Food system challenges for Ethiopia

PROJECT PROGRESS REPORT

Activity within the project “Multiple scales and extreme events”

KB program: “Food Security and Valuing Water”

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Summary

Our main task for 2019 has been to draft a research agenda for 2020-2022 to study required food system transitions for Ethiopia in order to achieve sustainable and healthy diets ("Zero Hunger") in 2050. We started our project work in 2019 with describing quantitatively parts of the food system in its current status and projected for 2050. From this partial knowledge of the food system and its interactions with drivers and outcomes, a goal-oriented approach was applied: "Which transitions are needed to achieve zero hunger in 2050 in a sustainable way"? So far, required transitions are described in terms of economic development, changing diets, land use, water distribution and fertilizer needs. We aim to develop a general approach, also applicable to other countries, in which we will link various scales from the (inter)national level to the field level by using different models.

Highlights

With a projected growth in both population (90 to 170-190 million people) and income (350 to 3000 US$/cap/d) from 2010 to 2050, a strong increase in food supply is needed to feed all people (>3x). Assuming an improved diet for the whole population in 2050, 97.5% of all required food produced in Ethiopia, large increases of agricultural land and nutrient inputs are needed. Whether or not these projected diets are healthy, is yet unknown and needs further study. Also, whether or not projected household incomes in 2050 will be sufficient to afford healthy diets, needs to be further investigated. Variability in per capita income and food consumption among the population in Ethiopia needs to be elucidated to evaluate and check that the number of undernourished people in 2050 declines to (practically) zero. In a first attempt, we estimated that roughly 50% more land, 3000% more N and 250% more P fertilizer would be required in 2050 relative to 2010. The extreme value for N, which is rather uncertain, is partly due to the imposed N requirement for maintaining soil fertility.

Important question(s): which economic development is needed to increase people's income to sufficient levels (taking spatial variability into account), how can a healthy diet be defined in terms of food crop and animal production demands, and which efficiency improvements in the food production system are feasible to produce more with less inputs.

The projected climate change for Ethiopia shows with a high certainty that temperature will increase further, but that the effect on precipitation still remains inconclusive. However, it is illustrated that the suitability of some areas, currently in use as agriculture, may decrease in the future due to more frequently occurring drought periods. This refers mainly to arable cropping in the mid-western part of the country. If this will occur, it will affect the livelihoods of many people, that are currently involved in agriculture, and possibly also achieving SDG 2 of "Zero Hunger" at the national level. Already in recent years, average rainfall variability has caused problems for agriculture (crops and livestock) and related food availability.

Important question(s): how will future climate affect local to national food production possibilities, and govern the spatial distribution of agricultural production within the country under the development of larger food requirements for the growing population towards 2050.

Ethiopia has three main international rivers, and neighboring countries of Ethiopia are more or less depending on these water flows. Via treaties and cooperation, the various countries in the region aim to optimize the water use for all people living in a wider area from Kenya to Egypt by distributing sufficient amounts to each country. However, increased use of this water for the irrigation of crops in Ethiopia, which is now at a very low level (< 2% of cultivated area), may be necessary to increase crop yields in the future. However, it is not yet clear whether (large-scale) irrigation projects in Ethiopia are needed in the future, because a large increase in crop yields may already be possible under rain-fed agriculture if infiltration of precipitation can be optimally achieved.

Important question(s): how will higher crop yields with/without irrigation, necessary to feed the growing population, affect the amount of water which is needed for the various other claims (such as for

neighboring countries, hydropower plants, and environmental flow requirements) under climate change scenarios?

Nutrient balances in the past tended to be (very) negative, resulting in declining soil fertility and therefore posing a possible threat to the sustainability of food production. Losses also seemed relatively high (same order of magnitude compared to harvested N and soil N depletion), which affect fertilizer efficiency and the environmental quality of a wider region. In recent years, more fertilizers have been applied, notably to cereal crops, improving crop yields, possibly soil fertility, but maybe also stimulating leaching losses. Reduction of losses works in more than one way: it improves the situation of the farmer (less fertilizer needed for crop production), it improves the environment at and surrounding the farm (less emissions), and it may also have a positive effect on improving soil fertility and halting land degradation.

Important question(s): how to better predict nutrient losses, and simultaneously find measures to reduce these losses, both at the local and the national level.

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1. Introduction

Countries have committed themselves in 2015 to achieve "Zero Hunger" (SDG2: *"End hunger, achieve food security and improved nutrition, and promote sustainable agriculture"*), and simultaneously also safeguarding "Life below Water" (SDG14) and "Life on Land" (SDG15: "*Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss*"). However, in many parts of the world, the current situation is far away from these ambitious goals. Especially, in developing countries, it remains a challenging task to transform current food systems into systems that ensure food security for all, while protecting biodiversity. On the other hand, also developed countries are struggling with the ensemble of SDG goals, e.g. halting biodiversity loss is often neglected in their pursue of more economic growth. Above-mentioned SDG's are at the heart of a new KennisBasis (KB) programme "Food Security and Valuing Water" that started in 2019. The second part of this programme title acknowledges the importance of water for people and wildlife. Knowledge about food system transitions is indispensable in the search for interventions that are both applicable in practice and have a positive effect on simultaneously achieving multiple SDG's. Understanding current and possible future food systems requires knowledge about inputs, interactions, scales, and outcomes for people and the natural environment. It brings together different (scientific) disciplines, as in real life where people and their activities also interact (household economy, arable farming, livestock husbandry, food transport and processing, etc.), and depend on the quality of the natural environment (soils, climate, biodiversity, etc.).

Within the project "Multiple scales and Extreme Events" (i.e. one of the projects of above-mentioned programme), part of the available resources has been used in 2019 to start with the research into the principal question of how to achieve zero hunger in a sustainable way in a country. Many answers are in principle possible to this question of "how". With the expertise available in our project, we focus on quantitatively describing a number of important interactions in the food system, which can be used to identify transitions needed for this goal. Our research is thus not only focussing on understanding the current food system, but also on describing a food system that is able to deliver sustainable food security in the future. We have chosen Ethiopia as a case study area, but aim to develop a generic approach that can also be applied to other countries.
Special attention will be given to connecting different scales in the food system. Most important scales that we envisage are: (1) international (food imports/exports and transboundary rivers), (2) national (policies on food security and infrastructure), (3) households (both urban and rural), and (4) field or herd (producing crops and animal products). Within WUR, often models and/or databases are available for one of these scales, sometimes for two, but seldomly for all together. Smart linking of these existing knowledge tools will be part of our approach to illustrate how interventions at one scale may affect outcomes or options at other scales.

This report does not yet contain final results, but should be seen as a first draft with the results of our analysis in 2019. A number of improvements and further detailing is needed in 2020, and will supersede the results in the present version of this report. Next to reporting our work in 2019 (chapters 2 – 5), it also has as purpose to describe the project agenda for coming years (chapter 6). This agenda draws on the findings of our research in 2019, notably on the projected economic development (section 2.1), on land requirements to adequately feed the future population (section 2.2), on future climate change that affects production conditions (chapter 3), on the national water balance with multiple claims from different sectors (chapter 4), and on nutrient balances (mainly nitrogen, phosphorus and potassium), and fertilizer requirements for sustainable production (section 2.2 and chapter 5).

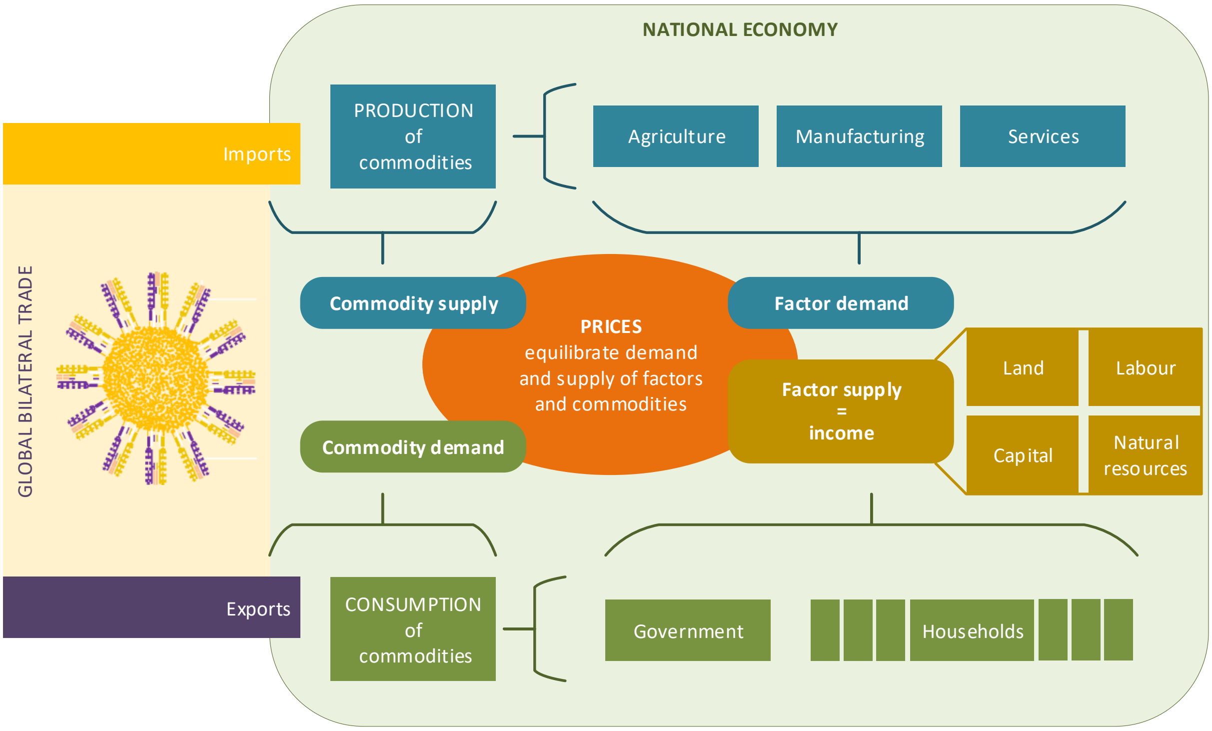
2. National analyses

2.1 Economic development

2.1.1 MAGNET and MagnetGrid models

The simulations use MAGNET (Modular Applied GeNeral Equilibrium Modelling Tool): an economy-wide model driven by changes in input and output prices steering allocation of competing (agricultural and non-agricultural) uses of primary factors and intermediate inputs, as well as income and demand responses (Woltjer et al. 2014). Being a global economy-wide model, all economic flows are traced, thus capturing feedback loops within the food system from farm to fork, as well as feedback loops of the food system with the rest of the economy (manufacturing and services), and including income effects at national level. MAGNET is an advanced recursive dynamic variant of the Global Trade Analysis Project (GTAP) model (Corong et al. 2017). Figure 2.1 summarizes how MAGNET traces the circular flow of money through national economies with interactions among countries driven by bilateral import and export flows.

Figure 2.1: The circular flow linking production, income and demand



US Dollar-based GTAP data (Aguiar, Narayanan, and McDougall 2016) are complemented in the MAGNET database with physical flows (from FAOSTAT, IEA and other sources) to improve the assessment of food system outcomes across multiple dimensions. Commodities available in the Ethiopian application are provided in Annex I. A total of 57 sectors cover 12 primary agricultural sectors, 11 processed food sectors, 31 industrial sectors and 3 service sectors. Sectors may produce multiple products. For example cake from vegetable oil production that can be used for livestock, either directly or through the production of feed. As a result of these by-products, the total number of commodities is 66.

A key strength of MAGNET is its modular structure, allowing fast uptake of developments across different strands of research, enabling the study of trade-offs across multiple domains like food security versus environmental concerns. In this study three modules are key: (i) *nutrient availability* in private consumption purchases capturing 23 macro- and micronutrients, drawing on data from Smith et al. (2016), (ii) *endogenous agricultural land supply,* drawing on data from FAOSTAT and (iii) *GHG emissions* (carbon dioxide, nitrous oxide, methane and fluorinated GHG) from the GTAP database, covering agricultural and non-agricultural production and consumption activities. Its breadth of scope allowed MAGNET impact assessments in different policy arenas, including: land-use change (Schmitz et al. 2014), conventional biofuel and second generation biofuel policies (Meijl et al. 2018), food security (Kuiper et al. 2019; Hasegawa et al. 2018) and climate change (Frank et al. 2019; Nelson et al. 2014).

As MAGNET is based on national level statistics and capturing global interactions, the MAGNET indicators do not capture sub-national differences across the population or agricultural production areas, which may be substantial. To better capture spatial variation, MAGNETGrid is currently developed. MAGNETGrid is a modular economic land use model adding spatial detail to macroeconomic foresight. Its innovative feature is to combine detailed spatially explicit biophysical information on suitability of land for specific agricultural activities, with projections of agricultural product and input prices reflecting economy-wide changes over time. Hence, MAGNETGrid allows to project and visualize future agricultural land-use change patterns that may emerge from a combination of climatic and socio-economic developments, quantify the impacts resulting from these trends and evaluate their potential trade-offs. MAGNETGrid combines these national level foresight results from MAGNET with bio-physical characteristics of land units determining their suitability for different types of agricultural activities (climate, topography and soil quality).

MAGNETgrid can show localized economic impacts from diverse drivers like income growth, changes in diet, climate change, policy reforms (taxes and subsidy schemes), climate mitigation or adaptation. It does this by projecting future land-use patterns regarding not only the profitability of single activities, but weighing these against the sunk costs of past investments and opportunity costs of foregone alternative activities - while respecting the total projected change in land area. This fourfold interaction between the past and future characteristics of spatial units and macro level projections provides a consistent approach to project land use developments under different scenarios, doing justice to both the projected macro level changes and the warranted reluctance of producers to radically transform their business with every small change in prices. Being spatially explicit, results of the MAGNETgrid can be visualized in a non-technical manner through maps showing the changes in land use at global, regional, country and local level. First results for downscaling of MAGNET results for Ethiopia are shown below in the section on changes in agricultural production.

2.1.2 Projected changes in income and employment

Using standard SSP 2 assumptions, reflecting a "business-as-usual" development (IIASA 2015) we project GDP and population growth for Ethiopia from 2011 to 2050. The resulting changes in per capita income, wages and employment are described in Table 2.1. GDP projections for Ethiopia are optimistic being over 16 times the 2011 GDP. While population is also projected towards doubling by 2050, this is far outpaced by the real GDP growth (the most often used measure for international income comparisons). The annual income per capita is thus projected to rise dramatically from 349 to 3045 $/capita (in constant 2011 dollars).

For Ethiopia MAGNET does not include different types of households and we can thus not assess the distribution of these national averages. From the work of Rao et al. (2019), we therefore added SSP2 projections of the GINI coefficient, which provides a measure of the distribution of income. A GINI of 0 implies that all have the same income, while a coefficient of 100 implies that one person receives all income. Alongside the increases in per capita income, the distribution is also projected to improve moderately, with the GINI declining from 39 to 36 by 2050. Based on these results, we expect that poverty will decline due to an overall increase in income and to a much lesser extent from improvements in the distribution of income.

Table 2.1: Income, population, wage and employment changes for Ethiopia

		2011	**2020**	**2030**	**2040**	**2050**
Index real GDP		1	2.15	4.64	8.70	16.34
Index population		1	1.21	1.46	1.68	1.87
Population (million)		89	109	131	150	167
Real GDP (mil. 2011 US $)		31179	66963	144573	271363	509349
Real GDP/capita		349	617	1107	1805	3045
GINI		39	39	39	38	36
Real unskilled wage (index)	Average	1	1.43	2.12	2.97	3.97
	Agriculture	1	1.28	1.70	2.15	2.57
	Non-agriculture	1	1.67	2.71	3.94	5.42
Real skilled wage (index)	Average	1	1.36	1.85	2.22	2.53
	Agriculture	1	1.32	1.76	2.16	2.51
	Non-agriculture	1	1.36	1.85	2.22	2.53
Real land price (index)	-	1	1.60	2.60	3.90	5.60
Employment (%)	Agriculture	54	43	34	27	21
	Processed food	7	6	6	5	4
	Industry	9	11	14	16	17
	Services	31	39	46	52	58
Unskilled employment (%)	Agriculture	64	58	53	49	46
	Processed food	8	8	8	8	7
	Industry	7	8	8	8	7
	Services	21	26	31	35	40
Skilled employment (%)	Agriculture	3	1	0	1	1
	Processed food	1	1	1	1	1
	Industry	17	21	23	25	25
	Services	79	78	76	74	73

Source: GINI projections from (Rao et al. 2019), other indicators from MAGNET simulations.

MAGNET does provide a glimpse at changes in income distribution through changes in wages and land prices. Rising incomes in a poor country like Ethiopia, increases demand for food, thus increasing domestic production. This increases demand (and supply) of agricultural land, reflected by rising land prices. These will raise the income of land owners, which generally will be rural farm households.

MAGNET distinguishes two types of labour, skilled and unskilled, which are associated with education levels. As poor households generally lack access to education, they will derive most of their income from unskilled labour. Furthermore, to capture the empirical evidence of persistent wage gaps between agricultural and non-agricultural wages, MAGNET includes segmented labour markets. These limit (but not prevent) mobility of labour between agriculture and non-agriculture and generate different wage developments.

Unskilled wages are projected to grow more than skilled wages, which may signal an improvement in the income distribution (in line with the projected GINI improvement). The major gains, however, are in the non-agricultural wages. With most poor being rural households which likely depend on agricultural wage income, this implies poverty will improve but rural poor (a smaller group) will gain more. As there is limited use of skilled labour in agriculture, there is less of a divergence for skilled wages and by association richer rural and urban households.

The bottom part of Table 2.1 shows the changes in employment by sector, both overall and by labour type. Structural transformation along the economic growth is obvious, from 2011 to 2050 agriculture and services trade places in terms of being the major employer. Industrial employment grows as well, but remains relatively modest, as seems typical for African countries that need to compete with the Asian economies. We also added the food processing sector which may provide a means to generate employment and backward linkages to domestic farmers (with rising incomes the share of processed food increases). In terms of employment its contribution remains stable and even declines in later stages (signalling increased reliance on imported processed foods).

Table 2.2: Macro and micro nutrients in food purchased by households (average per person, per day)

		2011			**2050**	
	Low	**Median**	High	Low	**Median**	High
Edible food (g)	793	**793**	793	1257	**1257**	1257
Calorie (kcal)	2118	**2152**	2208	3356	**3416**	3493
Protein (g)	57	**60**	63	93	**97**	101
Fat (g)	43	**46**	49	64	**69**	76
Carbohydrates (g)	43	**46**	49	64	**69**	76
Vitamin C (mg)	51	**59**	70	57	**66**	82
Vitamin A (microgram RAE)	90	**485**	653	122	**911**	1256
Folate (microgram)	298	**308**	704	389	**406**	859
Calcium (mg)	393	**433**	477	552	**598**	656
Iron (mg)	37	**59**	83	47	**72**	99
Zinc (mg)	11	**12**	12	17	**18**	20
Potassium (mg)	2393	**2457**	2618	3281	**3391**	3666
Dietary fiber (g)	28	**31**	42	39	**45**	58
Copper (mg)	2	**2**	2	3	**3**	4
Sodium (mg)	173	**177**	185	254	**263**	280
Phosphorus (mg)	1391	**1486**	1659	2035	**2163**	2450
Thiamine (mg)	1	**2**	2	2	**2**	3
Robiflavin (mg)	1	**1**	1	1	**2**	2
Niacin (mg)	12	**13**	14	17	**19**	22
B6 (mg)	2	**2**	2	2	**3**	3
Magnesium (mg)	660	**706**	764	924	**1004**	1088
Saturated fatty acids (g)	8	**9**	11	15	**17**	21
Monounsaturated fatty acids (g)	8	**9**	11	14	**17**	19
Polyunsaturated fatty acids (g)	6	**8**	9	10	**12**	15

Source: MAGNET projections.

2.1.3 Projected changes in food security

The MAGNET database includes estimates of the nutritional contents in the FAO food balance data from the GENuS dataset (Smith et al. 2016). As there are great uncertainties on the nutritional content of food for these estimates, median, low and high estimates are provided. It should be noted that we apply the same nutritional content parameters, these measures thus do not track changes in nutritional content with changing trade flows. The values also only capture part of food losses and waste along the supply chain and thus overestimate actual food intake. Combined with an unequal access to food across the population, linked to unequal income distribution and possibly location, these average underestimate the food security challenges faced by Ethiopia's population.

With these caveats in mind, the increase in calories from 2152 to 3416 (median values) is promising in terms of reducing hunger. People may still go hungry though, and additional household (or individual) level analyses are needed to assess the number of hungry. As expected with rising incomes, protein in the food increases substantially with 60% from 2011 to 2050. Associated with this change is an increasing share of saturated fats in total fats (up from 52 to 57 %).

Apart from hunger as measured by calories, availability of nutrients in food is also critical for malnutrition. Globally, vitamin A and iron are a major threat to health and development, but especially for children and pregnant women. The recommended[1] intake of Vitamin A is between 700 (female) to 900 (male) of retinol activity equivalents (RAE) per day. Our projection pictures a massive improvement in Vitamin A in food, up from 485 to 911 RAE per person/day. The 2050 number just reaches the male requirement, but will be an overestimation of actual intake given loss and waste, as well as distributional issues. At least for parts of the population a Vitamin A deficiency will thus persist until at least 2050 in this projection.

Prospects for iron look better. Here, recommended daily intakes are 8 mg for men and 18 mg for women (27 mg for pregnant women). Average iron availability in both 2011 (59 mg) and 2050 (72 mg) are well above these recommendations. Again this does not preclude deficiencies in sub-populations, but these can only be assessed with additional household (or individual) level data.

Zinc deficiency is often an issue in low-income countries with a diet dominated by cereals and contributes to stunting by hampering growth and recovery. Here, there are also distributional concerns as there is a consistent link between the dominance of cereals in diets and low incomes (Clements and Si 2015). Recommended daily intakes are 11 mg for men and 8 mg for women. While our projected average availability increases from 12 to 18, there are likely to remain zinc deficiencies in poor households relying on cereals.

2.1.4 Downscaling agricultural production changes

The MAGNET projections of production (in tons), land by sector (in km2) and producer prices ($/ton)are combined by MAGNETGrid to project future land use at grid level. Table 2.3 summarizes the areas in 2011 and 2050, as well as the percentage changes in area, yield and producer price. According to the land supply module MAGNET (using data from the IMAGE model on available), there is still scope to expand agricultural production, only 45% of the potential agricultural land is used in 2011. As a result, a massive expansion is projected in agricultural area (+36%) from 2011 to 2050. Being far away from the boundary to land expansion, increases in land prices are modest (see table 2.1). Land prices are the mechanism in MAGNET tempering land expansion - the more land is brought into production, the more expensive further expansion becomes as more and more remote and marginal lands are cultivated.

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[1] All recommended intake numbers are taken from The Harvard School of Public Health Nutrition Source website (https://www.hsph.harvard.edu/nutritionsource/)

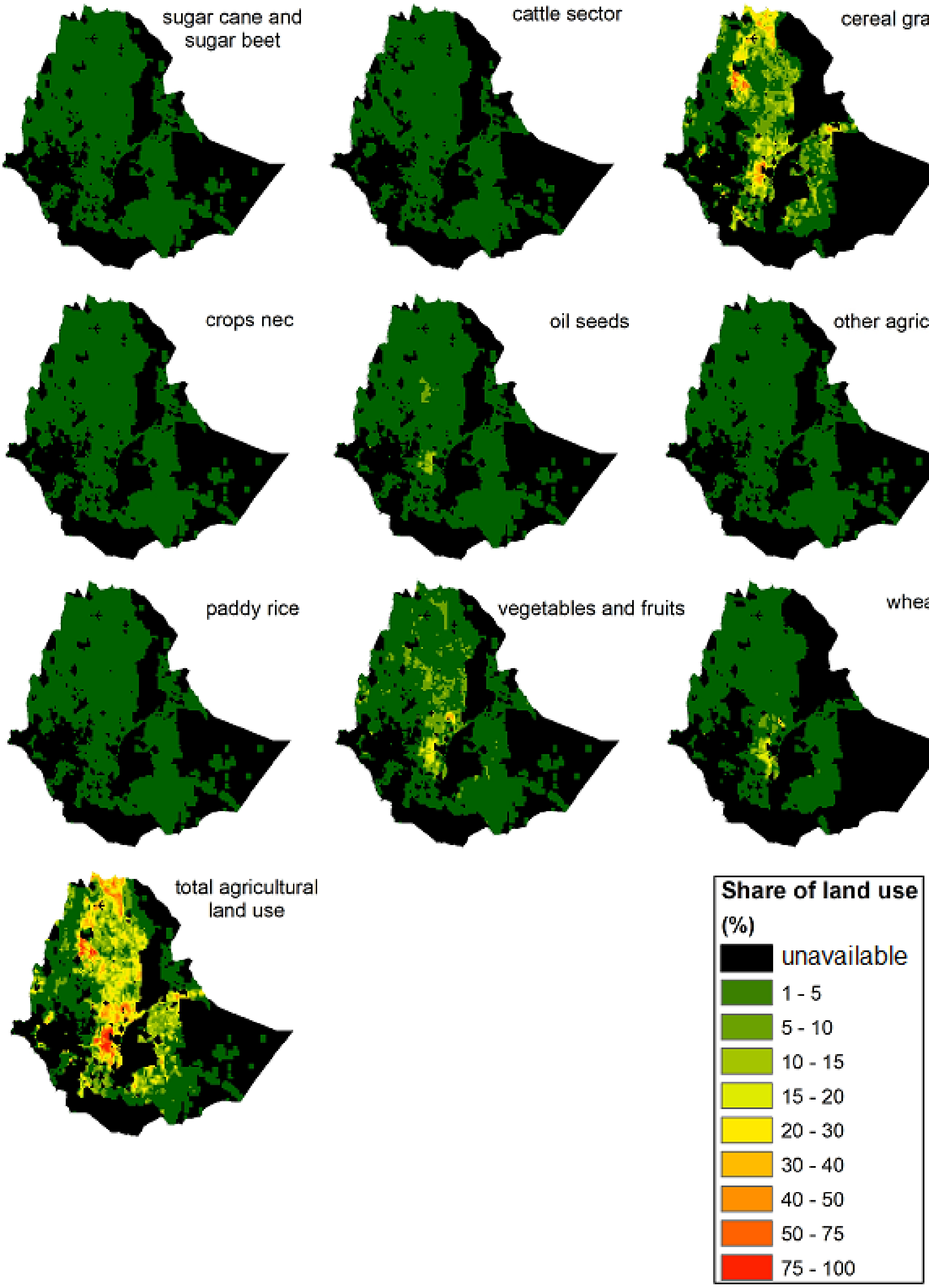
Table 2.3: Changes in area and key drivers of the MAGNETGrid allocation.

Sector	**Land (km2)**		**Changes 2011-2050 (%)**		
	2011	*2050*	*Area*	*Yield*	*Price*
Paddy rice	283	372	32	169	110
Wheat	13266	18249	38	160	69
Cereal grains nec	74943	76753	2	115	33
Vegetables & fruit	27515	31847	16	100	29
Oil seeds	8414	12542	49	156	85
Sugar cane, sugar beet	204	230	13	113	39
Other agriculture (non-food)	3026	4353	44	174	134
Crops nec	9247	12175	32	141	81
Cattle sector	220176	330749	50	181	141
Total agricultural land	*357072*	*487270*	*36*		

Source: MAGNET projections. Vegetable & fruit includes pulses and root crops, non-food refers to fiber crops and nec indicates all other crops not specifically mentioned. Land use for the cattle sector includes permanent pastures and meadows.

Currently, only current land use and production potential by sector are used to guide the allocation of the massive agricultural land expansion, resulting in the change from 2011 (Figure 2.2) to 2050 (to be developed). In the current demonstration version of MAGNETGrid, the land projections are allocated with no land use, agro-ecological and economic restrictions, which leads to inconclusive spatial patterns on future agricultural land. To improve that, additional information on the regional spatial infrastructure (affecting price transmission and marketing possibilities), unavailable areas for land allocation (urban, water bodies, built areas and native vegetation, among others) as well as localized supply responses derived from household survey data is expected to improve the downscaling procedures. These drivers play an important role on agricultural land use allocation, and have to be coherently aligned with overall assumptions of this case study.

Figure 2.2: Share of land use by sector, 2011



Source: MAGNET and MAGNETGrid (land use for the cattle sector refers to forage crops cultivated on cropland)

2.2 Land, N and P requirements

2.2.1 Introduction BIOSPACS

The model BIOSPACS simulates the N and P flows through the food system (production, processing and consumption) and across its boundaries as a function of food demand (e.g. Conijn et al., 2017). Food demand is calculated by the product of the number of people and an average per capita food consumption, which is further described by the food intake from 20 different food groups, including both vegetal- and animal-based food. Land, N & P chemical fertilizer requirements to produce the food are estimated for different crops, total cropland, and permanent grassland. Various internal feedbacks are taken into account, e.g. meat consumption and manure availability, and vegetal oil consumption and feed production. Next to required inputs and outputs (i.e. food supply as demanded by the population), also N and P losses and wastes are computed. Information about greenhouse gas (GHG) emissions, linked to different production processes in the agricultural part of the food system, is also available, but primarily for CH_4 and N_2O. Most data, that are needed for an initial description of the system, are taken from FAOSTAT, such as provided in the Food Balance Sheets, crop yield, fertilizer and manure data, GHG emissions, etc. However, some additional inputs have to be estimated as well.

2.2.2 N & P balance in 2010

As a first step, BIOSPACS has been parametrized for Ethiopia with data from 2010. This is referred to as current situation. Average food energy and protein supply to households in 2010 amount roughly 2100 kcal/cap/day and 61 g/cap/day (mainly containing plant protein: 86%). Due to household losses, intake levels are circa 10% lower, resulting in 1850 kcal/cap/day and 55 g/cap/day, respectively. The average intake level is only a little above the Minimum Dietary Energy Requirement (MDER) in Ethiopia which has been estimated at 1750 kcal/cap/day (source: FAO). Due to variability in the country, many people will have less than the MDER and the FAO has estimated the number of people undernourished at 28 million or 32% of the total population in 2009-2011. The situation in Ethiopia is improving (22 million and 21% estimated for 2016-2018), because the increase in food production has been higher than the population growth in recent years. This upward trend in production can partly be explained by an increase in the application of fertilizers, which are required to obtain higher crop yields.

The national N and P flows are illustrated in Figure 2.3, and total cropland (including permanent crops) and permanent grassland used for the food production equal 14 and 40 Mha, respectively. The area of required permanent grassland is twice the value as reported in FAOSTAT, due to the high demand from grazing animals, and assumed low grassland productivity (on average 2.2 ton DM/ha/y). Therefore, feed from an additional 20 Mha of "Other land" (originally 52 Mha in FAOSTAT) is needed and added to the category of permanent grassland (meadows and pastures in FAOSTAT) in the description of BIOSPACS for Ethiopia in 2010. Figure 2.3 shows that the N and P flows with net import of food (import – export) is less than 10% of the N and P supply in food to the households (for N: 25 versus 313 and P: 4.5 versus 54.2). This indicates that the population in Ethiopia is depending on domestically produced food for >90% in 2010. Ethiopia is mainly producing vegetal food (86% of vegetal and animal production), which is in line with the high share of vegetal protein in the total food protein supply (see above).

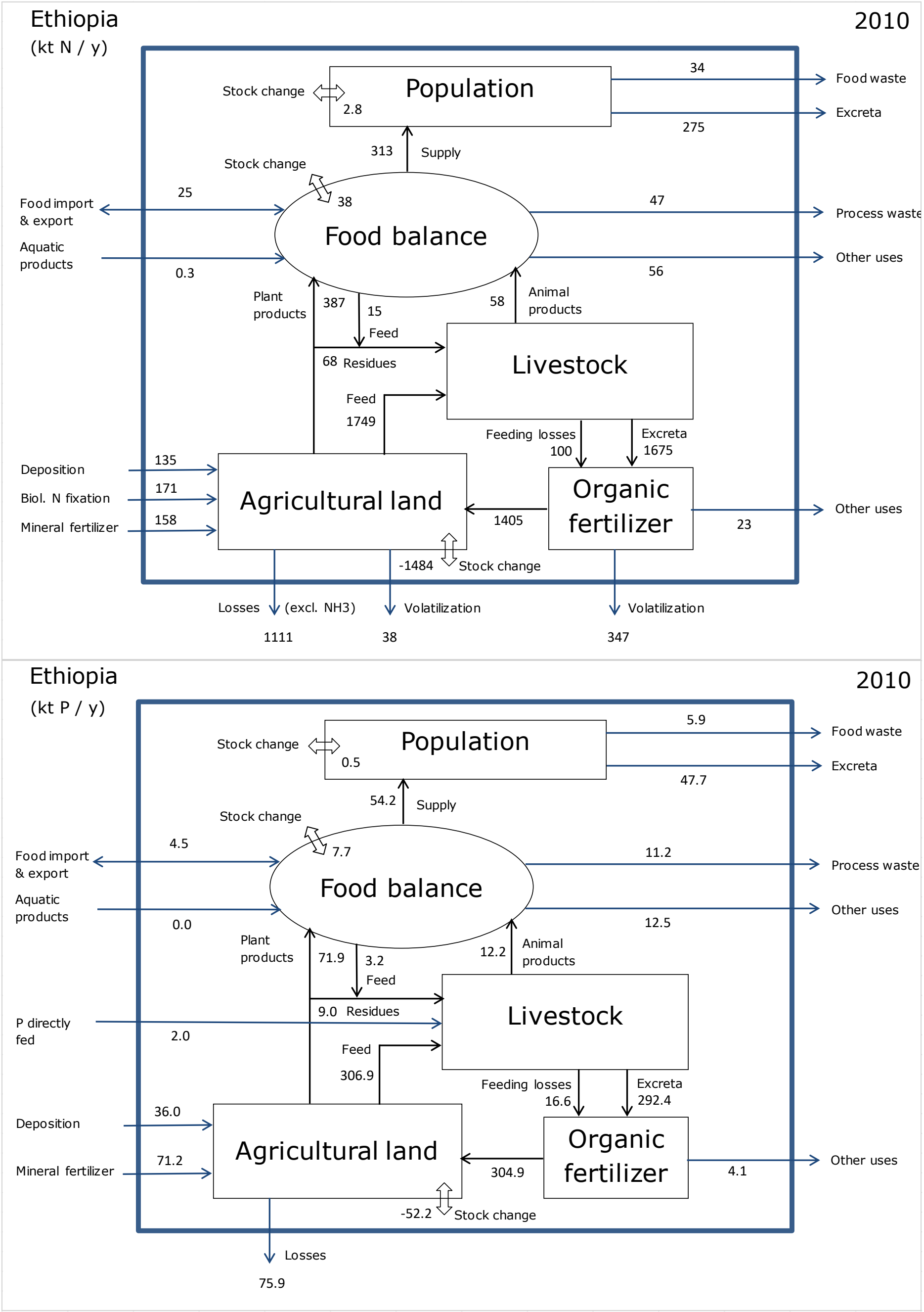


Figure 2.3. National N and P flows of the food system in Ethiopia in 2010. Inputs are shown at the left-hand side, losses at the bottom and 'outputs' (i.e. waste streams and other uses with relatively unknown destinations) at the right-hand side. Agricultural land includes both cropland and permanent grassland. Note: kiloton (kt) = million kg (Mkg) = gigagram (Gg).

In 2010 the N and P fertilizer inputs to agricultural land are rather low compared to the losses and the harvested flows. Especially for N, this is linked to a very high soil N depletion (denoted as "Stock change" in Fig. 2.3), which has been estimated at almost 10x the fertilizer N input. In the results for soil N depletion in 2010, permanent grassland "contributed" circa 1070 Mkg N, whereas cropland only 420 Mkg N, mainly due to the large difference in total area (40 versus 14 Mha). Large uncertainties exists in these estimates, notably with respect to the losses in permanent grassland and cropland. A comparison with monitoring data shows that e.g. more fertilizer was applied and more losses were estimated, and ultimately the depletion is 25% lower relative to the values of BIOSPACS for cropland (Table 2.4). However, direct comparison remains difficult because the data from Van Beek et al. were determined at a limited number of sites, and therefore it is unknown whether they are a good representation of the national situation. Also, there is a difference in year/period which may partly explain the difference in fertilizer inputs. Both BIOSPACS and Van Beek et al. estimate that N losses and soil N depletion are high relative to fertilizer input and harvested N. In BIOSPACS, it has been assumed that in 2010 permanent grassland does not receive any chemical fertilizers.

Table 2.4. N flows (kg N/ha/y) calculated with BIOSPACS for cropland in 2010 (left), and derived from Van Beek et al. (2016), based on a number of sites monitored in Ethiopia during 2012-2014 (right).

BIOSPACS, 2010		Van Beek et al.(2016), 2012-2014	
Manure+NH3	9.9	6.2	Organic fertilizer
Deposition	2.5	3.1	Atmospheric deposition
Biological N fixation	7.8	2.5	Biological fixation
Synthetic fertilizers+NH3	11.5	31.2	Mineral fertilizer
Seed input	0.7	-	
Losses (non-NH3)	25.2	35.6	Leaching + erosion
NH3 volatilization	3.7	3.8	Gaseous losses
Yield (main product)	28.8	22.3	Harvest
Byproduct	4.9	4.5	Crop residues
Stock change	-30.3	-23.1	Balance

A negative balance or stock change indicates soil N depletion (output > input) and can be regarded as an input from the soil N stock to the N balance. If these high depletion rates (Figure 2.3, Table 2.4) would continue for many years, productivity of land will decline, and ultimately land will degrade to a level that crop production is no longer economically feasible. To halt this depletion, either losses need to be reduced or inputs need to be increased to adjust the balance. BIOSPACS has been used to estimate the amount of additionally required N fertilizer that results in a zero soil N depletion. For cropland an extra amount of circa 360 Mkg N/y would be needed on top of 160 Mkg N/y applied in 2010 (see Table 2.5 for per ha values), whereas for grassland an additional 1090 Mkg N/y would be required. Especially, the value for grassland fertilization is uncertain, as it is difficult to determine the losses at permanent grassland. But when outputs (harvested grass + losses) exceed the inputs (manure, deposition and fixation), additional chemical fertilizer is needed to prevent soil N depletion and to maintain productivity.

Table 2.5. N flows (kg N/ha/y) calculated with BIOSPACS for cropland in 2010 with fertilizer consumption as provided by FAO (left: Current), with higher fertilizer input to simulate a situation with zero depletion/stock change in 2010 (middle: Adjusted), and for the increased population and food demand in 2050 (right: Scenario; see explanation in next section).

	Current, 2010	Adjusted for soil N	Scenario, 2050
Manure+NH3	9.9	9.9	23.2
Deposition	2.5	7.4	20.2
Biological N fixation	7.8	7.8	14.5
Synthetic fertilizers+NH3	11.5	37.8	78.2
Seed input	0.7	0.7	1.5
Losses (non-NH3)	25.2	19.8	42.7
NH3 volatilization	3.7	10.1	21.2
Yield (main product)	28.8	28.8	62.9
Byproduct	4.9	4.9	10.9
Stock change	-30.3	0.0	0.0

2.2.3 N & P balance in 2050

To estimate food system challenges, a scenario for the food system in 2050 has been defined, consisting of (1) zero soil N depletion, (2) 190 million people, according to UN projections supplied via FAOSTAT, (3) 50% higher food consumption, and (4) 100% increase in crop and grass yields. Imports and exports have been kept at their levels in 2010 (absolute values). The higher food consumption leads to an average food supply and intake of 3100 and 2800 kcal/cap/day, respectively. For this analysis, it has been assumed that this level would be sufficient to reduce the number of people undernourished to zero, but this assumption needs thorough checking. The doubling of the yields seems realistic because yields have improved in recent years with 25-50% (cereals, except rice), but remains uncertain due to the yet unknown effects of climate change and the development of prices towards 2050. Domestic food production needs to increase by more than 3x as a combined effect of higher population density, more food per capita, and almost (assumed) negligible contribution from net imports (Fig. 2.4). Large inputs of fertilizers will be needed: >5100 Mkg N/y (compare 150 Mkg N/y in 2010), and 450 Mkg P/y (compare 71 Mkg N/y in 2010). Avoiding soil P depletion would require another 60 Mkg P/y, in total 510 Mkg P/y. Losses of N and P to the environment (atmosphere and ground-/surface waters) will also be much larger than their levels in 2010 and special interventions may or will be needed to reduce them to acceptable levels (Fig. 2.4). If losses can be reduced, it will also have a positive (i.e. reducing) effect on fertilizer needs. Another option to reduce fertilizer requirements would be to stimulate recycling of nutrients, notably of the nutrients in human excreta.

Agricultural land use in this scenario for Ethiopia in 2050 would increase as well towards 19 Mha for cropland (+40%) and 65 Mha for permanent grassland (+60%). This is directly related to the total food demand and assumed crop yield increase. With higher crop yields (>2x compared to 2011), less land will be needed and vice versa. On the other hand, these land requirements may increase even further, if the average diet of the population in Ethiopia would shift more to animal protein from domestic production. Permanent grassland plays a dominant role in the results of BIOSPACS for Ethiopia (with respect to all major flows and requirements). It is related to the large number of grazing animals that are assumed to be fed with grass in Ethiopia. Considerable uncertainty exists within these estimations, but it nevertheless illustrates the importance of permanent grasslands, their productivity, required fertilization and associated losses.

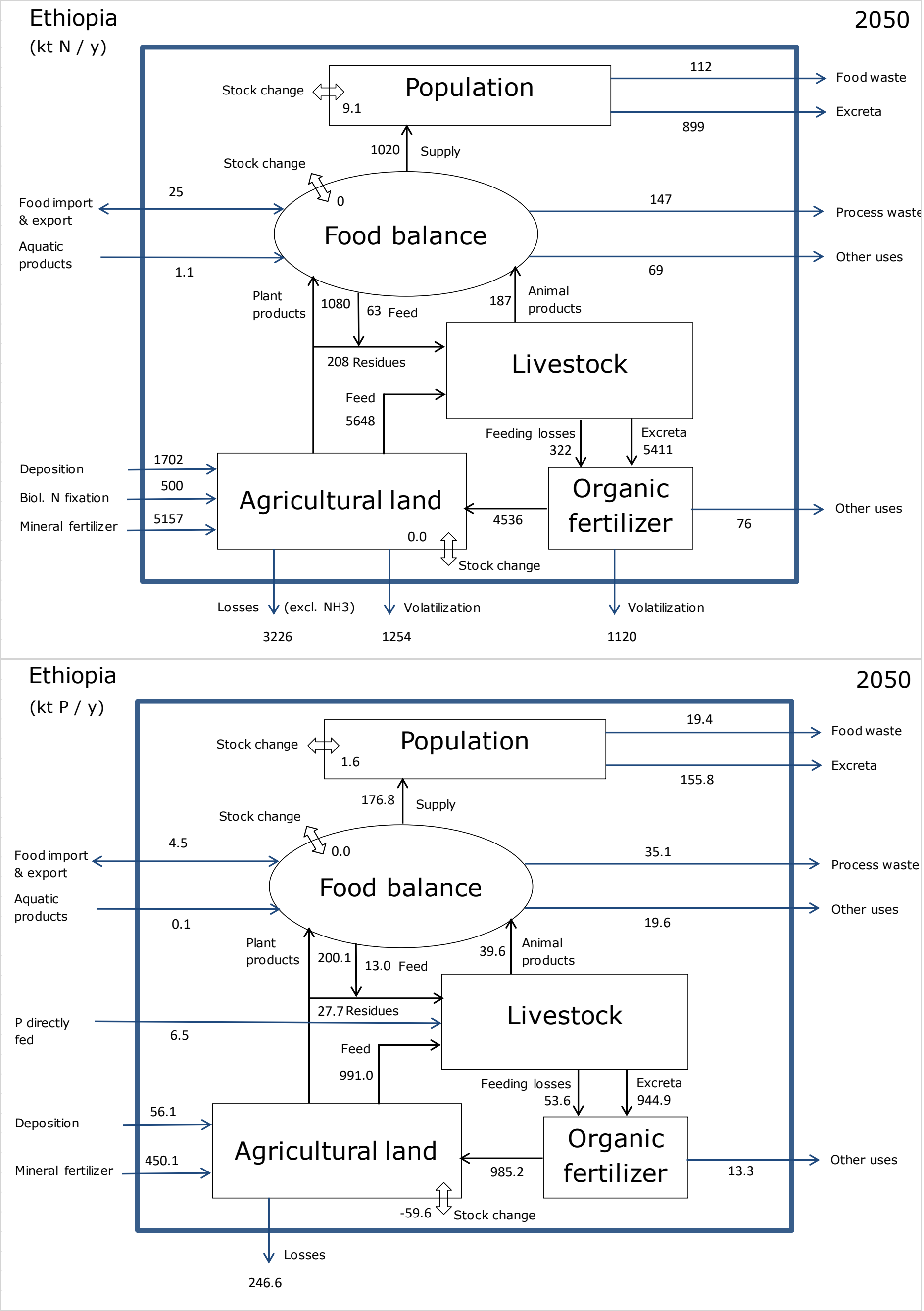


Figure 2.4. National N and P flows of the food system in 2050 from a scenario for Ethiopia. See also Figure 2.3 for more explanation.

Above insights come from a first analysis with BIOSPACS. At many "places" improvements can be made in the model to reduce uncertainties, for which more study and discussion with experts from Ethiopia is needed. After such improvements, a second run can be made and its results can be discussed with stakeholders. These new results may serve as "Food for Thought" and as input for other "lower scale" models to simulate what is needed to achieve the target of Zero Hunger in 2050, such as where to produce what, how much is possible at different locations, possible effects of climate change on productivity and how to mitigate/adapt, role of irrigation in crop production, etc. This can be an iterative process: if the targeted production of specific crops cannot be met, changes in e.g. human diet or net food imports can be analyzed with BIOSPACS to yield adjusted estimates of how much is required for achieving Zero Hunger.

3. Climate change

3.1 Introduction

Ethiopia is one of the most vulnerable countries in the world to imminent changes in climate (BZ, 2018). The country covers approximately 1.2 million square kilometres and is located in the Horn of Africa. It has around 102 million inhabitants, with a population growth rate of 2.8% (CIA, 2017). This rapid population growth sets high demands to Ethiopia's food production system and on its natural resources. With an economy based largely on rainfed agriculture in combination with widespread poverty, sparsely available health services, inadequate road infrastructure, and weak institutions, the welfare of the Ethiopian population is highly exposed to the devastating effects that climate change can have (World Bank, 2011). In this report we describe the current climate of the country, the projected climate changes, and the effects that these changes could have across different sectors and scales.

3.2 Country Overview

Ethiopia has a highly variable tropical climate, with temperate regions in the highlands and desert-like conditions in some of the lowlands (see Figure 3.1). Temperatures in the Ethiopian highlands range between 15 to 20°C and in the lowlands between 25 and 30°C. Rainfall is distributed differently throughout the year in different areas. Across most of the country there are two main rainy seasons: Belg, from January to May, and Kremt, from June to October (see Figure 3.2). In the West and North-West these seasons are barely pronounced and rainfall is therefore unimodal (see Figure 3, on the left). To the East and South the seasons are more pronounced. In the South-East the climate is drier and has two short rainy seasons: Gu (April and May) and Deyr (October and November). As agriculture in Ethiopia is highly dependent on rainfall (EPCC, 2015), the dominant type of agriculture in an area is highly linked to the rainfall pattern. The more rainy West and North-West areas are dedicated to cropping, while the more arid South and South-East is dedicated to (extensive) pastoral systems (USAID, 2010) (Figure 3, on the right). The main crops that are produced are teff, maize, and wheat (Admassu, Getinet, & Thomas, 2012), and most of the ruminant livestock kept are cattle, shoats (sheep and goats), and camels (USAID, 2010).

Despite the seasonality explained above, the Ethiopian climate is prone to extreme weather events. Rainfall is highly erratic and often falls in storms as a result of the varied topography, leading to flash floods in the highlands and large-scale river floods in the lowlands (GFDRR, 2019). Droughts are also a recurrent hazard, which occur due to the influence of El Niño Southern Oscillation (ENSO or El Niño) (Ethiopia, 2019). Historically, therefore, Ethiopia has been struggling with both floods and droughts at great human and economic cost (GFDRR, 2019).

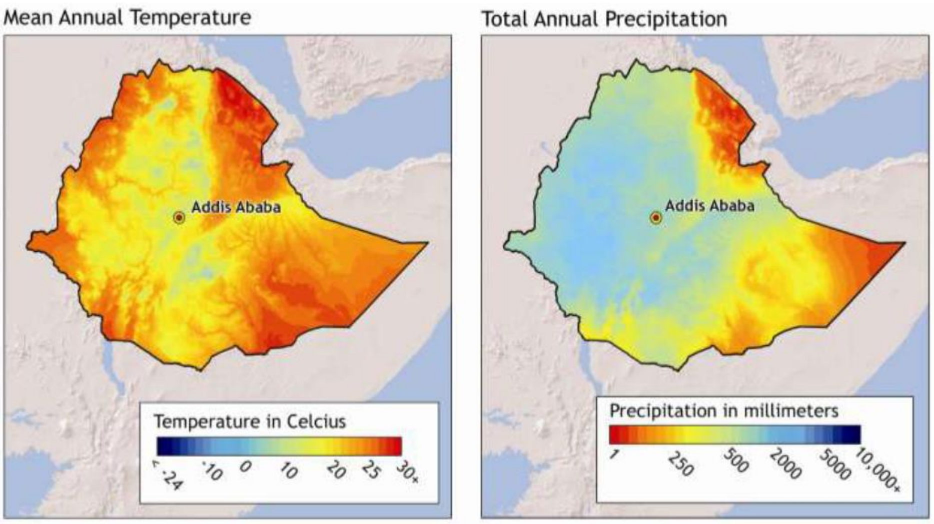


Figure 3.1. Mean temperature and annual precipitation across Ethiopia (World Bank, 2011).

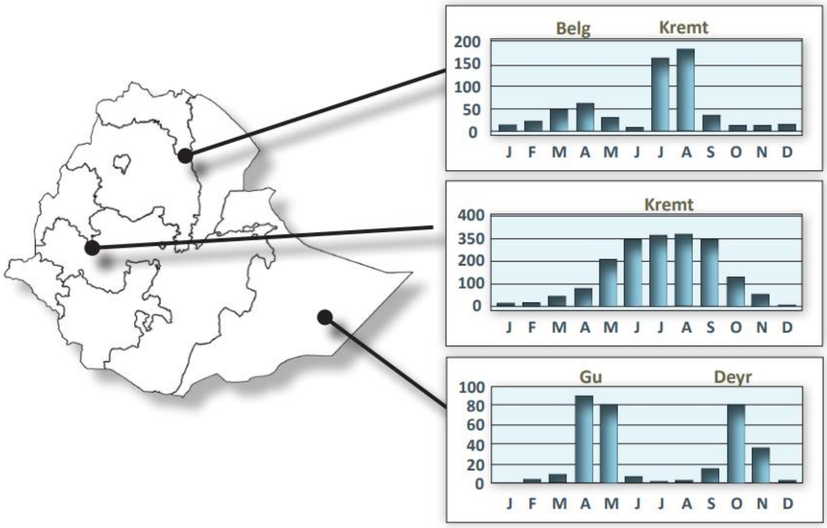


Figure 3.2. Different rainfall patterns across Ethiopia (USAID, 2010).

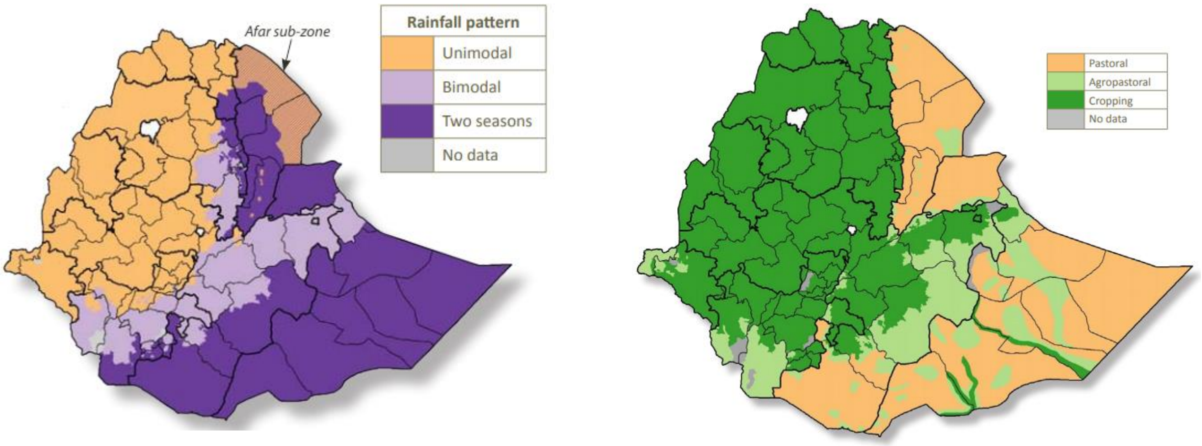


Figure 3.3. Left: rainfall patterns across Ethiopia. Unimodal areas (khaki) have one rainy season with one single peak in rainfall. Bimodal areas (light purple) have one rainy season, but within this season there are two peaks of rainfall. Areas with two seasons (dark purple) have two distinctive rainy seasons with a dry season in between. Right: Cropping (dark green), agro-pastoral (light green), and pastoral (khaki) areas of Ethiopia (USAID, 2010).

3.3 Projected Changes in Climate

Even though Ethiopia is one of the world's lowest emitters of greenhouse gasses per capita, it is one of the countries which is expected to be most strongly impacted by global climate change, and is in fact experiencing its effects already (BZ, 2018). Ethiopia is the 22nd most vulnerable country to climate change, and the 31st least ready country (out of 181 countries in the ND-GAIN index[2]), which means that it is highly vulnerable yet largely unprepared to address the effects of climate change (BZ, 2018). In this section, we describe the current trends in the Ethiopian climate and the projected changes for the future.

3.3.1 Increase in Temperature

For the past 40 to 50 years, temperatures in Ethiopia have been rising with 0.20 to 0.28 °C per decade (Eshetu et al., 2014). Projections for the future of different Global Climate Models (GCMs) used by the International Panel on Climate Change (IPCC) agree that the temperatures in Ethiopia will continue rising (World Bank, 2019). Given the high GHG concentration Representative Concentration Pathway 8.5 (RCP[3] 8.5), the projections agree on a temperature increase of around 1°C by 2030, 2°C by 2050, and 3°C by 2080 (compared to 1986-2005). The low GHG concentration RCP 2.6 leads to predictions of an increase in temperature of around 1°C by 2080. Figure 3.4 shows the predictions for 2040 to 2059 of the ensemble of all GCMs combined, and of two individual GCMs CSIRO_MK3_6_0[4] and MIROC5[5], which are shown as examples. The figures show that there is little difference between the predictions of the separate models and the ensemble.

3.3.2 Changes in Rainfall

Long term trends in rainfall are difficult to detect and to predict for Ethiopia due to its natural variability. Although precipitation has remained relatively constant over the past 5 decades when averaged on a national level, local conditions can be extremely divergent (Keller, 2009). Rainfall in Ethiopia is very complicated to model, as it is influenced by its irregular topography in combination with the movements of the Inter-Tropical Convergence Zone, and modulated by multiple large scale circulations systems[6] and climate modes[7] (Li et al., 2016). As a result, projections of different GCMs do not agree regarding future developments of rainfall across Ethiopia.

The ensemble of GCMs of the IPCC predicts that mean annual rainfall will increase by 58 mm in 2050 (given RCP 8.5). This is also reflected in the ensemble projections of monthly precipitation in Figure 3.5 (first column), which shows an increase in rainfall across the whole country. However, projections of the CSIRO_MK3_6_0 and MIROC5 models predict very different changes in rainfall patterns. Whereas the CSIRO model predicts *decreasing* rainfall in the North (green) and an *increase* in the South (blue), the MIROC5 model predicts the exact opposite, with *increases* in the North (blue) and *decreases* in the south (green). A study using only Regional (high resolution) Climate Models (RCMs) as opposed to Global Climate Models (GCMs) predicts increases in Kremt rainfall in some of the Northern areas and decreases in much of the South (Figure 3.6) (Li et al., 2016). Overall, it is therefore difficult to make predictions on the regional changes in rainfall amount.

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[2] The ND-GAIN Country Index summarizes a country's vulnerability to climate change in combination with its readiness to improve resilience (ND-GAIN, 2019).

[3] A Representative Concentration Pathway (RCP) is a greenhouse gas concentration (not emissions) trajectory adopted by the IPCC for its fifth Assessment Report (AR5) in 2014. It supersedes Special Report on Emissions Scenarios (SRES) projections published in 2000 (World Bank, 2019).

[4] Model developed by CSIRO (Commonwealth Scientific and Industrial Research Organization) in collaboration with the Queensland Climate Change Centre of Excellence (World Bank, 2019)

[5] Model developed by Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology (World Bank, 2019)

[6] Large scale circulation systems involved are the Tropical Easterly Jet (TEJ), the East African Low-Level Jet (EALLJ), and the Azores High/North Atlantic Subtropical High (NASH) (Li, Li, Ballard, Sun, & Jeuland, 2016)

[7] For example, El Nino Southern Oscillation (ENSO) affects the position of the TEJ, the Indian Ocean Dipole and Mediterranean Ocean sea surface temperatures affect EALLJ dynamics, and sea surface temperature anomalies over the North Atlantic can influence the variability of the NASH (Li et al., 2016)

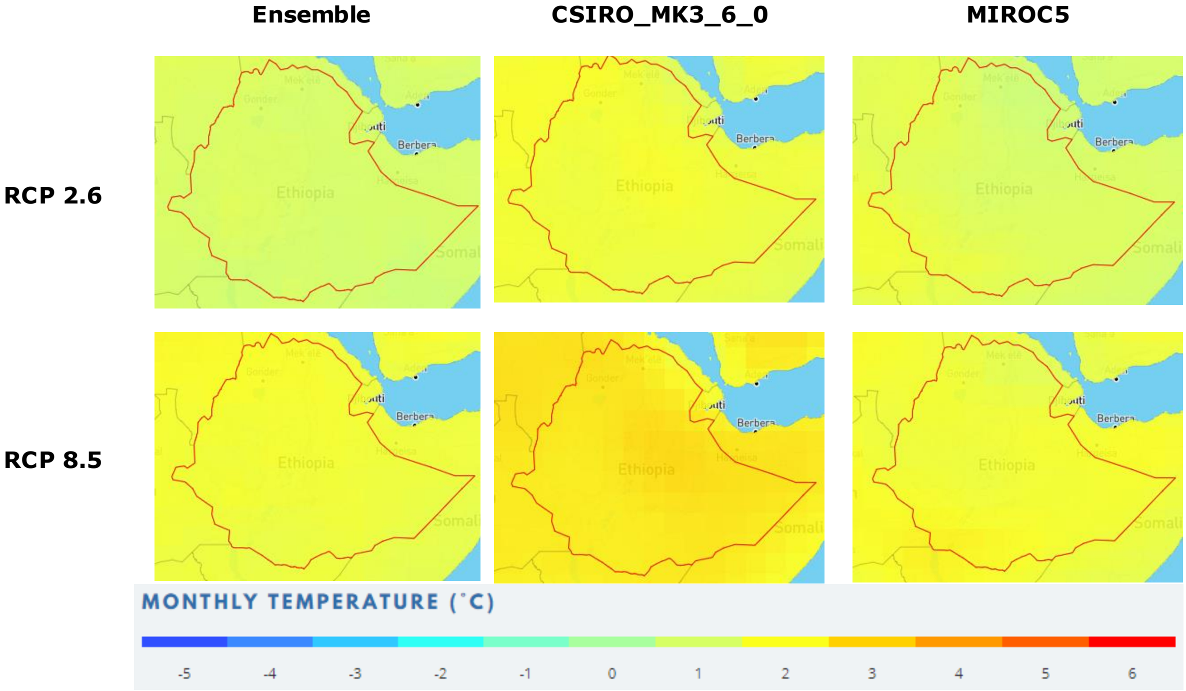

Figure 3.4. Projected changes in average monthly temperature in Ethiopia for 2040-2059 with respect to 1986-2005, given RCP 2.6 (low GHG concentration) and RCP 8.5 (high GHG concentration) of the IPCC model ensemble, the model CSIRO_MK3_6_0, and the model MIROC5 (World Bank, 2019).

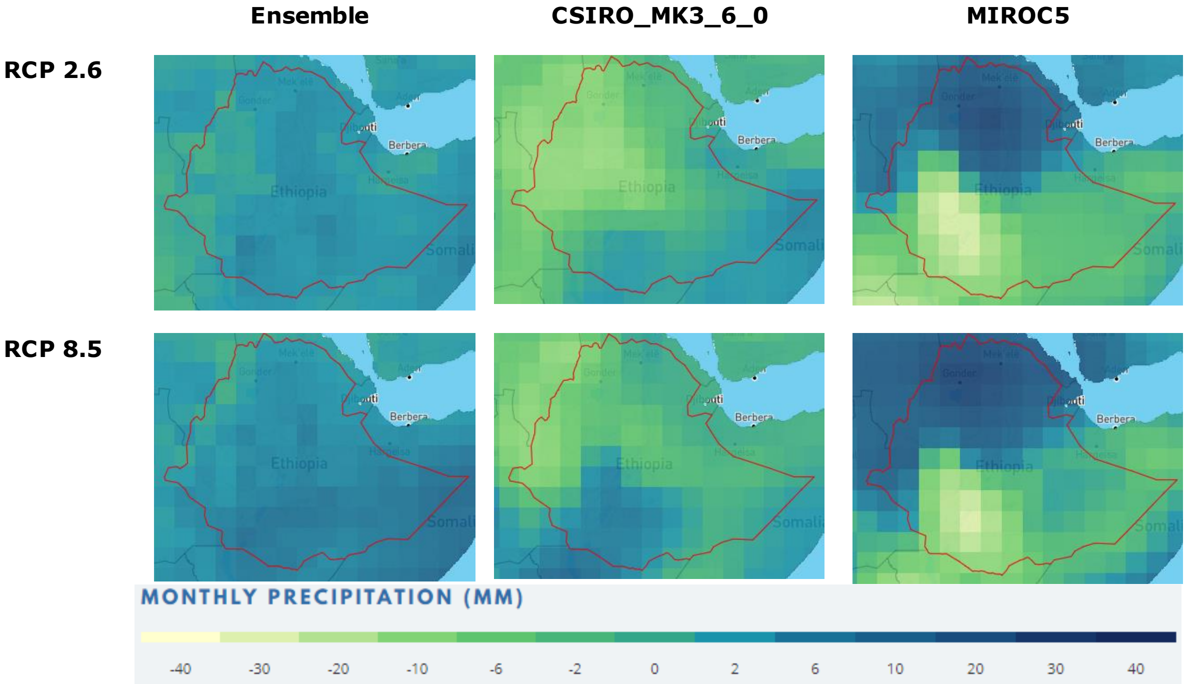

Figure 3.5. Projected changes in monthly precipitation in Ethiopia for 2040-2059 with respect to 1986-2005, given RCP 2.6 (low GHG concentration) and RCP 8.5 (high GHG concentration) of the IPCC model ensemble, the model CSIRO_MK3_6_0, and the model MIROC5 (World Bank, 2019).

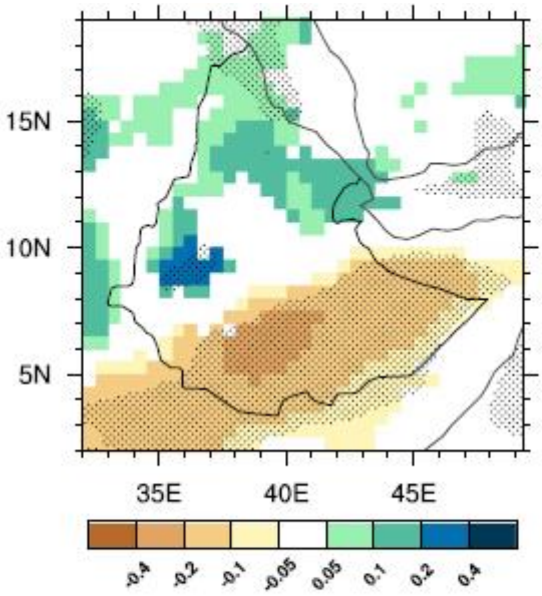

Figure 3.6. Changes in Kremt precipitation (mm/day) in 2050-2099 compared to 1950-1999 projected by the regional climate models (horizontal resolution <°2) under RCP 4.5. Only the grid cells where more than 70% of the models agree on the sign of the precipitation change are shown. In the dotted areas the precipitation change is significant at 90% confidence level (Li et al., 2016).

3.3.3 More Frequent Extreme Events

In the past decades, the incidence of droughts in Ethiopia has increased (USAID, 2016). Between 1900 and 2009, twelve extreme droughts were recorded (You & Ringler, 2010), of which seven occurred since 1980 (World Bank, 2010). The frequency and severity of flooding also appears to have increased (Aragie, 2013; Eshetu et al., 2014). Projections agree on the fact that this trend will likely continue in the future. According to the IPCC GCM projections, the proportion of total rainfall occurring in heavy events is expected to increase up to 18% (World Bank, 2019). This increasingly uneven distribution of rainfall could lead to an even higher incidence and intensity of floods and droughts.

3.4 Consequences of Climate Change

As stated above, Ethiopia is extremely vulnerable to the effects of climate change. With an economy based largely on rainfed agriculture (CIA, 2017), and electricity production based on hydropower (UKAID, 2017), changes in climate can not only lead to large scale food deficits but also resonate through the economy. In this section, we analyse the effects that the changes in climate described above can have at different scales, from crop field to national level, and across different sectors.

3.4.1 Scale 1: Field Level

Ethiopian agriculture consists mostly of small-scale subsistence rainfed farms. The main crops produced are teff, maize, wheat, sorghum, enset (banana), and coffee as a cash crop (BZ, 2018). In the South and South-East the main agricultural activity is extensive livestock rearing of cattle, shoats, and camels (USAID, 2010). Some of the possible effects of climate change are explained below. As changes in rainfall can vary geographically and in time, both increases and decreases in rainfall are discussed.

Change: Increased CO_2 concentration
Effects:

- An increase in CO_2 concentration can lead to increased yields, especially in C3 species such as wheat and enset. The yields are increased by increasing photosynthesis rates, leaf area index, and accumulation of biomass, and decreasing stomatal conductance and thereby loss of water through transpiration (Chauhan, Mahajan, Randhawa, Singh, & Kang, 2014).
- A higher CO_2 concentration can also have a negative impact on yield by decreasing the carbon:nitrogen ratio (Chauhan et al., 2014)

Change: Increased temperature
Effects:

- Increase in crop respiration rates (Chauhan et al., 2014; Ryan, 1991)
- Increase in rates of water loss by increasing evapotranspiration (Chauhan et al., 2014). Setegn et al. (2011) estimates that in the Northern highlands the actual evapotranspiration will increase by 7-16% by 2045-2065.
- Increased nutrient availability due to higher rates of organic matter decomposition and nutrient mineralization (Pregitzer & King, 2005).
- If temperatures increase past a certain optimum level, this can lead to decreased nutrient uptake (which is likely a consequence of decreased root growth) (see Figure 1 in Annex II) (Reich, 2015) (Pregitzer & King, 2005)
- Decrease in the Length of the Growing Period (LGP) due to accelerated growth and development of the plant, resulting in early maturity. As a consequence, the crop has less time for vegetative growth and for grain filling, leading to small sized and shrivelled harvests. (EPCC, 2015; Kassie et al., 2014). Kassie et al. (2014) estimates a reduction of maize growth duration of 14 to 33 days by 2050 in the Central Rift Valley of Ethiopia.
- Changes in composition of pastures (for livestock), such as changes in the ratio of grasses to legumes

Change: Decrease in rainfall
Effects:

- Decrease in groundwater recharge and availability (EPCC, 2015)
- Decrease in water available for irrigation from rivers and streams (EPCC, 2015)
- Decrease in uptake of mobile nutrients such as nitrate, as these depend on the mass flow of water for uptake (Reich, 2015).
- Water deficit conditions for the crops (EPCC, 2015)

Change: Increase in rainfall
Effects:

- Increased groundwater availability
- Increased incidence of flooding, leading to direct damage to the crops and livestock (EPCC, 2015)
- Increased incidence of waterlogging, leading to root damage of the crops and emissions of the greenhouse gas N_2O (Bakker, 2019; EPCC, 2015)
- Higher rates of erosion and run-off, causing declines in soil fertility (EPCC, 2015)
- Increase in nutrient leaching (EPCC, 2015)
- Lower incidence of drought events

Crop Productivity (Yields)

The effects outlined above of climate change on crop field conditions can have both positive and negative impacts on crop yields. For example, whereas increased water availability in current water scarce areas might lead to yield *increases*, increases in temperature in already dry and hot areas might lead to yield *decreases*. Figure 3.7 shows a geographic overview of predicted yield changes of maize, wheat, and sorghum in 2050 compared to 2000 (Admassu et al., 2012). Yields of maize are expected to increase before 2050 (Admassu et al., 2012; Kelbore, 2012), but are expected to decline afterwards due to continued temperature increases (Kelbore, 2012). For wheat and teff, yields are expected to decline (Kelbore, 2012; Mohammed, 2009). For an overview of the expected impacts per crop, see Table 1 in Annex II. In general, studies seem to agree that, despite a possible initial increase in productivity of some crops before 2050, overall yields of most crops will tend to decrease (EPCC, 2015).

Livestock Productivity

For areas with decreased rainfall (or higher drought incidence), livestock rearing will become increasingly difficult due to the scarcity of feed and water. Most ruminant cattle are fed either through extensive grazing on communal grassland or with crop residues. As climate extremes lead to reduced grazing land productivity and to losses in crop yields (and therefore in crop residues), feed will become increasingly scarce (EPCC, 2015). Changes in pasture composition, such as a shift in the ratio of legumes to grasses, might also affect the quality of the feed. Moreover, the increased incidence of droughts would also reduce the availability of water for livestock. The reduced availability of quality feed and water leads to weakening of the animals and to decreases (or stopping) of milk production. Moreover, the value of the livestock decreases as their body conditions worsens (Tibebu, 2013). Overall, therefore, livestock productivity and value is likely to decline in areas that will become more arid.

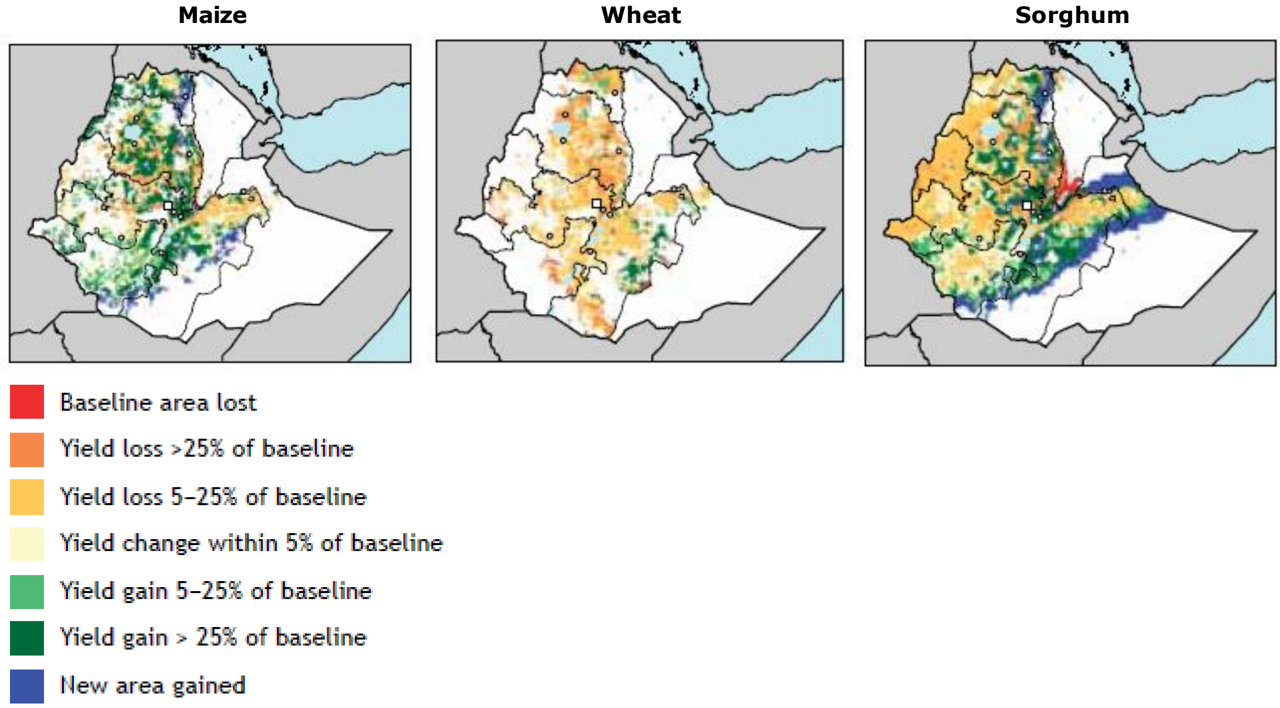

Figure 3.7. Yield change predictions of maize, wheat, and sorghum in 2050 compared to 2000, given greenhouse emission scenario A1B[8], using the Decision Support Software for Agrotechnology (DSSAT) model to compute crop yields based on climate predictions of the model MIROC 3.2 (see Figure 11, in Annex II). Note that the MIROC 3.2 predictions differ from the MIROC 5 prediction in Figure 3.5 (Admassu et al., 2012).

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[8] Greenhouse gas emission scenario A1B assumes fast economic growth, a population that peaks mid-century, and the development of new and efficient technologies, along with a balanced use of energy sources.

3.4.2 Scale 2: Farm and Household Level

The changes at field level prompted by climate change have an impact on farm productivity and household conditions. Some of these are explained below.

Income

A decrease in crop yields and livestock productivity can have a great impact on farm household incomes. Households that rely on mixed farming systems can to some extent buffer a decrease in income from crops with incomes from livestock, and vice versa. However, the income of households that are heavily reliant on only one of the two (the dark green and dark purple areas in Figure 3.8) are very vulnerable to productivity decreases.

Food security

Changes in productivity can also have an impact on farm household food security. As most production is subsistence farming, a large fraction of the food intake of a household originates from the household's own production (USAID, 2010). Figure 3.9 shows that a large share of households rely for more than 75% on their own crops for their food consumption. Households in pastoralist areas rely on livestock products such as dairy and meat for between 26 and 75% of their calorie intake. If crop and livestock production levels would decrease, this could pose a serious threat to the food security of most rural households.

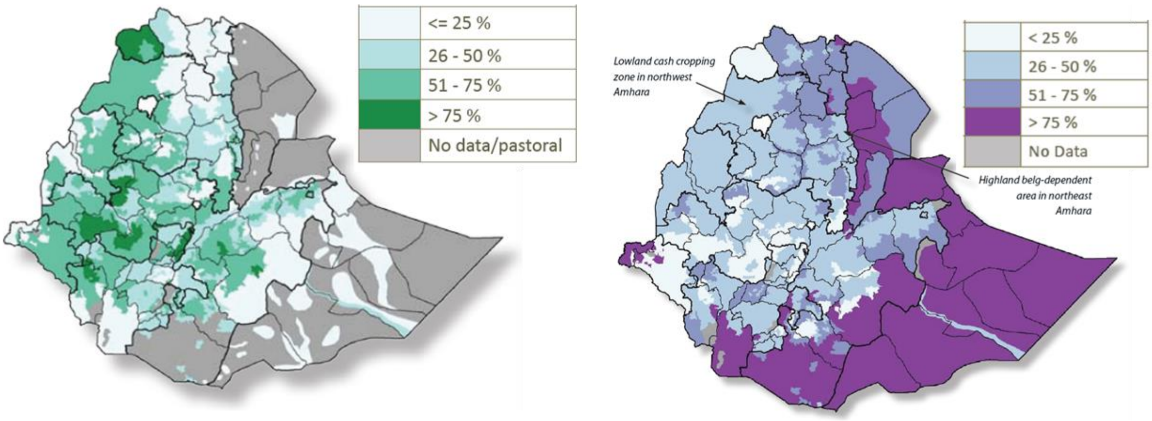

Figure 3.8. Contribution (%) of crops (left) and livestock (right) to total annual household cash income (USAID, 2010).

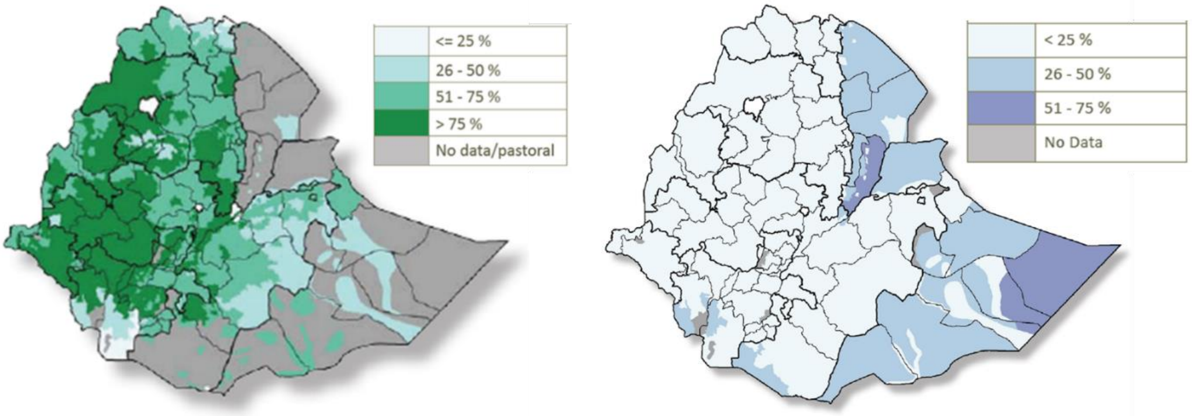

Figure 3.9. Contribution (%) of own crops (left) and livestock (right) to total annual household food intake in kcals (USAID, 2010).

Water security
A decrease in rainfall or an increase in drought incidence could pose a serious threat to the water availability of many households, especially in already arid areas. An increase in temperature in combination with a drought can lead water resources to dry up (Taye, Dyer, Hirpa, & Charles, 2018). As a result, households need to travel increasingly longer distances to obtain water. Women and children normally perform the task of fetching water, and the longer travelling time makes them more vulnerable to abuse. Moreover, the great time requirement of the task often leads to children leaving school (BZ, 2018).

Adaptive capacity
Due to the small farm sizes, households generally lack the financial resources to invest in improved farming methods to adapt to climate change. A decrease in farm income would therefore diminish a household's adaptive capacity even further (Yirgu, Nicol, & Srinivasan, 2013). At the same time, rainfall unpredictability has proven to be a disincentive to invest in agricultural improvements as well (Cipryk, 2009). Moreover, the adverse effects of climate changes on livestock health can become a problem for crop production, as ploughing is done mostly through animal traction. Therefore, as the adverse effects of climate change on a household become greater, it becomes more difficult for that household to adapt, leading to greater adverse effects in the next season.

3.4.3 Scale 3: Village or District Level

Suitable Production Areas
As climatic conditions change, the suitable areas for some crops might change given their optimal thermal zone and water requirements (Mekasha, Nigatu, Tesfaye, & Duncan, 2013). As there is no general consent on the rainfall predictions, there is also no clear prediction on the geographical shifts in production areas that might occur. For example, whereas the EPCC (2015) suggests a decrease in area of 18, 11, and 37% for maize, teff, and barley by 2050 (compared to 2013), predictions of Admassu et al. (2012) in Figure 3.7 show, for maize and sorghum, more area gained than lost. The USGS (2012) forecasts that, due to a decrease in rainfall, the total area suitable for cropping and for pastoralism will decrease by 16% compared to 2009 (Figure 3.10). Although predictions of different studies differ, most literature seems to agree that, for most crops, cropping area will diminish. It is expected that C3 species will be the most strongly affected, which are adapted to relatively cool temperatures (EPCC, 2015). These crops are currently grown on small areas in the highlands and will likely have to relocate upward along the altitudinal gradient, thereby reducing the suitable area for these crops. For instance, both wheat and coffee (C3 crops) have been predicted to be greatly affected in terms of cropping area (Davis, Gole, Baena, & Moat, 2012) (Waithaka, Nelson, Thomas, & Kyotalimye, 2013). For an overview of the expected impacts per crop, see Table 1 in Annex II.

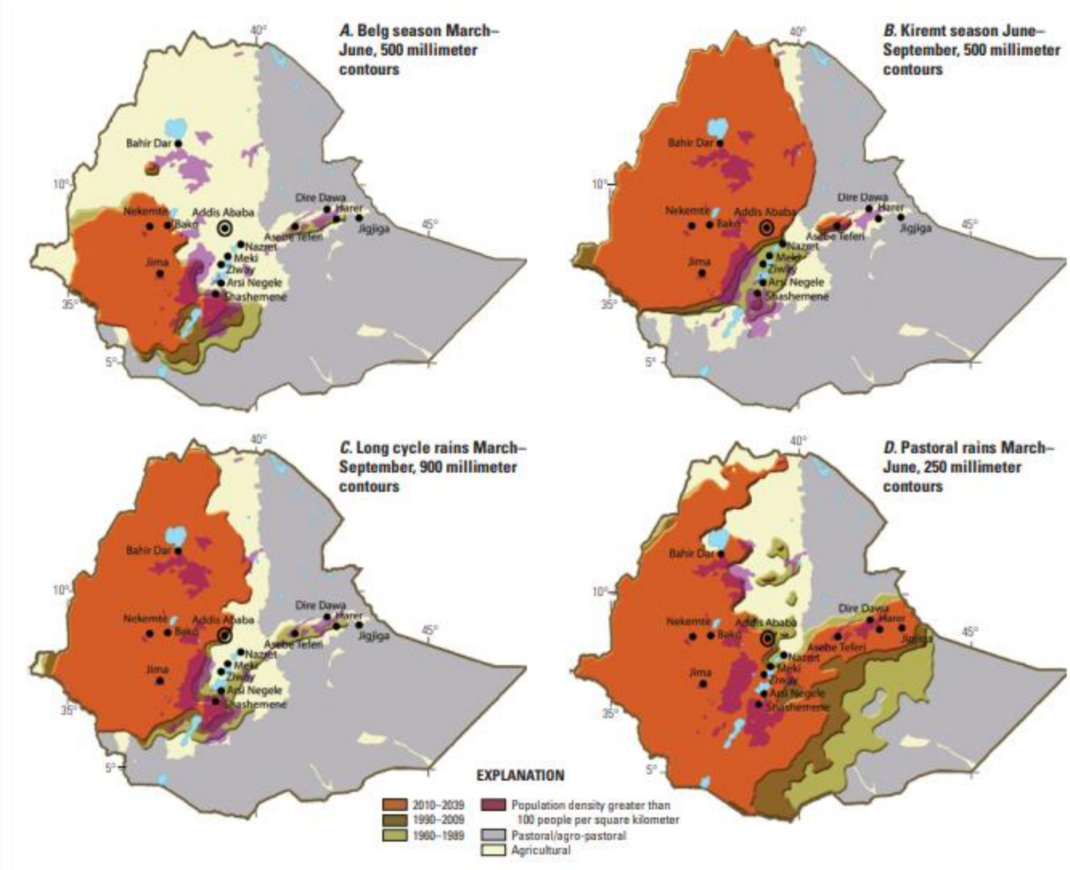

Figure 3.10. Areas suitable for agricultural production given a minimum of 500 mm rainfall per short season (A and B), 900 mm for a long cycle (C) and 250 mm for pastoral activities (D), as measured between 1960 and 1990 (green), 1990 and 2009 (brown) and projected from 2010 to 2039 (orange). Grey areas are traditionally used for pastoral systems and mixed systems, while beige areas are used for cropping systems. Green area is the area that was suitable for cropping between 1960 and 1990 but which has now been lost. The brown area is the area that was suitable between 1990 and 2009 and which is predicted to be lost (USGS, 2012).

Pests and disease incidence areas

Due to the changes in field conditions and seasonal extremes it is possible that the geographical distribution of some pests and vector-borne diseases in both crop and livestock will change. Areas which had thus far been inhospitable to certain insects and diseases due to low temperature and humidity can in the future become susceptible to them (EPCC, 2015). For example, the amount of land infested by the tsetse fly in 1992 was estimated to be between 135,000 and 180,000 km2, which increased to 220,000 km2 in 2004, likely due to increasing temperatures (NTTICC, 2004; Slingenbergh, 1992) according to EPCC (2015). The spread of wheat rust, a fungal crop disease, appears to be affected by ENSO (Scherm & Yang, 1995). As a consequence of these geographic changes, the pest and disease pressure on crop and livestock production might increase, leading to further decreases in productivity.

3.4.4 Scale 4: National Level

Food security

Due to the negative effects of climate change on agricultural productivity, combined with a possibly greater spread of pathogens and a decreasing production area, food security on a national level is likely to become increasingly insecure. This can lead to hunger and poverty, which in turn reduce the adaptive capacity of the population to climate change. Densely populated areas which are reliant on food surpluses from the rural areas are especially vulnerable (USGS, 2012).

Water security

As the incidence of droughts increases and temperature (and consequently evapotranspiration) increases, the water availability throughout the country will likely become more scarce and less stable. Water resources are competed for by household consumption, industrial consumption, irrigation, hydropower generation, and transboundary use (World Bank, 2010). As water becomes more scarce this can lead to shortages of water for the different sectors, and therefore to humanitarian, economic, and political problems.

Health

Climate change can have many different impacts on population health (Simane et al., 2016):

- The food scarcity prompted by climate change can lead to more under- and malnutrition
- The incidence of vector-borne and zoonotic diseases might increase due to the shift in their geographic spread (e.g. malaria and bilharzias)
- The incidence of water borne diseases such as diarrhea might increase due to the higher temperatures, as these are generally temperature dependent.
- Meningitis incidence can increase due to the higher dust levels in areas that will become more arid
- Increasing temperatures can lead to higher death rates amongst elderly people (WHO, 2015).

Energy

The current energy consumption in Ethiopia is dominated by the use of biofuels such as wood and charcoal, which account for approximately 90% of total energy profile (UKAID, 2017). Around 8.5% of the energy profile consists of fossil fuels, and around 1.5% of electricity. The biofuels are used for household cooking, which consists of 91% of Ethiopia's energy demand. Electricity is generally used only for lighting, in urban households, and for industrial processes. However, the yearly electricity demand growth is around 25%, and it is likely that this demand will continue to grow as population increases and wood fuel becomes more scarce. As the Ethiopian energy sector is completely reliant on hydropower, increasing rainfall variability as a result of climate change might become an obstacle to meet the growing demand for electricity. As water flows in some river basins might be diminished due to prolonged droughts and irregular rainfall, maintaining reliability of the electricity generation will become increasingly difficult.

Infrastructure

A possible effect of the predicted increase in flooding incidence and magnitude is greater damage of the country's infrastructure (World Bank, 2010). The roads specifically are likely to be affected, which are of great importance to the country's transport system. The increase in rainfall and flooding increases runoff and damages the structures.

Economy

As explained above, the main economic sectors likely to be affected by climate change are the energy sector, infrastructure, and agriculture (World Bank, 2010). The damage the energy and infrastructure are likely to be of great impact to the country's industry. Agriculture is a major part of the Ethiopian economy, contributing 32% of the GDP and employing 72% of the population (CIA, 2017). It also contributes 90% of national exports and is the main source of inputs for the country's industrial sector. Decreases in agricultural production through reduced yields, a shrinking production area, and increased pathogen spread, can therefore lead to major economic damage to the country. Eshetu et al. (2014) estimated that climate change will affect Ethiopia's GDP growth by 0.5 to 2.5% per year in the near future.

Conflicts
Increasing population density, combined with scarcity of food and water as well as a declining economy is a combination of factors that can easily lead to internal conflicts (Funk et al., 2012). This can in turn further damage the economy and food security. Moreover, the increasing water scarcity can lead to external conflicts over the allocation of water.

3.4.5 Overview

An overview of the consequences across the scales is provided in Table 3.1.

Table 3.1. Effects of current and predicted changes in climate in Ethiopia at field, household, district, and national level.

Change in climate	**Field level**	**Farm/Household level**	**Village/District level**	**National level**
Higher temperatures	• Heat stress for crop • Higher evapotranspiration, leading to higher water requirement • Higher pest and disease incidence for crops • Higher disease incidence for livestock • Change in pasture composition	• More frequent crop failures • Lower yields • Decreasing livestock health, value, and productivity • Decrease in food security • Decrease in income • Decrease in water security	• Food shortages • Loss of area suitable for cropping • Depletion of water resources • Shifts in pathogen spread	• Increasing conflicts over food and water (due to scarcity) • Decrease in GDP (due to decrease in production levels • Malnutrition (due to lower nutritional value of food and food shortage) • Higher disease pressure • Increased need for food imports • Unreliability of hydropower electricity (due to variable rainfall)
(local) decreasing rainfall, shorter rainy seasons, and more frequent droughts	• Decrease in groundwater recharge • Decrease in nutrient uptake • Water stress for crops			
Flooding	• Waterlogging, leading to root damage and N2O emission • Soil erosion			

3.5 Conclusions

Climate change is a highly pressing issue for Ethiopia. Models agree that temperature is likely to increase across the country, but disagree on the geographic predictions of changes in rainfall. There is agreement though, that the rainfall variability will increase. As a consequence, Ethiopia must prepare for both climate extremes: drought and flooding.

As a consequence of the more extreme climatic conditions, farm productivity levels are likely to decrease in some areas, and water will likely (periodically) become more scarce. It is possible that the suitability of some areas for the crops might change. Moreover, the geographic spread of human, crop, and livestock pathogens is also likely to be altered by climate change. Such a shift could put further pressure on agricultural productivity, and pose a threat to general health levels. An overall decrease in yields and production area could lead to serious food shortages and poverty countrywide. Water scarcity could also lead to conflicts in water distribution between households, irrigation, industry, hydroelectric energy, and transboundary use. The damage to the agricultural sector, road infrastructure, and reliability of hydropower could lead to a serious economic decline for Ethiopia.

4. Water Balance

4.1 Background

Ethiopia is a landlocked country in North-Eastern Africa bound by a number of countries: Eritrea and Djibouti to the North, Sudan and South Sudan to the west, Somalia to the east, and Kenya to the south. It is the second most populous country in Africa, next to Nigeria, with a steadily increasing population (Figure 4.1). Reports from World Bank and FAO estimated the population at 105 million people, in 2017. Although Ethiopia has the largest economy (in terms of gross domestic products) in East Africa, it actually has a low average GDP per capita at 586 US $ per year (equivalent to 1.60 US $ per day): its low per capita GDP is mainly a result of the high population size of Ethiopia (FAO, 2016), making it one of the poorest countries in the world. Globally, Ethiopia also has one of the least developed infrastructures for drinking water supply and sanitation: about 48% of the population has access to clean water, and only 11% has good sanitation (The Water Project, 2019).

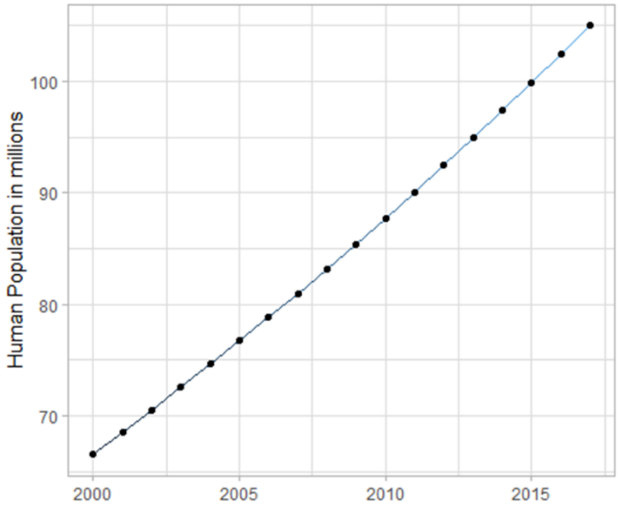

Figure 4.1: Population growth of Ethiopia in the 2000s (Source: World Bank)

The level of urbanization in Ethiopia, i.e. % of total population living in urban areas, increased from 14% in 1995 to 20% in 2017 (data from FAOSTAT). Projections for 2050, estimate a population of 190 million and 40% of that population possibly living in urban areas (World Bank, 2006). The capital Addis Ababa is 12 times larger than the next city and provides a fifth (1/5) of the country's overall GDP and 52% of the modern sector value (World Bank, 2006). Majority of the population living in rural areas is involved in low intensity agricultural productivity, growing only one crop per year (Awulachew et al., 2007). This is not sufficient to feed the population, resulting in about 32% of the population being undernourished (FAO, 2016). Although food aid is currently available, this is not sufficient, neither is it sustainable in the near future. A water crisis also looms overhead: the impact of the growing population and increased occurrence of droughts, deduces that there is an immediate need for the establishment of strategies for efficient water use. The SDG water indicator 6.4.2 of the country is 32% and this indicator specifies the current water withdrawal intensity of the country, therefore providing information on water availability (FAO, 2016). At 32%, Ethiopia is currently not water stressed and still has available water resources that can be utilised efficiently.

4.2 Water resources

Ethiopia has a surface area of approximately 110 million hectares consisting of 35.6 million hectares for current agricultural use (including cropland and pastures), 12.3 million of forests, water bodies cover about 10.4 million hectares, while approximately 52 million hectares is described as other land: possibly serving as woodland (21 million hectares), environmentally protected areas (26 million hectares) and 1.4 to 1.8 million hectares make up the wetlands (EPA, 2003; IUCN, 2010; FAO, 2016). Although the country has well-endowed water resources, it still suffers from high hydrological variability caused by environmental and socio-economic influences (World Bank, 2006). Ethiopia has 12 river basins that form four national drainage systems (Figure 4.2A), with approximately 122 billion m^3 of water (circa 13% of total precipitation in the country) available per year as surface water (Figure 4.2B). The drainage system "Rift valley" links to the river Omo-Gibe, whereas "Shebelli Juba" drains the south-eastern mountains, flowing towards Somalia and the Indian Ocean (FAO, 2016). Water in the North-East drainage system is only available as ground water (Figure 4.2B).

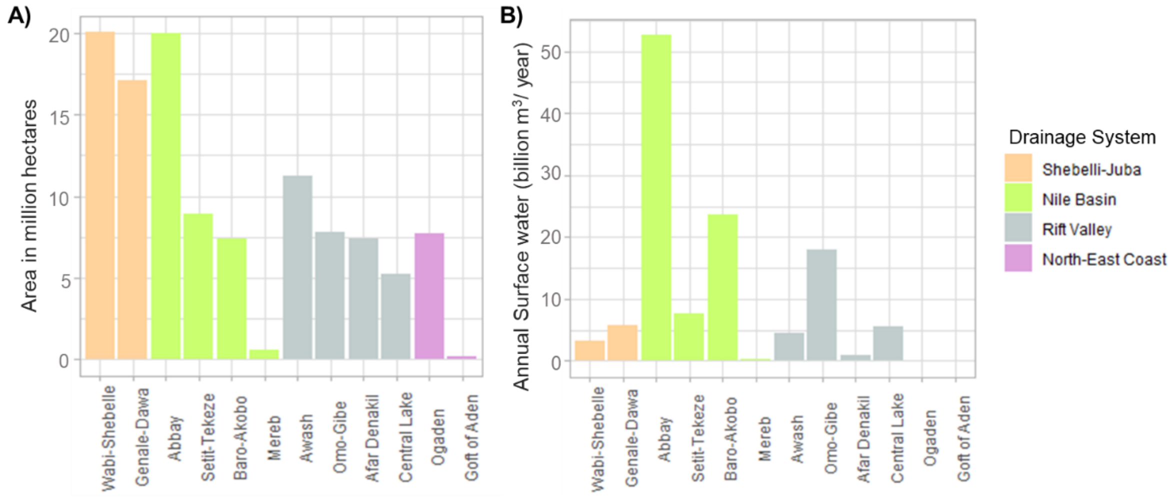

Figure 4.2: The water area (A) and internal surface water flows (B) of Ethiopia's 12 river basins. (Source: FAO, 2016).

Ethiopia has 11 fresh water lakes, 9 salt water lakes and 4 crater lakes (Table 4.1). Wetlands in the country are mainly located in the same areas as the lakes. All of the larger lakes are found in the Rift valley basin, except Lake Tana, and most are becoming increasingly saline due to diminishing surface water outlets and intensive irrigation (FAO, 2016). Although Ethiopia has huge potentials for renewable hydropower, wind and solar energy, electricity consumption is very low (only 5% of total energy consumption; World Bank, 2006). Presently, at least 17 dams run in Ethiopia, with a majority of them providing circa 90% of total electricity for the National grid (Table 4.1), which is only 2% of the country's hydroelectric potential. Most lakes are rich in different fish species but some lakes are rich sources of minerals (Table 4.1).

Table 4.1: Rivers, Lakes and Wetlands in Ethiopia. A brief description of the water body, total surface area, the metres above sea level, location and function of the water bodies (World Bank, 2006; Awulachew et al., 2007; FAO, 2016) *are indicated in the table. The river/ lake functions are listed in order of priority: D= drinking, F=flood management, Fi=fishing, H= hydropower, HB= habitat for birds, I=irrigation, L=livestock, M=mineral deposit, T=tourism, S=siltation sink*

#	**Water Sources**	**Description**	**Land surface area (km²)**	**Elevation MASL (m)**	**Location**	**Main Functions**
1	Abaya	Fresh water lake	1 140	1 285	Rift Valley	Fi
2	Abbe	Salt water lake	320	243	Afar Region	M
3	Abiyata	Salt water lake	180	1 573	Rift Valley	M
4	Afambo	Fresh water lake	26	339	Afar Region	I, L
5	Afrera	Salt water lake	100	-102	Afar Region	M
6	Ardibo	Crater lake	14.9	2 1 36	Northeast	Fi
7	Ashenge	Salt water lake	20	2 409	Tigray Region	HB
8	Awassa	Fresh water lake	92	1686	Rift Valley	Fi
9	Bario	-	22.16	339	Afar Region	-
10	Beseke	Salt water lake	30	950	Rift Valley	I
11	Chamo	Fresh water lake	317	1 110	Rift Valley	Fi
12	Chew Bahir	Salt water lake	308	570	Rift Valley	HB
13	Gummare	Fresh water lake	63	-	Afar region	-
14	Haik	Fresh water lake	22.5	2 030	Amhara Region	-
15	Haramaya	Fresh water lake	-	2 010	Rift Valley	I,
16	Kadabassa	-	-	562	Afar Region	-
17	Karum	Salt water lake	50	-120	Afar Region	M
18	Koka	Reservoir	236	1 595	Rift Valley	H, Fi
19	Langamo	Fresh water lake	230	1 585	Afar region	T
20	Shala	Crater lake	370	1 558	Rift Valley	HB
21	Tana	Fresh water lake	3 000	1 788	Bahir Dar	Fi, HB
22	Turkana	Salt water lake	6 750	361	Rift Valley	H, Fi
23	Zengena	Crater lake	1	2 500	Bahir Dar	M
24	Ziway	Fresh water lake	440	1 636	Rift Valley	Fi
1	Amerti Neshe	Dam	0.04	38	Nile basin	H, I
2	Chomen Lake	Reservoir	0.65	20	Nile basin	H, D, I
3	Dire	Dam	0.02	-	Afar region	D
4	Genale Dawa III	Dam	2.6	110	Shebelle-Juba	H, F
5	Genale Dawa IV	Dam	0.18	39	Shebelle-Juba	H, I
6	Gidabo	Dam	0.06	21.3	Rift Valley	I, F, Fi
7	Gilgel Gibe I	Dam	0.92	40	Rift Valley	H, F, S
8	Gilgel Gibe III	Dam	14.7	243	Rift Valley	H, F, Fi
9	Grand Ethiopian Renaissance dam	Dam	74	155	Nile basin	H, F, Fi
10	Kessem	Dam	0.5	90	Afar region	I, D
11	Koka Lake	Reservoir	1.9	47	Afar region	H, F, Fi
12	Koysha	Dam	6	179	Rift Valley	H, F
13	Melka Wakena	Dam	0.75	42	Shebelle-Juba	H
14	Neshe	Dam	0.15	38	Nile basin	H, I
15	Rib	Dam	0.23	74	Nile basin	I, F, D
16	Tekeze	Dam	9.3	188	Nile basin	H, F, Fi
17	Tendaho	Dam	1.9	53	Afar region	I, D, F

Majority of the national surface water resources occur in the Rift valley and Nile Basin (Figure 4.2 and Table 4.1). A geographical representation of important rivers and lakes in Ethiopia is displayed in Figure 4.3. These water bodies cover approximately 9.5% of the total surface area of Ethiopia, and are wide spread across the country (Figure 4.3). Most of the rivers are seasonal and only the Nile basin does not face water shortages presently (FAO, 2016).

Figure 4.3: Map of Ethiopia with water distribution and flow of water resources across the nation (Source: World Bank, 2006)

Ethiopia does not receive water from neighbouring countries (either by surface water or groundwater flows), which means that the water flows in the rivers and lakes (Figure 4.3) are fed by the precipitation in Ethiopia. Water loss via evaporation increases during dry seasons, reducing outflow to other countries. During dry periods, water flow originates from springs (FAO, 2016). The topography of Ethiopia greatly influences its water flow: a number of highlands with peaks of between 1500 to 4500 m contribute to the major rivers (World Bank, 2006). Currently, about 80.4% (96.5 billion m^3 per year) of total surface water leaves Ethiopia and flows to its neighbouring countries. Every year, estimations of 64.6, 13, 8.2, 10 and 0.7 billion m^3 leave the country into Sudan, South Sudan, Somalia, Kenya and Eritrea, respectively (Table 4.2).

Table 4.2: Water flow from Ethiopia into neighbouring countries. The volume of surface water, originating rivers, corresponding river basin and destination country (FAO, 2016) *are displayed in the table.*

Total Surface water (billions m³/ year)	**Breakdown**	**River**	**River Basin**	**Destination Country**
64.6	52.6	Abbay	Nile	Sudan
	4.3	Atbara		
	7.6	Setit-Tezeke		
13		Baro, Akobo	Nile	South Sudan
8.2	5.9	Juba	Shebelli-Juba	Somalia
	2.3	Shebelle		
10		Omo River into Lake Turkana	Rift Valley	Kenya
0.7		Mereb	Nile	Eritrea

Rivers in the Nile, Rift Valley and Shebelli-Juba basins are shared between Ethiopia and ten other countries: Burundi, Democratic Republic of Congo, Egypt, Eritrea, Kenya, Rwanda, Somalia, Sudan, Tanzania and Uganda. About 12%, 49% and 46% of the Nile, Rift valley and Shebelli-Juba basins respectively, are within Ethiopia (FAO, 2016). Water in the Nile, Awash and Omo rivers originates from Ethiopian highlands and only river Genale in the Southeast permanently flows into the sea via Somalia (Figure 4.3 and Table 4.2). The northern and central highlands drain westward into the Abbay-Tekeze, a branch of the main Nile known as the Blue Nile, and Baro: another branch of River Nile and also known as the White Nile (Table 4.2). The eastern highlands drain into Awash, which never reaches the sea, but is eventually absorbed into a series of marshes and lakes close to the Djibouti border (Figure 4.3). In the south, the Omo river drains into Lake Turkana and a number of streams flow into the other Rift Valley lakes (Table 4.2). In the southeast, the mountains of Arsi, Bale, and Sidamo drain towards Somalia and the Indian Ocean (World Bank, 2006). Lake Abbe is the only significant transboundary lake, shared with Djibouti, and the water flows from the Awash river (FAO, 2016).

Tensions in sharing international rivers has inhibited economic growth, hence the government of Ethiopia promotes cooperation amongst the countries through the Nile Basin initiative (NBI) and other programs (World Bank, 2006). Initially, the NBI agreement of 1929 and 1959 allocated Nile's water to only Egypt and Sudan, but an agreement signed in 2010 included Ethiopia, Kenya, Rwanda, Uganda and Tanzania (FAO, 2016). Ethiopia, Sudan and Egypt are currently preparing long-term investments in hydropower, irrigation and flood management. This cooperation could potentially transform and also provide new opportunities in all involved countries (World Bank, 2006). Development of the Grand Ethiopian Renaissance dam in 2017 is one of such examples: it should provide water for irrigation and flood mitigation in Sudan, apart from its use in Ethiopia (FAO, 2016). The dam should be completed in 2022 and recently tensions between Egypt and Ethiopia on the dam filling was reported, but seems to be currently resolved (Egypt Today, 2019)

4.3 Rainfall and seasons

Based on data from the Global Precipitation Climatology Centre (GPCC; http://gpcc.dwd.de), the mean annual rainfall in Ethiopia is 812.4 mm with a spatial variation between 91 and 2122 mm (all mean values refer to the period: 1951 to 2001). In this period, the highest rainfall occurred in the western highlands, ranging spatially from 1600 to 2122 mm per year, and in the lowest rainfall areas, located in the eastern lowlands of the country, it ranged from 91 to 600 mm (Awulachew et al., 2007). The annual long-term water input via precipitation is about 900 billion m³/year (World Bank, 2006; FAO, 2016). Ethiopia also has a high rainfall variability over time, that is usually accompanied with endemic events of drought and famine, occurring every 3-5 years (Figure 4.4). Recently, Ethiopia had severe drought occurrences in years 2015 to 2017. The drought of 2015/2016 is considered the worst in over 30 years (FAO, 2016).

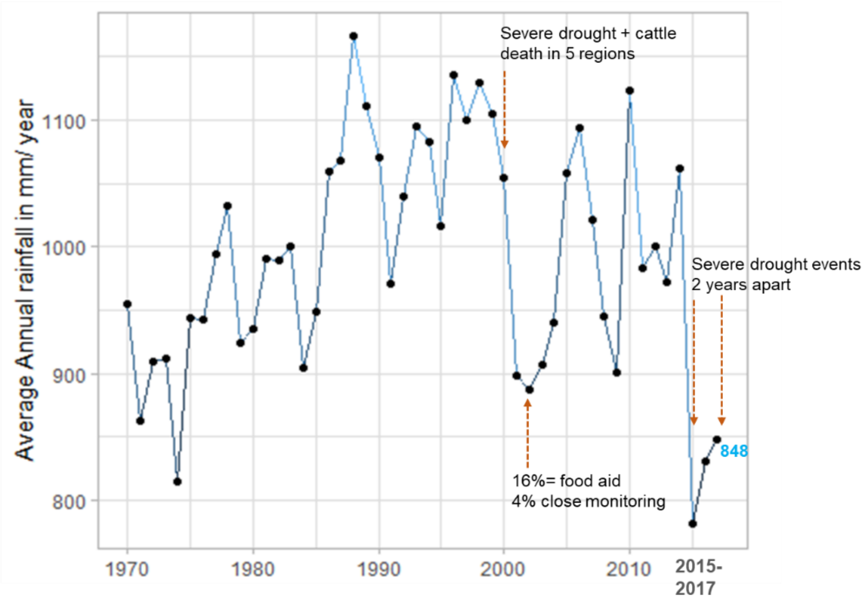

Figure 4.4: Annual rainfall in Ethiopia over time (World Bank, 2006; FAO, 2016; Abebe, 2017).

Based on its water balance, Ethiopia can be divided into 3 agro-climatic zones (Figure 4.5). The first zone consists of lowlands in the eastern, southern and northern part of the country, having little rainfall and no significant growing season. The second zone, located in the western part of the country has one raining season and a single growing period. Lastly, a large number of lowlands in the mid-western part of the country have two raining and also two growing periods yearly: Meher (major crop season) with harvests in November/ December and Belg (minor season) with harvest in June/ July (FAO, 2016).

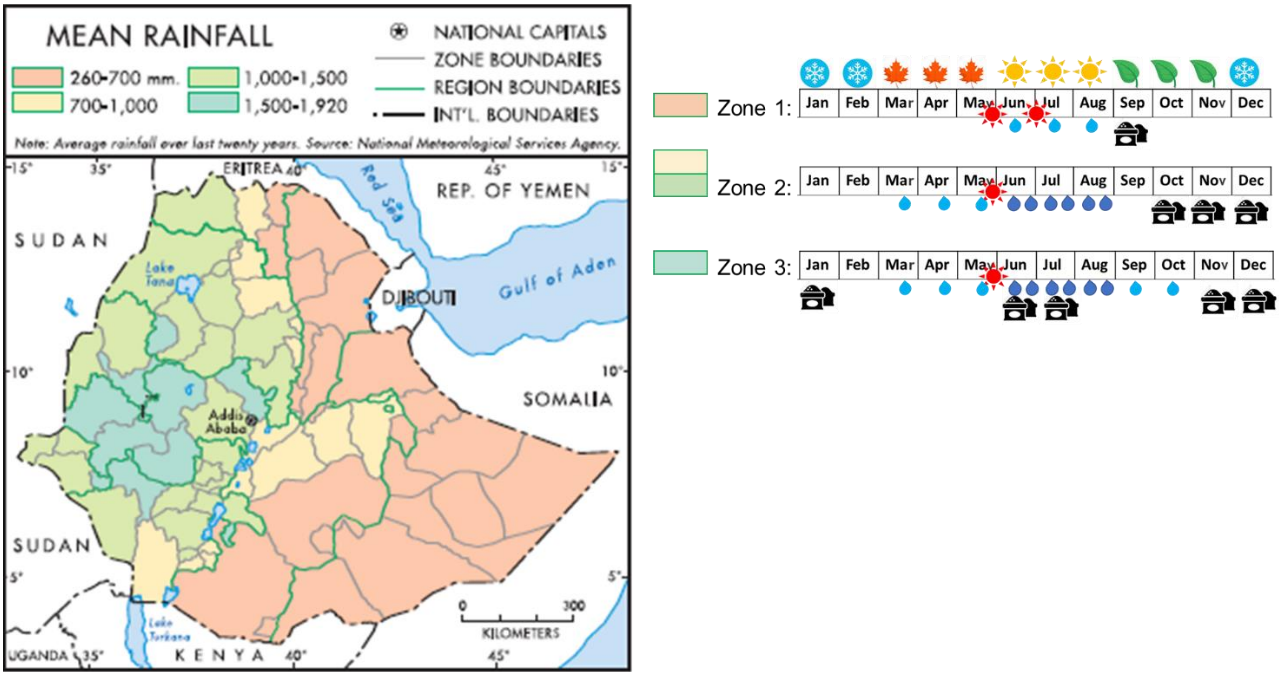

Figure 4.5: Average rain fall and farming seasons across Ethiopia (Source: World Bank, 2006).

4.4 Water use

Ethiopia utilises only a small portion of its available surface water. The present total renewable water resources annually is determined at a volume of 122 billion m³/year, consisting of 120 billion from surface water and nett 2 billion from groundwater (due to the overlap between surface water and groundwater, 18 billion m³ has been attributed to surface water in above values). Around 89.3 billion m³/year of water is required for sustaining the natural environment and resources (FAO, 2016), which leaves 32.7 billion m³ for other purposes. A total estimate of 10.55 billion m³ per year is currently withdrawn (FAO, 2016). Resulting in an additional volume of approximately 22.15 billion m³/year of available water for potential development and use, with the SDG indicator 6.5.4 determined at 32% (FAO, 2016). Hence, roughly two times more water is potentially available in Ethiopia for use in agricultural areas and other sectors, compared to current withdrawals. The agricultural sector uses the highest percentage (91.83%) of withdrawn water (Figure 4.6: crops and livestock), and accounts for 9.7 billion m³ of water per year. This sector employs 83% of the population and is responsible for 42% of national GDP (MoA, 2011). Water use in households (domestic use) and for livestock make up 7.68% and 6.51% of the total, respectively, while industries use less than 1% of total water (Figure 4.6).

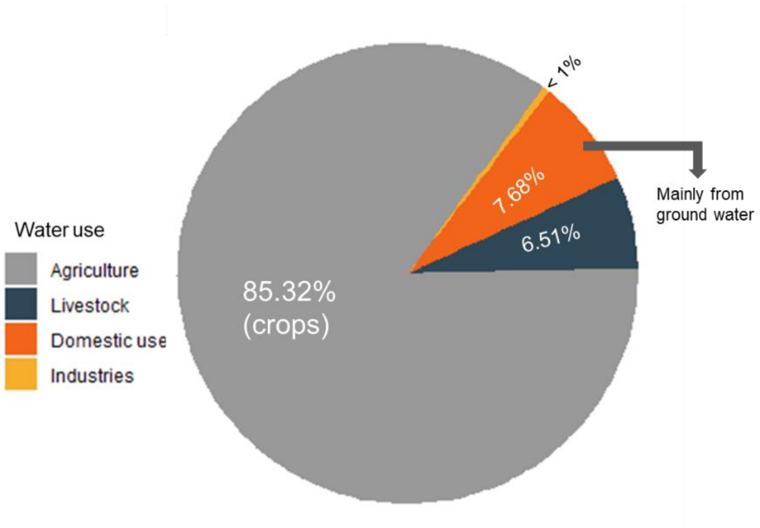

Figure 4.6: Water use distribution across the sectors in Ethiopia (Source: FAO, 2016).

Crop cultivation is mainly rainfall dependent, while water for domestic use is primarily supplied from ground water (World Bank, 2006), although some lakes also provide drinking water (Table 4.1). The water use distribution has not changed over time (World Bank, 2006; FAO, 2016). Surface water has a high utilisation potential based on its availability as calculated in the paragraph above. Groundwater on the other hand, has a lower potential than surface water: about 50% of the water may be extractable (World Bank, 2006; FAO, 2016).

4.5 Agriculture and irrigation

Agricultural land use accounts for 36% of total land area in Ethiopia: consisting of an estimated 20 million hectares for permanent meadows and pastures, and approximately 16.3 million hectares of cultivated cropland containing permanent and temporary arable crops (FAO, 2016). Small-holder cereal farming is the dominant agricultural system in Ethiopia, utilising approximately 10 million hectares of arable land (World Bank, 2006). Coffee is the most important cash crop of Ethiopia, responsible for 40 to 60% of total agricultural GDP. Oil seeds, cereals, sugarcane, cotton, khat, incense (harvested from shrubs such as Acacia, Boswellia and Commiphora), spices, flowers and natural gum are also exported, while palm oil, raw sugar and wheat are the major crops imported into the country (FAO, 2016). Coffee, cereals, pulses and oilseeds production are prone to fluctuations in rainfall, drought events and market prices: crop production decline by 10% in most cases and up to 30-40% reduction in coffee production was reported during extreme drought events (World Bank, 2006).

Ethiopia has the largest population of livestock in Africa with 50 million units each of cattle and chicken, and 20 million units each of goats and sheep (CSA, 2015). Livestock production accounts for 11% export earnings (second to coffee), and provides 40 to 90% of cash income in rural households (World Bank, 2006). Livestock grazing is mainly in the highlands and is integrated into all types of highland farming systems. Fishery is not very popular in Ethiopia, but fish consumption has increased over the years (World Bank, 2006). The Rift Valley lakes are the major fishing hubs in the country (Figure 4.1). About 40 000 to 50 000 tons of fish are harvested yearly, resulting in only 20 to 30% of potentially available fish currently being caught (World Bank, 2006), offering room for expansion. Fertilizers and use of improved seeds are some of the measures that may be taken to improve agriculture. Currently, fertilizer application is mainly used in the cultivation of cereals, which is the dominant crop group, whereas about 14 and 7% of the farm area is used for growing pulses and oilseed crops, respectively (World Bank, 2006). Cattle and poultry excreta may serve as manure to improve the organic matter content in farmland soils. Ethiopia was until the late 1950s, self-sufficient in food production, but was also not a food exporter during this period (World Bank, 2006). The average per capita food production in Ethiopia was 280 kg per year in the 1960s. Food production remained stagnant over the last decade and in the last 30 years, food production per capita declined to 160 kg per year, making more than 50% of the population food insecure (World Bank, 2006). In recent years, fertilizer use and food production have increased in an attempt to keep up with the population growth (see section on nutrient balances).

Agriculture in Ethiopia is mainly sustained by rainfall, and rainwater harvesting, also known as micro-irrigation, has been reported to cover around 0.13 million hectares of farmland, i.e. less than 1% of total cropland (FAO, 2016). Previous reports indicated that only about 0.20 million hectares of land (< 2% of arable land) was irrigated, consisting of the following irrigation practices: 38% traditional, 20% modern communal, 4% modern private and 38% irrigation from public schemes (World Bank, 2006). The Ministry of Water Resources identified 560 potential sites on the river basins for irrigation, covering around 3.7 million hectares of land (Awulachew et al., 2007; World Bank Database 2006). Majority of the irrigation schemes focused on a mixture of small and medium-scale systems, and some large-scale systems were constructed in Afar and Oromia regions (Awulachew et al., 2007).

AQUASTAT database (FAO, 2016) estimated only 2.7 million hectares (circa 17% of total cropland), 1 million less than previously determined in Awulachew et al. (2007), as potential land for irrigation. This was based on studies that investigated available and equipped land-water resources. The Nile Basin is estimated to supply 49.1% of the total potential, while Rift Valley and Shebelli-Juba would supply the remaining 27.4% and 23.5% respectively (FAO, 2016). In 2015, only 0.86 million hectares was equipped for irrigation: 0.2 million hectares for small-scale schemes (size < 50 hectares) and 0.66 million hectares for medium and large-scale schemes. Another 1.1 million hectares exist as non-equipped cultivated wetlands and inland valley bottoms, bringing the current total water-managed area to 1.96 million hectares (FAO, 2016), which is 12% of cultivated land. This can be raised to 17%, if full irrigation potential is utilised, which indicates that >80% of cropland in Ethiopia still depends on local rainfall. There was a positive correlation between households that irrigated their crops, and the use of labour, seed, pesticide and fertilizer (FAO, 2008). Agricultural practises e.g. the irrigation of khat (Ethiopia's second leading export crop), sometimes competes with water supply for domestic purposes (World Bank, 2006).

4.6 Hydro-economic modelling

A national model has been developed to quantify the economic impact of Ethiopia's water resources, management and variability, for the years 2003 to 2015 (12 years in total) based on hydrological data

(World Bank, 2006). The hydrological data consisted of information on annual rainfall and water resources in Ethiopia. Degrading landscapes, variation in precipitation (including drought and flooding events), marketing and transportation costs, economic fragmentation, and infrastructures were factors incorporated into the model. The model was run with three scenarios, with respect to the input of rainfall data. The first was referred to as "*Smoothed rainfall*" which serves as the baseline scenario and used the average rainfall (from 1995 – 2002) as input for each year of the 12-year period. "*Stylised single drought*" is similar to the baseline scenario, but included a single 2-year drought event (considered as a single shock event) in the 12-year period. The "*Historical variability*" scenario did not use the average rainfall, but instead incorporated historical hydrology data, including drought and flooding events.

In the baseline scenario of "*Smoothed rainfall*", annual GDP growth rate (2003 – 2015) will be 2.9%, and per capita incomes will fall, because in the model both the national economy and the agricultural sector will grow at a lower rate than the projected population growth (in absence of increased investments). The poverty rate, i.e. the percentage of people living in poverty, will increase from 29% in 2003 to 41% in 2015 (11 million people more than in 2002). A single drought event in the 12-year period, i.e. the "*Stylised single drought*" scenario, will reduce GDP growth to 2.6% (–10% compared to the baseline scenario), and the poverty rate to 46% (additional 5 million compared to the baseline scenario). The "*Historical variability*" scenario has the strongest effect by reducing GDP growth to 1.8% (–38% compared to the baseline scenario), and increasing poverty rate to 51% (in total 51 million people).

The model highlighted coordinated investments in irrigation and market infrastructure. Regulations on efficient water use and storage infrastructures can be designed at all scales, and is essential in the Ethiopian highlands. Investments in irrigation and market infrastructures were estimated to increase GDP growth by 53% and 42% respectively, and reduce poverty rates by 7% and 5 % respectively, by the year 2015 in the "*Historical variability*" scenario. A combination of irrigation and market infrastructure investments resulted in a 93% increase of GDP growth and 12% poverty rate reduction. Irrigation programs directed at cereal farms to produce this internally-consumed crop and for farms that produce coffee exported as a cash crop, are potential examples of utilisation.

5. Nutrient Balance

5.1 Soil fertility

Declining soil fertility is a major issue in Ethiopia, affecting crop productivity and therefore contributing to overall food insecurity in the country. Severe top soil erosion (31% of total land is currently eroded, and this is increasing), the prevalence of acidic soils (about 40% of soils in the country is affected), significantly depleted soil organic matter and nutrient (both macro and micro) levels, and degraded physical properties of the soil are the main factors contributing to poor soil fertility (Zeleke et al., 2010). Other related factors are: over-use on specified arable land, a general lack of awareness / education on soil fertility, and competing use of animal dung as fuel and cost of fertilizers (Zeleke et al., 2010). An analysis of the soil fertility in Amhara region (North Western Ethiopia) indicated that black soils are considered fertile, while white and red soils are poor in fertility (Ayalew, 2015). Soil fertility was based on crop yield, topography of farmland, soil depth, colour, texture, water-holding capacity and the absence or presence of stones. This was determined by the farmers, who had a better overall perception of the soils on their farms, compared to scientists (Ayalew, 2015).

Another assessment of soil fertility conducted by CASCAPE, indicated that of the mapped area 25.9%, 21.6%, 20.3% and 13.9% were vertisol (clay), nitisol (30% clay), luvisol (humus layer, fertile) and leptosol (gravel/stony) soils, respectively (Leenaars et al., 2016). Cambisols, which are described as very productive soils, accounted for only 4.9%, indicating that only about a quarter (1/4) of the mapped area contained soils (luvisol and cambisol) with high fertility. This study was based on satellite images, onsite soil sampling and soil profiles from 30 districts in 4 different regions of Ethiopia (Oromia, Amhara, Tigray and Southern Nations Nationalities and Peoples' Region), where CASCAPE operated (Leenaars et al., 2016). Historically, Ethiopian highlands which cover about 40% of the total land area, have extremely low soil carbon content historically (Shiferaw et al., 2013).

Farmers manage soil fertility by practicing crop rotation, mulching with crop residues and applying animal manure (Ayalew, 2015). However, Bationo et al. (2006) mentioned that fertilizer use without nutrient recycling back into the soil is commonly practised in sub-Sharan Africa. A switch to integrated soil management practises, such as soil and water conservation, increased use of manure and fertilizers, pest and disease management, use of improved seeds, intercropping and investment in the production of alternative fuel materials has been proposed (Zeleke et al., 2010).

5.2 Fertilizer use

The necessity for increased agricultural production coupled with poor soil fertility, highlights the importance of fertilization. Ethiopia imports most of its fertilizers (Endale, 2011), and reports in 2019 indicate that about 1300 million kg of fertilizers was imported for the Meher crop growing season (June to August), and that annual fertilizer costs for the country are equivalent to one billion US dollar (New Business Ethiopia, 2019). Commonly used fertilizers by farmers are DAP (diammonium phosphate) and urea, and application varies amongst the crops cultivated (Endale, 2011). NPS (nitrogen-phosphate fertilizer supplemented with sulphur) was introduced in 2014/2015, and has gradually replaced DAP use, to meet the sulphur requirements of the crops (International Fertilizer Development Center, 2016). On average, fertilizer consumption for Ethiopia was less than 40 kg/ha, which is much lower than in Latin America (54 kg/ha), South Asia (80 kg/ha) and Southeast Asia (87 kg/ha; International Fertilizer Development Center, 2016). Fertilizers are mainly applied for cereal cultivation: 396 million kg, then pulses and oilseeds accounting for 16 and 13.6 million kg, respectively in 2007/2008 (CSA, 2008; Endale, 2011). The cereals teff, wheat, maize, barley and sorghum account for 40%, 29%, 20%, 9% and 2% respectively of total cereal fertilizer input, with application rates of 40, 57, 29, 22 and 3 kg/ha respectively for the different cereal crops. With these fertilization rates, average yields are quite low for these cereal crops with 851, 1311, 1810, 1164 and 1212 kg/ha respectively (CSA, 2008; Endale, 2011). Application rates are substantially lower than the recommended rate of 200 kg/ha (CSA, 2008; Endale, 2011), which would give a total fertilizer use for the whole country of 3100 million kg (based on 15.5 Mha arable land).

Statistical data from 2015 (CSA, 2015) indicated an increase in fertilizer application and also crop productivity. The total national levels of urea and DAP fertilizers were 698 million kg for cereals, 26.8 million kg for pulses and 10.3 million kg for oilseeds (CSA, 2015; International Fertilizer Development Center, 2016). Interestingly, teff still uses the largest share of fertilizers but at a lower percentage (32%), while maize and wheat account for 29% and 25%, respectively of total cereal fertilizer input (CSA, 2015; International Fertilizer Development Center, 2016). Although, fertilizer application increased, with teff, maize and wheat at an application rate of 110, 177 and 147 kg/ha, respectively, these rates are still under the recommended rate of 200 kg/ha for small cereals and 300 kg/a for maize (the recommended rates equal 20 kg P for all cereals, 64 kg N for small cereals and 110 kg N for maize). Crop yields for these cereals were 1575, 3431 and 2543 kg/ha, respectively (CSA, 2015; International Fertilizer Development Center, 2016), which is an increase of roughly 100% compared to the values reported above.

Although fertilizer application in Ethiopia is above the average of sub-Saharan Africa, the nutrient use efficiency is much lower than in other countries: e.g. Ethiopia has nutrient use efficiency values of 9 to 17 kg of maize per kg of applied N, which is half and a third lower than the values for Kenya and Tanzania respectively (Zeleke et al., 2010). Values reported above (fertilizer application of 177 kg/ha and maize yield of 3431 kg/ha) suggest a strong improvement of the nitrogen use efficiency in more recent years.

5.3 Nutrient balances

A national study on macronutrient levels was performed by Stoorvogel and Smaling in 1990, and projected balances of -47, -7 and -32 kg/ha per year for soil nitrogen (N), phosphorus (P) and potassium (K), respectively. Field studies by Eyasu (2002) indicated an annual balance of -102 kg/ha for soil nitrogen in southern highlands, while Amare et al. (2006) reported projected balances in central highlands of -72, -8 and -66 kg/ha per year for N, P and K respectively, (see also Zeleke et al., 2010). The next national study was performed for 5 years and ended in 2015. The results indicated deficiencies of 3 to 6 nutrients in the soils of most parts of the country (International Fertilizer Development Center, 2016). Monitoring nutrient inflow and outflow for a 3 year period (2012 to 2014), indicated a variation in nutrient balances among 6 districts of Ethiopia (van Beek et al., 2016). Average annual nutrient balances in kg/ha for N, P and K were respectively -83, 5 and -16 for Addis Ababa; -19, 17 and -5 for Bahir Dar; -7, 5 and -1 for Haramaya; -17, 9 and -21 for Hawassa; -37, 6 and -3 for Jimma; and -33, 9 and -2 for Mekelle (van Beek et al., 2016). Average N, P and K balances were -23 ± 73, 9 ± 29 and -7 ± 64 kg ha-1, respectively, for 2012 – 2014, and were characterized by high variability and large uncertainty levels. Hence, soil stocks of N and K are depleted, whereas the positive balance for P indicates accumulation in the soil.

6. Options for a research agenda (2020-2022)

6.1 Linking models

6.1.1 National level model connections.

To improve the consistency of the socio-economic (MAGNET) and nutrient based (BIOSPACS) analyses, key parameter and scenario assumptions in the two models need to be compared and where possible aligned. The complexity of these alignments varies. Exogenous drivers in both models, like population growth, are easy to adjust. Exogenous drivers in one model which are endogenous in the other, are relatively straightforward after consolidating model definitions, for example trade in primary products (endogenous in MAGNET but exogenous in BIOSPACS). Most complex adjustments refer to variables that are endogenous in both models, like output per hectare. In these cases the different paradigms come into play and alignment may only be possible to a certain extent to avoid straight jacking one or the other model. For example, output per hectare in MAGNET is to a large extent driven by relative prices of land, labour, capital and key inputs like fertilizer (crops) or feed (livestock), that determine whether production increases are extensive (i.e. use similar amounts of land per ton of product) or intensive (i.e. less land is used per ton of product due to increased use of labour or other inputs).

6.2 Socio-economic challenges

6.2.1 Heterogeneity in food security impacts.

The MAGNET results provide a first glimpse of varying income developments of different household groups (e.g., different growth rates of skilled and unskilled wages). While the first MAGNETGrid results provide an idea of local changes in production, these are currently driven only by biophysical spatial heterogeneity. As MAGNET supply responses are used in the downscaling, all farmers are implicitly assumed to respond in the same way. While adding the impact of infrastructure on regional price-transmission will improve the localized response, these do not address the varying vulnerability and coping possibilities at household level. To better capture variability in income, food consumption and production changes, a methodology will be developed and tested with Ethiopian data to put household survey data on a map. If we succeed, this will not only greatly enhance current macro-micro poverty and food security analyses in adding a geographical dimension (for example allowing targeted regional interventions). It would also allow us to account for local changes in agricultural production possibilities due to nutrient depletion or climate change, which will affect rural incomes and therefore their food security challenges (e.g. wage labours will be affected differently than land owning farmers; specialized farm households will respond differently from farmers combining crop and livestock production).

6.2.2 Defining a healthy diet

Defining a healthy diet needs to consider not only the calorie intake (such as the MDER in section 2.2.2), but also aspects like the nutritional contents (see Table 2.2) and a balance between various food items (vegetables, fruit, vegetal and animal products, etc.). The nutritional concentrations (Smith et al. 2016) will be combined with the main minimum daily requirements in order to translate a healthy diet towards its underlying food components in terms of the different crop and animal product types that are used in both MAGNET and BIOSPACS. Possibly, different healthy diets can be defined that represent different scenarios. However, a healthy diet for one person will not be sufficient as an average for a whole country due to the variability in income and food consumption (see 6.2.1). Based on this variability, a factor will be determined (with a value > 1) that increases the demand for crop and animal products, as derived for one person, towards the average demand for the whole country, in an attempt to take uneven consumption in a country into account. These national level diets, expressed in crop and animal products, will be used as input for BIOSPACS to estimate corresponding land and fertilizer requirements and environmental emissions. They will also serve as a benchmark for the food supply projections that are computed with MAGNET, based on economic developments.

6.2.3 Estimating required income development

Next to the (potential) availability of food items for the healthy diet, zero hunger for all also means that everyone can afford this diet. That requires sufficient household income development to be able to purchase this diet in 2050. The results of MAGNET in section 2.1 assumed a SSP2 ("business-as-usual") development until 2050. Together with the assumed variability in 2050 (GINI coefficient?), it will be checked whether this leads to sufficiently high household incomes throughout the population of Ethiopia. If not (if a number of people can still not afford the healthy diet), the required economic development needs to be defined to achieve zero hunger for all. Part of this search into the required economic development will also consider the relation between import and export of foods and required domestic food production. These international trade flows affect both food prices as well as the national income, and also influence the domestic production demands.

6.3 Land use and productivity

It is likely that climate change will affect production possibilities in Ethiopia in 2050. While most sources agree on temperature increase, the spatial distribution of precipitation change remains very uncertain. Both higher and lower annual precipitation totals have been predicted for the future. Higher temperatures already indicate that more water is needed to produce the same amount of food, with lower precipitation amplifying and higher precipitation compensating for this increased water demand. The analyses with the models MAGNET and BIOSPACS result in demands for crop and animal production that need to be produced domestically in order to achieve zero hunger in 2050. However, questions need to answered where and whether this amount of production can be realized in 2050 in Ethiopia. This means that the outcomes of the (inter)national analyses should be linked with analyses of lower scales, notably the field or herd scale. Two mutually affecting aspects need to be looked into simultaneously, for the assessment of the possibilities of Ethiopia to become food secure: (1) how much can be produced locally, and (2) where can land expansion take place. These two aspects together will determine whether it is in principle possible to produce enough food. In this respect we need to take climate change predictions into account to determine reasonable production potentials in 2050. We envisage a possible iterative process among domestic food production demand, local production potentials and optimal spatial distribution of food production. There are a number of tools available to look for an optimal spatial distribution of crop and grass areas. The model iCLUE from WEnR (ref.) is one of them and offers great flexibility, among others to include 'no-go' areas such as nature reservations, infrastructure that may enhance the cultivation of new areas, and buffer zones with lower priority around areas with restrictions. There are also many options to estimate the production possibilities at the local level (e.g. crop-soil models). One of them is the model chain of GYGA (Global Yield Gap Analysis) that already has simulated rain-fed and irrigated potentials for a number of crops for Ethiopia. This should then also be done for the future climate in 2050 to check whether potentials may have changed. GYGA tools can also be linked to assessments of fertilizer requirements, which are needed to boost productivity, and which can be linked to the estimations from BIOSPACS and MAGNET (see also section 6.5).

6.4 Water requirements

Obviously, changing production areas and local productivity will affect the water flows in the country. One of the main question is whether and where irrigation equipment needs to be maintained or developed for food security. Current results of GYGA for Ethiopia illustrate that rain-fed potentials contribute substantially more to the yield gap closure compared to additional irrigation, but it is not clear whether that will also be the case in 2050. Next to agriculture, also other sectors require a part of the total amount of available water in the country, including the neighboring countries that rely on sufficient water input via transboundary rivers that originate in Ethiopia. Fair water distribution among all claims will probably become more difficult in the future, when climate change and demand growth will narrow the water surplus in the area. To check the availability of water with the total requirement increase (among others for producing enough (=more) food), a catchment simulation approach is needed, where all incoming and outgoing water flows can be taken into account in one analysis. If competing claims occur (required amount > available amount), they should be made visible for careful policy making in how to distribute the water. A catchment model that includes water demand for crops and other vegetation types, irrigation options, and other water claims (environmental, hydropower, international, households, including livestock, etc.) should be used. Again, it needs to be checked whether the water supply from precipitation poses limits to the required domestic food production in 2050, and if so whether food import can be augmented or other water claims can be sufficiently decreased in the future.

6.5 Nutrient input and output challenges

The results on nutrient balances (notably N and P) clearly illustrate the need for higher nutrient inputs to increase crop productivity (e.g. Table 2.4 and Chapter 5). Given a certain food demand, there is a simple trade-off between productivity and land use: higher yields per ha leads to lower land use and vice versa. However, in practice, the choice between intensification (higher yields) and extensification (more land use) is much more complex and strongly influenced by price developments of land, other inputs, crops, etc. The projections of MAGNET and BIOSPACS illustrate a direction towards 2050 in which land expansion will take place, next to yield improvements, and a massive increase in fertilizer application is needed for higher yields and maintaining soil fertility. Given the target of zero hunger in 2050 and how that translate into new agricultural areas and higher yield levels (see above sections in this chapter), the question needs to be addressed how much additional fertilizer is required to realise the required yields throughout Ethiopia and how that depends on local conditions. Additional fertilizer is also needed to combat declining soil fertility, increasing soil erosion and land degradation, and should not only be focussed on macro- but also on micro-nutrients.

Special attention is needed for decreasing nutrient losses in order to increase the fertilizer efficiency, but above all to decrease emissions to the environment. This is linked to sustainable production while higher application rates in general cause higher emissions, but may decrease land requirement for food production, which is another aspect of sustainability. There have been studies that use general equations to estimate losses (a.o. in Van Beek et al., 2016), studies that have linked the losses to field water flows (e.g. percolation and runoff in NARC), and in BIOSPACS losses are also calculated as function of crop and average field conditions. These relations need to be improved and applied to the situation in 2050, i.e. for all (incl. new) locations where food is to be produced with the climate conditions of 2050. With better estimations of the losses, the fertilizer requirement for realizing required yield levels can be more accurately assessed, and also the total emission towards the environment in the whole country can be better estimated (compare high values projected for 2050 in Figure 2.4). Total losses should be compared with the environmental boundaries for nutrient emissions to check its effect on sustainability, e.g. related to biodiversity.

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Annex I

Table 1. MAGNET sectors (58) and the mapping to sectors used in MAGNETGrid (9).

	No.	MAGNET code	Description	GRID_sector
Crops	1	pdr	Paddy rice	pdr
	2	wht	Wheat	wht
	3	grain	Cereal grains nec	gro
	4	oils	Oil seeds	osd
	5	sug	Sugar cane, sugar beet	c_b
	6	hort	Vegetables, fruit, nuts	v_f
	7	crops	Crops nec	ocr
	8	oagr	Other agriculture	pbf
Livestock	9	cattle	cattle sector	ctl
	10	othctl	sheep,goats,horses	ctl
	11	pltry	poultry sector	xag
	12	wol	Wool, silk-worm cocoons	ctl
	13	pigpls	Pig and other animal product	xag
	14	milk	Raw milk	ctl
Processed food	15	bfmt	beef meat	xxx
	16	othcmt	Meat: other cattle,sheep,goats,horse	xxx
	17	pulmt	poultry meat	xxx
	18	othmt	Other meat product nec	xxx
	19	dairy	Dairy products	xxx
	20	sugar	Sugar and molasses	xxx
	21	vol	Vegetable oils and fats	xxx
	22	pcr	Processed rice	xxx
	23	ofd	Processed food	xxx
	24	feed	Animal feed	xxx
Fish	25	wfish	Wild fish	xxx
	26	aqcltr	Aquaculture	xxx
	27	fishp	Fish processing	xxx
Forestry	28	frs	Forestry	xag
	29	plan	Plantation	xag
Industries	30	c_oil	Crude oil	xxx
	31	petro	Petroleum, coal products	xxx
	32	res	residue sector	xxx
	33	biod	Biodiesel	xxx
	34	biog	Biogasoline	xxx
	35	ftfuel	ftfuel 2nd gen biofuel	xxx
	36	eth	ethanol 2nd gen biofuels	xxx
	37	gas	Gas	xxx
	38	coa	Coal	xxx
	39	ely_c	electricity from coal	xxx
	40	ely_g	electricity from gas	xxx

	41	ely_n	electricty from nuclear	xxx
	42	ely_h	electricty from hydro	xxx
	43	ely_w	electricty from wind and solar	xxx
	44	bioe	bioelectricity 2nd gen	xxx
	45	pla	pla biochemical	xxx
	46	pe	pe biochemical	xxx
	47	bfchem	bioplastics	xxx
	48	lsug	ligno sugar	xxx
	49	ely	Electricity	xxx
	50	othcrp	Chemical,rubber, other plastic prods	xxx
	51	fert	fertilizer	xxx
	52	f_chem	mixed fossil biochemical sector	xxx
	53	othind	Other industry	xxx
	54	pel	pellet sector	xxx
Services	55	gas_dist	Gas manufacture, distribution	xxx
	56	trans	Transport sector	xxx
	57	ser	Services	xxx

Annex II

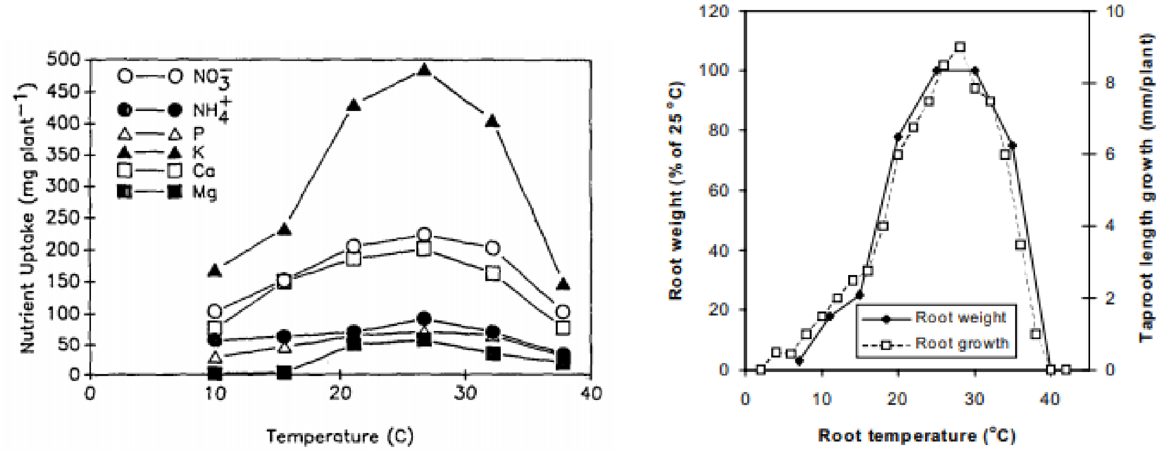

Figure 1. Left: uptake of macro-nutrients for tomato at different temperatures after two weeks (Tindall, Mills, & Radcliffe, 1990). Right: Soil temperature response of maize root dry weight, closed: 24 days after germination and pecan seedling tap-root length; open: after four days (Pregitzer & King, 2005).

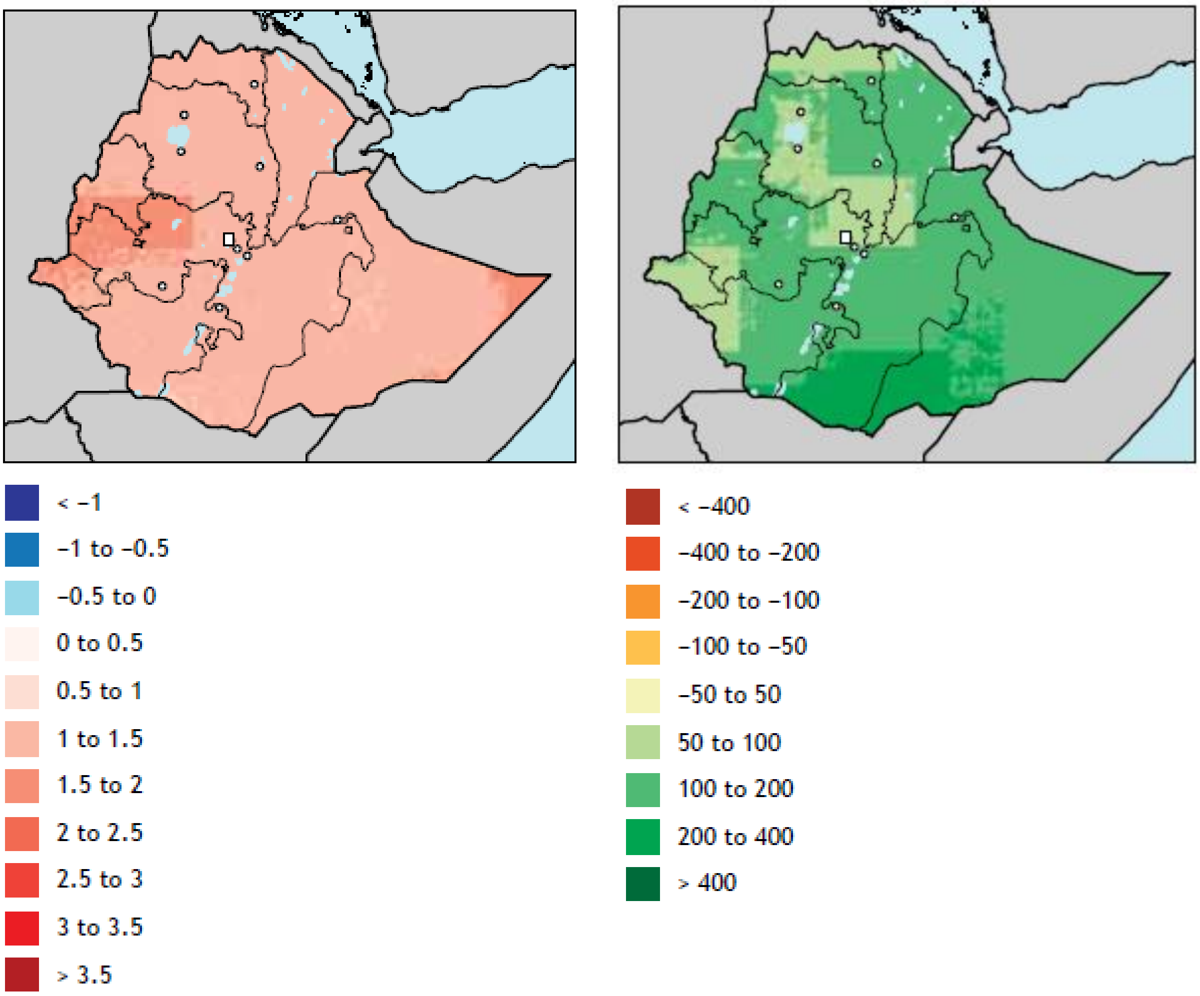

Figure 11. Predictions of change in average yearly temperature (left, °C) and rainfall (right, mm) in Ethiopia of the global climate model MIROC 3.2 in 2050 compared to 2000.

Table 1. Consequences of climate change on productivity and cropping area for some common crops in Ethiopia. Source: (BZ, 2018).

Crops	**Overview**
Teff and other cereals	Teff is highly important for household income, as most households sell it for cash and consumer maize or wheat. It has a relatively high climatic adaptability and is suitable for storage in different temperature regimes, and is therefore already cultivated in different climate zones (Admassu et al., 2012) Under large climate change effects, it is likely that teff production will move further upslope, to relatively colder areas. For other cereals such as barley, it has been reported that highland farmers are already suffering production losses (Yirgu et al., 2013).
Maize	Maize also performs well in a range of agro-ecological settings, but is highly responsive to water availability. Most models suggest a gain in maize yields of over 25% in the eastern highlands at the edge of the Great Rift Valley and in the north central highlands. Some also show new areas gained in eastern Amhara and Tigray. These gains are however offset by yield decreases in the southwest and east, and in some cases even a complete loss of cultivable land
Wheat	Wheat yields are expected to reduce substantially in almost all current cropping areas. Some areas will be lost, even where rainfall will increase – presumably due to heat stress.
Sorghum	Sorghum has been characterized as 'best adapted to the adverse effects of climate'. It is widely cultivated in drought-prone areas, which suggests that it will be able to cope with increasingly dry circumstances in other areas. Under climate change, sorghum yields are expected to increase by over 25% and sorghum-growing areas are likely to expand, especially in central Ethiopia. In western and north-western parts, however, yields may decrease.
Enset	Enset or "false banana" is an important staple crop in parts of Ethiopia, especially in the south. Effects of increasing temperatures and rainfall variability on the crop have not been reported, but it has been suggested that there is a climate-related expansion of crop diseases that affect enset.
Coffee	Coffee is an important export crop for Ethiopia. Climate change effects on coffee are unclear. It has been suggested that higher temperatures adversely affect yields in current coffee areas, especially in the south, because coffee plants require temperatures below 22°C. Moreover, coffee yields may be adversely affected by the coffee berry borer, which likes high temperatures. On the other hand, climate change may create opportunities for new coffee areas on higher altitudes.