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Impacts of considering climate variability on investment decisions in Ethiopia

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Abstract

Extreme interannual variability of precipitation within Ethiopia is not uncommon, inducing droughts or floods and often creating serious repercussions on agricultural and nonagricultural commodities. A dynamic climate module is integrated into an economy-wide model containing a detailed zonal level agricultural structure. This coupled climate-economic model is used to evaluate the effects of climate variability on prospective irrigation and infrastructure investment strategies, and the ensuing country-wide economy. The linkages between the dynamic climate module and the economic model are created by the introduction of a climate-yield factor (CYF), defined at the crop level and varied across Ethiopian zones. Nine sets of variable climate (VC) data are processed by the coupled model, generating stochastic wet and dry shocks, producing an ensemble of potential economic prediction indicators. Analysis of gross domestic product and poverty rate reveal a significant overestimation of the country's future welfare under all investment strategies when climate variability is ignored. The coupled model ensemble is further utilized for risk assessment to guide Ethiopian policy and planning.

JEL classification: Q18, Q25, Q54

Keywords: Economy-wide model; Ethiopia; Investment strategy; Agriculture; Risk; Climate variability

1. Introduction

Although Ethiopia is rich in culture, history, and natural resources, it is often remembered more for its disastrous droughts and floods, starving population, and struggling economy. Its heavy reliance on agriculture, combined with its susceptibility to frequent climate extremes, has left it in a precarious position, striving to not only stay on par, but to prevent vast numbers of people from falling deeper into disparity. With 85% of the population living in rural areas, agriculture plays an important role in physical and economic survival.

This work is part of an ongoing study focusing on relevant and realistic potential investment strategies within Ethiopia. The hope is that these strategies may provide insights into how Ethiopia should best proceed in the years to come, both on regional and country levels, for rural and urban alike. Goals set forth by the Ethiopian government are included explicitly, including plans for development in agriculture, water resources, and roadway infrastructure. To assist in this activity, an economy-wide model with a spatial agricultural structure was developed (see Diao et al., 2005 and Diao and Nin Pratt, 2007 for details). The model is designed to assess investment strategies and afford recommendations based on forecasts of economic indicators.

The climate in Ethiopia is generally associated with tropical monsoon-type behavior, experiencing significant June–September rainfall, yet measurably cooler in its high plateau and central mountain range elevations. It is the influence of climate extremes on crop production, though, both annual and seasonal, which may substantially impact regional economic production, resulting in reduced or negative growth rates. Therefore, due to the importance of climate on the economy of Ethiopia, a dynamic climate module is developed and linked to the existing economy-wide model, in lieu of previously utilized average, static climatic variables. The motivation for this work is to assess whether the inclusion of climate variability in the model, both annually and seasonally, has a significant effect on prospective investment strategies and the resulting country-wide economy. If the effect is remarkable, the implications may be significant, and aid in providing guidance and direction

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to strategic planners, as well as protection of the investments through wise developmentt decisions.

2. Background

A growing number of articles on the influence of including climate variability in models and assessments are appearing in agricultural and economics literature. The general trend in modeling, especially considering the increased ease and decreased processing time, is to include climate variability not only for more representative and descriptive results, but to allow for risk assessment as well (Ferreyra et al., 2001; Letson et al., 2001; Ludena et al., 2003; Taylor and Young, 1995). Numerous studies indicate that agriculture is particularly sensitive and vulnerable to climate variability, more so than almost any other activity (Dixon and Segerson, 1999). Agriculture is often very productive in a multitude of geographic settings under the influence of mean climate variables, but is frequently susceptible to crop failure during extreme climate events (Salinger et al., 1997). Additional research has also shown that agriculture is especially vulnerable in developing countries during extreme or semi-extreme events due in large part to limited infrastructure and its inability to endure atypical climate fluctuations. Patt (1999), in a paper concerning the treatment of low probability events, claims that extreme climate events often dominate decision making. With this in mind, more climate-varying agriculture models are being built for comparison to mean climate models or even actual field data if available, and are showing that variability is of importance (Mendelsohn and Neuman, 1999).

3. Climatic data

The climatic data utilized in the climate module are part of the Climate Research Unit (CRU) TS 2.0 dataset, obtained from the University of East Anglia (Mitchell et al., 2004). They consist of gridded data in $0.5^\circ \times 0.5^\circ$ cells, containing 100 years of monthly data. Much of the data from 1901 to 1960 are synthetic data, and are obtained based on 1961–1990 averages and gridded anomalies (Block and Rajagopalan, 2007). As a result of the sparse and spotty precipitation gauges in the country, the upper Blue Nile basin regional precipitation from the CRU dataset (1961–2000) was validated to ensure its spatial and temporal representation by comparison with other global precipitation datasets (Block and Rajagopalan, 2007).

4. Model framework

The original economy-wide, multi-sector, and multi-regional model developed by Diao and Nin Pratt (2007) serves as the foundational model for this study. The model is benefit-only, comprises Ethiopia's 11 administrative regions and 56 zones, and attempts to simulate growth impacts of agricultural and nonagricultural investment strategies. It is agriculturally focused, with 34 agricultural commodities (cereals, cash crops, and livestock products), yet includes two aggregate nonagricultural commodities as well. Both agricultural production and consumption are defined at the zonal level; the demand side is further disaggregated into rural and urban sectors. Alternative technologies in crop production (rain-fed vs. irrigated, use of modern inputs vs. traditional inputs) are explicitly captured in the model. While the model assumes an integrated domestic market, differences in producer and consumer prices across zones are reflected in the trade/transportation margins calibrated according to the average distance from each zone to the capital city of Addis Ababa. Prices for many agricultural products and the aggregate service sector are endogenously determined by the equilibrium between domestic supply and demand; however, exports and imports do occur when the domestic prices fall or rise to export or import parity prices, reflected by exogenous world prices. While production factors such as labor and capital are not explicitly modeled, production value at the commodity level is adjusted to reflect its value-added part. Incomes of households, which are defined at the zonal level for the rural and urban separately, are endogenous variables and fully determined by production revenue. The model is calibrated to the base year (2003) in which most economic data are available. While all results of the model in the base year are consistent with the data used for calibration, additional information, such as average growth rate in yield and area expansion calculated from past years, is applied to subsequent years. Thus, outcome of the model is a series of growth paths for all endogenous variables, such as level and growth rate of gross domestic product (GDP), output of agricultural, and level and changes in domestic prices. Relevant multi-market model equations are presented in the Appendix; calibration details may be obtained upon request.

The model was expanded to include an agricultural water extension, via a climate module, in order to capture the important links between water demand–supply and economic activity in the agriculture sector. Given the high dependency on rainfall for agricultural production, the large share of the total economy accounted for by agriculture, and weak linkages between domestic prices at the regional level and world markets in Ethiopia, hydrologic variability has potentially serious impacts on both agriculture and the whole economy. Moreover, with high transportation costs and poor access conditions to distant markets, the local impact of hydrologic variability cannot always be buffered or ameliorated through market links to other regions. There can be significant "threshold" effects whereby prices have to rise above critical values before inducing trade with other regions or fall below a certain level to get access to world markets.

4.1. Climate-related equations

The yield function (Eq. 1), representing all agricultural commodities and defined for different technologies, is a function of both producer price and climatic conditions:

$$Y_{R,Z,i,t} = \mathrm{YA}_{R,Z,i,t} P_{R,Z,i,t}^{\alpha_{R,Z,i}}. \quad (1)$$

$Y_{R,Z,i}$ is the yield for crop i in zone Z of region R. $P_{R,Z,i}$ is the producer price for the same commodity, i, while $\mathrm{YA}_{R,Z,i}$ represents a climate shift parameter. This parameter is primarily a function of specific climate-yield factors (CYFs), which are derived from monthly climate data at the zonal level (Eq. 2):

$$\mathrm{YA}_{R,Z,i,t+1} = \mathrm{CYF}_{R,Z,i,t+1}\mathrm{YA}_{R,Z,i,t}\left(1 + g_{Y_{R,Z,i}}\right). \quad (2)$$

CYF, described in detail in the following section, is crop, zone, and climate specific. g_Y is the annual growth rate in yield productivity, based on historical data, and also varies by zone and crop. For irrigated crops, $\mathrm{YA}_{R,Z,i}$ is not CYF dependent, and is assigned a value 50% higher than $\mathrm{YA}_{R,Z,i}$ (producing a full yield) for the identical rain-fed crop, as prescribed by the agricultural survey data utilized in this study. This enhancement can be attributed to additional fertilizers, pesticides, and better seed a farmer will apply, given the knowledge that sufficient irrigation water is available.

4.2. Climate-yield factor development

The development of the CYF is based on procedures summarized by the United Nation Food and Agriculture Organization's (FAO; FAO, 1984, 1998) for drought conditions, and recommendations from peer-reviewed literature for flood conditions. The CYF for each crop in each zone is a single value that attempts to encompass crop location, soil, and hydrologic characteristics, planting dates, crop duration, effective precipitation, and evapotranspiration. It is essentially a measure, using all the aforementioned parameters, of the yield potential of rain-fed crops, based on water constraints or overabundance, for a given crop. Values for CYF range from 0 to 1, where a CYF of 1 implies no water constraint or overabundance. A CYF equal to 1 does not ensure full yield, however, as other variables, such as seed quality, pests, natural disasters, and farm management, to name a few, may ultimately reduce the final yield; it simply implies that water availability will not reduce the yield. CYFs below 0.5 are typically assumed to result in crop failure. Fig. 1 presents a generic sketch of the relationship between CYFs and effective precipitation, where points A and D represent extreme drought and flood conditions, respectively. Between points A and B, more effective precipitation returns a greater yield per crop area. From points B to C, more effective precipitation produces no more yield, but neither is the yield reduced. Finally, beyond point C, the effective precipitation has become more than the crop can sustain, and the yield decreases. It is conceivable that if the effective precipitation is too large, no yield is possible, resulting in a CYF of 0. This sketch is for illustrative purposes only, and does not infer that the CYF and effective precipitation form a linear relationship. Rather, this relationship is specific to each crop, to each climate, and to soil types and conditions, among other factors, and may take on a variety of shapes.

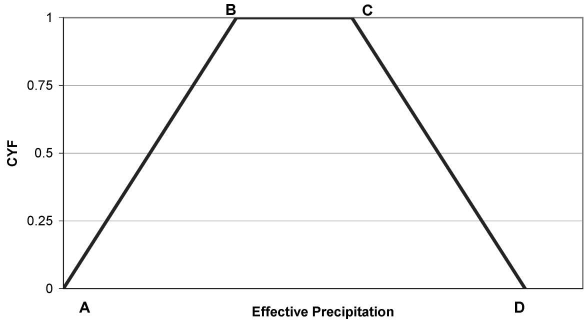


Fig. 1. Generic relationship between CYF and effective precipitation.

CYFs are developed in an iterative stage, first accounting for normal or potential drought conditions (Fig. 1, points A–C), and subsequently considering potential flood conditions (Fig. 1, points C–D). CYF is initially a function of crop (ETC) and actual (ETA) evapotranspiration, as well as Ky, the yield response factor (Eq. 3):

$$\mathrm{CYF}_{S,C} = 1 - \mathrm{Ky}_{S,C}\left(1 - \frac{\mathrm{ETA}_{S,C}}{\mathrm{ETC}_{S,C}}\right), \quad (3)$$

where S refers to either a seasonal or crop stage (vegetation, flowering, yield, and ripening) value; C implies the specific crop considered. Ky values are pre-defined for each crop stage and for the season as a whole (FAO, 1984), and indicate crop resistance to drought. The limiting CYF value (i.e., the lowest value) for each crop in each zone is retained. Typically, it is the seasonal CYF that produces the most restrictive value.

The second step in CYF development evaluates excess precipitation conditions warranting CYF reductions. Such conditions may flood crops, rot or suffocate roots, wash out roads, and instigate an economic situation not entirely different than during drought conditions. Literature tends to support the notion that yields of rain-fed crops decline during flood conditions. Several factors are involved in determining the severity of crop loss, including the timing of flooding during the crop's life cycle, the frequency and duration of flooding, and the air–soil temperatures during flooding (Belford et al., 1985). Precipitation/irrigation versus crop yield curves (Linsley et al., 1992) indicate varying degrees of crop yield losses, dependent upon crop type and location; in all cases, though, yields decrease when applied water is above a threshold value.

CYFs are reduced by means of a flood factor (FF) if the year is deemed significantly wet. Smedema and Rycroft (1983) show that water-logging damage to rain-fed crops is directly related to the return period of the rainfall event, and these impacts are not constant over the growing season. Following Smedema and Rycroft (1983), FFs are calculated twice in the evaluation of flooding on agricultural commodities: during the vegetative/flowering and harvest stages, the points when the crop is most vulnerable to flooding, and when the yield is most likely to be negatively shocked. The largest FF value for each of these two crop stages of each year is retained for evaluation.

The magnitude of the FF, and its corresponding probabilistic chance of occurring, determines the extent to which the CYFs are affected through a series of CYF reduction equations (not included here, but akin to Smedema and Rycroft [1983]). Based on the aforementioned literature and other available guidelines (Salter and Goode, 1967), a very conservative approach has been adopted, due to limited available specific data for varying Ethiopian crops and regions.

Validation of CYFs by comparison with observed crop yields is not trivial due to externalities other than climate and limited data availability, specifically at the zonal level. Not surprisingly, precipitation and crop production are highly linked in Ethiopia as the vast majority of crops are rain-fed (Lemi, 2005), and while precipitation is not the solitary driver of CYF values, a general relationship is expected. Fig. 2 illustrates time-series of Ethiopian country-wide maize production, average precipitation, and average CYF departures from the mean. While the similarity in trends is clearly perceivable, they become much more evident as the spatial scale diminishes. Fig. 3 demonstrates maize production and CYFs for the Gojjam region in northwest Ethiopia. While these figures do not specifically validate the yield–CYF relationship, the underlying intention is validating the importance and need of climate information for comprehensive assessment.

Table 1 lists the seven cereal crops for which the CYF is computed, the recommended planting month, and typical harvest month for the Meher (main) cropping season. These dates were used exclusively throughout the entire country in determining CYF values, although variations certainly exist (FAO, 1984, 1998, 2004).

Livestock and nonagricultural production also exhibit negative impacts from excess precipitation and floods, due to damage to infrastructure and linkages to agricultural goods. The same process has been adopted as for agricultural commodities, although only the largest FF value from the Meher season months is retained. In lieu of CYFs being reduced, growth of

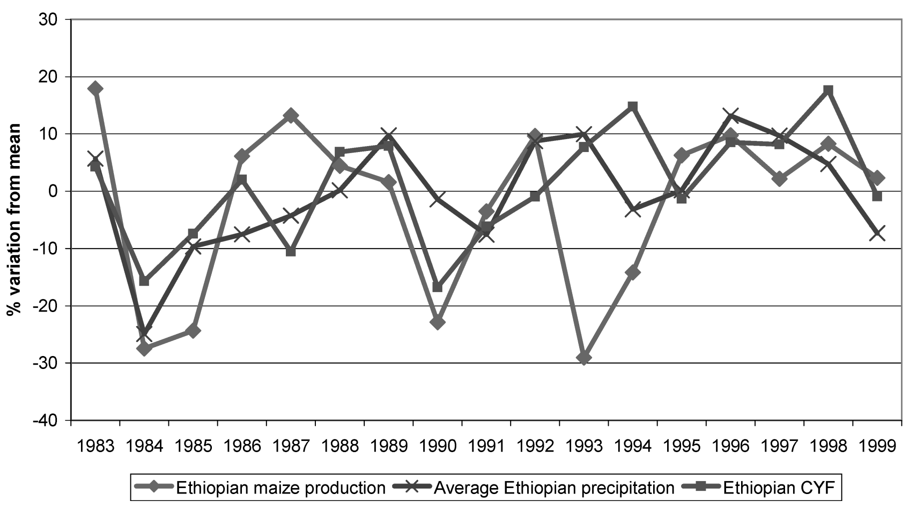


Fig. 2. Time-series of Ethiopian country-wide maize production, average precipitation, and average climate-yield factor (CYF) departures from the mean.

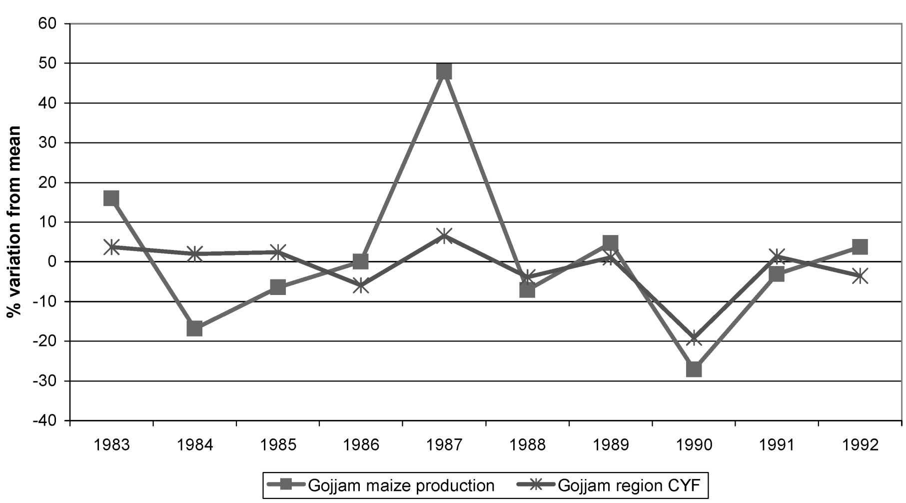


Fig. 3. Time-series of Gojjam maize production and average Gojjam climate-yield factor (CYF) departures from the mean.

Table 1
Cereal crop planting and harvest months

	Meher season	
Cereal crop	Planting month	Harvest month
Barley	May	September
Maize	May	October
Millet	June	October
Oats	June	October
Sorghum	May	September
Teff	June	September
Wheat	June	October

the supply intercept of the specific commodity is slowed or reversed. This reduction is especially crucial to infrastructure, as significant flooding events may damage roads, and pose serious transportation problems.

4.3. Investment strategies and simulations

Two major strategies, investment in irrigation for agriculture and investment in road construction and maintenance, are simulated in the model. Irrigation investment focuses on providing sufficient water to crops, while road investment promotes access for farmers to transport their agricultural products to a market, both for country-wide use and as an export.

The model brings agricultural supply, demand, and market opportunity issues together to assess the alternatives in investment strategies. The analysis gives a broad picture about agricultural growth and poverty reduction, and reveals some important economic linkages among agricultural sectors, between demand and supply, between exports and domestic markets, and between production and farmer income. It is not the purpose of the model to guide a specific investment decision for any agricultural sector in a specific region. Additionally, the analysis reveals the complexity of economic linkages and trade-offs among different investment goals. Model results are limited to four economic indicators for this study, including total GDP growth rate, agricultural GDP growth rate, nonagricultural GDP growth rate, and poverty rate. Income in the model is endogenous and determined by production revenues. Given that the model does not explicitly include inputs, producer prices are adjusted to represent value added, and the aggregation of agricultural production at the value added prices forms agricultural GDP. For the two nonagricultural sectors, the sector-level GDP is used to represent production output with unit prices. Poverty rate is defined as the percentage of population below the national poverty line, which is derived from household total expenditures and variable from year to year.

All model simulations are run over a period of 12 years (2003–2015). The base simulation is considered "business as usual," and predicts future conditions if current practices remain unchanged, with no additional infrastructure investments or major policy changes; other parameters stay within the confines of historical growth rates.

The irrigation simulation implements Ethiopia's Irrigation Development Program, as planned by the Ethiopian Ministry of Water Resources. Approximately 200,000 ha of crop area are currently being irrigated in Ethiopia, accounting for just over 2% of all cropland. The new program details the addition of 274,000 ha of irrigated cropland, more than doubling the current investment. Just under one half (46%) of the newly irrigated crops will be devoted to small-scale projects, and the remainder to large and medium-scale projects. One half of the newly irrigated cropland is assumed to be cereal crops and one half cash crops.

The roads simulation models change in transportation infrastructure, as envisioned by the Ethiopian government. The goal is to improve road conditions, reduce transportation costs, and increase farmers' accessibility to major markets. Ethiopia's road network currently consists of approximately 3,800 km of paved road and 29,000 km of unpaved, gravel, or earth roads. This density is below the all-African average, and results in 70% of all farmers not being within a one-half day's walk of a paved road. The Ethiopian Government's 10-year Road Sector Development Program (RSDP, 1997–2007) includes creating new roads and maintaining existing ones. The first half of the program (1997–2002) focused on rehabilitating the existing road network with only modest amounts of new road, and was substantially successful. The second half of the program also has a rehabilitation component, but aims to increase the road network by 5,000–8,000 km of all types of road. Road construction costs in Ethiopia are highly variable and relatively unknown, due to the extreme terrain and torrential rains. For the purpose of a roads simulation, two fundamental principles are utilized as proxies to reflect this infrastructure improvement. The first is to gradually lower the marketing margins between producers and consumers and between surplus and deficit regions over the 12 years, and the second is to increase the productivity of the service sector, also gradually over the same time frame.

The final simulation incorporates irrigation and road investments simultaneously into the model. Both plans, as previously described, are implemented in full, with the simulation assessing the benefits of both. The greater level of investment in multiple sectors produces a positive feedback between the agriculture sector and the market/infrastructure sector, improving the potential for positive results.

5. Methods for modeling with static or variable climate

The crux of this study lies in exploring the consequences of accounting for variable climate (VC) in the agro-economic model. By solely utilizing average or static climate (SC) values (or CYFs), year-to-year changes and extreme events incurred by climate fluctuations are not reproduced or represented explicitly in the model. This methodology is deterministic, dampening out climate variability effects, producing a relatively smooth growing trend, and generating one set of scenario results for each investment strategy. Alternatively, if the model is run stochastically with varying CYFs, the effects of VC may be more realistically mapped and an ensemble of potential outcomes produced. CYFs were computed annually for 1901–2000. To assess SC implications for the Ethiopian economy, only the *mean* CYF annual values for each crop are retained, implying that yields for rain-fed areas do not vary from year to year based on climate effects. Contrarily, for evaluation of VC effects, the model incorporates a new CYF each year. Utilizing the 100 years of available CYF data, nine different 12 year combinations are formed: 1900–1912, 1913–1924, 1925–1936, 1937–1948, 1949–1960, 1961–1972, 1973–1984, 1985–1996, and 1989–2000. This set is minimal, corresponding to a stylized stochastic process, as opposed to other approaches that generate ensembles using a random or weighting scheme for assimilating months (e.g., Prairie et al., 2000), but does offer insights into the variability and its response on the economy.

6. Results of static climate and variable climate modeling

Figs. 4 and 5 illustrate GDP and poverty rate indicators for model runs utilizing static (mean CYF) and variable (nine sets of dynamic CYF) climate series for the base case. Due to a lack of climate variation and influence, the static climate run projects constant, linear year-to-year growth. Conversely, the VC runs vary interannually, occasionally dramatically. Excessively wet or dry conditions may instigate negative shocks to the economy, and often create situations from which the country may not be able to rebound (to the static climate condition) within the 12-year simulation. The timing of these droughts and flooding events, whether early or late in the 12-year simulation, also plays a significant role. Positive gains under favorable conditions are also evident in the figures, on occasion outpacing static climate growth.

In the case of both GDP and poverty rate, the VC mean quickly departs from the static trend, indicating a lower economic welfare, but follows a similar trajectory over the 12 years. The vast majority of individual variable climate years lie to one side of the deterministic line, signifying the difficulty in returning to a state of constant growth once a shock to the system has occurred. Plots of GDP and poverty rate (not included) under the investment simulations appear similar to Figs. 2 and 3 for the base case, excepting a generally larger increase for GDP and a lessening of the poverty rate over the 12-year timeframe.

A comparison of economic indicators from the static and VC model runs for the base and investment simulations are tabulated in Tables 2–5, utilizing the initial and final (first and twelfth year) values. The variability within the 12 years is not addressed. The range of VC column provides maximum and minimum values from the nine individual sets. Percent differences for relevant economic predictors are also included. In contrast to the base case, and given the benefit-only nature of the model, both static and VC means for the investment simulations have been amplified due to the growth of irrigated agriculture, better transportation and easier flow of commodities to and from markets, or a combination of the two. More interestingly, for every economic indicator assessed, VC mean results always produce a smaller increase or greater decline in comparison to the static climate conditions, favoring inferior economic projections. A closer examination of the maximum (for GDP) or minimum (for poverty rate) projection from the nine VC runs demonstrates that conditions equivalent to or bettering the static climate run are never attained. Even given the limited number of VC runs, this has serious implications. Climate clearly plays an important role, with negative shocks outweighing positive gains under current conditions in Ethiopia.

Table 2
Economic indicators for static and VC runs of the base simulation (2003–2015)

Simulation—base economic indicator	SC	VC (mean)*	Range VC		% Difference (SC and mean VC*)
			Min.	Max.	
GDP growth rate	2.82	1.78	1.23	2.32	−36.9%
Ag GDP growth rate	2.44	1.47	0.58	2.06	−39.8%
NAg GDP growth rate	3.32	2.17	0.68	2.71	−34.6%
Poverty rate in 2003 (%)	41.55	41.55	–	–	–
Poverty rate by 2015 (%)	42.98	54.77	46.82	65.52	11.8%

*Mean of 9–12-year sets.
Notes: SC = static climate; VC = variable climate; Ag GDP = agricultural gross domestic product; NAg GDP = nonagricultural gross domestic product.

Table 3
Economic indicators for static and variable climate runs of the irrigation simulation (2003–2015)

Simulation—irrigation economic indicator	SC	VC (mean)*	Range VC		% Difference (SC and mean VC*)
			Min.	Max.	
GDP growth rate	3.68	2.73	2.25	3.22	−25.8%
Ag GDP growth rate	3.95	3.13	2.39	3.62	−20.8%
NAg GDP growth rate	3.31	2.14	0.66	2.69	−35.3%
Poverty rate in 2003 (%)	41.55	41.55	–	–	–
Poverty rate by 2015 (%)	39.27	50.50	42.70	61.36	11.2%

*Mean of 9–12-year sets.
Notes: SC = static climate; VC = variable climate; Ag GDP = agricultural gross domestic product; NAg GDP = nonagricultural gross domestic product

Table 4
Economic indicators for static and variable climate runs of the roads simulation (2003–2015)

Simulation—road economic indicator	SC	VC (mean)*	Range VC		% Difference (SC and mean VC*)
			Min.	Max.	
GDP growth rate	3.58	2.53	2.00	3.08	−29.3%
Ag GDP growth rate	2.60	1.64	0.75	2.22	−36.9%
NAg GDP growth rate	4.78	3.61	2.11	4.16	−24.5%
Poverty rate in 2003 (%)	41.55	41.55	–	–	–
Poverty rate by 2015 (%)	39.82	51.71	43.37	62.96	11.9%

*Mean of 9–12-year sets.
Notes: SC = static climate; VC = variable climate; Ag GDP = agricultural gross domestic product; NAg GDP = nonagricultural gross domestic product.

Table 5
Economic indicators for static and variable climate runs of the irrigation/roads combination simulation (2003–2015)

Simulation—irri/roads economic indicator	SC	VC (mean)*	Range VC		% Difference (SC and mean VC*)
			Min.	Max.	
GDP growth rate	4.40	3.43	2.95	3.92	−22.0%
Ag GDP growth rate	4.13	3.29	2.56	3.78	−20.3%
NAg GDP growth rate	4.77	3.59	2.09	4.14	−24.7%
Poverty rate in 2003 (%)	41.55	41.55	–	–	–
Poverty rate by 2015 (%)	36.15	47.74	39.77	58.77	11.6%

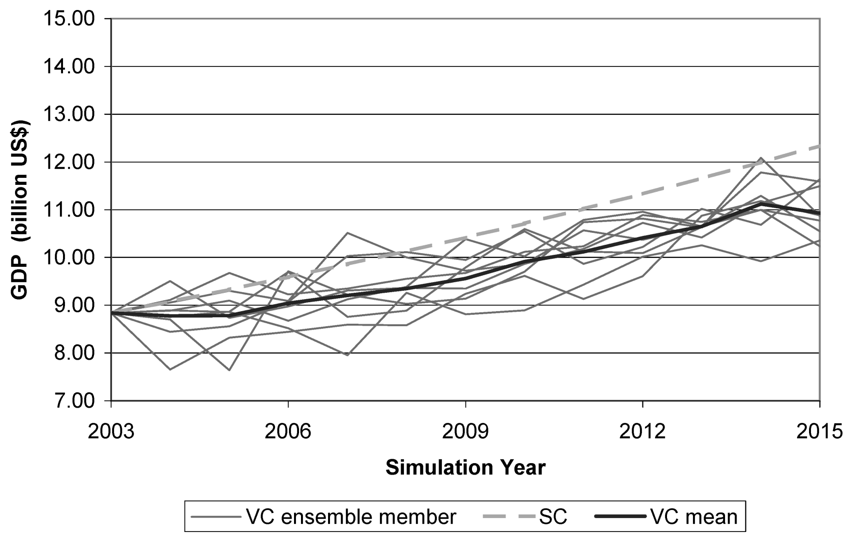
*Mean of 9–12-year sets.
Notes: SC = static climate; VC = variable climate; Ag GDP = agricultural gross domestic product; NAg GDP = nonagricultural gross domestic product.

Tables 2–5 also demonstrate expected gains due to specific investment. Over the course of the irrigation simulation (Table 3) the agricultural GPD growth rate escalated significantly compared to the base simulation, with little difference in nonagricultural GDP. Poverty rates also declined. Almost the opposite occurred under the roads simulation, with a boon to the nonagricultural GDP; however, a small improvement in agricultural GDP is noticeable, stemming from positive feedbacks to farmers of improved market access conditions. The irrigation and roads combination simulation predicts strong growth in both sectors, beyond sectoral growth projected from either individual investment, further demonstrating positive bidirectional feedback between investment types.

While future model versions aim to explicitly include investment costs, an evaluation of investments from a benefit-only perspective is still revealing. Table 6 displays 2003 net present value of GDP under static and variable climatic conditions for all simulations. As previously interpreted, static climate conditions appear to predict overzealous conditions of the future Ethiopian economy; future returns are consistently lower when climate variability is explicitly included. In fact, static climate runs project returns in excess of two standard deviations above the mean VC projections. Accounting for costs may paint a clearer picture, but reduced GDP levels under VC conditions may help to explain the historically low level of investment in Ethiopia.

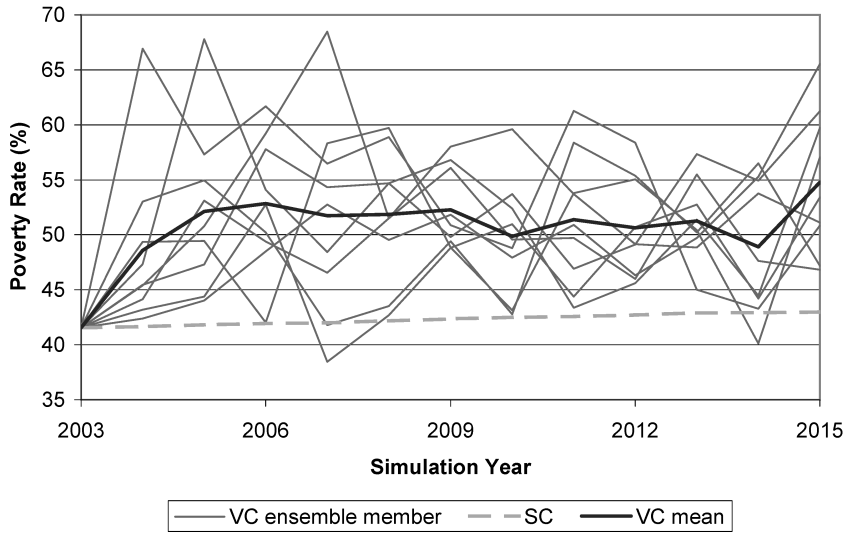
Isolating the effects of each investment by removing the base condition is also enlightening for interpretation of investment impact. Table 7 exhibits means and standard deviations of differences between investment and base simulations for 2003 net present GDP utilizing the VC runs. In each instance, the identical climate conditions were employed for investment and base simulations, retaining the difference. While direct comparison of irrigation and road investment means may not be justifiable, due to different investment levels, evaluation of their respective simulation variance indicates that funding irrigation may tend to better buffer against long-term variability, compared to funding roads. This may be attributable to directly addressing climate variability, clearly one of the top culprits in increasing economic vulnerability; shielding against climate effects in this agriculturally dominated country through roads investment is more indirect. Year-to-year variability, however, is not necessarily substantially reduced, making investment choices less clear. Additionally, as in Table 6, the advantages of investing in both types is evident through the combination simulation with the overall mean greater than the sum of irrigation and road investments alone, and the variance less than the two combined. These results tend to favor simultaneous investment.

These results underscore the fact that predictions of economic conditions are frequently overestimated when yearly climate variability is ignored. The ramifications of this may be severe, as an unexpected decline in the economy is often much



Notes: SC = static climate; VC = variable climate.

Fig. 4. Annual GDP for static and variable climate runs of the base simulation (2003–2015).



Notes: SC = static climate; VC = variable climate.

Fig. 5. Annual poverty rate for static and variable climate runs of the base simulation (2003–2015).

more difficult to address than a surprise upswing. The addition of VC in the model aids in more sensible predictions and provides a framework, including realistic ranges of economic values, from which Ethiopian planners may make strategic decisions, given some sense of probabilistic risk. No investment strategy can ensure economic success; it is the probabilistic chance of the economy falling within some acceptable range of economic values for a given investment strategy that becomes of interest.

Probability density functions (PDFs), assuming normal distribution, for GDP and poverty rates are included in Figs. 6 and 7, respectively, under the irrigation investment strategy. The function gives an indication of the probability of a given GDP or poverty rate value occurring in the last year of any VC run. The value in the final year from the static climate approach has also been included as a vertical line. The figures again give credence to the notion that the static climate approach is recurrently an overestimation of the GDP and an underestimation of the poverty rate at the end of the simulation time period. Similar findings under the road and combination investments are observed. The probability of attaining the level prescribed by the static climate run, according to the PDF for the irrigation simulation, is very small: less than 0.4% in the GDP case, and just over 4% in the poverty case. This implies that if the static climate approach is used in policy-making, the predicted GDP will only be surpassed, on average, approximately once in every 250 simulations. An assessment of risk levels for planning purposes naturally flows from the PDF. Table 8 demonstrates sample risk levels and associated GDP and poverty rates for the combination approach.

7. Summary and discussion

This research highlights the importance of accounting for VC in economic modeling, utilizing potential investment strategies in Ethiopia as a case study. An agro-economic country-wide model assessing irrigation and road-building investments is forced with both average, static climate, and VC conditions over a 12-year simulation. The motivation for this work is to evaluate whether the inclusion of climate variability in the economic model has a significant effect on prospective investment strategies and the resulting country-wide economy. Results indicate that static climate conditions frequently underestimate the negative effects of VC, and do not clearly represent the difficulties in recovering from extreme climate events. Modeling

Table 6
Net present value of gross domestic product in 2003 for static and variable climate runs of all investment simulations (2003–2015) in billion US dollars

Investment	SC	VC (mean)*	VC (STD)
Irrigation	13.58	8.68	2.22
Roads	12.90	7.75	2.32
Combination	16.60	11.43	2.34

*Mean of 9–12-year sets.
Notes: Discount rate = 10%. SC = static climate; VC = variable climate; STD = standard deviation.

Table 7
Net present value of gross domestic product in 2003 for isolating investment effects (investment minus base simulation) utilizing variable climate runs (2003–2015) in million US dollars

Investment (minus base)	VC (mean)*	VC (STD)
Irrigation	3.64	0.022
Roads	2.71	0.122
Combination	6.40	0.139

*Mean of 9–12-year sets.
Notes: Discount rate = 10%. VC = variable climate; STD = standard deviation.

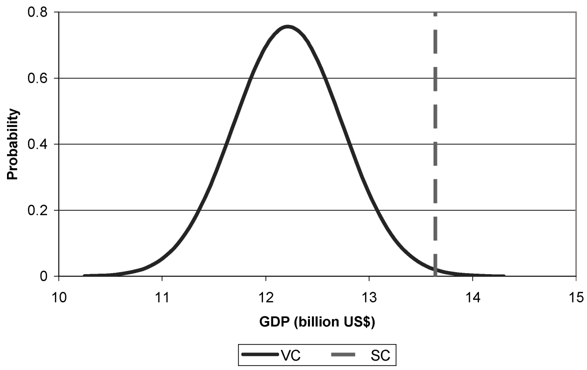


Fig. 6. Probability density function of gross domestic product in 2015 under the irrigation simulation.

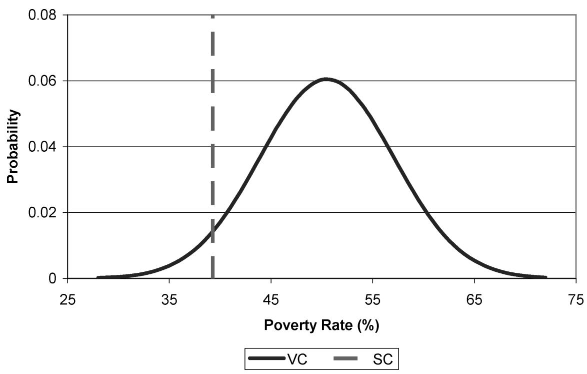


Fig. 7. Probability density function of poverty rate in 2015 under the irrigation simulation.

with VC appears to be essential and warranted when modeling investment in sectors that are responsive to climate extremes. Another benefit of the VC approach is the ability to analyze the results from a probabilistic standpoint. This in turn allows for policy decisions to be made and presented in a risk-based framework.

In addition to stressing the importance of including VC, the research also provides insights into preferred investment strategies. For an individual comparison, the irrigation strategy tends to fair better than the roads strategy from a benefit perspective. This is due in part to the fact that additional irrigation has particularly strong impacts on reducing the negative effects on production and farm income of drought. Since drought has a persistent impact on income and food security, prevention or reduction in severity of drought has long-term benefits. It is also valuable to emphasize that the combination strategy of both irrigation and roads is slightly greater than the sum of the two individual strategies, due in large part to positive feedbacks between sectors, warranting a strong consideration of simultaneous investment.

Potential future extensions of this work are numerous. One area for development is expanding the VC ensemble. Additional runs need not be in chronological order, but could follow traditional *K-nearest neighbor* techniques to generate plausible 12-year segments (Prairie et al., 2000). The broader ensemble would provide more confidence in probability and risk assessment levels. A second avenue for future work involves incorporating costs into the agro-economic model, and formulating a true investment analysis considering returns. Ultimately this step will be necessary prior to development of final investment policies in Ethiopia.

Table 8
Risk levels and associated gross domestic products and poverty rates under the irrigation and roads combination simulation in 2015 utilizing variable climate runs

Risk levels for GDP (billion US$)		Risk levels for poverty rate (%)	
$\mu = 13.25$	$\sigma = 0.579$	$\mu = 47.74$	$\sigma = 6.711$
Level of risk	Associated GDP	Level of risk	Associated poverty rate
50%	13.25	50%	47.74
25%	12.86	25%	52.24
10%	12.51	10%	56.33
1%	11.90	1%	63.38

Appendix: Equations in the spatial, multi-market model of Ethiopia agriculture

1. Demand functions:

(Zonal level per capita)

$$\mathrm{Dpc}_{R,Z,i,t} = \prod_j \mathrm{PC}_{R,Z,j,t}^{\varepsilon_{R,Z,j}} \mathrm{GDPpc}_{R,Z,t}^{1-\sum_j \varepsilon_{R,Z,j}},$$

where $\mathrm{Dpc}_{R,Z,i}$ is per capita demand for commodity i in region R and zone Z, and $\mathrm{PC}_{R,Z,i}$ is consumer price for i in region R and zone Z. $j = 1, 2, \ldots, 36$ (including two aggregate nonagricultural goods). $\mathrm{GDPpc}_{R,Z}$ is per capita agricultural and nonagricultural income for region R and zone Z.

2. Supply functions:

2.1 *Yield function (for crops)*

$$Y_{R,Z,i,t} = \mathrm{YA}_{R,Z,i,t} P_{R,Z,i,t}^{\alpha_{R,Z,i}},$$

where $Y_{R,Z,i}$ is the yield for crop i and $P_{R,Z,i}$ is producer price for i; $\mathrm{YA}_{R,Z,i}$ is the shift parameter, which depends on CYF coefficient derived from 100 years' monthly climate data at zonal level, fertilizer, and other input use, and time trend growth rate (varies by zone). For irrigated crops, $\mathrm{YA}_{R,Z,i}$ does not depend on CYF and is 50% higher than $\mathrm{YA}_{R,Z,i}$ for the same crops depending on rainfall only.

At this moment, only CYF coefficients have been developed, and the estimation of other coefficients (for fertilizer and other input use) are in progress. If we choose the mean value of CYF, the shift coefficient in yield function looks like:

$$\mathrm{YA}_{R,Z,i,t+1} = \mathrm{CYF}_{R,Z,i,t+1} \mathrm{YA}_{R,Z,i,t}(1 + g_{Y_{R,Z,i}}),$$

where CYF is the climate-yield factor coefficient with a value between 0.5 and 1.0. Here 1.0 implies that on average there is no shortage in rainfall affecting the yield, and when the coefficient is less than 0.5, the crop fails to grow. Kc varies by crops, depending on the drought-tolerant ability of a specific crop and suitability of the climate condition (which varies by zone). g_Y is annual growth rate in yield productivity and varies by zone and crop.

2.2 *Area function (for crops)*

$$A_{R,Z,i,t} = \mathrm{AA}_{R,Z,i,t} \prod_j P_{R,Z,j,t}^{\beta_{R,Z,j}},$$

where $A_{R,Z,i}$ is the yield for crop i and $P_1, P_2, \ldots, P_J$, is the vector of producer prices; AA is the shift parameter (the trend in area).

Trends in area function:

$$\mathrm{AA}_{R,Z,i,t+1} = \mathrm{AA}_{R,Z,i,t}(1 + g_{A_{R,Z,i}}),$$

where g_A is annual growth rate in area expansion and varies by zone and crop.

2.3 *Total supply of crops*

$$S_{R,Z,i,t} = Y_{R,Z,i,t} A_{R,Z,i,t}.$$

2.4 *Supply function for livestock and nonagriculture*

$$S_{R,Z,i,t}^{\mathrm{LV}} = \mathrm{SA}_{R,Z,i,t}^{\mathrm{LV}} \prod_j P_{R,Z,j,t}^{\beta_{R,Z,j}^{\mathrm{LV}}}.$$

Trends in livestock and nonagricultural supply function:

$$\mathrm{SA}_{R,Z,i,t+1}^{\mathrm{LV}} = \mathrm{SA}_{R,Z,i,t}^{\mathrm{LV}}(1 + g_{S_{R,Z,i}}),$$

where g_S is annual growth rate in productivity and varies by zone and commodity.

g_Y, g_A, and g_S are exogenous variables in the model and are affected by the investment shocks in the scenarios.

3. *Relationship between producer and consumer prices*

We assume that there are domestic market margins between import parity prices and consumer prices, which is defined by zone; and export parity prices and producer prices, defined also by zone. Moreover, within the country, due to difference in food deficit or surplus, and different distances to the national major market centers, there are price gaps across regions. To simplify the model, we assume that Addis Ababa is the only market center and the traveling time from Addis Ababa is used as proxy for domestic marketing costs (marking margins). Specifically, we define import/export parity prices as the prices in Addis Ababa markets (if tradable), such that

Import parity prices:

$$\mathrm{PC}_{i,t}^{\mathrm{Addis}} = (1 + W\mathrm{margin}_i)\mathrm{PWM}_i,$$

where *W*margin is the marketing margins between CIF prices and Addis Ababa consumer prices. If commodity i is importable, this equation holds. Consumer's prices in the other zones with food surplus are

$$\mathrm{PC}_{R,Z,i,t} = (1 - D\mathrm{gap}_{R,Z,i})\mathrm{PC}_{i,t}^{\mathrm{Addis}}$$

and consumer's prices in the other zones with food deficit or balanced food are

$$\mathrm{PC}_{R,Z,i,t} = (1 + D\mathrm{gap}_{R,Z,i})\mathrm{PC}_{i,t}^{\mathrm{Addis}},$$

where *D*gap is domestic price gap between consumer prices in Addis Ababa and in other regions and such gap varies by zone according to the distance to Addis Ababa. In general, for food surplus regions, producer prices are lower than that in Addis Ababa, while in food deficit or balanced regions, consumer prices are higher than that in Addis Ababa.

Export parity prices:

$$P_{i,t}^{\mathrm{Addis}} = (1 - W\mathrm{margin}_i)\mathrm{PWE}_i,$$

where P is producer prices and PWE is the FOB prices and the equation holds only when commodity i is exportable. There are marketing margins between producer and consumer prices, i.e.,

$$\mathrm{PC}_{i,t}^{\mathrm{Addis}} = (1 + D\mathrm{margin}_i^{\mathrm{Addis}})P_{i,t}^{\mathrm{Addis}}$$

and similarly for other zones:

$$\mathrm{PC}_{R,Z,i,t} = (1 + D\mathrm{margin}_{R,Z,i})P_{R,Z,i,t},$$

where *D*margin is domestic marketing margins between producer and consumer prices and varies according to distances to Addis Ababa.

4. *Exports and imports*

Trade (either exports or imports) is determined by the difference between Addis Ababa's prices and import/export parity prices, i.e., if

$$P_{i,t}^{\mathrm{Addis}} = (1 - W\mathrm{margin}_i)\mathrm{PWE}_i; \quad E_{i,t} > 0,$$

E_i is exports of commodity i; if

$$\mathrm{PC}_{i,t}^{\mathrm{Addis}} = (1 + W\mathrm{margin}_i)\mathrm{PWM}_i; \quad M_{i,t} > 0,$$

M_i is imports of commodity i; if

$$\mathrm{PC}_{i,t}^{\mathrm{Addis}} < (1 + W\mathrm{margin}_i)\mathrm{PWM}_i \text{ or}$$
$$P_{i,t}^{\mathrm{Addis}} > (1 - W\mathrm{margin}_i)\mathrm{PWE}_i$$

both E_i and M_i are zone and commodity i is in autarky.

5. Regional crop deficit and surplus

The model can identify which zones are food crop deficit or surplus, but cannot identify trade flows among the zones. That is, total deficit and surplus are cleared (balanced) at the national market and there is no regional market. A regional food crop *i*'s deficit/surplus is defined as

$$\text{DEF}_{R,Z,i,t} = D\text{pc}_{R,Z,i,t}\text{PoP}_{R,Z,t} - S_{R,Z,i,t}$$

positive means deficit.

6. Balance of demand and supply at the national level

$$\sum_{R,Z} S_{R,Z,i,t} + M_{i,t} - E_{i,t} = \sum_{R,Z} D\text{pc}_{R,Z,i,t}\text{PoP}_{R,Z}.$$

7. GDP and per capita zonal income function

$$\text{GDP}_{R,Z,t} = \sum_{j} P_{R,Z,j,t} S_{R,Z,j,t}; \quad j = 1, 2, \ldots, 36 \text{ (including nonagriculture)}.$$

Income per capita:

$$\text{GDPpc}_{R,Z,t} = \frac{\text{GDP}_{R,Z,t}}{\text{PoP}_{R,Z,t}}.$$

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