voahanginirina, 2020). Peanut cultivation is prevalent in most regions, except for some parts of the eastern coast, where annual rainfall ranges from 2,500 to 3,500 mm over 200 to 250 days, far exceeding the optimal rainfall conditions of 500 to 1,000 mm per growing season. Peanuts are also not grown in high-altitude areas exceeding 1,500 m, where temperatures are too low. Additionally, in the extremely arid southern region, peanut cultivation is limited by annual rainfall measuring less than 300 mm. Rising temperatures can potentially lead to drought and heat stress in peanuts, especially under rainfed conditions. All peanut growth simulations described below were simulated with the crop model APSIMX (see Section 3 in Supplementary Information) and run for three different time periods: the recent past around the year 2000 (1985–2014), the near-future around 2030 (2015–2044), and the mid-term future around 2050 (2035–2064). Future crop growth simulations were carried out for the three different emissions scenarios: low (SSP1-RCP2.6), medium to high (SSP3-RCP7.0), and high (SSP5-RCP8.5). In 2023, CO_2 levels in the atmosphere reached 424 ppm, more than 50 % higher than at the beginning of the industrial age, and CO_2 levels are expected to continue rising if humans continue to burn fossil fuels for energy (NOAA Climate.gov, 2023). As peanuts are very responsive to the effects of CO_2 fertilization, a comparison of peanut crop growth under two conditions was conducted: one with a constant CO_2 concentration of 350 ppm and the other involving progressively rising CO_2 concentrations. The extent of CO_2 concentration rise differs based on the emissions scenario. Under the SSP1-RCP2.6 scenario, the projected atmospheric CO_2 concentration for the year 2050 is approximately 470 ppm, while it is anticipated to reach around 540 ppm under the SSP3-RCP7.0 scenario and about 563 ppm under the SSP5-RCP8.5 scenario.

When atmospheric CO_2 concentration is fixed at 350 ppm, simulation results indicate that climate change impacts on peanut yields are largely negative across Madagascar. In this scenario, peanut yields are projected to decrease by 6 % on national average. It is projected that the decrease in yields becomes larger with higher emissions scenarios and also with longer time horizons. While yield decreases are around 3 % in the low emissions scenario and near-future, the decline amounts 11 % in the high emissions scenario and mid-future. However, various regional differences remain (Hampf et al., in preparation b). Figure 14 shows the impact of climate change on peanut yields across Madagascar according to the three different emissions scenarios and two periods (near-future, mid-term future) with

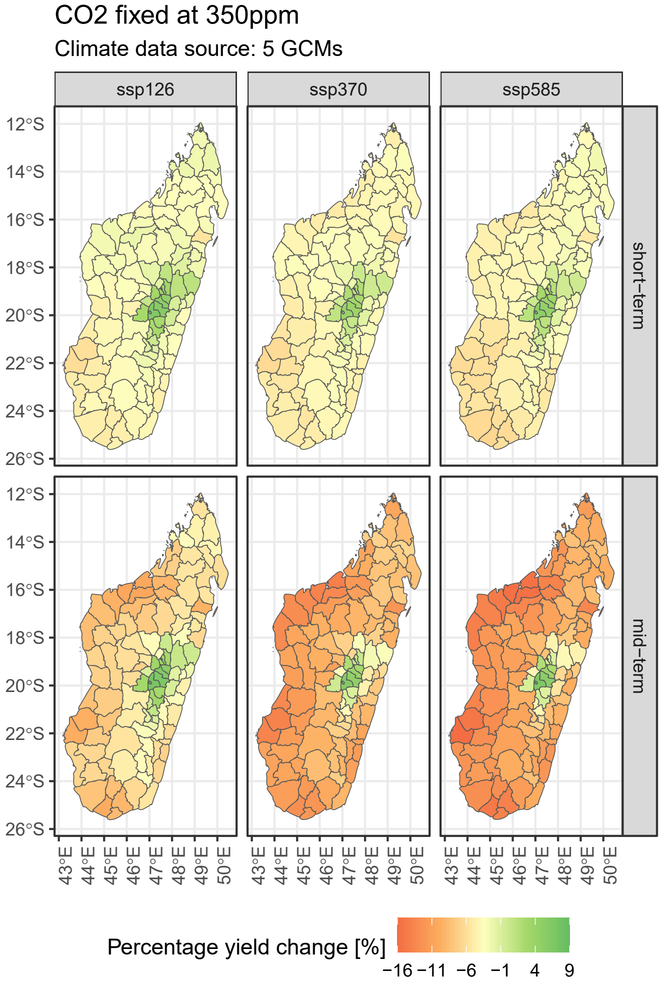

Figure 14: Projected climate change impacts on peanut yields across Madagascar for the time periods 2030 (2015–2044, short term) and 2050 (2035–2064, mid-term) under SSP1-RCP2.6, SSP3-RCP7.0 and SSP5-RCP8.5 scenario with fixed CO_2 at 350 ppm.

atmospheric CO_2 concentration fixed at 350ppm. It has to be noted that this scenario is hypothetical as these projected changes in the climate and their impacts in reality cannot occur without the simultaneous increase in CO_2 concentration. However, the simulation of the change in peanut yields at different CO_2 concentrations illustrates the important role of the CO_2 fertilization effect.

When considering projected increasing atmospheric CO_2 concentrations, the picture is almost completely reversed (Figure 15). Now, climate change is projected to increase, rather than decrease, peanut yields by 5 % across Madagascar, indicating that the CO_2 fertilisation effect is likely to compensate the negative impacts of increasing temperatures and declining precipitation. At national level, the yield increase slightly varies between emissions scenarios and periods, ranging from a 4.4 % increase in the mid-term period for the low emissions scenario, to 6.4 % in the mid-term period for the high emissions scenario. Again, there are some noticeable regional differences to be considered.

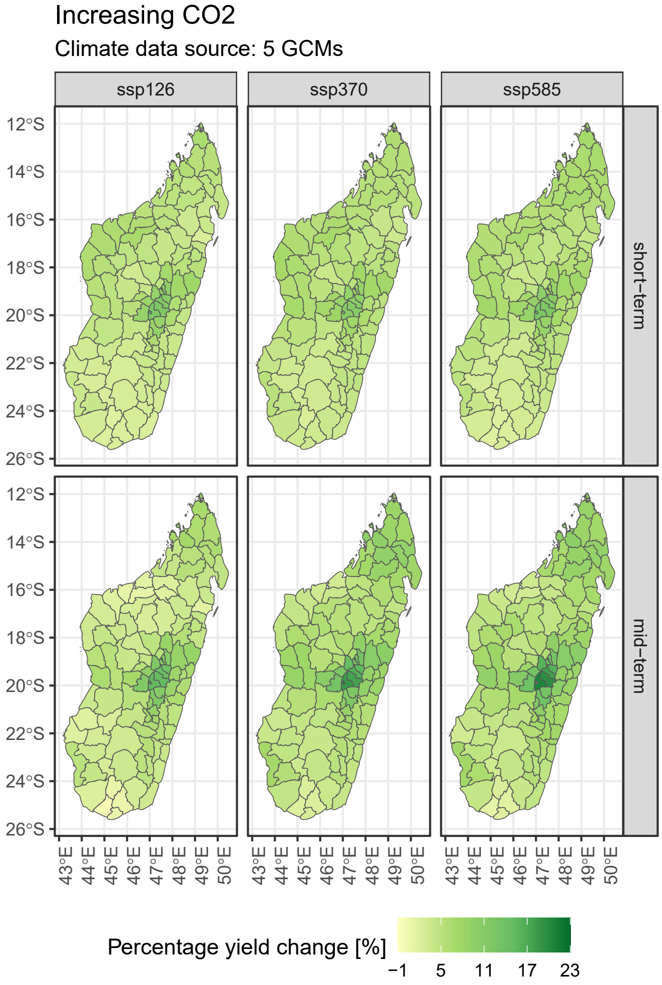

Figure 15: Projected climate change impacts on peanut yields across Madagascar for the time periods 2030 (2015–2044, short term) and 2050 (2035–2064, mid-term) under SSP1-RCP2.6, SSP3-RCP7.0 and SSP5-RCP8.5 scenario with increasing CO_2 concentrations.

While western and southern Madagascar are projected to benefit the least, the region of Vakinakaratra is projected to experience the largest yield increase of up to 23 % (Hampf et al., in preparation b).

These findings are in line with Faye et al. (2018) who also projected positive changes on peanut yields in Senegal between 2.4 % to 8.3 % in the dry season and increases of between 11 % and 19 % for the rainy season.

4. Adaptation strategies

Farmers deal with the uncertainty of future weather conditions on a daily basis, and are pro-active agents who respond to a changing environment. However, projected increases of climate variability have the potential to put farmers' capacities to the test and create substantial challenges, especially for small-scale subsistence farmers (Crane et al., 2011).

As climate change continues in Madagascar, certain areas like the regions of Vatovavy and Fitovinany, are expected to experience a decrease in suitable land for growing important crops like coffee and pepper (see Chapter 3). To cope with this situation, farmers will need to implement locally specific adaptation measures which can range from technological intensification measures, e.g. through the sustainable use of fertilizer and improved cultivars, to infrastructural measures, like flood protection and cyclone-resistant infrastructure, and nature-based adaptation solutions. Examples for the latter are the adjustment of planting dates, and agroecological approaches such as agricultural diversification, sustainable water and soil management practices, mixed crop-livestock systems or agroforestry (Berrang-Ford et al., 2021; Bezner Kerr et al., 2022). Apart from these field-level adaptation options, several institutional measures, such as early warning systems and climate services can also contribute to risk reduction. To manage risks posed by climate change in agriculture, there are various approaches to consider. These include the diversification of livelihoods or having family members migrate to different areas. Farmers can also enhance their ability to adapt and reduce climate-related risks by involving their community in climate adaptation efforts (Ensor et al., 2018) or by using integrated strategies that tackle both adaptation and mitigation at the same time (Harvey et al., 2014). Given the complexity of climate impacts, it's essential to combine and integrate these different adaptation options while considering the local situation, various sectors, and gender aspects.

In this report, two adaptation options that could contribute to reducing the risks in agriculture are analysed: the selection of locally adapted varieties and the flexible adjustment of planting dates. The two measures were selected because they were shown to be preferred strategies by smallholder farmers (Magesa et al., 2023; Zeleke et al., 2023) and are relatively easy to implement, on the condition that e.g. improved seeds are accessible and optimum sowing dates are known among farmers and extension workers (Zeleke et al., 2023). It is important to note that these two adaptation options are not meant to provide silver-bullet solutions but should be interpreted as two possible options within the wider context of building climate-resilient agri-food systems.

In the following subsections, we will evaluate the two adaptation strategies by examining their impact on crop yields under changing climatic conditions, using peanut production as an example. Additionally, we will analyse the institutional support needed for implementing each strategy effectively and delve into the gender-specific factors associated with them.

4.1 Selection of locally adapted varieties

As different plant varieties vary in their sensitivity to temperature, switching varieties can be a helpful adaptation option for farmers (Zabel et al., 2021). Farmers can for example use adapted traditional varieties and landraces or decide on using commercially improved seeds. Landraces tend to have high levels of genetic variation that is tightly coupled with the environmental variation presented in a region (Mercer et al., 2012). Its success does not depend on whether e.g. droughts become more frequent as a result of climate change or whether they are a normal feature of climate variability. Local and collective conservation of landraces is a robust adaptation option as it gives smallholders the flexibility to respond to future changes independently of commercial sources of improved seeds (Vasconcelos et al., 2013). However, the utilization of commercially improved varieties, whether for annual or perennial crops, can also support stable and reliable agricultural production and simultaneously play a crucial role in mitigating the adverse effects of climate change on agricultural systems. Improved varieties can exhibit enhanced tolerance to abiotic stressors like drought (Fisher et al., 2015), increased resistance to biotic stressors such as diseases and pests, and improved use of nutrients. These traits potentially allow for a more efficient agronomic management, including shorter growing cycles (González Guzmán et al., 2022; Voss-Fels et al., 2019). By minimizing the negative effects of rising temperatures while increasing plant growth due to elevated CO_2 concentrations in the atmosphere, yields can often be increased through improved varieties (Zabel et al., 2021). The specific criteria and definition of improved varieties may vary depending on each country's legislation and international agreements (ACTESA, 2014; Munyi, 2022). In Madagascar, breeding activities and the production of foundation seeds are carried out by research centres like FOFIFA and FIFAMANOR (Randrianatsimbazafy, 2022). Additionally, high-quality foundation seeds with desirable genetic traits are imported to create certified seeds, which are then made available for sale to farmers. For the modelling in this report two local peanut cultivars, namely the improved variety Fleur 11 and the traditional variety Kanety, were added to the peanut module in APSIMX and compared. The cultivar Fleur 11 is considered to be a more drought-tolerant cultivar with a short cycle of approximately 90 days and is adopted throughout the country. The cultivar Kanety is considered a traditional cultivar that is well adapted to local conditions and has a medium cycle length of 90–120 days (IISD, 2022).

4.1.1 Modelling results of Fleur 11 and Kantey under different climate scenarios

Figure 16 shows the simulations of APSIMX comparing the use of the cultivars Kanety and Fleur 11 with a fixed sowing date (November 10th – more information on sowing dates can be found in Chapter 4.2). The results show that average yields for both cultivars increase under climate change conditions, but yields for Kanety are generally higher than those of Fleur 11. The simulation results are supported by findings from a field experiment conducted in Androy where the cultivar Kanety also yielded more than the cultivar Fleur 11 (FOFIFA, 2022). This discrepancy could potentially be attributed to the shorter growing cycle of Fleur 11, resulting in smaller grain sizes. Furthermore, Kanety is traditionally adapted to Androy and is therefore well-suited to the local conditions (FOFIFA, 2022).

However, the cultivar Fleur 11 may still exhibit benefits to local farmers. For example, anecdotal reports from GIZ field technicians suggest Fleur 11 being easier to husk manually. Furthermore, the short cycle of Fleur 11 is beneficial when being used in rotation with other crops where an early harvest of the first crop is essential to allow for two harvests per season. Generally, drought resistant varieties can be considered as a hedging strategy for smallholder farmers. A field trial by Berchie et al. (2012) has shown that particular heat-tolerant varieties still produce yields even under severe drought conditions, when other varieties may fail completely, and thus may contribute to farmers' food security in more extreme conditions. Our results show that both varieties have advantages and disadvantages. Overall, the Kanety variety is projected to lead to higher yields than Fleur 11 under climate change conditions in Madagascar. Nevertheless, it is important to carefully consider which variety to use, always taking local conditions and preferences into account.

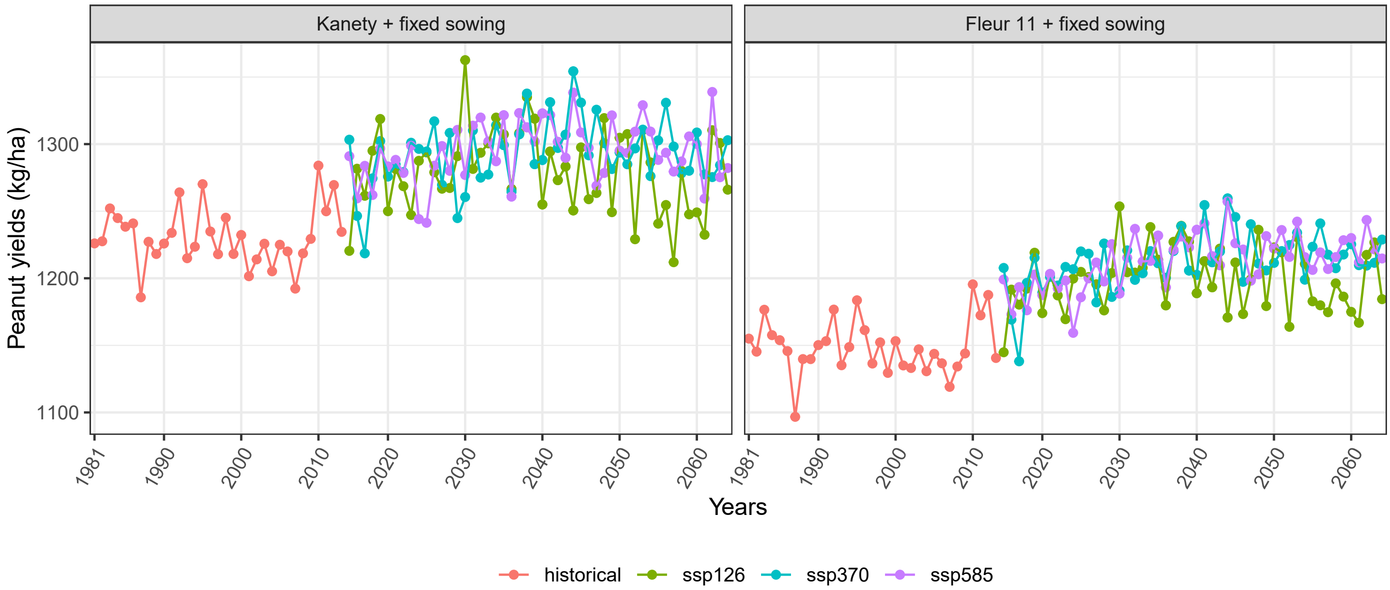

Figure 16: Simulated peanut yields per year for the cultivars Kanety and Fleur 11 following a fixed sowing date according to the agricultural calendar (MINAE, 2022). The results are averaged across Madagascar.

4.1.2 Gender dimensions of the use of adapted varieties

The significance of gender differences in farming should not be underestimated, as male and female farmers often experience unequal control and access to critical productive resources (Quisumbing et al., 2014). This disparity is particularly evident among smallholder farmers, where gender roles, responsibilities, and resource access may vary widely. The introduction of new plant varieties can have far-reaching effects on the distribution of workloads, resources, and decision-making power between male and female smallholders in low-income countries (FAO, 2011). As a result, male and female producers often make distinct choices concerning the crops and varieties they cultivate. Gender-specific preferences for crop traits are often linked to the specific agricultural and household activities for which individuals are responsible (Weltzien et al., 2019). For example, improved maize varieties that require longer cooking times, thus requiring more firewood and more female labour, were less preferred by women (Hellin et al., 2010). Women in West Africa who are predominantly responsible for rice harvests, specifically prefer tall rice varieties for ease of harvesting (Gridley, 2002). Additionally, women often prioritize traits associated with food security, such as resistance to storage pests, other host plant resistances to pathogens and pests, early maturity, and multiple harvests, more than men.

Women may also identify harvestable products beyond grain, such as leaves for food and stalks for fuelwood, as important (Weltzien et al., 2019). Apart from varying trait preferences, female and male farmers also encounter different barriers in adopting new plant varieties. A study by Alhassan et al. (2018) found that women rice farmers in Northern Ghana perceived the use of improved varieties as highly effective for adapting to climate change. However, this strategy involved costs that most female farmers in the study region could not afford. High cost and inaccessibility of improved seeds have been reported as important constraints for female farmers. According to Amoah et al. (2021), the main obstacle for women, apart from the high costs, was the limited access to credit facilities. Female farmers more frequently perceived these two constraints as significant barriers to adopting new crop varieties compared to their male counterparts. Although the importance of differentiating user preferences based on gender is increasingly recognized, integrating gender-differentiated preferences systematically into breeding programs remains limited (Weltzien et al., 2019). It is important to note, however, that trait preferences do not necessarily conform to traditional divisions of labour between men and women. Furthermore, such trait preferences are not fixed over time and are likely to evolve as women's rights and responsibilities change (Weltzien et al., 2019).

4.1.3 Institutional support requirements

In most Sub-Saharan African countries, the seed industry is still developing. During the last decades, Madagascar has produced many new and better performing varieties with traits such as improved nutritional value and drought tolerance, frost resistance or early maturity. The country has established its own breeding programs and has put in place a formalized variety release process, supported by a policy and regulatory framework (Ariga et al., 2019). However, the effective implementation of those frameworks face obstacles, such as weak enforcement of the seed policy regulations, inadequate resources, and poor coordination among the institutions responsible for overseeing the seed sector (Komen & Wafula, 2021). As a result, some crop varieties available in the market have been around for more than 15 years, such as varieties of maize and peanut (Ariga et al., 2019). The multiplication of seeds for farmers is done through Seed Multiplication Centres (SMC) and Seed Grower Groups (SGG). Seed distribution takes place through local shops, which act as seed retailers/stockists. The majority of seed companies and agro-dealers are strategically located in regions with intense agricultural activities, such as Antananarivo, Antsirabe, Marovoay, Ambatondrazaka, and Fianarantsoa. However, for smallholders, the average distance to an agro-dealer is approximately 70 km (Randrianatsimbazafy, 2022). The combination of these factors leads to a large share of farmers who still rely on open-pollinated varieties from previous harvests. Besides weak seed production and distribution linkages, they face further challenges with the adoption of new crop varieties such as limited availability, lack of knowledge, high costs and risk aversion (Ariga et al., 2019). The adoption of improved seeds is therefore often limited to innovative farmers served by NGOs and a network of agro-dealers (Ariga et al., 2019).

Accordingly, institutional support could enhance the access to and knowledge about locally well adapted varieties, by enhancing the distribution infrastructure to reduce the distance to seed distribution centres and facilitate access to adapted seeds. Furthermore, improved communication and collaboration among stakeholders in the seed sector are essential to enhance seed dissemination and overcome technical challenges (OECD, 2021). The results of this report shed light on the benefits of traditional cultivars, which are generally better adapted to abiotic stress than modern cultivars (Mohammadi et al., 2014). Supporting their cultivation can result in advantages to face climate change, especially if consumer demand increases. Therefore, policies and implementation activities should acknowledge and highlight the value of local landraces, as some farmers also report a preference for traditional landrace varieties (Ariga et al., 2019). Preserving local traditions, agronomic practices, and associated knowledge is crucial, and such conservation efforts can be institutionalized through in-situ conservation projects, local seed banks, collaborations with national or international gene banks, and diversity fairs (Röhrig et al., 2021). In terms of improved

seeds, the model simulations in this report suggest that breeding strategies which focus on developing crop varieties with a strong growth response to elevated CO_2 are most promising. Breeding for improved photosynthetic and water-use efficiency is a key strategy in maximizing the benefits of elevated CO_2. Finally, regardless of whether traditional seeds or improved seeds are locally used, it is important to support marginalized groups and recognize their needs in order to improve climate resilience for all smallholder farmers.

4.2 Flexible planting dates

In the realm of agricultural management strategies, the timing of planting is recognized as a crucial factor influencing agricultural productivity. Planting crops earlier in the planting season has the potential to significantly increase dry-matter accumulation and improve crop yields compared to normal planting times (Bannayan et al., 2013). However, planting crops too early might lead to crop failure (Laux et al., 2010). Conversely, late planting refers to planting crops after the traditional planting season or when the planting season is delayed, for example until severe hazards have passed. While late planting holds a few advantages for crop production, such as avoiding drought stress during early growth stages due to more available water (Bannayan et al., 2013), there are also potential disadvantages. Planting crops late can reduce the crops' valuable growing time and subsequently lower yields. Additionally, late planting might delay or reduce crops' initiation and maturity, exposing them to higher temperatures during maturation and increasing the risk of scarce rainfall in the final stages of crop growth (Buddhaboon et al., 2011). The decision for the optimal planting time depends on various factors, including local climate conditions, crop varieties, and cropping techniques (Kruger, 2016). Several researchers have shown that changing the planting date of various crops can be a good solution to improve yields under the impacts of climate change (Desiraju et al., 2010; Waha et al., 2013; Yegbemey et al., 2014). Adapting the sowing date to coincide with the main rainy season is a strategy employed by farmers to mitigate the adverse effects of climate change on crop yields, and this practice is already prevalent in various countries, like Ethiopia, South-Africa and India (Waha et al., 2013). Simulation studies conducted for Cameroon revealed that optimal planting dates result in higher crop yields for maize and peanut compared to traditional planting dates when considering potential climate changes (Laux et al., 2010; Tingem & Rivington, 2009). Altering crop planting dates can increase yields, and some farmers in Madagascar have already reported managing planting schedules to avoid hazard-prone times (Delille, 2011; Kruger, 2016). A study by Kruger (2016) revealed that 34 % of Malagasy farmers who took part in the study adopted early planting before the traditional planting season. Although those farmers generally avoided late planting due to the associated risks, approximately 61 % of them agreed that planting after floods to utilize residual moisture is also a valuable technique.

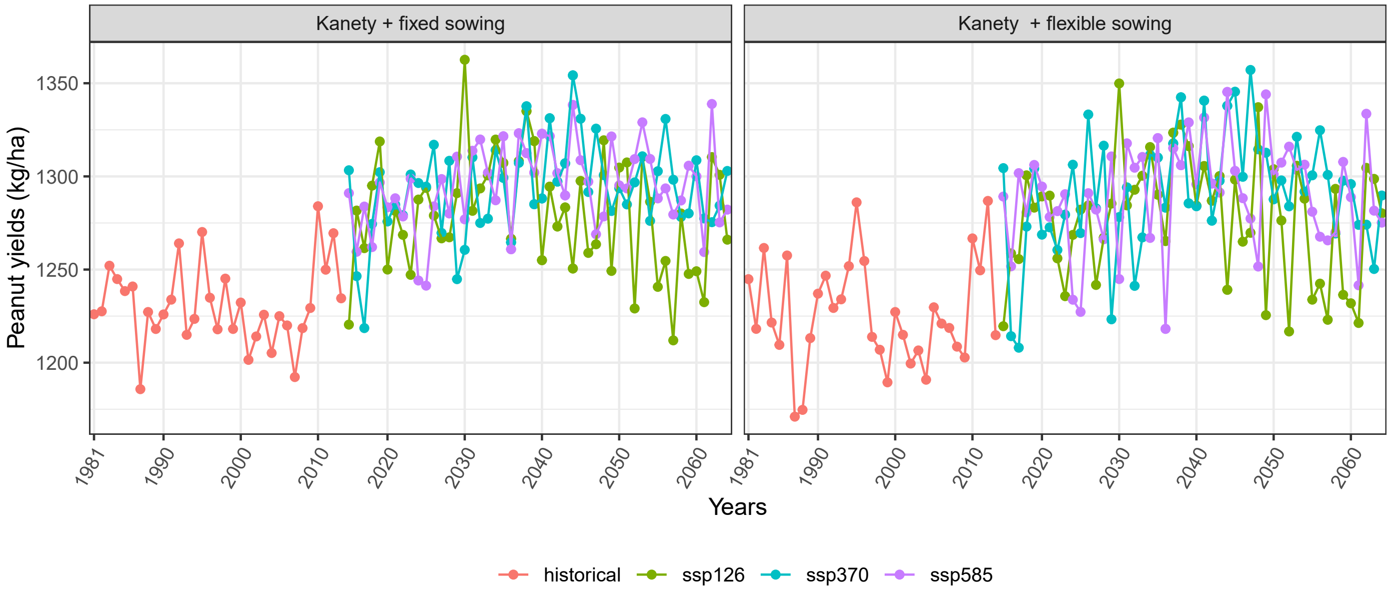

Figure 17: Simulated peanut yields per year with fixed and with flexible sowing dates averaged across Madagascar.

4.2.1 Modelling results of flexible planting dates under different climate scenarios

In this report, sowing dates and sowing rules are defined in accordance with the agricultural calendar of peanuts for the growing season 2022–2023 (MINAE, 2022), which provides information on recommended sowing periods for the main growing regions across the country. The calendar indicates that peanut is mainly planted between November 1st and December 30th. Flexible planting dates were therefore defined in that sowing takes place during this period, and is triggered as soon as at least 25 mm of rainfall has fallen in five days. In simulations with a fixed sowing date, November 10th was assumed as the time of planting. Based on data from field experiments, row spacing was set to 50 cm and space between plants to 25 cm, resulting in a planting density of eight plants per m² (FOFIFA, 2022). It was further assumed that peanuts are exclusively rainfed.

The APSIMX model results indicate that using flexible planting dates under climate change conditions results in similar yields as the use of fixed planting dates. Simulated yields for a scenario with fixed and for a scenario with flexible planting dates lead to on average 1,280 kg/ha. However, yields display a slightly increased variability using flexible planting dates, implying that the selected sowing rule may lead to suboptimal growing conditions.

In the simulations for this study, peanut is grown during the rainy season. The duration of the rainy season in Madagascar is four months (November – March), so that both varieties, Kanety and Fleur 11, have enough time to mature without being exposed to drought stress. At the beginning of growth, the water requirement of the plants is still very low, so even if the rainy season starts late, the plants will not be exposed to drought stress. However, further investigation is needed to better understand the effect of sowing dates on plant physiology and the relationship between plant physiology and growth temperature.

4.2.2 Gender dimensions on the use of flexible planting dates

Previous studies found that adjusting planting dates is one of the climate adaptation strategies most frequently adopted by various types of farmers throughout Africa (see e.g. Alhassan (2019), Arimi (2014), Belay et al. (2017), Bryan et al. (2013) and Solomon & Edet (2018)). Several studies took a closer look at the gender dimension of this adaptation option and found that both male and female headed households adjust their planting dates in accordance with environmental changes (Adzawla et al., 2019; Assan et al., 2018; Kristjanson et al., 2017). However, there are also some studies that find a positive correlation between gender and the adjustment of planting dates. A study by Maja et al. (2023), conducted in the east of Ethiopia, revealed that households led by men showed a higher probability of adjusting their planting dates compared to those led by women. This preference was primarily traced back to the fact that men were more actively involved in agricultural activities, granting them better insights into climate change and the advantages of adopting adaptive technologies, leading to a smoother adoption process. In addition, the study showed that education level, access to information and extension services, and farm income influenced the adoption of flexible planting dates. These socioeconomic characteristics may also intersect with farmer gender and further reinforce inequalities. Correspondingly, Ali et al. (2020) and Deressa et al. (2009) discovered a similar trend in Togo and Ethiopia, respectively, where male-headed households exhibited a greater probability to adjust planting dates as an adaptation strategy compared to their female-headed counterparts. In contrary, Alhassan et al. (2019) concluded that within their study in the northern region of Ghana, women showed a greater likelihood of adapting planting dates. According to the authors, this is because women are more vulnerable to climate change and thus more likely to use adaptation measures. Access to credit was discovered to positively influence the use of changing of planting dates by women farmers in the Upper West Region of Ghana (Owusu & Yiridomoh, 2021). Additionally, the availability of agricultural extension services for female farmers was found to enhance their ability to acquire knowledge on effectively responding to climatic changes by adjusting planting dates (Maja et al., 2023). In many Sub-Saharan African countries, female farmers encounter difficulties in accessing agricultural extension services due to factors such as the gender imbalance among agricultural extension agents and the cultural or religious backgrounds of these agents. In certain African communities, female farmers become more accessible when contact is established through individuals who share similar cultural or religious backgrounds with them (Owusu & Yiridomoh, 2021).

4.2.3 Institutional support requirements

The results of this report highlight that crop calendars are an important tool that provides timely information about local crop production for farmers. The 2022–2023 crop calendars (MINAE, 2022) were launched in written format with tables, in Malagasy and French, as well as in voice recordings so that they can be distributed to remote areas, through channels such as the Airtel network and other mobile services (Orange actu Madagascar, 2022). In order to react to the changing climatic conditions, the Ministry of Agriculture and Livestock, the research institute FOFIFA, and the Ministry of Transport and Meteorology plan to develop an innovative crop calendar for the 2023–2024 season, integrating accurate weather forecasts and adaptation strategies (L'Écho du Sud, 2023). Results of the household survey of Weituschat et al. (in preparation) reveal that 14.9 % of 624 households in the three regions Atsimo Atsinana, Anosy and Androy received information or advice about general farming practices in the last 12 months from farmer peer advise groups and 19.7 % from extension officers. However, only 9 % of the content of the extension advice related to the timing of crop management (e.g. planting or harvesting). These results highlight the need to pay particular attention to these two information channels with regard to the dissemination of crop calendars. Nevertheless, 44 % of the interviewees stated that neighbours, friends or family are their most important source of information. Training for Lead Farmers (paysans leaders) could therefore be a useful way to equip farmers with knowledge about climate change adaptation.

As stated in the sub-chapter on gender dimensions, flexible planting dates are commonly considered the simplest approach to climate change adaptation and are more feasible for many farmers than alternative options, such as using improved crop varieties (Debaeke et al., 2017; Singh et al., 2017). However, given that the timing of agricultural operations frequently depends on a limited window of rainfall, establishing the best time for planting requires robust weather information (MacCarthy et al., 2017; Tingem et al., 2009). This aspect is particularly important, as precipitation is projected to become much more variable under climate change scenarios (see Chapter 2.2). Oyekale (2015) examined access to weather forecasts in East and West Africa and found that 62.7 % and 56.4 % of farmers in East and West Africa, respectively, had access to forecasts on the onset of rainfall and around 49.4 % and 41.9 % of farmers in East and West Africa, respectively, were provided with advice of extension services around the onset of rainfall.

This data shows that many farmers are not adequately provided with weather information. However, local or Indigenous knowledge on weather forecasting should also be considered, as it has been shown to be an important source to smallholder farmers in various regions of Sub-Saharan Africa (Radeny et al., 2019). An empirical study by Taruvinga et al. (2016), conducted in the Eastern Cape Province of South Africa, furthermore highlights that successfully adapting planting dates is associated with factors like education, wealth, type of land ownership, access to informal credit, and membership in agricultural community groups. Institutional support should therefore focus on disseminating knowledge through the distribution of crop calendars and better access to extension services, while also specifically targeting farmers with specific support requirements, like resource-poor or female-headed households, to enable equity in the adoption of adequate planting dates.

5. Discussion and conclusion

This report provides an in-depth analysis of climate risks for coffee, vanilla, pepper and peanut production systems in Madagascar, together with an assessment of the feasibility and benefits of the selection of locally adapted varieties and flexible planting dates as adaptation strategies. The impacts of climate change on the agro-climatic suitability of three major cash crops, namely coffee, pepper and vanilla were examined using suitability analyses. Simulation results suggest that coffee Arabica is the most affected crop with an overall decrease in suitability of 7 % across the country. Since most coffee currently produced in Madagascar is Robusta, this will likely only affect a small number of farmers (MAEP, 2004). Coffee Robusta is less heat sensitive than coffee Arabica and thus the simulated suitable area remains almost stable under climate change. Regions like Atsimo Atsinanana, that were simulated to be unsuitable for the production of coffee Robusta and pepper under recent past climate conditions, were predicted to become suitable for these crops under future climate conditions. The emergence of new suitable land in previously unsuitable areas opens up opportunities for crop diversification and increased resilience to climate change. Lastly, simulation results indicate a slight increase in suitability for vanilla production, particularly in the main growing region Sava, but also in Atsimo Atsinanana, thus safeguarding an important source of income for local farmers and guaranteeing the sustainability of Madagascar´s most valuable export product.

Process-based models were used to analyse the effects of climate change on peanut yields. The results show that rising temperature and reduced rainfall amounts when considered in isolation are likely to decrease peanut yields across Madagascar. However, elevated atmospheric CO_2 is projected to offset these negative impacts so that yields are actually projected to increase by 4.4 % to 6.4 % on the national level and depending on the emissions scenarios. These findings suggest that the most promising breeding strategies are the ones that aim to make plants better at using resources like sunlight and water. Another result is that a shift from crops that are less suitable for future climatic conditions to peanuts could be an effective strategy for farmers to adapt to climate change and benefit from projected increasing yields.

Furthermore, the efficiency of the two adaptation strategies flexible planting dates and the selection of locally adapted varieties was analysed. Our simulation results suggest that replacing the widely adopted cultivar Fleur 11 with the traditional cultivar Kanety could lead to increases in yields, as Fleur 11 has a shorter growing cycle and thus accumulates less biomass and grain during its growing season. The findings are in accordance with data from field experiments. However, the short cycle cultivar Fleur 11 may still exhibit benefits to local farmers when being used in rotation with other crops where an early harvest is essential to allow for two harvests per season or in the case of extreme drought. Interestingly, opting for flexible planting dates as opposed to a fixed planting date does not result in enhanced yields. This phenomenon could be attributed to the selected criterion, where sowing is triggered when at least 25 mm of rainfall occurred over five days within the planting window spanning from November 1st to December 30th. Possibly following this rule leads to suboptimal sowing dates either at the very beginning or at the end of the sowing window. In summary, our results show that using a variety that is locally well adapted and considering crop calendars for farm management practices are low-threshold adaptation options that can help farmers adapt to climate change. However, the strategies explored might have limitations in helping smallholder farmers improve their resilience to climate change in the long term. The combination with other strategies, like the use of early-warning systems that provide information on the timing, length, and amount of rainfall, could be helpful for farmers in determining planting schedules and crop selection. For example, as part of the PrAda Project, GIZ Madagascar has initiated a hotline service that offers tailored agricultural calendars for crops like peanuts, onions, rice, corn and ginger, based on the caller's specific location (Weiskopf et al., 2021). Such services can likely support farmers in adapting to a changing climate in Madagascar.

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A report prepared by the Potsdam Institute for Climate Impact Research (PIK) together with the Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH on behalf of the German Federal Ministry for Economic Cooperation and Development (BMZ). The analyses have been conducted as part of the project **AGRICA – Climate risk analyses for adaptation planning in sub-Saharan Africa.**

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