Federal Ministry for Economic Cooperation and Development

Potsdam Institute for Climate Impact Research

Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH

Climate risk analysis for identifying and weighing adaptation strategies in Ethiopia's agricultural sector

Factsheet on the study approach and methods

Supplement to a study prepared by the Potsdam Institute for Climate Impact Research (PIK) for the Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH on behalf of the German Federal Ministry for Economic Cooperation and Development (BMZ), in collaboration with the Ethiopian government and as contribution to the NDC Partnership.

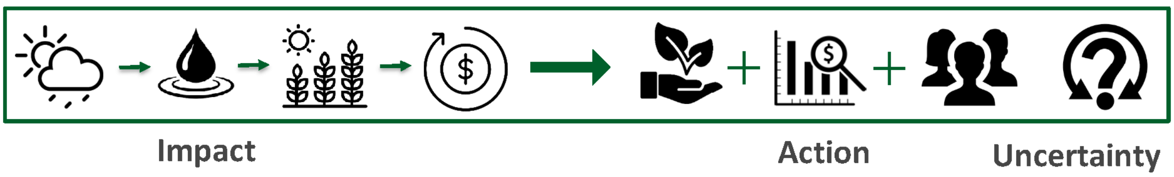
This factsheet presents the **key analysis steps** of the climate risk study, explaining the different **methods, models** and **data used**. Further information can be found in the full climate risk study as well as in the supplementary material to the study.

Study objective

While many countries recognise adaptation as an important component of their responses to climate change, little guidance on how to operationalise adaptation goals exists. As part of their international commitments, such as under the Paris Agreement, countries seek to develop and implement adaptation policies and investment plans, for instance as part of their Nationally Determined Contributions (NDCs) and National Adaptation Plans (NAPs). Oftentimes, only limited information on climate risks – upon which climate change adaptation decisions are based – is available. This constitutes the gap climate risk analyses seek to address, by providing evidence for substantiating political commitments and planning regarding adaptation. The climate risk analysis conducted for Ethiopia focuses on the evolving trends for temperature and precipitation, future water availability, the suitability of land for crop production and the spatial vulnerability of the agricultural sector. Based on this information, adaptation strategies are selected and analysed with regard to their feasibility, cost effectiveness and socio-economic aptitude for local conditions. The study results provide decision-makers in Ethiopia with costed adaptation scenarios, based on state-of-the-art climate risk modelling, as well as concrete recommendations for making agriculture more climate resilient. The findings can feed into national adaptation planning processes, such as within Ethiopia's Climate Resilient Green Economy Strategy (CRGE), especially for Agriculture and Forestry, the Ethiopian NAP process, Ethiopia's NDC implementation and update, National Communications to UNFCCC and other relevant climate change policies.

Study approach

The study models the full **impact** chain from a changing climate to changing water availability and resulting climate impacts on the agricultural sector, while taking into account the spatial differences of vulnerability to climate change in Ethiopia's regions and zones. The results then feed into an **action** dimension to assess different adaptation strategies with regard to their risk reduction potential, their cost-effectiveness and other socio-economic evaluation criteria, such as stakeholder interest and development co-benefits. The **uncertainty** attached to the results is critically discussed and recommendations targeting decision-makers are given.



Throughout the study design and implementation, special attention was given to informing and **consulting key stakeholders in Ethiopia** in order to ensure that the study **takes into consideration their interests** and **uses their local expertise, especially with regard to feasible adaptation strategies**. This was undertaken through **consultation workshops with the Ethiopian government, an expert elicitation survey** and **qualitative interviews** conducted with farmers, experts and other local key informants, such as from academia, civil society and the private sector.

Methodological innovation and value added

The climate risk study provides a **scientific and standardised analysis** for adaptation action in Ethiopia's agricultural sector, within the context of its NDC, NAP process and the Climate Resilient Green Economy Strategy (CRGE), especially for agriculture and forestry. Thereby, it combines several **innovative elements**:

- **Modelling the impact chain**: A detailed **quantitative analysis** of climate risks in the agricultural sector **under different emissions scenarios** is taken up in a comprehensive, model-based adaptation assessment, including **economic potentials**, to select suitable and effective adaptation strategies under future climate change projections.

- **State-of-the-art climate impact modelling**: The climate risk analysis is based on **state-of-the-art climate impact models.** In particular, data from the **Inter-Sectoral Impact Model Intercomparison Project (ISIMIP)** are used, which are at the forefront of climate impact modelling and reduce modelling uncertainty by drawing on multiple impact models.

- **Quantification of climate change impacts on the agricultural sector**: An important component of the risk analysis is the **projection of yield losses** of the key staple crops in Ethiopia as well as the resulting production losses, crop suitability changes and vulnerability of the agricultural sector in the different regions of the country.

- **Combination of bottom-up and top-down elements**: While the climate risk analysis is mainly model-based, **input from relevant Ethiopian stakeholders** was collected and **integrated into the study** at several important stages, especially with regard to selection and assessment of the adaptation strategies.

- **Stakeholder engagement and consultation in Ethiopia**: The **consultation and inclusion** of relevant **stakeholders from Ethiopia** in the study process also helped to ensure **local ownership** of the results and to facilitate the transfer **of the findings** into policy processes (see next section on stakeholder engagement).

- **Based on partner country's political priorities**: The **starting point** for selecting the adaptation strategies were relevant **Ethiopian policy documents**, such as Ethiopia's CRGE-Strategy, its NDC and the regional NAP prioritisation process, to ensure political coherence and country ownership.

- **Concrete recommendations for action and investment**: Based on the climate risk study, specific **recommendations for adaptation action and investment** as well as for **transforming agriculture** to become more resilient under future climate projections are provided and can **inform national governments and other local stakeholders** as well as **German and international development cooperation**.

- **A scalable approach**: While this study focused on the whole of Ethiopia, the approach can be transferred to **different spatial scales**. For example, a study at **district-level** could use more local datasets and focus specifically on the needs of local decision-makers and implementers of climate change adaptation plans.

Stakeholder engagement

Relevant stakeholders from government, civil society, academia and the private sector in Ethiopia were engaged throughout the study. Representatives from the following Ethiopian ministries and commissions contributed to the study: Environment, Forest and Climate Change Commission (EFCCC), Ministry of Agriculture (MoA), Ministry of Water, Irrigation, and Electricity (MoWie), Planning and Development Commission (PDC), Agricultural Transformation Agency (ATA) and the National Disaster Risk Management Commission (NDRMC). They were informed about the study process and contributed with conceptual inputs and technical expertise as well as local insights during two workshops held in Addis Ababa. At a kick-off workshop, the study design and the selection of adaptation strategies for the analysis within the study were discussed, especially with regard to their relevance for local stakeholders and national policy processes. During the actual study phase, the research team interviewed 33 stakeholders in order to integrate local knowledge into the report, which proved especially useful for the assessment of the feasibility of analysed adaptation strategies. In addition, an expert elicitation survey[1] brought valuable insights for the selection and evaluation of the adaptation strategies. In the final stages of the study completion, a validation workshop was conducted with the above-mentioned Ethiopian stakeholders to discuss the study results and to identify entry points for their transfer and integration into existing policy processes for adaptation, such as the NAP and NDC process. The findings of the study were also presented at a meeting of the NDC Partnership and will inform the Partnership's activities.

[1] Expert elicitation refers to formally acquiring information and judgement from experts on specific topics of interest. It is useful especially in situations where available data and models cannot provide required information.

Data and methods

This section gives an overview on the methods and data used for the different steps of the analysis that are part of the climate risk analysis, presented in chronological order according to the chapters of the study. Throughout the study, two CO_2-emissions scenarios were used as input scenarios for projecting future climatic changes: the low-emissions scenario RCP2.6 (Representative Concentration Pathway), which is in line with the trajectory set out in the Paris Agreement, and the high-emissions scenario RCP8.5, which is consistent with a scenario without climate policy.

Changing climatic condition: Based on RCP2.6 and RCP8.5, changes in climatic conditions for Ethiopia were analysed for 2030, 2050 and 2090, as averages over 20-year periods, in reference to 2007. The analysis comprises long-term annual mean temperature, the number of very hot days and very hot nights per year, long-term annual mean precipitation, and heavy and very heavy precipitation events.

The simulated past and future climate data was obtained from ISIMIP2b data (Inter-Sectoral Impact Model Intercomparison Project). The ISIMIP was created to offer a framework for the comparison of climate impact projections in different sectors. The data were bias-corrected[2] with the observation-based EWEMBI data (Lange, 2019). Historical simulations cover the years 1861-2005 and projected simulations cover the years 2006-2100. All data sets have a spatial resolution of 0.5° x 0.5°, corresponding to approximately 50km x 50km at the equator. The ISIMIP data used in the study consists of three climate models: HadGEM2-ES, GFDL-ESM2M and MIROC5 (Frieler et al., 2017). The indicators analysed in this study are: the annual average mean air temperature, annual number of very hot days (maximum temperature above 35°C), very hot nights or tropical nights per year (minimum temperature above 25°C), annual average precipitation amount, number of days with heavy precipitation (exceeding the 95th percentile calculated from EWEMBI for 2007)[3] and very heavy precipitation per year (exceeding the 99th percentile of EWEMBI in 2007) and precipitation and temperature in different seasons along the year considered relevant for agriculture. Since multi-model means usually show better results than single-model results, the results in the study are averages over the three models. All climate data analyses are based on a 20-year average, meaning that the mean annual temperature in 2030 is calculated as an average over the mean temperature between 2021 and 2040.

Changing water availability: To assess the impacts of climate change on water resources (precipitation, groundwater recharge, actual evapotranspiration and river discharge) in Ethiopia, an eco-hydrological model developed at PIK was used to simulate the hydrological processes in the Awash and Blue Nile river basins. The model is driven by climate input of RCP2.6 and RCP8.5 from three global climate models.

The Soil and Water Integrated Model (SWIM), an eco-hydrological model developed by Krysanova et al. (2005), was used to simulate the hydrological processes in the Awash and Blue Nile river basins. To set up the SWIM model, a number of data and information was collected and converted into appropriate format. A digital elevation model (DEM) was obtained from the Shuttle Radar Topography Mission (SRTM) (CGIAR-CSI, 2017) with 90m resolution. Soil parameters were derived from the Harmonised World Soil Database (HWSD v1.2) (FAO et al., 2012). The land use data is retrieved from World Land Cover BaseVue 2013 developed by MDA (MDA BaseVue, 2019) with 30m resolution, but aggregated to 90m. The SWIM model was set up, calibrated and validated using daily and monthly data for a number of gauges in the Blue Nile and Awash River basins. The river discharge was provided by the Global Runoff Data Centre (GRDC, 2017). Annual absolute and relative changes in river discharge at the two outlets are given, as well as average monthly changes in three future periods: 2021-2040, 2041-2060 and 2080-2099. Although the main goal was to assess the climate change impact on the hydrological cycle without changes in water management and land use, existing and planned reservoirs were also included in the modelling process in both basins, as a second analysis. Land use was considered as stable over the years.

---

[2] Bias-adjustment methods aim to reduce systematic errors (bias) of climate models in comparison to observations. The method used to produce EWEMBI adjusts the distribution of the simulated data to the distribution of the observed data while preserving the simulated trends. While the application of bias-adjustment methods is controversial, it is necessary for climate impact modelling, as the impact models are calibrated with observational data.

[3] The absolute value of this threshold depends on time and location of interest. For illustration, in 2007 the daily average heavy precipitation extreme threshold was 16.6 mm over the whole of Ethiopia.

Climate impacts on agricultural production: To test weather influence on the Ethiopian crop production, we applied two established crop yield simulation models, a semi-statistical model developed at PIK, and a process-based crop model. Moreover, we used machine-learning ensemble crop suitability modelling to evaluate the suitability of sorghum, maize, wheat and teff under climate change projections.

For the analysis of climate change impacts on crop production in Ethiopia, three different models were employed: 1) the semi-statistical crop yield simulation model AMPLIFY (Agricultural Model for Production Loss Identification to Insure Failures of Yields), which was developed at PIK (Gornott & Wechsung, 2016 and Schauberger et al., 2017), 2) the process-based crop model APSIM (Agricultural Production Systems sIMulator) (Holzworth et al., 2014) and 3) the machine-learning ensemble crop suitability models. Input data are zone-level yield data for maize, wheat, sorghum and teff from 2006 to 2016, pooled in a panel to increase statistical power for AMPLIFY. Weather data are derived from ERA-Interim (Dee et al., 2011). For APSIM, maize yield was simulated from 2006 to 2016 for 18 zones, which had complete maize yield records for the time period and for which reliable management data could be compiled.

AMPLIFY: AMPLIFY is a statistical crop model based on physiological mechanisms, using historical weather and yield data as well as remote sensing information to assess crop yields and yield losses. Importantly, the tool differentiates between weather-related and non-weather-related (agronomic management, socio-economic) yield perils. In the climate risk analysis, exogenous variables in the AMPLIFY model are different weather indices measured during the growing season. The model quality is measured by reproduction of the observed yield time series on national level, with an additional out-of-sample quality test.

APSIM: A process-based crop simulation model represents the response of crops to varying weather conditions that affect germination, growth and development of the harvested portion of the plant by incorporating site-specific soil properties, water availability and management decisions (Robertson, Nelson, Thomas, & Rosegrant, 2013). APSIM is such a model that can be used to simulate in great detail the complex climate-soil-crop systems (Holzworth et al., 2014). In the comprehensive climate risk analysis, the module APSIM-Maize 7.1 (Brown et al., 2014) was used to simulate the yield response of maize. The objectives of using APSIM in the study were to use common zone-level management data on maize production to calibrate and evaluate the performance of APSIM for Ethiopia, to evaluate the impacts of climate change on yield on maize and to identify the most promising management strategies for stabilising maize production under projected climatic conditions.

Crop suitability models: Machine-learning ensemble crop suitability modelling was used to evaluate the suitability of land to grow sorghum, maize, wheat and teff under current and projected climate change as well as the impact of different adaptation strategies on the suitability of the land for growing these respective crops. The crops were selected based on their importance with regard to harvested area for agriculture in Ethiopia, availability of yield data, as well as the capacity of the crop models for those specific crops. Suitability models capture the production potential for agricultural crops, since crop production is influenced by the weather signal and, as such, can be explained by dominant biophysical parameters like weather and soils (Hummel et al., 2018; Moat et al., 2017). Since the results are spatially explicit, thus showing how results differ across regions, the suitability models identify the areas where adaptation strategies are mostly required to avert the consequences of a predicted decline in climatic suitability of the crops. Eight biophysical parameters[4] were used in modelling the suitability of four crops under current and future climatic conditions. An ensemble model consisting of eight machine-learning algorithms was fitted using the points from the districts which, based on observed data, were determined as suitable and the stack of the eight environmental variables (seven weather-based and one soil organic carbon) with sampling for pseudo absences, performing three model runs for each. Nine different models were used which are Maximum Entropy (MAXENT), Generalised Boosted Models (GBM), Generalized Linear Models (GLM), Random Forest (RF), Generalized Additive Models (GAM), Flexible Discriminant Analysis (FDA), Multivariate Adaptive Regression Spline (MARS), Classification Tree Analysis (CTA) and Artificial Neural Networks (ANN). These models were chosen based on their data requirements and the availability of crop data for the specific models.

[4] The eight parameters were: 1) Total precipitation in the growing season; 2) Total precipitation between March and September; 3) Sum of precipitation in the crop sowing month; 4) Precipitation coefficient of variation; 5) Diurnal temperature range between March and September; 6) Mean temperature growing season; 7) Mean temperature between March and September; 8) Top soil organic carbon content (top 20 cm).

Economic impacts on crop production and spatial vulnerability: Next to the biophysical impacts of climate change on crop production, we also assessed the economic impacts and the vulnerability of different zones in Ethiopia to such impacts. For the economic analysis, a net present value approach was used, whereas an index-based approach formed the vulnerability assessment.

The economic approach is explained in the section on economic assessments of adaptation strategies.

Employing an index-based approach, the vulnerability assessment combines environmental and socio-economic data from different sources (agricultural surveys, climate and remote sensing data) to capture the multi-dimensional attributes of vulnerability. The vulnerability assessment is based on the definition of vulnerability to climate change as a function of exposure, sensitivity and adaptive capacity of a system (McCarthy et al., 2001). This analysis focuses on 64 administrative units (zones) where Meher crop production is important and where data is available from the Annual Agricultural Sample Survey by the Central Statistical Agency of Ethiopia (CSA). Climate data to estimate the exposure to climate change was collected from the WATCH-ERAinterim (WFDEI) dataset, which is ERAinterim reanalysis data. The WFDEI dataset is also bias-adjusted with observational data with a 0.5° resolution (~50km) (Weedon et al., 2014). Socio-economic data on agriculture was extracted from the Annual Agricultural Sample Survey for 2015/16 Meher Season (CSA, 2016). Data for Normalized Difference Vegetation Indices (NDVI) was downloaded using MODIS (Moderate Resolution Imaging Spectroradiometer) 250m resolution data. The selection of the indicators used for the analysis was based on a review of the related literature on vulnerability mapping studies in sub-Saharan Africa. The final selection of the 19 indicators used in this study was based on the relevance to agricultural systems in Ethiopia and availability of data. Normalisation of indicators was done using the linear (minimum-maximum) scaling, which scales the data in the range of 0 to 1 (Tate, 2012). Normalised values of all the indicators were aggregated to obtain the final vulnerability index. We performed correlation analysis among these indicators before the start of the indexing analysis to ensure that none of the variables is over-represented. After the correlation analysis we selected a total of 15 indicators.

Assessment of adaptation strategies: In order to identify and assess the feasibility and suitability of different adaptation strategies for Ethiopia's agricultural sector, a multi-criteria assessment was conducted. In addition, barriers to adaptation and the adaptation context were analysed. The following adaptation strategies were assessed: Irrigation, improved crop management, agroforestry, fodder and feed improvement and crop insurance.

A multi-criteria framework for assessing agricultural adaptation strategies for the context of Ethiopia was used, building on the country-specific climate risks as modelled and analysed in the study, as well as country-specific measurement and adaptation information to analyse a list of nine criteria: 1) Risk response (risk mitigation vs. risk sharing or transfer); 2) Risk mitigation potential; 3) Cost-effectiveness; 4) Risk gradient (risk-independent vs. risk-specific); 5) Upscaling potential; 6) Co-benefits for Sustainable Development Goals (SDGs); 7) Potential maladaptive outcomes; 8) Stakeholder interest; 9) Institutional support requirements (institution-led vs. autonomous). A focus was placed on criteria 2) and 3) for performance assessment based on PIK's impact models, both biophysically and economically. Indicator 2) was assessed using the crop model APSIM and the crop suitability models, described on page 4.

Economic analysis of adaptation strategies: For analysing the cost-effectiveness of adaptation strategies in Ethiopia, the net values of crop production (NVP) were compared across different scenarios, namely between an adaptation scenario (irrigation) and non-action. In addition, a micro-economic cost-benefit analysis was conducted for assessment of further adaptation strategies: irrigation, crop switching, agroforestry and fodder and feed improvement.

Macroeconomic analysis: A comparative static analysis was conducted based on three scenarios: the baseline scenario, the climate change scenario and an irrigation scenario. Input data included crop yield and area data and parameters collected, wherever possible, from the empirical literature on Ethiopia, as well as price data from the literature. Specifically, the gross values of production and the net values of crop production were compared among the scenarios. The reference scenario for climate change impacts was the baseline scenario. For the irrigation as adaptation scenario, the climate change impact scenario was the reference scenario. This is because the rationale for adaptation strategies is to dampen the economic consequences of climate change. Impacts of climate change were modelled as changes in crop yields. The impacts here refer to the changes in anticipated (counterfactual) yield (in the 2040s) relative to the present (actual) yield and area suitability (in the 2010s). The exercise involved imposing these anticipated changes on the current crop production system. All assumptions were derived from the impact modelling results as well as relevant literature. The results under the climate change scenarios represent the costs of climate change or the costs of inaction, whereas the results under the adaptation scenario was compared to the no-adaptation case and the baseline scenario. This is in order to account for the cost-effectiveness of adaptation strategies as compared to a scenario without adaptation action or to a counterfactual world with no climate change impacts.

Microeconomic analysis: A second approach follows the rationale of a micro-level cost-benefit analysis, which uses a dynamic approach and considers the costs and benefits of adaptation strategies over time, from 2020 until 2050. Like the first approach, it is based on different scenarios in order to calculate the economic efficiency of implementing different adaptation strategies. The action scenario is compared with two baseline scenarios: one with climate change impacts, but no adaptation, and the other without climate change impacts and no adaptation, all other things being equal. In addition to net values of production, for the micro-level analysis other indicators for cost-efficiency, such as benefit-cost ratios (BCR), internal rates of return (IRR) and payback periods for farmers are also calculated. Since the time dimension in this approach requires comparing impacts at different periods of time, future values need to be discounted to present values to allow for comparison. For the purpose of our analysis, this was done using the current inflation rate, which is 6%, according to World Bank data. Not all costs and benefits can be monetised and included in quantitative cost-benefit analyses, for instance factors related to wellbeing, equity and the environment are often difficult to quantify. Here, the costs included in the calculations are: 1) Establishment costs of the initial investment, including foregone revenues from production option before action/adoption of the adaptation strategy; 2) Maintenance costs (labour costs for management, fertiliser etc.); 3) "Re-establishment" costs, where the adaptation infrastructure or inputs need to be renewed. The benefits are increases in agricultural production due to the adaptation strategy implemented.

Soft assessment indicators: In addition to the biophysical and economic indicators, the multi-criteria assessment also contained several socio-economic and institutional indicators. Those indicators were assessed based on expert and key informant interviews, an expert survey, input from two stakeholder workshops with the Ethiopian government and empirical literature.

In total, 33 individuals were interviewed for the study using semi-structured questionnaires, to elicit expert knowledge regarding adaptation, adaptive capacity and the five selected adaptation strategies in Ethiopia. The interviews were transcribed, coded and analysed using thematic analysis following the Attride-Stirling model[5] (Attride-Stirling, 2001) in order to identify key themes and perceptions of experts. Further, an expert survey conducted via email with 22 respondents, containing mostly closed questions on the selected adaptation strategies, and two stakeholder workshops with the Ethiopian government held in Addis Ababa importantly added to the assessment. In addition, key policy documents were consulted, such as Ethiopia's CRGE-Strategy and its regional NAP prioritisation outcomes. Empirical evidence on adaptation strategies in Ethiopia was drawn from a diverse body of literature and used to complement the assessment.

Uncertainty analysis: The uncertainty attached to modelling results, methodological approaches and to data quality was critically reflected to guide interpretation of the results.

The results presented in the study are subject to a number of uncertainties and limitations, which must be thoroughly considered for adequate interpretation, as well as for drawing policy implications and recommendations. The last chapter of the study discusses the uncertainties attached to the different types of analysis throughout the study and highlights their relevance in the context of Ethiopia. Major sources of uncertainty include the different input data used, such as climate model data, river discharge data, crop yield data and price data. The models and approaches used also come with uncertainties attached, as they can only partially represent and project climate risk and adaptation strategies.

5 The Attride-Stirling model provides a framework for analysis of qualitative data, such as interviews. Analysis is organised into basic themes, organising themes and overarching global themes, arranging them into networks to facilitate analysis, identify salient themes and uncover meanings in textual data.

This factsheet is based on a study prepared by the Potsdam Institute for Climate Impact Research (PIK) for the Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH on behalf of the German Federal Ministry for Economic Cooperation and Development (BMZ). The report aims to contribute to Ethiopia's NDC implementation and to the objectives of the NDC Partnership.

In contribution to:

NDC PARTNERSHIP
ACCELERATING CLIMATE AND DEVELOPMENT ACTION

References

Attride-Stirling, J. (2001). Thematic networks: an analytic tool for qualitative research. *Qualitative Research*, 1(3), 385–405.

Brown, H. E., Teixeira, E. I., Huth, N. I., & Holzworth, D. P. (2014). The APSIM Maize Model. APSIM Initiative: Toowoomba, Australia.

CGIAR-CSI. (2017). CGIAR-CSI SRTM 90m DEM Digital Elevation Database.

Central Statistical Agency of Ethiopia (CSA) (2016). Ethiopia - socioeconomic survey 2014-2015. Washington D.C.: The World Bank.

Dee, D. P., Uppala, S. M., Simmons, A. J., Berrisford, P. , Poli, P., Kobayashi, S., Andrae, U., Balmaseda, M. A., Balsamo, G., Bauer, P., Bechtold, P. , Beljaars, A. C., van de Berg, L., Bidlot, J., Bormann, N., Delsol, C., Dragani, R., Fuentes, M., Geer, A. J., Haimberger, L. , Healy, S. B., Hersbach, H. , Hólm, E. V., Isaksen, L., Kållberg, P, Köhler, M., Matricardi, M., McNally, A. P., Monge-Sanz, B. M., Morcrette, J., Park, B., Peubey, C., de Rosnay, P., Tavolato, C., Thépaut, J. & Vitart, F. (2011). The ERA-Interim reanalysis: configuration and performance of the data assimilation system. *Q.J.R. Meteorol. Soc.*, (137), 553–597.

FAO/IIASA/ISRIC/ISSCAS/JRC. (2012). Harmonized World Soil Database.

Frieler, K., Lange, S., Piontek, F., Reyer, C. P. O., Schewe, J., Warszawski, L., Zhao, F., Chini, L., Denvil, S., Emanuel, K., Geiger, T., Halladay, K., Hurtt, G., Mengel, M., Murakami, D., Ostberg, S., Popp, A., Riva, R., Stevanovic, M., Suzuki, T., Volkholz, J., Burke, E., Ciais, P., Ebi, K., Eddy, T. D., Elliott, J., Galbraith, E., Gosling, S. N., Hattermann, F., Hickler, T., Hinkel, J., Hof, C., Huber, V., Jägermeyr, J., Krysanova, V., Marcé, R., Müller Schmied, H., Mouratiadou, I., Pierson, D., Tittensor, D. P., Vautard, R., van Vliet, M., Biber, M. F., Betts, R. A., Bodirsky, B. L., Deryng, D., Frolking, S., Jones, C. D., Lotze-Campen, H., Sahajpal, R., Thonicke, K., Tian, H. & Yamagata, Y. (2017). Assessing the impacts of 1.5 °C global warming – simulation protocol of the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP2b), *Geosci. Model Dev.*, 10, 4321–4345.

Gornott, C. & Wechsung, F., (2016). Statistical regression models for assessing climate impacts on crop yields: A validation study for winter wheat and silage maize in Germany. *Agricultural and Forest Meteorology*, (217), 89–100.

GRDC, 56068 Koblenz, G. (2017). The Global Runoff Data Centre.

Holzworth, D. P., Huth, N. I., Zurcher, E. J., Herrmann, N. I., McLean, G., Chenu, K., ... & Brown, H. (2014). APSIM–evolution towards a new generation of agricultural systems simulation. *Environmental Modelling & Software*, 62, 327–350.

Hummel, M., Hallahan, B. F., Brychkova, G., Ramirez-Villegas, J., Guwela, V., Chataika, B., Talsma, E. F. (2018). Reduction in nutritional quality and growing area suitability of common bean under climate change induced drought stress in Africa. *Scientific Reports*, 8(1), 16187.

Krysanova, V.; Hattermann, F. & Wechsung, F., (2005). Development of the ecohydrological model SWIM for regional impact studies and vulnerability assessment. *Hydrological Processes,* 19, 763–783.

Lange, S. (2019). EartH2Observe, WFDEI and ERA-Interim data Merged and Bias-corrected for ISIMIP (EWEMBI). V. 1.1. GFZ Data Services. http://doi.org/10.5880/pik.2019.004

McCarthy JJ, Canziani OF, Leary NA et al (2001). Climate change 2001: impacts, adaptation and vulnerability. Cambridge University Press, Cambridge.

MDA BaseVue 2013 Global Land Cover available on ArcGIS Online. (2019). Retrieved August 9, 2019, from https://www.esri.com/arcgis-blog/products/defense/defense/mdas-basevue-2013-global-land-cover-available-on-arcgis-online/.

Moat, J., Williams, J., Baena, S., Wilkinson, T., Gole, T. W., Challa, Z. K. & Davis, A. P. (2017). Resilience potential of the Ethiopian coffee sector under climate change. *Nature plants*, 3(7), 17081.

Robertson, R., Nelson, G., Thomas, T., & Rosegrant, M. (2013). Incorporating process-based crop simulation models into global economic analyses. *American Journal of Agricultural Economics*, 95(2), 228–235.

Schauberger, B., Gornott, C. & Wechsung, F., (2017). Global evaluation of a semiempirical model for yield anomalies and application to within-season yield forecasting. *Global change biology*, 23(11), 4750–4764.

Tate, E. (2012). Social vulnerability indices: a comparative assessment using uncertainty and sensitivity analysis. *Natural Hazards*, 63(2), 325–347.

Warszawski, L., Frieler, K., Huber, V., Piontek, F., Serdeczny, O., & Schewe, J., (2014). The Inter-Sectoral Impact Model Intercomparison Project (ISI–MIP): Project framework. *Proceedings of the National Academy of Sciences*, 111(9), 3228–3232.

Weedon, G. P., Balsamo, G., Bellouin, N., Gomes, S., Best, M. J., & Viterbo, P. (2014). The WFDEI meteorological forcing data set: WATCH Forcing Data methodology applied to ERA-Interim reanalysis data. *Water Resources Research*, 50(9), 7505–7514.