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Prediction of the impact of climate change on coffee and mango growing areas in Haiti

Full Technical Report

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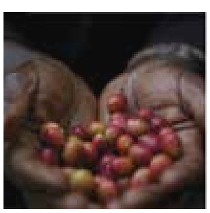

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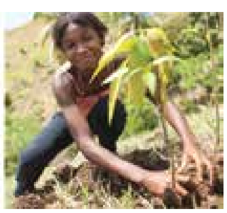

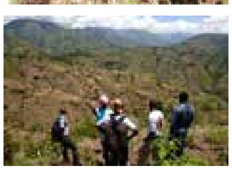

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Prediction of the impact of climate change on coffee and mango growing areas in Haiti

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1. Executive summary and main findings

A. Methodology and carried out spatial analysis

The potential impact of climate change on agricultural crop production varies spatially and depends on crop specific biophysical constraints. For selecting the environmental factors we apply a climate-only approach because climatic variables are expected to change substantially over the modeled time period and generally accepted future projections are available.

Bioclimatic variables (BC) are often used in ecological niche modeling and they represent annual trends, seasonality and extreme or limiting environmental factors. For the current climate (baseline) we used monthly data from the WorldClim (WC) database sourced from global weather stations. For future climates, we used the Global circulation models (GCM) with short- mid- & long-term predictions. We acknowledge the uncertainty of climate predictions and the differences between the GCMs used for the modelling. We used 19 different GCMs in our study and produced final maps showing descriptive statistics of different predictions on a pixel basis.

We reviewed several crop suitability models before deciding upon the most appropriate model to use in the analysis. Maximum entropy (Maxent) is a niche modeling method that has been developed involving species distribution information based only on known presences. Maxent is the most adapted model to use for coffee and mango. To identify adequate diversification options for coffee farmers we analyzed crop-climate-suitability of selected crops from current agricultural portfolios of Haiti. We selected these crops based on their importance to food security and livelihood income as well as on crops recently adopted by development organizations. We compared climate-suitable area-outcomes with a land availability-index for agriculture production and extracted spatial statistics from the climate-suitability layers based on the 5 land-availability layers using a Geographical Information System (GIS).

L'impact potentiel du changement climatique sur la production des cultures agricoles varie dans l'espace et dépend des contraintes biophysiques spécifiques à chaque culture. Pour sélectionner les facteurs environnementaux nous appliquons une approche centrée sur le climat car les variables climatiques devraient changer de manière substantielle sur la période de temps modélisée et des projections futures globalement acceptées sont disponibles.

Les variables bioclimatiques (BC en anglais) sont souvent utilisées dans la modélisation de niche écologique. Elles représentent les tendances annuelles, la saisonnalité, les facteurs limitant et les conditions extrêmes. Pour le climat actuel (ligne de base) nous avons utilisé des données mensuelles de la base de données WorldClim (WC) provenant de stations météorologiques globales. Pour les climats futurs, nous avons utilisé des modèles de circulation générale (GCM en anglais) avec des prévisions à court, moyen et long terme. Nous mentionnons l'incertitude des prévisions climatiques et des différences entre les GCM utilisés pour la modélisation. Nous avons utilisé 19 différents GCM dans notre étude et produit les cartes finales montrant les statistiques descriptives de différentes prévisions, sur la base du pixel.

Nous avons revu plusieurs modèles d'aptitude climatique pour les cultures avant de décider lequel était le plus approprié à utiliser dans cette étude. L'entropie maximum (Maxent) est une méthode de modélisation de niche écologique qui a été développée en associant l'information de distribution des espèces uniquement aux sites de présence connus. Maxent est le modèle le plus adapté pour le café et la mangue. Pour identifier les options de diversification les plus adéquates pour les producteurs de café nous avons analysé l'aptitude climatique pour les cultures sélectionnées à partir du portefeuille agricole actuel de Haïti. Nous avons sélectionné ces cultures en se basant sur leur importance pour la sécurité alimentaire et les revenus générés ainsi que sur les cultures récemment adoptées par les organisations de développement. Nous avons comparé les résultats des zones climatiques aptes avec un index de disponibilité du sol pour la production agricole. En utilisant un système d'information géographique (GIS en anglais), nous avons extrait des statistiques spatiales à partir des couches d'aptitudes climatiques et des 5 couches de disponibilités du sol.

B. Key results for coffee and mango

According to the ensemble of the 19 Global Circulation Models (GCM) temperature in Haiti will increase an average of 0.9°C in 2020 and **1.8°C by 2050**. The average temperature of the hottest month will increase **from 30.9°C to 32.9°C by 2050** and the driest month is projected to get **10% less rainfall**. Overall the climate is expected to become more seasonal in terms of variability through the year in temperature and more seasonal in precipitation. Although rainfall decrease is generally moderate in all future predictions, this combined with increasing minimum, mean and maximum temperatures can cause water deficits due to higher evapotranspiration rates of plants triggering soil **water deficits and heat stresses**. Increased temperature stresses and in particular high night time temperatures (> 18 °C) and drought conditions have substantial effects on biomass production and the reproductive stages of several plants and crops.

The altitude of **coffee** plantation in Haiti ranges between 400 meters in the North to 1,300 meters in the South. Changes in temperature and rainfall patterns will cause a **general decrease of areas suitable for coffee** and reduce areas which currently possess high suitability. Suitability will climb up altitudinal gradients to currently cooler climates. Models predict that coffee **will lose suitability in lower altitudes** (up to 1200 meters above sea level) and will gain suitability in higher areas with a maximum suitability between 1500m.a.s.l. and 1800m.a.s.l. in 2050. Changing climatic conditions in Haiti could lower the quality and yields of current coffee producing regions and this is likely to be most prevalent in lower-altitude zones. Furthermore, economic losses in the future could ensue if adaptation efforts are not implemented.

Mango will **remain a highly suitable** crop in many regions of Haiti. Some areas will reduce from excellent to very suitable and shift geographically from concentrated areas close the coast to inland areas with higher altitude**. Altitudes from 500 to 700m.a.s.l. will benefit** from increasing climate suitability mostly because of increased temperatures.

D'après l'ensemble des 19 modèles de circulation générale (GCM en anglais), la température en Haïti augmentera en moyenne de 0.9°C en 2020 et de 1.8°C d'ici 2050. La température moyenne du mois le plus chaud augmentera de 30.9°C à 32.9°C d'ici 2050 et on projette une chute de 10% des précipitations pour le mois le plus sec. En général le climat devrait devenir plus saisonnier, en termes de variabilité de la température et de répartition de la précipitation au long l'année. Même si les diminutions en termes de précipitations sont en général modérées dans toutes les prévisions futures, ceci combiné avec une augmentation des températures minimum, moyennes et maximum peut causer des déficits en eau. En effet, des taux d'évapotranspiration supérieurs des plantes déclencheraient des déficits en eau du sol et des stress thermiques. Une augmentation des stress thermiques, et en particulier des températures nocturnes élevées (>18°C), et des conditions de sécheresse ont des effets substantiels sur la production de biomasse et sur les étapes de reproduction de plusieurs plantes et cultures.

Les zones de plantation de café en Haïti se situent à des altitudes comprises entre 400 mètres dans le Nord et 1 300 mètres dans le Sud. Les changements des régimes de températures et de précipitations causeront une diminution générale des zones aptes à la culture du café et réduira les zones qui possèdent actuellement une forte aptitude climatique. L'aptitude climatique s'élèvera selon des gradients altitudinaux vers des climats actuellement plus froids. Les modèles prédisent que le café perdra en aptitude climatique dans les basses altitudes (en dessous de 1 200 mètres au-dessus du niveau de la mer) et gagnera en aptitude dans les zones plus hautes avec un maximum entre 1 500 et 1 800 mètres en 2050. Les changements des conditions climatiques en Haïti pourraient diminuer la qualité et les rendements des régions actuelles de productions de café et ceci serait d'autant plus vrai dans les zones de basses altitudes. Des pertes économiques dans le futur pourraient s'ensuivre si des efforts d'adaptation ne sont pas mis en œuvre.

La mangue restera une culture hautement apte dans de nombreuses régions d'Haïti. Certaines zones passeront d'excellentes à très aptes et se déplaceront géographiquement depuis des zones concentrées proches de la côte vers des zones plus hautes à l'intérieur des terres. Les altitudes de 500 à 700 mètres au-dessus du niveau de la mer bénéficieront d'une augmentation de l'aptitude climatique principalement grâce à une augmentation des températures.

C. Diversification options

The potential impact of climate change on agricultural crop production varies spatially and depends on crop specific biophysical constraints. In Haiti, land for agriculture use extends to more than 1.7 million hectares, occupying more than 60% of the country. Conditions for agricultural production are driven by different climate patterns among other constraints like soil erosion, highly varying soil capacity and land use prevalence's. In this study selected 6 crops as diversification options for coffee farmers together make use of more than 0.7 million hectares (~60%) of agriculture land in Haiti. 400 thousand hectares (14%) of Haiti's agricultural land are available and soil capacity is medium to excellent in these areas; 530 thousand hectares (19%) are available but farmers are producing on soil with limited capacity; other 300 thousand hectares have no soil limitations but needs land use change to produce annual crops (parts of it are currently used for agro-forestry systems or are in remaining forests).

Haiti possesses excellent suitability for cocoa and is not predicted to be affected by changes from long-term climate patterns. There are still a lot of potential areas inside existing and potentially new agro-forestry systems that could be created in the future. Haiti's cocoa producers have an opportunity to benefit from an increasing global demand for cocoa production.

Highly suitable environments for growing common beans in Central America and the Caribbean are most limited at present by maximum temperatures. Our analyses show that suitability of beans will decrease quite substantially in several areas of Haiti which are currently important producing areas. Loss will be up to 70% in areas without limitations in soil capacity and good availability for annual crop production if no adaptation measures are taken. There is a strong need for the introduction of improved varieties that are less susceptible to heat, and a need to equip farmers with tools and provide them with the knowledge to close yield gaps on existing production. Statistical studies of maize yields have clearly indicated a strong negative yield response to accumulated days above 30 °C and more seasonal rainfall during the growing season (increased water stress for plants). We emphasize that appropriate crop development and management strategies for dealing with extreme heat on maize varieties should be a priority for future work in Haiti. Suitability of sorghum will increase in

L'impact potentiel du changement climatique sur les productions des cultures agricoles varie spatialement et dépend des contraintes biophysiques spécifiques à chaque culture. En Haïti, les terres destinées à l'agriculture s'étendent sur plus de 1,7 million d'hectares, soit 60% de la surface du pays. Les conditions de production agricole dépendent des différents régimes climatiques, ainsi que d'autres contraintes, telles que l'érosion des sols, la capacité du sol très variable et la prévalence de l'utilisation des terres. Les 6 cultures sélectionnées dans cette étude comme des options de diversification pour les producteurs de café rassemblent plus de 0,4 millions d'hectares (~60%) des terres agricoles en Haïti. 400 000 hectares (14%) des terres agricoles d'Haïti sont disponibles et la capacité du sol est moyenne à excellente dans ces zones; 530 000 hectares (19%) sont disponibles mais les agriculteurs produisent sur des sols avec une capacité limitée, d'autres 300 000 hectares n'ont pas limitations liées au sol mais nécessitent un changement d'utilisation du sol pour produire des cultures annuelles (une partie d'entre eux est actuellement utilisée pour les systèmes agro-forestiers ou sont des forêts restantes).

Haïti a une excellente aptitude climatique pour le cacao et ne semble pas être affecté par les changements de régimes climatiques à long terme. Il y a encore beaucoup de zones potentielles à l'intérieur des systèmes agro-forestiers existants et potentiels qui pourrait être créés à l'avenir. Les producteurs de cacao d'Haïti ont l'opportunité de profiter d'une augmentation globale de la demande pour la production de cacao.

Les environnements très aptes pour cultiver le haricot commun en Amérique Centrale et dans les Caraïbes sont actuellement limités principalement par la température maximum. Nos analyses montrent que l'aptitude climatique pour la culture du haricot diminuera assez sensiblement dans plusieurs zones d'Haïti qui sont actuellement d'importantes zones de production. Si aucune mesure d'adaptation n'est prise, les pertes iront jusqu'à 70% dans les zones où la capacité du sol et la disponibilité pour les cultures annuelles ne sont pas limités. Il est nécessaire d'introduire des variétés améliorées moins sensibles à la chaleur, d'équiper les agriculteurs avec les outils et les connaissances nécessaires pour combler les écarts de rendements sur la production existante. Les études

Haiti between 4 and 8% in available land with no or low limited soil capacity by 2050. There are many species of yams and we selected the 3 main ones for the Caribbean. Results show that cushcush yam is losing suitability in important areas, white and yellow yam is gaining suitability and available areas remain more or less constant all over Haiti by 2050. Finally malanga is shifting its geographical areas of suitability but generally losing suitability and areas. Groundnut or peanut provides an opportunity for the future, with a two fold increase in the areas on available land with no limitations of soil by remaining suitability almost all over Haiti.

statistiques sur les rendements du maïs ont clairement indiqué une réponse négative des rendements à une accumulation de jours au-dessus de 30°C et des différences marquées dans la distribution des pluies durant la saison de croissance (augmentation du stress hydrique pour les plantes). Nous soulignons que des stratégies appropriées pour la gestion et le développement des cultures afin de lutter contre les stress thermique sur les variétés de maïs devraient être une priorité des futurs travaux en Haïti. L'aptitude climatique pour la culture du sorgo augmentera en Haïti entre 4 et 8% dans les terres disponibles avec une capacité du sol nulle ou limitée en 2050. Il y a de nombreuses espèces d'ignames et nous avons sélectionné les 3 principales pour les Caraïbes. Les résultats montrent que l'igname cushcush perd de en aptitude sur une surface importante, les ignames blanc et jaune gagnent en aptitude et les zones disponibles se maintiennent plus ou moins constantes partout en Haïti en 2050. Finalement, les zones géographiques d'aptitude climatique pour le malanga se déplacent mais globalement les valeurs diminuent en aptitude et en surface. Les arachides sont une belle opportunité pour le futur, l'aptitude climatique se maintient presque partout en Haïti et les surfaces de terres disponibles sans limitation dues au sol sont multipliées par deux.

D. Recommendations and next steps

There are many opportunities to adapt to changes and for those coffee farms whose suitability will drop but not decrease drastically, proactive adaptation is a crucial strategy. Agroforestry systems such as coffee systems are not only important as a commodity and cash income generator for smallholder but also as a provider of ecosystem services. A decrease in coffee suitability is likely going to threaten the environmental services coffee systems provide, such as soil cover, carbon sequestration, biodiversity and water storage. Therefore a key strategy needs to focus on maintaining the environmental services with a different agroforestry system. In this context cocoa is a promising option. We distinguish 3 general strategies to adapt to the change of coffee suitability. The three strategies are interlinked and will replace each other over time. Areas that will increase in suitability need strategic investment. Areas that will lose some suitability are likely to be maintained through targeted strategies such as irrigation, shade management and change to more drought resident varieties. Areas that are likely to suffer from significant decrease in suitability need to start diversifying in order to switch to different crops, such as cocoa, once coffee is not suitable any more.

Il y a de nombreuses opportunités d'adaptation aux changements et, pour les fermes de production de café dont l'aptitude baissera mais ne chutera pas radicalement, l'adaptation proactive est une stratégie cruciale. Les systèmes agroforestiers, tels que les systèmes caféiers, ne sont pas seulement important en tant que source de produit de consommation et générateurs de revenus pour les petits propriétaires mais ils sont aussi fournisseurs de services écosystémiques. Une diminution de l'aptitude climatique pour le café peut mettre en danger les services ecosystémiques fournis par les systèmes caféiers tels que la couverture du sol, la séquestration de carbone, la biodiversité et le stockage d'eau.
En conséquence, une stratégie clé doit chercher à maintenir les services environnementaux avec un système agro-forestier différent. Dans ce contexte le cacao est une option prometteuse. On distingue 3 stratégies générales d'adaptation au changement d'aptitude climatique pour le café. Les trois stratégies sont interconnectées se succéderont au fil du temps. Les zones où l'aptitude augmentera ont besoin d'investissements stratégiques. Les zones qui perdront en aptitude peuvent être maintenues grâce à des stratégies ciblées telles que l'irrigation, la gestion de l'ombrage et l'utilisation de variétés résistantes à la sécheresse. Les zones qui pourraient subir une chute significative de l'aptitude doivent, une fois que le café n'est plus apte, commencer à se diversifier afin de passer à de nouvelles cultures, telles que le cacao.

2. Background and context

This work is built on the ongoing activities of the Catholic Relief Services (CRS) with the aim of improving livelihoods for Haitian farmers through coffee and mango value chains in the southwestern departments of the country. In 2010, after the earthquake, CRS in collaboration with the International Center for Tropical Agriculture (CIAT) carried out an assessment of the current state of these value chains and provided in its final reports several recommendations to improve current production quality and quantity (Rodríguez et al. 2011, Castañeda et al. 2011). The ministry of agriculture, natural resources and rural development developed a National Agricultural Investment Plan which highlighted the agricultural sectors vital importance to not only domestic food security, but also to the economic recovery and the social stability of Haiti after the earthquake. The present study aims to contribute to the ongoing long-term strategic investments in these value-chains by predicting the impact of short- mid- & long-term climate change on coffee and mango. Further potential impacts on crops proposed to be diversification options for coffee farmers will be assessed by analyzing their climate-suitability to ensure that strategic adaptation work will be done on current and future suitable crops in Haiti. The potential impact of climate change on agricultural crop production varies spatially and depends on crop specific biophysical constraints. In Haiti, land for agriculture use extends to more than 1.7 million hectares, occupying more than 60% of the country. Conditions for agricultural production are driven by different climate patterns among other constraints like soil erosion, highly varying soil capacity and land use prevalence's. In this study selected 6 crops as diversification options for coffee farmers together make use of more than 1.4 million hectares (~80%) of agriculture land in Haiti in 2011.

The main objectives carried out during this project have been: (i) reviewing and comparing methodologies for crop suitability modeling and compiling necessary information; (ii) identifying environmental factors and generating a climate database for current and future conditions; and (iii) predicting and validating current and future suitability of coffee, mango and diversifications crops in Haiti.

3. Methodology

A block diagram of the methods used is shown in Figure 1. We used the elements described below throughout the research project:

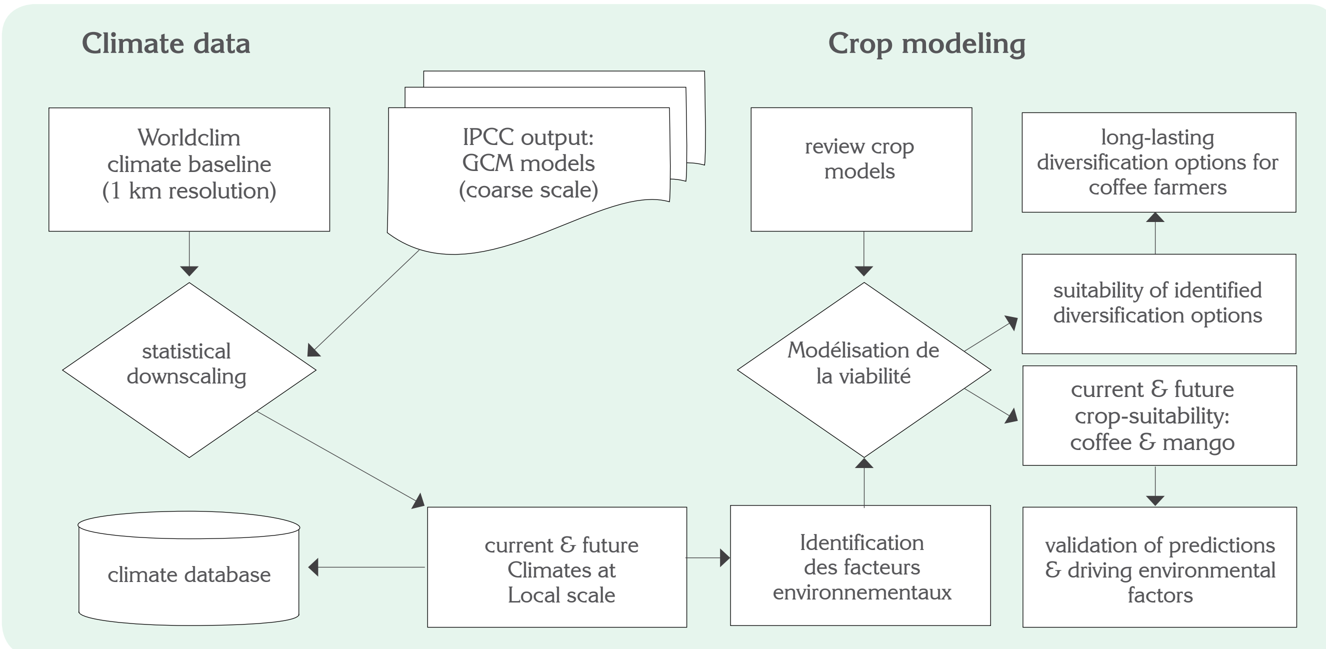


Figure 1. Block diagram of the methods.

3.1. Climate data generation

To predict anticipated changes of future climate we needed to establish a baseline which we can use to compare outputs of global circulation models (GCM) with current climate conditions. These GCM's possesses a very coarse spatial resolution and it was therefore necessary to downscale them for climate change predictions on a local scale.

For the current climate (baseline) we used monthly data from the WorldClim (WC) database (publicly and freely available at http://www.worldclim.org). WC provides interpolated global climate surfaces using latitude, longitude, and elevation as independent variables and represents long term (1950–2000) monthly means of maximum, minimum, mean temperatures and total rainfall. Input data for the WC database were sourced from global weather stations including ~47,000 weather stations with monthly information on precipitation, ~23,000 stations with mean temperature data and ~13,000 locations. Passing through a quality checking algorithm input data were finally interpolated to a 30 arc second spatial resolution, commonly referred to as '1-km' resolution (Hijmans et al. 2005).

The WC data for Haiti is derived from 103 stations with precipitation recordings, 93 stations with mean temperature, and 18 stations with minimum and maximum temperatures (Figure 2).

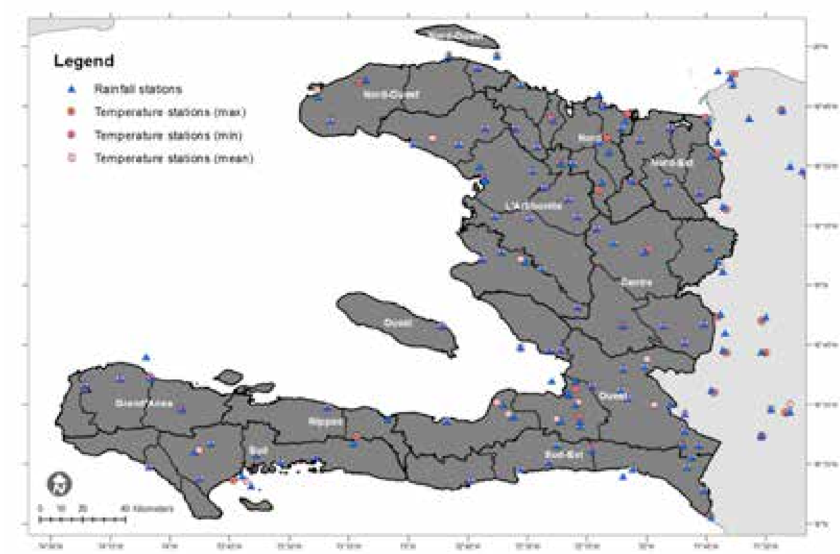


Figure 2. Meteorological stations on which WC is based in Haiti.

For future climates, we used the Global circulation model (GCM) outputs from the Intergovernmental Panel on Climate Change (IPCC), Fourth Assessment Report (AR4) (Solomon et al. 2007). We downloaded data from the Earth System Grid (ESG) data portal. The data portal provides many different GCM's developed by different global climate research centers (Table 1). In view of the uncertainty attached to these models in predicting future climatic conditions we used all available models evaluated through the World Climate Research Program (WCRP) in several phases of the Coupled Model Intercomparison Project (CMIP) (Covey et al. 2003).
The IPCC further provides different scenarios of future greenhouse gas emissions. The Special Report on Emissions Scenarios (SRES) provides scenarios based on demographic, economic, and technological driving forces within four main storylines (IPCC 2000). In this study we used the SRES-A2 scenario, it describes a heterogeneous world in which population is increasing and economic development occurs primarily at the regional scale. Economic growth and technological change are slower than in other storylines.

Table 1. List of GCMs used in this study

GCM model	Institute	Country
BCCR-BCM2.0	Bjerknes Centre for Climate Research	Norway
CCSM3	National Center for Atmospheric Research	USA
CGCM3.1(T47)a	Canadian Centre for Climate Modeling & Analysis	Canada
CNRM-CM3	Centre National de Recherches Météorologiques	France
CSIRO-Mk3.0c	CSIRO Marine and Atmospheric Research	Australia
CSIRO-Mk3.5	CSIRO Marine and Atmospheric Research	Australia
ECHAM5/MPI-OM	Max Planck Institute for Meteorology	Germany
ECHO-Ga	Meteorological Institute of the University of Bonn	Germany / Korea
GFDL-CM2.0	Geophysical Fluid Dynamics Laboratory	USA
GFDL-CM2.1	Geophysical Fluid Dynamics Laboratory	USA
GISS-ER	Goddard Institute for Space Studies	USA
INGV-SXGc	Instituto Nazionale di Geofisica e Vulcanologia	Italy
INM-CM3.0b	Institute for Numerical Mathematics	Russia
IPSL-CM4	Institut Pierre Simon Laplace	France
MIROC3.2 (medres)	Center for Climate System Research	Japan
MRI-CGCM2.3.2a	Meteorological Research Institute	Japan
PCMc	National Center for Atmospheric Research	USA
UKMO-HadCM3	Hadley Centre for Climate Prediction and Research	UK
UKMO-HadGEM1	Hadley Centre for Climate Prediction and Research	UK

The downloaded GCM data are formatted at a yearly temporal scale and we calculated three 30-year periods in order to represent a short-, mid- and long-term prediction of climate (2010-2039 representing 2020, 2020–2049 representing the 2030 time slice and 2040–2069 representing 2050). The spatial resolution of GCMs is too coarse to analyze the direct impacts on farmers' production (Jarvis et al. 2010). We therefore downscaled the outputs of each GCM based on the sum of interpolated anomalies to the 30 arc-second resolution (approximately 1km) of the monthly climate surfaces of WC. This method produced a smoothed, interpolated surface of changes in climates forecast derived from the particular GCMs which was then applied to the baseline climate of WC (Ramirez-Villegas & Jarvis 2010).

Resulting climate surfaces for Haiti were finally compiled in a climate-database including the current climate from WC and downscaled future climate predictions from GCM's for the IPCC emission scenario A2. Finally we generated summary graphs of current and future climate for specific municipalities.

3.2. Environmental factors

Plant species' occurrence is not only defined however by climate variables, and exclusion of other important variables (such as soil type) may reduce the ability to assess the required environmental growing conditions (Stanton et al. 2011). Climatic variables are expected to change substantially over the modeled time period and generally accepted future projections are available, even if those projections are uncertain. We apply a climate-only approach in this research-project in order to address the projects goal of estimating the impacts of climate change on crops suitability in the study area.

Bioclimatic variables (BC) are often used in ecological niche modeling and they represent annual trends, seasonality and extreme or limiting environmental factors. BC were derived from monthly temperature and rainfall values in order to generate more biologically meaningful variables (Busby 1991) following the method of Ramirez & Bueno-Cabrera (2009). The set of resulting covariates includes 19 bioclimatic variables (see Table 2) were used in several studies to empirically model the current and future distribution of species (Davis et al. 2012, Jarvis et al. 2012, Laderach et al. 2009, Laderach et al. 2013).

Table 2. List of derived bioclimatic variables used as environmental factors

ID	Variable name	Units
P1	Annual mean temperature	°C
P2	Mean diurnal temperature range	°C
P3	Isothermality	N/A
P4	Temperature seasonality (standard deviation)	°C
P5	Maximum temperature of warmest month	°C
P6	Minimum temperature of coldest month	°C
P7	Temperature annual range	°C
P8	Mean temperature of wettest quarter	°C
P9	Mean temperature of driest quarter	°C
P10	Mean temperature of warmest quarter	°C
P11	Mean temperature of coldest quarter	°C
P12	Annual precipitation	mm
P13	Precipitation of wettest month	mm
P14	Precipitation of driest month	mm
P15	Precipitation seasonality (coefficient of variation)	%
P16	Precipitation of wettest quarter	mm
P17	Precipitation of driest quarter	mm
P18	Precipitation of warmest quarter	mm
P19	Precipitation of coldest quarter	mm

3.3. Crop prediction models

We reviewed several crop suitability models before deciding upon the most appropriate model to use in the analysis. In the following a short description of each model is provided:

EcoCrop (EC) is a crop niche prediction model with the same name as the Food and Agriculture Organization (FAO) Ecocrop database (FAO, 2000). The basic model uses environmental ranges as inputs to determine the main niche of a crop, and then produces an overall crop suitability as a percentage and separated suitability values for temperature and precipitation as output. EC is a very useful model for situations where evidence data available for specific crops is insufficient and one is therefore forced to use environmental ranges. The original model (Hijmans et al. 2001) was implemented in the Diva-GIS software (Hijmans et al. 2012). EC predicts crop-climate suitability using the following parameters: plant killing temperature; minimum, minimum optimum, maximum optimum and maximum temperature; minimum, minimum optimum, maximum optimum and maximum amount of rain water required; and length of growing season. The EC model is a general approach to suitability modeling, considering only temperature and rainfall as determinates of crop suitability, information on soil data and crop management are not accounted for in the model. Furthermore, the models accuracy directly depends upon the quality of expert knowledge used to set the crop parameters. Nevertheless Ramirez-Villegas et al (2011) extended the model providing a calibration-process of the temperature and rainfall ranges using crop presence data.

Maximum entropy (Maxent) is a niche modeling method that has been developed involving species distribution information based only on known presences and is a general-purpose method for making predictions or inferences from incomplete information. Similar to logistic regression, MAXENT weighs each environmental variable by a constant. The probability distribution is the sum of each weighted variable divided by a scaling constant to ensure that the probability value ranges from 0 to 1. The information available about the target distribution often presents itself as a set of real-valued variables, called ‘features’, and the constraints are that the expected value of each feature should match its empirical average (“average value for a set of sample points taken from the target distribution”, Phillips et al., 2006). Each feature, the environmental variables, gets weighted according to how much complexity it adds to the model. The probability distribution is the sum of each weighed variable divided by a scaling constant to ensure that the probability value ranges from 0 to 1. The program starts with a uniform probability distribution and works in cycles adjusting the probabilities to maximum entropy. It iteratively alters one weight at a time to maximize the likelihood of reaching the optimum probability distribution. Maxent is considered as the most accurate model performing extremely well in predicting occurrences in relation to other common approaches (Elith et al., 2006; Hijmans and Graham, 2006), especially with incomplete information. It works well with little sample sites of occurrence data and with both continuous and categorical environmental variables. Finally, sample selection bias is the biggest problem for this presence-only method.

Crop Niche Selection in Tropical Agriculture CaNaSTA (O’Brien, 2004) is not a “traditional” niche modeling method as it uses Bayesian statistics to not only predict presence or absence of a specific crop, but also appraises its performance. Bayesian methods provide “formalism for reasoning under conditions of uncertainty, with degrees of belief coded as numerical parameters, which are then combined according to rules of probability theory” (Pearl, 1990). The CaNaSTA algorithm creates conditional probability tables of all predictor variables against response variable categories (O’Brien, 2004). The primary model output is a discrete probability distribution at each location. A certainty value is also associated with each location, derived from the number of occurrences in the trial data with a particular combination of predictors and responses. CaNaSTA only works with its own data sets, and the analyses require time-consuming preparation and some expertise of the user on Bayesian Statistic. Sample selection is a key factor for avoiding bias in prior probabilities. Local and regional diversity is taken into account by the Bayesian algorithm. The model is slower than the other models because of its more complicated algorithm. However this algorithm makes it a powerful model to evaluate not only presence but also crop performance. Furthermore, it provides a local certainty evaluation for the probability values.

The Decision Support System for Agrotechnology Transfer (DSSAT) is a crop simulation model that simulates growth, development and yield as a function of the soil-plant-atmosphere dynamics (Jones et al. 2003). For the 28 available crops, simulations are conducted at a daily step and, in some cases, at an hourly time step depending on the process and the crop model. The plant and soil water, nitrogen and carbon balances are updated, as well as the crop's vegetative and reproductive development stage. DSSAT integrates the effects of soil, crop phenotype, weather and management options to simulate multi-year outcomes of crop management strategies. The crop models require daily weather data, soil surface and profile information, and detailed crop management as input for running the crop models and evaluate crop model simulation and outputs. Weather data must include daily values of incoming solar radiation, maximum and minimum daily air temperature and daily total rainfall for at least the duration of the experiment and preferably should begin a few weeks before planting and continue a few weeks after harvest. Desired soil data consist of soil classification (SCS), surface slope, color, permeability, and drainage class and horizons profile data. Management data includes information on planting date, dates when soil conditions were measured prior to planting, planting density, row spacing, planting depth, crop variety, irrigation, and fertilizer practices. For model evaluation crop growth data, soil water and fertility measurements are needed. Based on crop processes DSSAT gives precise results for potential yields, plant phonologic stages, weight, harvest date, water soil and nitrogen quantity integrating interactions between parameters from weather, soil, management and genetic characteristics. However, the most limitative factor of this powerful model is that it is only available for the best known crops and it needs a large amount of precise daily data.

Models selection

From the above described models (Ecocrop, Maxent, CaNaSTA and DSSAT), Maxent is the most adapted model to use for coffee and mango when presence data is available As noted previously, Ecocrop is recommended for studying overall trends however the three other models are more precise. DSSAT is the most powerful model but calibration is available for neither coffee nor mango. For CaNaSTA, data preparation may be highly time consuming as crop performance must be evaluated to calibrate prior probabilities. Finally, Maxent appears as the best compromise between data and results precision and time consumption. However, presence data samples must be well selected. Records should spread across the whole area of interest and each one should bring new information to the model calibration. Minimum data sample recommended is 30 well distributed points.

Model validation

Using all crop evidence points, 25 Maxent runs were performed, each using 75% of the points for the training and the remaining 25% for testing of the model. Default settings were used in Maxent so that the complexity of the model varied depending upon the number of data points used for model fitting. Two measures of model skill were used: the area under the ROC (receiver operating characteristic) curve (AUC) (Peterson et al., 2008) and the maximum possible Cohen's kappa (Manel et al., 2001) (kmax), applied a random selection of pseudo-absences equal to twice the number of presences (Serra-Diaz et al. 2013). These two measures were used due to the potential caveats that can arise from the use of AUC as the only model evaluation measure (Lobo et al., 2008).

Uncertainty of model prediction

It is very important to address and acknowledge the uncertainty of climate predictions and the differences between the GCMs used for the modelling. Jarvis et al. (2012) state that impact assessment methods are sensitive to uncertainties and assessing the climate-inherent uncertainty in climate change impact assessment projects explicitly entails the usage of different GCMs. To consider climate-inherent uncertainty we used 19 different GCMs in our study and produced final maps showing descriptive statistics of different predictions on a pixel basis: (i) the change of the ensemble mean, (ii) the percentile rank using first quartile (25th percentile) and third quartile (75th percentile), and (III) the agreement among (19) Maxent outputs calculated as percentage of models predicting changes in the same direction as the average of all models at a given location or pixel.

3.4. Diversification options

For the evaluation of best diversification options for coffee farmers, analysis must focus on identifying general tendencies for several crops and localizing their future potential areas on climate suitability. Therefore, Ecocrop is the most appropriate model to fulfill these requirements.

To identify adequate diversification options for coffee farmers we analyzed crop-climate-suitability of selected crops from current agricultural portfolios of Haiti. We selected these crops based on their importance to food security and livelihood income as well as on crops recently adopted by development organizations in order to improve future agricultural production of smallholder farmers in Haiti.

As described above, we selected Ecocrop as the most appropriate tool to model diversification options and we compared climate-suitable area-outcomes with land suitable for agriculture production. We did this by intersecting the climate-suitability with the land-use and soil-capacity layers taking account of availability for agricultural use of potential suitable croplands (Jarvis et al. 2010).

To assess land availability for agricultural production we downloaded Haiti's land cover (1:300,000 scale) and Haiti's soil use capacity for agriculture

(1:250,000 scale) from http://haitidata.org. We combined both layers and reclassified them into 5 main categories:

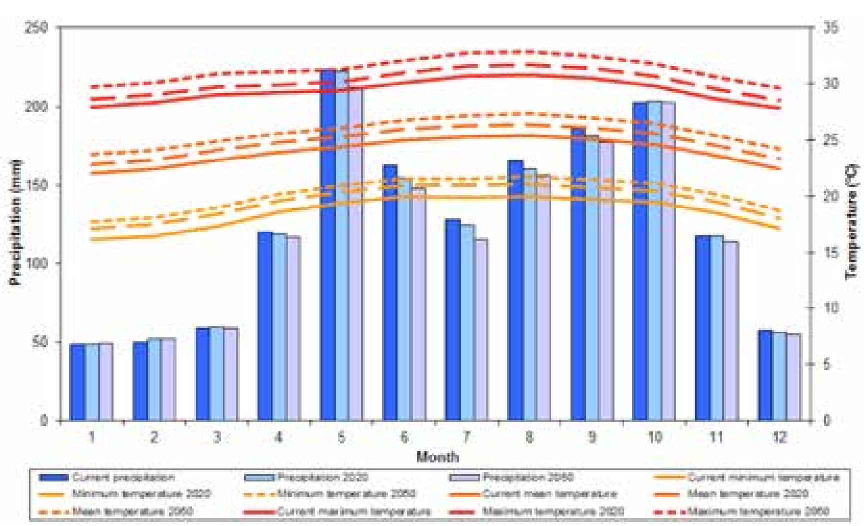
- Land available for agriculture production (currently crop- & pasture-land) with medium to excellent soil capacity (available and no limitations; AV-NL)
- Land available for agriculture production with lower or medium limitations on soil capacity (available but soil capacity is limited; AV-LL)
- No limitations on soil capacity, but land use needs to be changed (currently forests, agro-forestry's, savannas)
- Limited soil capacity and land use needs to be changed (LL-CH)
- Land is not available (populated areas, water bodies or barren lands) and soil capacity is very limited or excluded for agriculture production (NA-EX)

In the following we extracted spatial statistics from the climate-suitability layers based on the 5 land-availability layers using a Geographical Information System (GIS). Final outputs are the mean suitability value within each land-availability layer and the standard deviation of suitability and the number of pixels used to calculate the areas possessing crop suitability.

4. Results

4.1. Predicted climate change for Haiti

After downscaling monthly averaged data of GCMs to local level we extracted 19 bioclimatic variables from current and future (2020, 2030 and 2050) climate data and generated a general climate change description for Haiti and the southwestern part of the country. The climate trend analysis (averaged 30 years) of Haiti show a bimodal rainfall pattern with two rainy seasons, one in in May and another in August to October, followed by drier month from December to March with maximum rainfall reaching 50mm per month.



General climatic characteristics for Haiti

- The rainfall decreases from 1520 millimeters to 1457 millimeters in 2050 passing through 1498 in 2020
- Temperatures increase and the average increase is 1.8 ºC passing through an increment of 0.9 ºC in 2020
- The mean daily temperature range increases from 10.8 ºC to 11.1 ºC in 2050
- The maximum number of cumulative dry months decreases from 5 months to 4 months

Extreme conditions

- The maximum temperature of the year increases from 30.9 ºC to 32.9 ºC while the warmest quarter gets hotter by 1.9 ºC in 2050
- The minimum temperature of the year increases from 16.1 ºC to 17.7 ºC while the coldest quarter gets hotter by 1.7 ºC in 2050
- The wettest month gets drier with 233 millimeters instead of 237 millimeters, while the wettest quarter gets drier by 17 mm in 2050
- The driest month gets drier with 37 millimeters instead of 41 millimeters while the driest quarter gets drier by 3 mm in 2050

Climate Seasonality

- Overall this climate becomes more seasonal in terms of variability through the year in temperature and more seasonal in precipitation
-

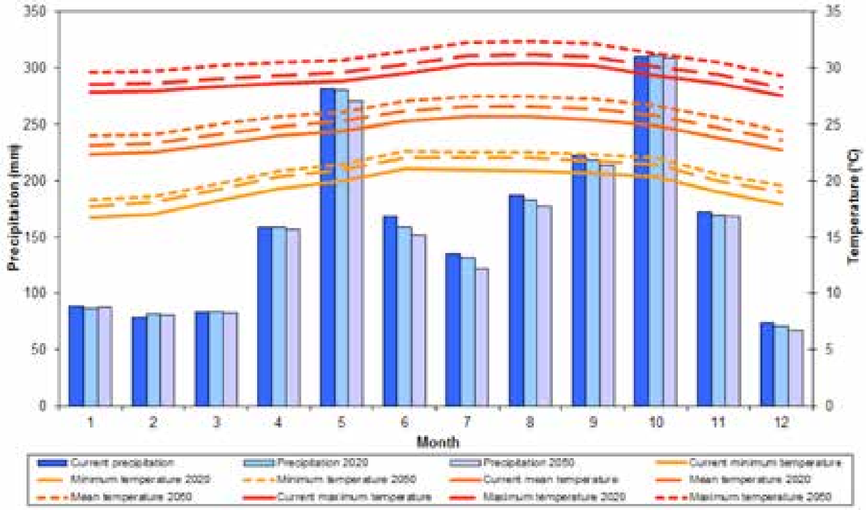
Variability between models

- The coefficient of variation of temperature predictions between models is 1.6%
- Temperature predictions were uniform between models and thus no outliers were detected

- The coefficient of variation of precipitation predictions between models is 4.9%
- Precipitation predictions were uniform between models and thus no outliers were detected

Figure 3. Climate change predictions for Haiti.

According to the ensemble of the 19 GCMs, temperature in Haiti will increase by an average of 0.9°C in 2020 and 1.8°C by 2050. The mean daily temperature range will increase from 10.8°C to 11.1°C by 2050. The temperature of the hottest month will increase from 30.9°C to 32.9°C while the warmest quarter will be 1.9°C hotter by 2050. The minimum temperature of the coldest month will increase from 16.1°C to 17.7°C, while the coldest quarter will be 1.7°C hotter by 2050. Total annual rainfall will decrease marginally (1%) by 2020 and will continue decreasing (4%) until 2050, while the maximum number of cumulative dry months decreases from 5 months to 4 months. May will remain being the wettest month getting 2% drier, while the wettest quarter will get drier 3% by 2050. The driest month is projected to get 10% drier while the driest quarter gets marginally drier with 1% less rainfall by 2050. Overall the climate is expected to become more seasonal in terms of variability through the year in temperature and more seasonal in precipitation (Figure 3).



General climatic characteristics for Haiti

- The rainfall decreases from 1961 millimeters to 1886 millimeters in 2050 passing through 1934 in 2020
- Temperatures increase and the average increase is 1.7 ºC passing through an increment of 0.9 ºC in 2020
- The mean daily temperature range increases from 9.6 ºC to 9.9 ºC in 2050

Extreme conditions

- The maximum number of cumulative dry months keeps constant in 3 months
- The maximum temperature of the year increases from 30.5 ºC to 32.5 ºC while the warmest quarter gets hotter by 1.8 ºC in 2050
- The minimum temperature of the year increases from 16.8 ºC to 18.3 ºC while the coldest quarter gets hotter by 1.7 ºC in 2050
- The wettest month gets wetter with 313 millimeters instead of 313 millimeters, while the wettest quarter gets drier by 17 mm in 2050
- The driest month gets drier with 62 millimeters instead of 68 millimeters while the driest quarter gets drier by 6 mm in 2050

Climate Seasonality

- Overall this climate becomes more seasonal in terms of variability through the year in temperature and more seasonal in precipitation
-

Variability between models

- The coefficient of variation of temperature predictions between models is 1.4%
- Temperature predictions were uniform between models and thus no outliers were detected

- The coefficient of variation of precipitation predictions between models is 4.2%
- Precipitation predictions were uniform between models and thus no outliers were detected

Figure 4.Prévisions de changement climatique pour les départements du sud-ouest.

Le Figure 4 montre l'analyse des tendances de climat pour le département du Sud d'Haïti. Les changements prévus sont semblables pour la température et les régimes de précipitations, sauf que les précipitations sont généralement plus élevées dans les Départements du sud, et Octobre remplace Mai comme mois le plus humide.

4.2. Prévisions climatiques futures aux échelles régionales spécifiques

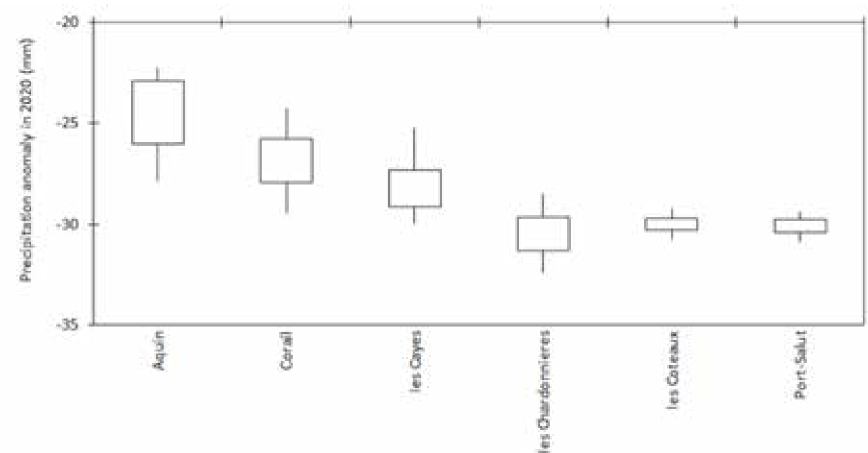


Figure 5. Mean annual precipitation change by 2020 in the project target communities.

The edges of the boxes indicate the mean maximum and mean minimum values of predictions from GCMs and the ends of the line the maximum and minimum values. The mean maximum and mean minimum values are defined by the mean + or – the standard deviation.

Generally changes in rainfall are negative for all 6 regions. By 2020 the regions of Port Salut, les Coteaux and Chardonnieres are those with the greatest losses in precipitation of about -30 mm (Figure 5), similar by 2030 where negative changes are up to 47 mm in these municipalities (Figure 6).

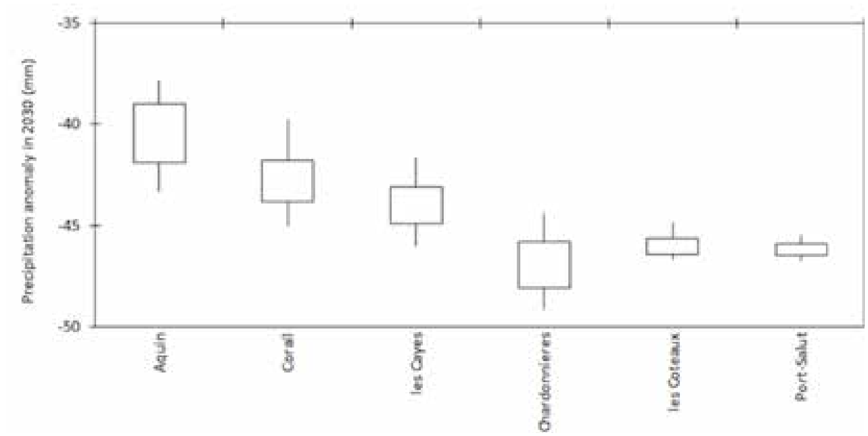


Figure 6. Mean annual precipitation change by 2030 in the project target communities.

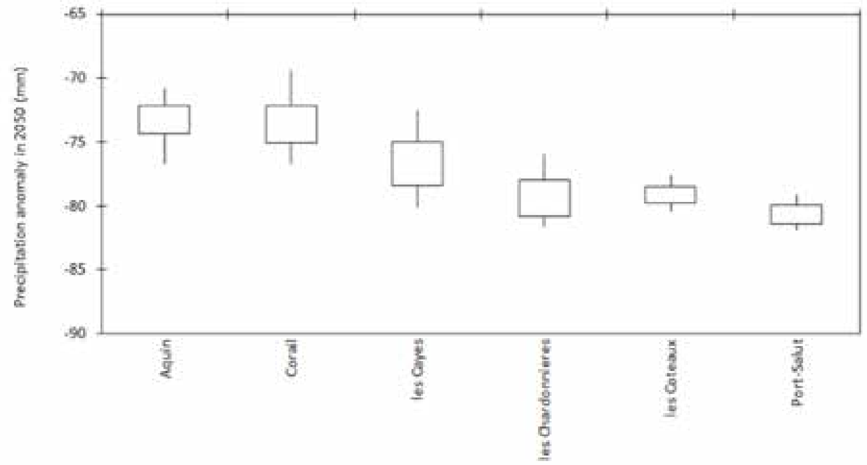


Figure 7. Mean annual precipitation change by 2050 in the project target communities.

By 2050 rainfall is reduced in all municipalities, with losses generally between 70 and 80 mm (Figure 7).

Although rainfall decrease is generally moderate in all future predictions, this combined with increasing minimum, mean and maximum temperatures can cause water deficits due to higher evapotranspiration rates of plants triggering soil water deficits and heat stresses. Increased temperature stresses and in particular high night time temperatures (> 18 °C) and drought conditions have substantial effects on biomass production and the reproductive stages of several plants and crops.

4.3. Impact of climate change on Coffee

Coffee in Haiti

Figure 8 shows the various coffee growing regions in Haiti. Though coffee is grown in all of Haiti's ten departments, the intensity of cultivation varies considerably, and in general there are five main growing areas, each located in different departments of the country. In order of the quantity of coffee produced, these are: Grand'anse, Southeast (Thiotte and Jacmel), North, and Center (Baptiste and Cahos). The five areas are divided into two zones: North and South. Grand'anse and Southeast are in the South of the country, and together form the largest area of national production (Arias et al., 2006).

Coffee-producing areas in the south are mostly concentrated in the Grand-Anse Department. By 1995, the Grand-Anse, South and North Departments made up half of the total national coffee plantation. Six municipalities in the southwest are potential regions to produce high-quality coffee: Beaumont, Roseaux, Jérémie, Tiburon, Les Anglais, Port-à-Piment. (Rodríguez et al., 2011)

Characteristics of producing zones (Amaya et al., 1999)

North (Plaisance and Dondon): In Plaisance and Dondon, coffee production takes place at altitudes of 400–700 meters above sea level.

Plaisance has bad roads and a clayish soil; its production is falling. Both Plaisance and Dondon are dominated by very small farms in which coffee is part of a traditional subsistence farming system, along with cacao, plantains, avocado, mangoes, bananas, bread fruit and other crops that are very important for risk management and family subsistence. The predominant coffee variety is Typica.

Center (Baptiste and Savanette): In the Center department, Baptiste is a traditionallcoffee-producing area. Here production takes place in very small farms at altitudes ranging between 1,000 and 1,200 meters above sea level. In this area the soil is stony. Coffee farming here is more specialized than in the North. Producers use fertilizers and other inputs, and according to accounts from farmers interviewed by the team, this was a major coffee-producing area before low coffee prices discouraged production and major exporters abandoned their operations. The Typica variety predominates here.

South-East (Thiotte): Thiotte continues to be one of the major producing areas in the country (60,000 bags). Production takes place in farms ranging from small to medium size (from 1 to 16 ha) at altitudes between 900 and 1,500 meters above sea level. The Typica variety predominates. The altitude of coffee plantation ranges between 400 meters in the North to 1,300 meters in Thiotte and Beaumont.

Coffee plantations were historically more widespread in nine departments of the country. Currently, however, except for the areas of Thiotte, Baptist, Beaumont and Dondon where the density of coffee plantation is still high, coffee plantations in other areas is limited. (Haiti Coffee Supply Chain Risk Assessment, 2010)

Figure 8. Haiti coffee sector map

Impact of climate change

In the next section we quantify the impact of climate change on the suitability of land to produce coffee in Haiti. Changes in temperature and rainfall patterns will cause a general decrease of areas suitable for coffee and reduce areas which currently possess high suitability (very good and excellent) for coffee production (Figure 9). Suitability is predicted to climb up altitudinal gradients to currently cooler climates. Models predict that coffee will lose suitability in lower altitudes (up to 1200 meters above sea level, or m.a.s.l.) and gain suitability in higher areas with a maximum suitability between 1500m.a.s.l. and 1800m.a.s.l. in 2050 (Figure 10).

Changing climatic conditions in Haiti could lower the quality and yields of current coffee producing regions and this is likely to be most prevalent in lower-altitude zones. Furthermore, economic losses in the future could ensue if adaptation efforts are not implemented. However, there are many opportunities to adapt to such changes and for those coffee farms whose suitability will drop but not decrease drastically, adaptation is a crucial strategy. These strategies include improved agronomic management, drought- and heat-resistant varieties, irrigation and shade cover.

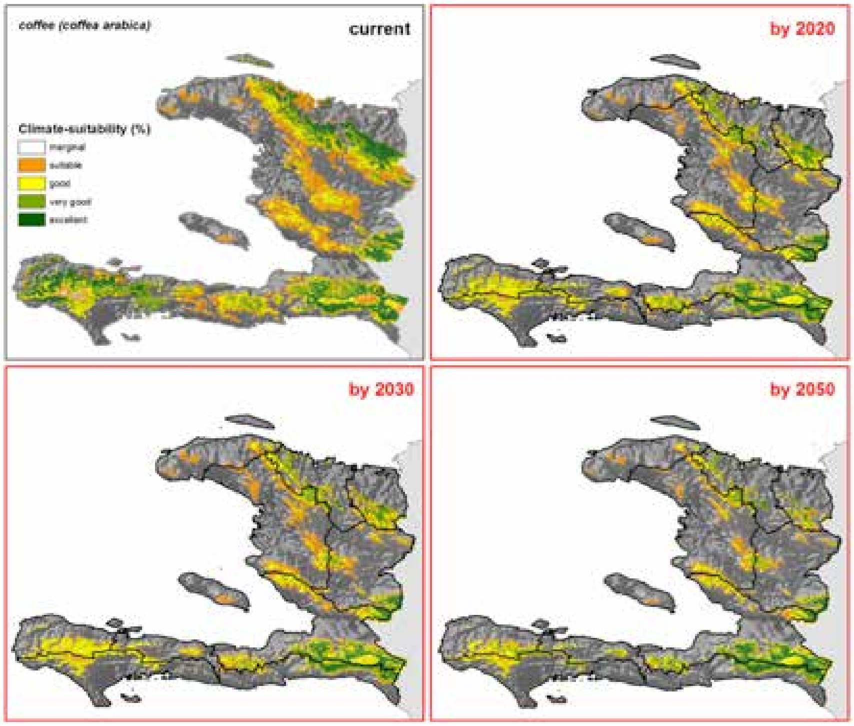


Figure 9. Coffee climate-suitability.

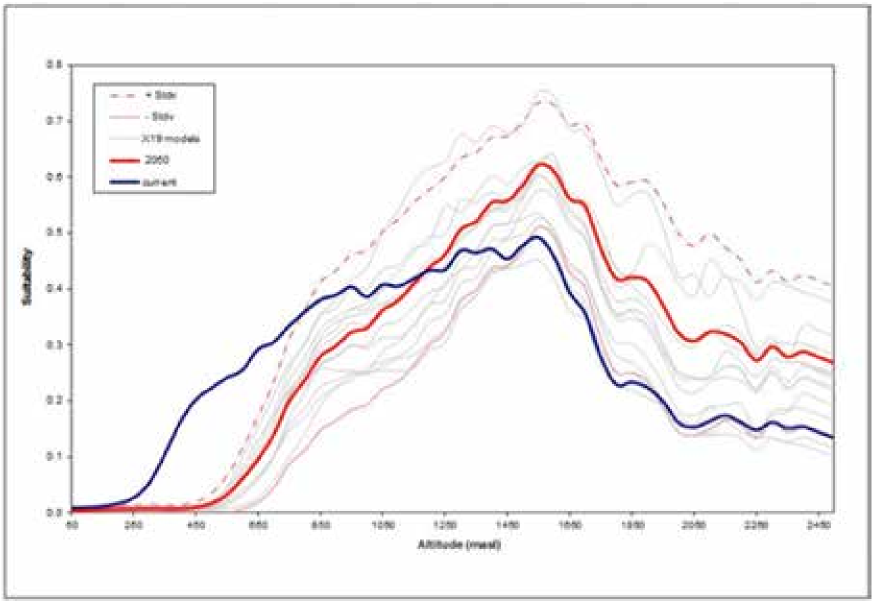


Figure 10. Coffee suitability by altitude.

4.4. Impact of climate change on Mango

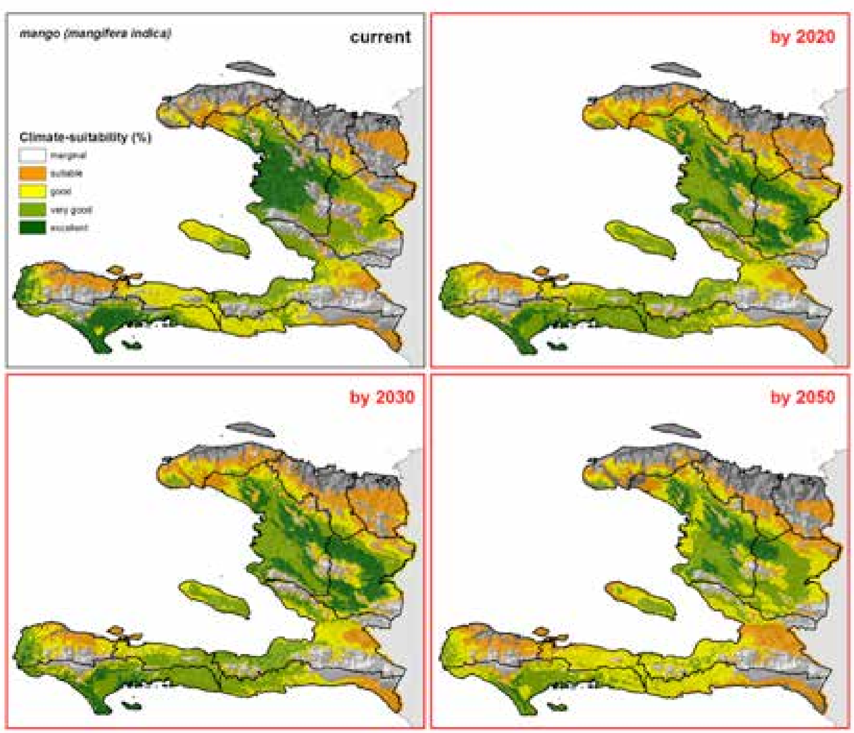


Figure 11. Climate-suitability of mango.

In the future mango will remain a highly suitable crop in many regions of Haiti. From 2020 predictions show that some areas will reduce from excellent to very suitable and shift geographically from concentrated areas close the coast to inland areas with higher altitude (Figure 11). Altitudes from 500 to 700m.a.s.l. will benefit from increasing climate suitability mostly because of increased temperatures (Figure 12), but solar radiation is very important for high quality mango production and inland areas could be less favored because of more frequent cloud cover (which is not included in our modeling). Generally, strategies to improve the mango value-chain in Haiti will not face major constraints from climatic conditions and should focus in organizational and marketing development of existing collaborative networks within the industry. Also a lot can be done improving agronomic management and capacity building for farmers including pest & disease control techniques and improved planting systems.

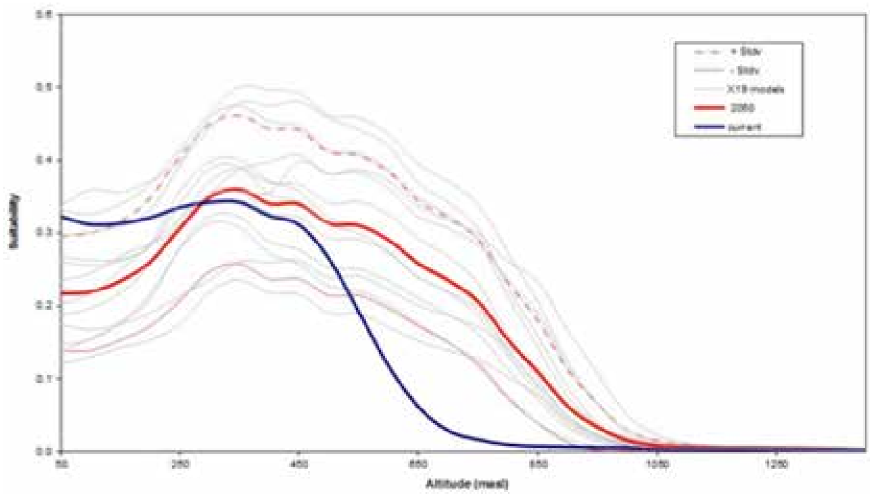


Figure 12. Mango suitability and altitude.

4.5. Uncertainties, driving factors and cross validation

Maxent model validation

The performance of the Maxent model was generally high for coffee, with AUC (kappa) values ranging between 0.76 (0.85) and 0.89 (0.94) for the test data (25%), and almost no variation for the train data (75%) (Figure 13), in the case of mango (Figure 14), high variation can be observed for the test data with AUC values (kappa) between 0.72 (0.71) and 0.98 (0.89). The high performance of the model also produced relatively low baseline uncertainties. These uncertainties are mostly caused by model parameters (i.e. a different Maxent regression model is generally obtained for each of the duplicates) and by the locations of input evidence data.

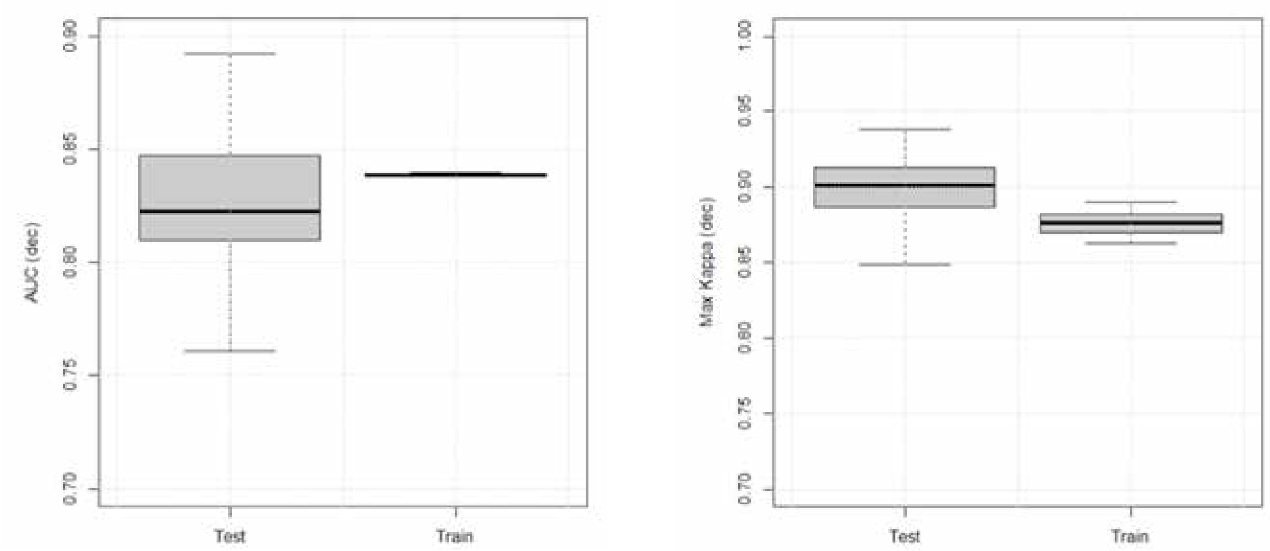


Figure 13. Performance of the Maxent model for coffee across the 25 replicates.

AUC, and maximum Cohen's kappa. Thick black horizontal line shows the median, box extends to 25-75% and whiskers show 5-95% of the distributions.

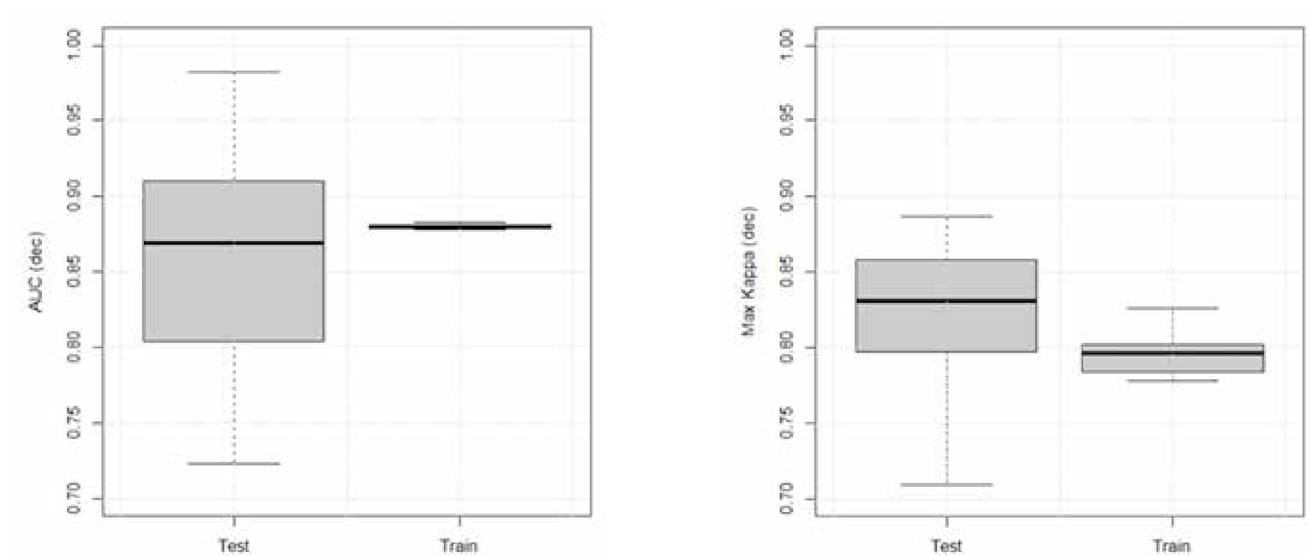


Figure 14. Performance of the Maxent model for mango across the 25 replicates

AUC, and maximum Cohen's kappa. Thick black horizontal line shows the median, box extends to 25-75% and whiskers show 5-95% of the distributions.

Environmental factors that drive suitability

In this section we show the contribution of different bioclimatic variables to the predicted change in suitability for coffee and mango, separated by two geographic regions; the Southeast and Northern part and the Southwestern part of Haiti.

According to the regression analysis of suitability change by 2050, an increase in precipitation of the wettest quarter (bio_16) would favor the coffee suitability in the southeast and northern Haiti, however in this area precipitation of the wettest quarter decreases on an average 18.5 mm by 2050 and explains part of the suitability loss in this area (Figure 15).

The dry period corresponds to the quiescent growth phase of the crop and is important to stimulate flowering (Damatta et al., 2007), therefore an increase in the rainfall of dry season could lead to nitrogen deficiencies, acceleration the fruit fall or a reduction in plant growth. The most influential variable for suitability change is the precipitation of the driest quarter (bio_17). 1mm more precipitation during this phase will decreases suitability by 7.1% (Figure 15).

Variable	Unstandardized Coefficients		Standardized Coefficients	t	Sig.	Change
	B	Std. Error	Beta			
bio_13	-.010	.003	-.253	-3.151	.002	-5.3 mm
bio_16	.005	.002	.354	3.100	.002	-18.5 mm
bio_17	-.071	.005	-.747	-13.081	.000	-0.56 mm
bio_8	-.010	.002	-.639	-5.001	.000	18.3 °C
R^2 = 0.83, n=162, Dependent variable = Suitability change 2050						

Figure 15. Driving factors coffee-model in North & Southeast

Variable	Unstandardized Coefficients		Standardized Coefficients	t	Sig.	Change
	B	Std. Error	Beta			
bio_18	-.004	.001	-.285	-5.016	.000	-27.5 mm
bio_3	.199	.052	.201	3.840	.000	-0.4
bio_8	-.028	.002	-1.037	-15.078	.000	17.9 °C
R^2 = 0.96, n=45, Dependent variable = Suitability change 2050						

Figure 16. Driving factors coffee-model in Southwest.

Figure 16 shows for the Southwest that the increase of temperature is related to loss of suitable areas for coffee. In general, the increase of the mean temperature of the wettest quarter (bio_8) on an average 1.8°C by 2050, explains suitability loss in this part of Haiti.

For mango, precipitation variables explain mostly the projected change on suitability in the Southest and North of Haiti. An increase in precipitation of the coldest quarter (bio_19) would not favor the suitability of the crop and would lead to 7% decrease of each increasing unit of rainfall (Figure 17).

Variable	Unstandardized Coefficients		Standardized Coefficients	t	Sig.	Change
	B	Std. Error	Beta			
bio_13	.009	.002	.565	5.488	.000	-7.8 mm
bio_14	.016	.004	.319	3.943	.000	-2.2 mm
bio_16	-.007	.001	-1.097	-8.013	.000	-20 mm
bio_17	.058	.007	.798	8.908	.000	0.2 mm
bio_19	-.072	.005	-1.593	-13.847	.000	1.7 mm
R^2 = 0.77, n=152, Dependent variable = Suitability change 2050						

Figure 17. Driving factors mango-model in North & Southeast.

Variable	Unstandardized Coefficients		Standardized Coefficients	t	Sig.	Change
	B	Std. Error	Beta			
bio_18	0.003	0.000	0.685	7.897	0.000	-37 mm
bio_13	0.013	0.005	0.244	2.816	0.007	-1.5 mm
R^2 = 0.69, n=56, Dependent variable = Suitability change 2050						

Figure 18. Driving factors mango-model in Southwest.

In the southwest of the island an increase of the precipitation of wettest month (bio_13) and the precipitation of the warmest quarter (bio_18) would generate gains in mango suitability. However, the point's regression analysis shows decreases in these two variables and explains the loss of projected suitability (Figure 18). It must be noted that a water shortage is detrimental to the crop, affecting fruit growth by reducing the size that influences the production of the crop.

Uncertainties of future suitability predictions

Uncertainty in our suitability modeling was addressed by using all available GCMs and the implementation of separate runs using the Maxent-model. Results were compared using the means of the descriptive statistics. We calculated the mean value for each grid cell of all 19 GCMs on emission scenario SRES-A2, the average of the first quartile of models which can also be called the pessimistic scenario, the average of the third quartile also stated the very optimistic scenario, and the percentage of agreeing models on their prediction direction (negative, no- or positive-change) on each grid cell. Results show in Figure 19 that there is uncertainty of model outputs but some areas show still high agreement between models. For example Valliéres in the Northeast of Haiti shows negative suitability change in the pessimistic and optimistic scenario with high agreement among models (light grey areas), while Croix-des-Bouquets and Belle-Anse show positive change in some areas in both scenarios. In the southwest around Pic Macaya National Park the average of all models and the optimistic scenario show positive change, while the pessimistic shows no change. Uncertainty of mango maxent modeling (Figure 20) shows high difference between the pessimistic and the optimistic suitability change scenario. Like coffee some areas show positive changes in all 3 scenarios (Centre, Ouest and Nord).

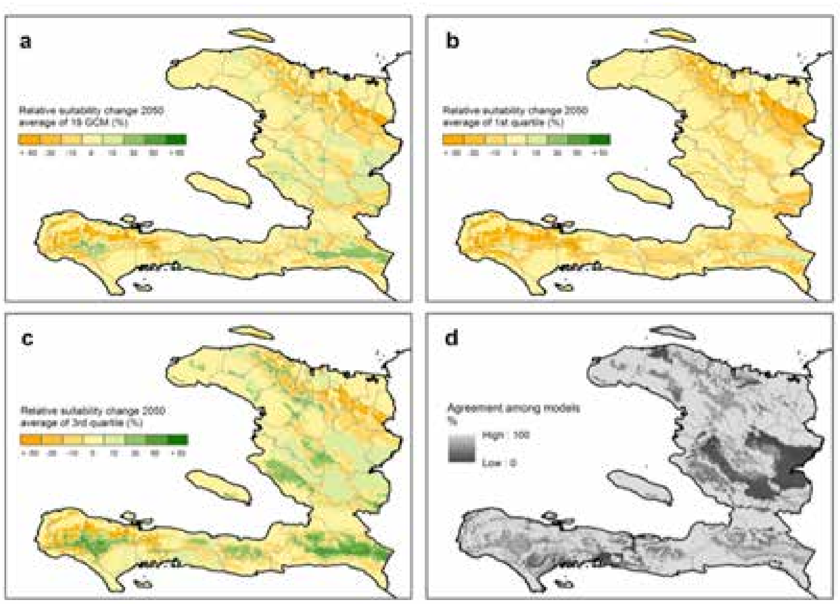


Figure 19. Uncertainty of coffee-maxent-model outputs using 19 GCMs.

a *Relative yield change as average of 19 GCMs for 2050,* ***b*** *average of the 1st quartile of GCMs,* ***c*** *average of 3rd quartile of GCMs, and* ***d*** *breadth of GCMs agreeing in suitability change prediction by Maxent.*

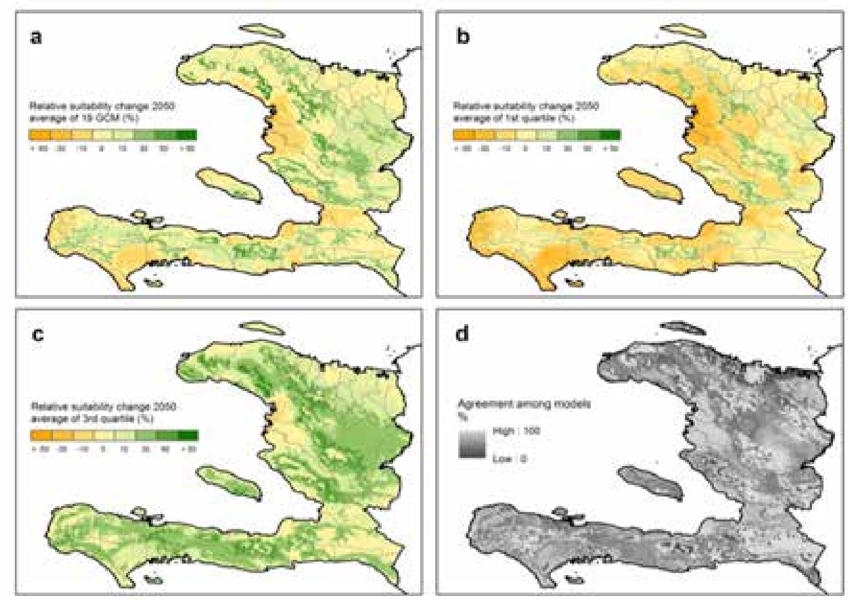


Figure 20. Uncertainty of mango-maxent model.

4.6. Diversification options

The potential impact of climate change on agricultural crop production varies spatially and depends on crop specific biophysical constraints. In Haiti, land for agriculture use extends to more than 1.7 million hectares, occupying more than 60% of the country (FAO 2013). Inside these areas conditions for agricultural production are driven by different climate patterns among other constraints like soil erosion, highly varying soil capacity and land use prevalence's. We assessed the constraints of climate on different crop diversification options using GCMs and the empirical crop model EcoCrop. The results for the spatial changes of crop-climate-suitability were then compared with indicators for land availability and soil capacity (Figure 21) to finally obtain a classification of different diversification options for coffee farmers in Haiti.

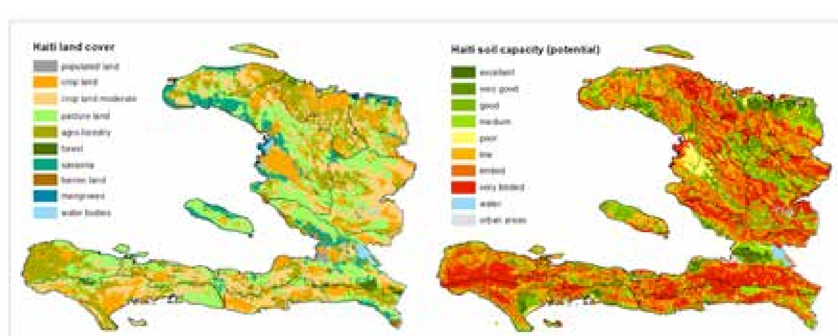


Figure 21. Geographic datasets

Haiti's landcover (1:300,000 scale) - year 2008 and Haiti's soil use capacity for agriculture (1:250,000 scale) - year 1998; created by the Haitian National Centre for Geospatial Information (CNIGS); downloaded from: http://www.haitidata.org

We selected 6 different crops including staple and cash crops. Maize, sorghum, dry beans and yams are crops with total harvested areas in Haiti ranging between 46 and 430 thousand hectares. Groundnuts (peanuts) are mainly grown by low-resource farmers on hillside farms with low soil capacity and their role and market potential is still poorly investigated. Due to it being grown in agroforestry systems, cocoa has a high potential to contribute to both livelihood adaptation and climate change mitigation. All 6 crops together make use of more than 0.7 million hectares (~60%) of agriculture land in Haiti in 2011 (Table 3).

Table 3. Harvested areas of diversification crops in Haiti (areas in hectares

	Dry beans	Yams	Maize	Groundnuts	Sorghum	Cocoa	All crops
2009	102,240	58,582	379,000	25,000	120,000	21,963	706,785
2010	98,196	54,846	402,000	22,280	166,678	21,966	765,966
2011	90,804	46,240	430,000	24,521	149,935	21,971	763,471

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To assess land availability for agricultural production we calculated available areas within 5 categories and compared climate-suitability extracting zonal statistics. Results show, that 396,983 hectares (14%) of Haiti's agricultural land are available and soil capacity is medium to excellent in these areas. Further 532,131 hectares (19%) are available but farmers are producing on soil with limited capacity. Almost the same size as available areas we have areas were a land use change is necessary at least for some crops like maize, sorghum or beans. Other crops like cocoa and coffee are already grown there, for example in agro-forestry systems and could be expanded in these areas. Distribution of areas within the 5 categories is similar in the 3 southwestern departments (Table 4)

Table 4. Land availability for agricultural production intersected with soil capacity in Haiti.

Land use availability is categorized as AV (available land), CH (needs land use change) and NA (not available). Soil capacity is categorized as NL (No limitations), LL (lower limitations) and EX (excluded).

	AV-NL	AV-LL	NL-CH	LL-CH	NA-EX	Total (ha)
Country (Haiti)	396,983	532,131	294,688	646,124	880,082	2,750,008
Southwestern departments (Sud, Nippes, Grand Anse)	80,641	121,957	58,968	175,801	140,624	577,991

Cocoa

From the perspective of climate Haiti possess excellent suitability for cocoa in many areas and this is not predicted to be affected by changes from long-term climate patterns. Figure 22 shows that the suitability index remains almost the same or will increase slightly in most regions. Although suitability will increase more in areas not available (+10 in the entire country and +15% in southern departments) categorized as NA-EX, there is still a lot of potential areas inside existing and potentially new agro-forestry systems that could be created in the future. Haiti's cocoa producers have an opportunity to benefit from an increasing global demand for cocoa production. The main problems of small production volumes, low quality and continuing issues with fragile producer organizations should be the main focus for development organizations in their attempts to improve the sector.

Country (Haiti)									Southwestern departments (Sud, Nippes, Grand Anse)								
	Current			future 2050			change			current			future 2050			change	
index	AREA (ha)	S (%)	STD	AREA (ha)	S (%)	STD	S	AREA	index	AREA (ha)	S (%)	STD	AREA (ha)	S (%)	STD	S	AREA
AV-NL	224,915	87	19	204,506	90	17	3	-9%	AV-NL	59,651	82	18	57,577	87	17	5	-3%
AV-LL	372,757	87	18	367,945	91	16	4	-1%	AV-LL	106,526	86	18	106,775	91	15	6	0%
NL-CH	146,348	89	17	141,039	90	17	1	-4%	NL-CH	46,709	87	17	44,220	88	17	2	-5%
LL-CH	453,232	86	18	450,412	90	17	4	-1%	LL-CH	156,470	88	17	154,396	90	16	2	-1%
NA-EX	456,385	86	19	502,679	92	15	5	10%	NA-EX	100,967	85	18	115,237	91	15	7	14%

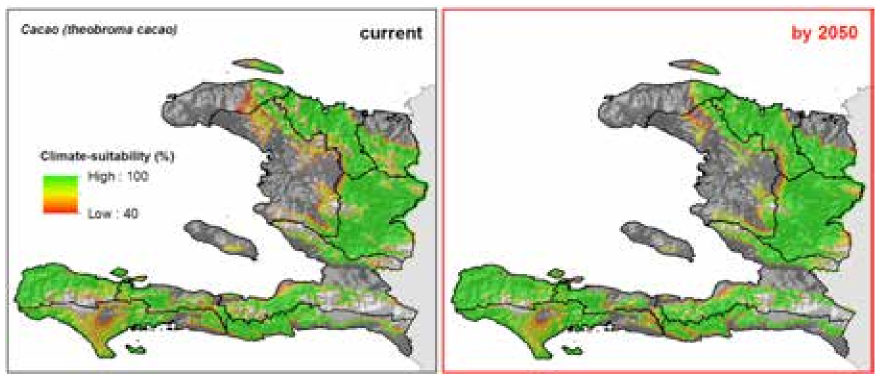
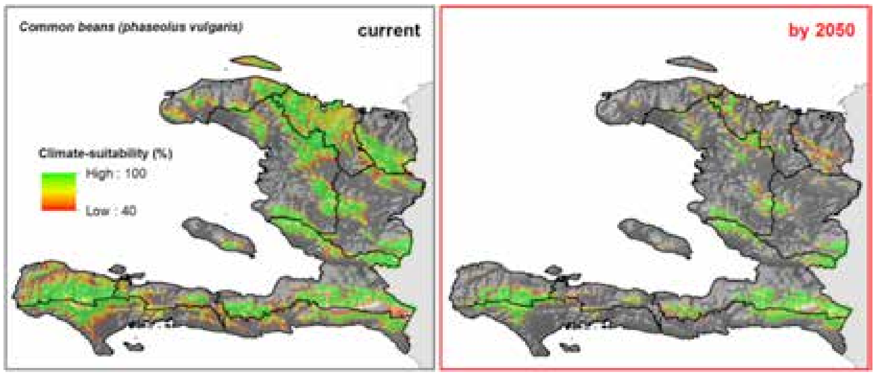


Figure 22. Current and future suitability (by 2050) of cocoa.

Columns show land availability-index, area in hectares(ha), suitability (S), standard deviation of suitability within category (STD), future suitability and suitability change; for Haiti and southwestern departments.

Common beans

Beans are one of the main crops grown in Haiti, and local varieties tend to produce poorly due to high occurrence of diseases and low access for farmers to improved varieties. Instead of taking into account local varieties in our suitability analysis we used overall climatic parameters for common beans based on outputs from many years of research on beans at the International Center for Tropical Agriculture and related research institutes in the region. Unlike the Andean gene pool, which is adapted to cooler climates, the Mesoamerican gene pool is adapted to higher temperatures at low (400 masl) to medium altitudes (2000 masl). Highly suitable environments for growing beans in Central America and the Caribbean are most limited at present by maximum temperatures (Beebe et al. 2011). Our analyses show (Figure 23) that suitability of beans will decrease quite substantially in several areas of Haiti which are currently important producing areas (up to -70% of areas climate-suitable, available and without limitations in soil capacity). In the region, currently most areas are limited by maximum temperatures and could benefit from heat tolerance resistant varieties (Beebe et al. 2011). There is a strong need for the introduction of improved varieties that are less susceptible to heat, and a need to equip farmers with tools and provide them with the knowledge to close yield gaps on existing production.



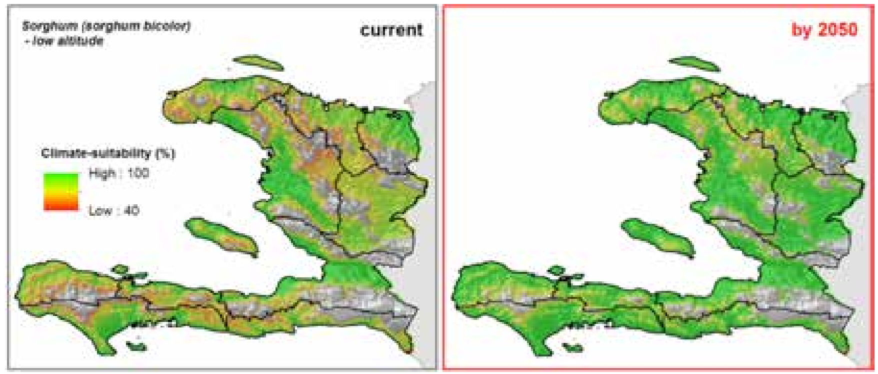
Country (Haiti)									Southwestern departments (Sud, Nippes, Grand Anse)								
	Current			future 2050			change			current			future 2050			change	
index	AREA (ha)	S (%)	STD	AREA (ha)	S (%)	STD	S	AREA	index	AREA (ha)	S (%)	STD	AREA (ha)	S (%)	STD	S	AREA
AV-NL	114,822	70	19	34,679	79	20	9	-70%	AV-NL	21,654	69	23	6,637	73	19	4	-69%
AV-LL	279,257	78	20	110,757	75	21	-3	-60%	AV-LL	71,432	75	20	22,483	73	21	-2	-69%
NL-CH	90,265	74	20	28,789	81	20	7	-68%	NL-CH	22,898	72	22	5,890	84	20	12	-74%
LL-CH	406,607	79	20	153,732	74	22	-5	-62%	LL-CH	116,813	74	20	30,697	79	22	5	-74%
NA-EX	461,695	82	20	262,581	81	20	0	-43%	NA-EX	112,997	84	18	69,275	83	19	-2	-39%

Figure 23. Current and future suitability (by 2050) of common beans.

Maize and sorghum

Statistical studies of maize yields have clearly indicated a strong negative yield response to accumulated days above 30 °C (see predicted increase of averaged hottest month temperature from 30.9 to 32.9°C by 2050 in chapter 4.1) and seasonal rainfall. This is associated with increased evaporative transpiration which contributes to water stress and this water stress is three times more responsive to 2 °C warming than to a 20% precipitation reduction (Lobell et al. 2013). Taking into consideration this specific response of maize to increased high temperature days, modeling climate-suitability on a monthly timescale is highly uncertain as influences of maximum temperature are not well represented using monthly averaged climate data and using 30 °C as a maximum temperature parameter. Preliminary Ecocrop runs show high impacts on suitability due to climate change (up to 30% suitability reduction) and large area losses for production by 2050. We decided therefore not to include results of maize in this report to avoid premature assumptions but emphasize that appropriate crop development and management strategies for dealing with extreme heat on maize varieties should be a priority for future work in Haiti.

Following the calibrated climate parameters of Ramirez-Villegas et al. (2011), sorghum will increase its suitability in Haiti between 4 and 8% in available land with no or low limited soil capacity. These areas will increase by 15% on country scale and 13% in the 3 southwestern departments. Highest area and suitability increases will be spatially located in land not available and/or with high limitations on soil capacity for agricultural production.

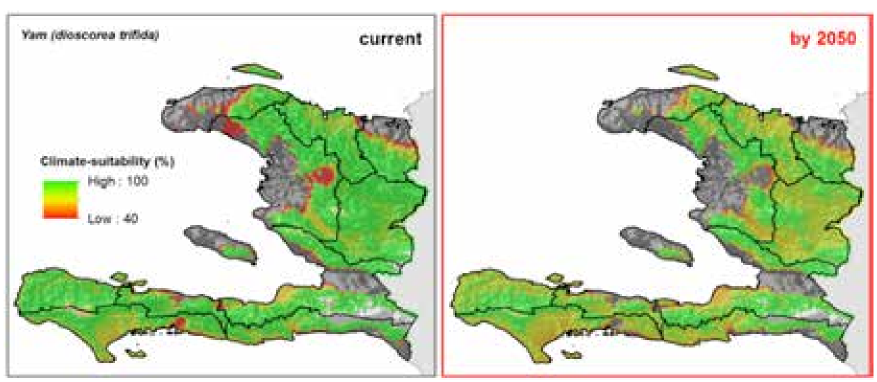


Country (Haiti)									Southwestern departments (Sud, Nippes, Grand Anse)								
	Current			future 2050			change			current			future 2050			change	
index	AREA (ha)	S (%)	STD	AREA (ha)	S (%)	STD	S	AREA	index	AREA (ha)	S (%)	STD	AREA (ha)	S (%)	STD	S	AREA
AV-NL	354,339	90	10	364,129	97	7	6	3%	AV-NL	74,999	93	10	77,488	97	7	4	3%
AV-LL	396,319	85	11	442,613	93	10	7	12%	AV-LL	105,032	84	12	115,403	92	11	8	10%
NL-CH	256,857	89	10	267,725	96	7	7	4%	NL-CH	55,586	90	10	57,411	96	8	6	3%
LL-CH	441,368	82	10	519,189	91	10	9	18%	LL-CH	152,156	82	11	162,278	92	10	10	7%
NA-EX	560,007	86	11	650,272	92	10	6	16%	NA-EX	83,379	79	13	104,037	86	12	8	25%

Figure 24. Current and future suitability (by 2050) of sorghum.)

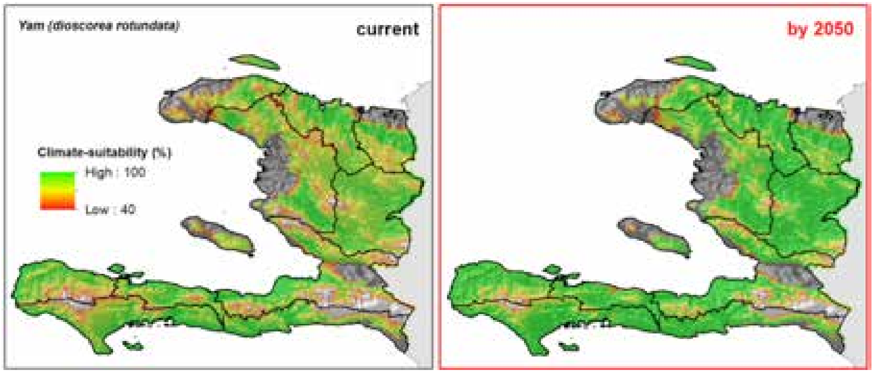
Yam and malanga

There are approximately 600 species of yams (Dioscorea spp.) and 6 of them are the most cultivated species in the Caribbean (D. alata, D. cayenensis, D. rotundata, D. trifida, D. esculenta and D. bulbifera). In our study we modeled 2 varieties of yam and malanga (dasheen) using ecocrop to determine climate-suitability. Results show that cushcush yam (D. trifida) is losing suitability and area in AV-NL and AV-LL areas (-11 to -14% suitability and up to -10% areas, Figure 25). White and yellow yam is gaining suitability and available areas remain more or less constant all over Haiti by 2050 (see Figure 26). Finally malanga is shifting its geographical areas of suitability but generally losing suitability and areas.



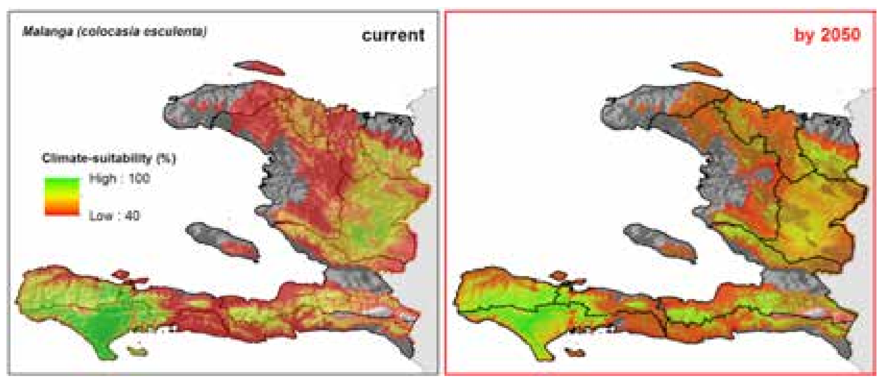
Country (Haiti)									Southwestern departments (Sud, Nippes, Grand Anse)								
	Current			future 2050			change			current			future 2050			change	
index	AREA (ha)	S (%)	STD	AREA (ha)	S (%)	STD	S	AREA	index	AREA (ha)	S (%)	STD	AREA (ha)	S (%)	STD	S	AREA
AV-NL	304,229	90	13	276,270	76	13	-14	-9%	AV-NL	77,074	88	11	69,607	74	12	-14	-10%
AV-LL	455,721	95	9	444,770	85	13	-11	-2%	AV-LL	121,210	95	7	119,136	82	12	-12	-2%
NL-CH	214,213	91	13	192,145	79	15	-12	-10%	NL-CH	59,319	91	9	55,669	76	13	-15	-6%
LL-CH	573,115	96	10	551,379	87	13	-8	-4%	LL-CH	174,888	97	6	173,229	84	10	-12	-1%
NA-EX	634,177	95	11	612,025	89	13	-6	-3%	NA-EX	135,563	96	9	134,402	91	12	-5	-1%

Figure 25. Current and future suitability (by 2050) of yam (Cushcush yam)



Country (Haiti)									Southwestern departments (Sud, Nippes, Grand Anse)								
	Current			future 2050			change			current			future 2050			change	
index	AREA (ha)	S (%)	STD	AREA (ha)	S (%)	STD	S	AREA	index	AREA (ha)	S (%)	STD	AREA (ha)	S (%)	STD	S	AREA
AV-NL	336,668	89	14	324,887	93	14	4	-3%	AV-NL	80,309	92	12	80,558	95	12	3	0%
AV-LL	462,856	83	15	465,843	92	13	9	1%	AV-LL	120,962	84	14	121,708	94	10	10	1%
NL-CH	240,015	86	16	228,483	92	16	6	-5%	NL-CH	59,651	91	13	60,149	96	10	4	1%
LL-CH	590,870	81	15	592,114	91	13	10	0%	LL-CH	170,325	86	14	174,556	94	11	9	2%
NA-EX	652,927	78	17	656,992	87	16	9	1%	NA-EX	123,119	76	17	131,415	86	15	10	7%

Figure 26. Current and future suitability (by 2050) of yam (white and yellow yam)

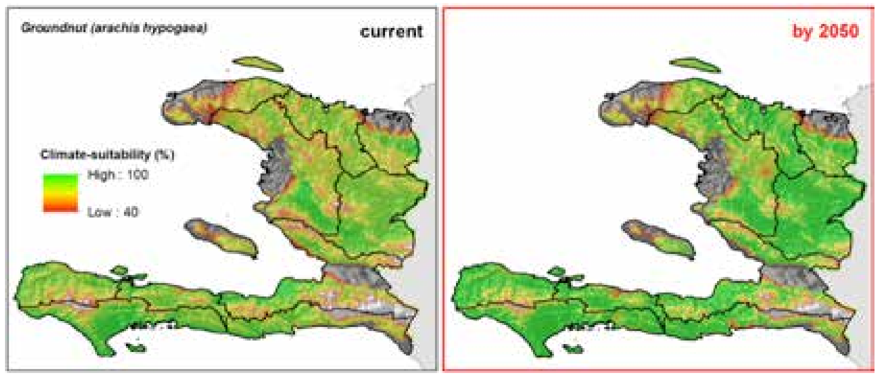


Country (Haiti)									Southwestern departments (Sud, Nippes, Grand Anse)								
	Current			future 2050			change			current			future 2050			change	
index	AREA (ha)	S (%)	STD	AREA (ha)	S (%)	STD	S	AREA	index	AREA (ha)	S (%)	STD	AREA (ha)	S (%)	STD	S	AREA
AV-NL	169,993	69	17	148,506	60	12	-10	-13%	AV-NL	54,922	81	19	48,451	68	15	-13	-12%
AV-LL	321,403	64	17	267,642	60	15	-5	-17%	AV-LL	103,705	80	18	93,169	72	17	-7	-10%
NL-CH	117,809	66	16	99,640	59	13	-7	-15%	NL-CH	35,675	76	19	29,535	69	16	-7	-17%
LL-CH	397,398	62	16	326,214	58	15	-3	-18%	LL-CH	134,568	74	18	118,058	70	17	-4	-12%
NA-EX	498,365	63	15	435,229	60	15	-3	-13%	NA-EX	122,455	80	14	116,730	77	13	-4	-5%

Figure 27. Current and future suitability (by 2050) of malanga (dasheen)

Groundnut (peanut)

Peanut is an important secondary crop grown throughout most of rural Haiti; little research exists on the market potential of Peanut and its role in improving rural farm income. Our climate-suitability analysis reveals that climate change could provide an opportunity for this crop, with a two fold increase in the areas on available land with no limitations of soil by remaining suitability-index all over Haiti areas. Southwestern departments will maintain an average suitability index of 93% (13% standard deviation) by 2050 (see Figure 28).



Country (Haiti)									Southwestern departments (Sud, Nippes, Grand Anse)								
	Current			future 2050			change			current			future 2050			change	
index	AREA (ha)	S (%)	STD	AREA (ha)	S (%)	STD	S	AREA	index	AREA (ha)	S (%)	STD	AREA (ha)	S (%)	STD	S	AREA
AV-NL	337,663	84	15	693,662	84	16	0	105%	AV-NL	80,558	91	13	80,060	93	13	2	-1%
AV-LL	478,785	81	14	608,790	88	14	7	27%	AV-LL	121,791	87	12	121,791	95	9	8	0%
NL-CH	250,634	79	16	242,338	86	18	6	-3%	NL-CH	60,066	89	12	60,232	93	12	4	0%
LL-CH	606,301	78	14	479,366	90	13	11	-21%	LL-CH	174,390	85	11	175,220	94	10	9	0%
NA-EX	685,200	75	15	330,695	90	16	14	-52%	NA-EX	130,419	77	14	136,227	86	15	9	4%

Figure 28. Current and future suitability (by 2050) of groundnut (peanut).

Conclusions

We assessed the impact of short- mid- & long-term climate change on coffee and mango production systems in Haiti. Further potential impacts on crops proposed to be diversification options for coffee farmers were assessed by analyzing their climate-suitability to ensure that strategic adaptation work will be done on current and future suitable crops. We reviewed several crop suitability models before deciding upon the most appropriate model to use in the analysis. Maximum entropy (Maxent) is a niche modeling method and was selected to model potential current and future distribution of coffee and mango. Ecocrop, a crop niche prediction model using climatic ranges as input to determine a suitability index, was used for assessing diversification options. We then compared climate-suitable area-outcomes with a land availability-index for agriculture production and extracted spatial statistics from the climate-suitability layers based on the 5 land-availability layers using a Geographical Information System (GIS).

Results show that changes in temperature and rainfall patterns will cause a general decrease of areas suitable for coffee and reduce areas which currently possess high suitability and coffee will lose suitability in lower altitudes. Mango will remain a highly suitable crop in many regions of Haiti. The assessment of diversification options for coffee farmers shows that suitability for cocoa and is not predicted to be affected by changes from long-term climate patterns and Haiti's cocoa producers could be part to meet the global demand for high quality cocoa production. For existing maize productions we emphasize that appropriate crop development and management strategies for dealing with extreme heat on maize varieties should be a priority for future work in Haiti. Different yams are losing and gaining depending on specific variety and need to be selected in order to develop their production. Sorghum and Groundnut are promising due to predicted increased suitability in the future.

Changes in temperature and rainfall will also change prevalence of pest and disease. Although we didn't quantify the impact of climate change on major pest and diseases for Haiti in this study, it is important to focus in future work on how coffee species, mangoes and other crops in Haiti are influenced by pests and diseases under accelerated climate change.

There are many opportunities to adapt to changes and for those coffee farms whose suitability will drop but not decrease drastically, proactive adaptation is a crucial strategy. Agroforestry systems such as coffee systems are not only important as a commodity and cash income generator for smallholder but also as a provider of ecosystems services. A decrease in coffee suitability is likely going to threaten the environmental services coffee systems provide, such as soil cover, carbon sequestration, biodiversity and water storage. Therefore a key strategy needs to focus on maintaining the environmental services with a different agroforestry system. In this context cocoa is a promising option. We distinguish 3 general strategies to adapt to the change of coffee suitability. The three strategies are interlinked and will replace each other over time. Areas that will increase in suitability need strategic investment. Areas that will lose some suitability are likely to be maintained through targeted strategies such as irrigation, shade management and change to more drought resident varieties. Areas that are likely to suffer from significant decrease in suitability need to start diversifying in order to switch to different crops, such as cocoa, once coffee is not suitable any more.

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