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Food loss and waste in maize in Mozambique and its economic impacts: a system dynamics assessment approach

Meizal Popat [a,b], Oscar Cacho[a], Garry Griffith[a] and Stuart Mounter[a]

[a]UNE Business School, Armidale, Australia; [b]University Eduardo Mondlane, Faculty of Agronomy and Forestry Engineering, Maputo, Mozambique

ABSTRACT

Food loss and waste are of global concern. In developing countries like Mozambique, it seems to be a major issue at the upstream end of supply chains, which is also regarded as postharvest losses (PHL). In this study, PHL is analysed in the context of maize in Mozambique, which is the most important crop in that country. The analysis focuses on empirically testing a simulation modelling approach for determining the short and mid-run economic impacts of PHL. A system dynamics model is applied. This model acknowledges climate, management, and domestic and regional marketing related factors as major drivers of PHL. A novel result from this study suggests climate related factors as the cause of a systematic amount of PHL at about 70,000 tons per year. However, marketing forces also play an important role to explain the overall PHL, particularly in periods domestic production increases sharply. The impact of potential interventions in the value chain are also tested.

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1. Introduction

Sustainable Development Goal 2 (SDG 2) aims to end hunger, achieve food security and improved nutrition, and promote sustainable agriculture by 2030 (UN 2020). This is a challenge, considering that over 10 percent of the global population suffer from undernourishment and food insecurity (FAO, IFAD, UNICEF, WFP, & WHO 2018). This represents nearly 821 million people, and about 236 millions of them live in Sub-Saharan Africa (SSA), where up to one in three people suffer from lack of adequate access to food in some regions (FAO et al. 2018).

Achievement of SDG 2 will require not only increased agricultural productivity and improved access to markets, but also a reduction in postharvest losses. A substantial amount of food is lost between farms and consumer households every year, estimated at about 1.3 billion tons (FAO 2018b). A significant percentage of the global population lacking access to food would benefit if this loss could be reduced (Miljkovic and Winter-Nelson 2020).

The pattern of food loss and waste along a value chain is asymmetric across economies. In developed economies the problem is more accentuated at the consumption level (i.e., food waste); whereas in developing economies, losses tend to be concentrated between production and processing stages (FAO 2011), normally regarded as postharvest losses (PHL). Overall, an effective and efficient reduction of food loss and waste requires the ability to overcome some major challenges such as the ability for effective measurement and monitoring of losses and waste; identification of

CONTACT Meizal Popat meizal.popat@gmail.com UEM-FAEF, Av. Julius Nyerere, Campus Universitário, Maputo, Mozambique

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the major locations and constraints along value chains where excessive food loss and waste occur; as well as, assessment of the trade-offs between the costs and benefits from food loss and waste reduction amongst others (Cattaneo et al. 2020; Miljkovic and Winter-Nelson 2020).

Most recent estimates point to food loss and waste in SSA at nearly 20 percent of global food wastage (FAO 2019). In that region, PHL in grains is estimated at about 10–20 percent of the total production, valued at around $USD 4 billion a year (Chegere 2018). There are also empirical findings pointing to losses in cereals and pulses at about 22.5 percent due only to storage (FAO 2019). Nevertheless, it has been acknowledged that PHL estimates are largely unprecise mainly due to methodological aspects (Affognon et al. 2015; Sheahan and Barrett 2017).

PHL in maize has been the largely researched topic in the region (Affognon et al. 2015). Some studies point to estimates of up to 46 percent PHL in maize across SSA (Swai et al. 2019). Evidence from Malawi, Tanzania and Uganda point to higher temperatures and humidity, along with inappropriate management practices and unfavourable marketing conditions, as the key drivers of increased PHL levels (Kaminski and Christiaensen 2014). Swai et al. (2019) and Chegere (2018) identified harvesting and drying processes related practices, shelling and cleaning, storage, transportation and marketing as some of the key determinants for PHL in maize.

In Mozambique, climate conditions are also generally regarded as one of the key drivers of PHL by farmers. Currently, the country is ranked 13th worldwide and third in Africa for its vulnerability to natural hazards caused by climate conditions (GFDRR 2019; Irish Aid 2018). Almost every year Mozambique is affected by some sort of natural hazard such as floods, droughts or cyclones (GFDRR 2019; Irish Aid 2018). Between 1956 and 2016, for instance, the country experienced 34 events of floods, 13 droughts and 22 cyclones (World Bank 2019). Early in 2019 the country was also affected by two major cyclones, *Idai* and *Kenneth*. The occurrence of such hazards has a strong impact on agriculture (at pre and postharvest stages), which is the dominant sector contributing to the country's GDP.

Other important drivers of PHL in SSA include agricultural pests, postharvest management practices and marketing barriers. Attacks by pests, particularly insects, aligned with poor storage practices can cause PHL of over 50 percent in maize at the farm level (Swai et al. 2019). Marketing also plays an important role in PHL levels. This is partly because farmers are often located relatively far from major marketplaces, but also due to their limited ability to exploit inter-temporal arbitrage opportunities (Hengsdijk and de Boer 2017; Kaminski and Christiaensen 2014).

In Mozambique, pests have been identified by farmers across the country as a main cause of PHL, along with the lack of adequate storage facilities (MASA 2015, 2016). The routine practice of laying produce on the ground during the drying process, which also creates favourable conditions for the upsurge of pests, is linked with the high levels of PHL reported as well (Cugala et al. 2012; Hugo 2008). Nevertheless, information about PHL (or food loss and waste in general) is scarce in the country and, when available, displays high variability (Kaminski and Christiaensen 2014). Since 2000, available estimates on PHL in maize range from as low as about 3 percent (FAO 2018a) to over 25 percent (Popat et al. 2020).

Market access and incentives to trade play also an important role to the levels of PHL observed in Mozambique. Past studies have found poor integration of domestic markets as well as between some domestic and regional markets (Tostão and Brorsen 2005; Traub et al. 2010). Limited tradability is explained by the historically prohibitive transportation costs in Mozambique, particularly between the North and South regions (Coughlin 2006). This may result in excess stocks at the upper end of the supply chain with consequent food loss and waste. Nonetheless, that has not been properly explored in part due to limited information available.

An adequate understanding of these and other drivers of food loss and waste, along with adequate measurements methods for the magnitude of the losses and waste, are regarded as crucial for the design of effective policies and actions to deal with this problem (Cattaneo et al. 2020). From a policy perspective, there is a need to identify possible intervention points along the value chain and assess the effects of those interventions.

Chegere (2018) and Popat et al. (2020) are amongst the few that attempted to attain monetary value to PHL, which is crucial for effective policy decisions. Chegere (2018) estimates that PHL in maize in Tanzania equates nearly $USD59 per household, whilst Popat et al. (2020) estimate the economy-wide cost of PHL in maize in Mozambique at about $USD 28 million per year. In both cases, the authors suggest that the magnitude of the cost is substantial relative to the size of the economy, which justifies some form of government intervention. In the case of Mozambique, policies to deal with food loss and waste in general, and PHL in particular, are scarce (FANRPAN 2017; FAO 2017).

The complexity in analysing the drivers of food loss and waste (and PHL) can be effectively addressed using a system dynamics approach. In this study, a system dynamics model is developed and tested to assess the economic impact of PHL at the farm level as an endogenous problem. The model considers biophysical and marketing factors and incorporates management decisions and policies that may reduce PHL. The model is applied to the maize value chain in Mozambique. Some applications of system dynamics models to agricultural supply chain problems have been reported in recent years (e.g., Dizyee, Baker, and Rich 2017). Nonetheless, to the authors' knowledge, this study is the first applying a system dynamics model to food crop problems for Mozambique in particular, and, more broadly, the first applying this type of model to assess the economic implications of losses and waste in food crops. This research makes a strong contribution as well to the scarce literature on PHL in Mozambique.

The rest of this article comprises of three main sections. The next section evolves on the methodology, where the system dynamics model applied is described, along with the data used to calibrate the model for the application to Mozambique. Next, the results are presented and discussed from the standpoint of model adequacy first, followed by policy analysis and projections of future trends. The article ends with conclusions and policy recommendations.

2. Methodology

2.1 Maize value-chain overview in Mozambique

Before describing the methodology in detail, it is important to understand the maize value-chain in Mozambique. The majority of maize production is concentrated in the Central and Northern provinces of the country. Together, these two regions contribute about 90 percent of national maize production (MASA 2015, 2016) and are regarded as a maize surplus region, whilst the South is a deficit region for maize as well as for other crops. Overall, the majority of the maize consumed in the South is supplied through imports, whilst informal exports from the surplus region to neighbouring countries have been recurrent (Popat et al. 2020). There is some evidence of high PHL at the farm level occurring in the surplus region (Cugala et al. 2012). In recent years, some mega investments in road infrastructures were expected to result in improved agricultural trade domestically. Despite some evidence of positive impacts from these investments (e.g., the Zambezi River Bridge) towards market integration and reduced transaction costs (Popat et al. 2021), dependence on maize imports by the South and PHL in the North and Centre are still observed.

2.2 System dynamics model

A system dynamics model is used in this study to assess the mid and long run economy-wide costs of PHL in maize in Mozambique. This modelling framework was established over four decades ago; nonetheless, applications to agricultural supply chain problems are recent. A comprehensive description and examples of past studies using system dynamics to agricultural supply chain problems is presented in a separate article.

One of the main advantages of system dynamics modelling is its ability to efficiently mimic a real-world system by integrating large and complex sets of information that can be used for exante analyses, which is important for policy decisions. System dynamics is also regarded as an appropriate model to analyse complex problems even when data availability is limited (Forrester 1996). Likewise, as in the case of this study, information required for system dynamics models can be complemented by ex-post parameters obtained from different techniques such as econometric models.

In line with the research objectives, a system dynamics model comprised of biophysical, management and marketing subsystems is developed. The biophysical subsystem is designed to represent the importance of climate as a driving factor of PHL in Mozambique. Stella (version 1.9.5) is the software used to construct this model.

2.2.1 Biophysical subsystem

In the biophysical subsystem maize yield is expressed as a function of climate variables using Equation 1, a long-established function to describe the relationship between crop yield response and water usage (Steduto et al. 2012). The main assumption underpinning this equation is that water restrictions activate a crops' biological processes to minimise evapotranspiration, leading to reduced yield (Steduto et al. 2012).

$$Y_a = \left[1 - K_y\left(1 - \frac{ETa}{ETx}\right)\right]Y_x \tag{1}$$

Where,

$$ETx = K_c ETo \tag{2}$$

and

Y_a = actual yield (ton/ha);
Y_x = potential yield (ton/ha);
ETa = crop's actual evapotranspiration (mm);
ETo = reference evapotranspiration (mm);
ETx = crop's potential evapotranspiration (mm);
K_c = crop coefficient for evapotranspiration;
K_y = crop's yield response factor.

In Equation 1, *ETo* itself is a function of a set of climate variables and, according to Raes and Munoz (2009) it is consistently estimated by the Penman-Monteith approach (see Appendix A). *ETa*, on the other hand, is difficult to estimate with precision; unless accurate measures of daily water balance are available (Steduto et al. 2012).

Due to limited availability of information to model *ETo* and *ETa* accurately using the approaches recommended, proxy functions for these two variables are defined as in Equations 3 and 4. Based on past observations, these two equations are modelled graphically[1] in Stella.

$$ETo = f(Temp) \tag{3}$$

$$ETa = f(Rain) \tag{4}$$

Where *Temp* and *Rain* are the annual average temperature (in degrees Celsius) and total rainfall (in

Table 1. Parameters used in the system dynamics model.

Parameter	Unit[a]	Value	Source
Ky	Unitless	1.25	(Steduto et al. 2012)
Kc	Unitless	1.1	(Allen et al. 1998)
r	%	2	Calculated (between 2000 and 2017)
r_{pop}	%	3.08	Calculated (between 1997 and 2017)
Yx	ton/ha	2	(Brito and Holman 2012)
Z	USD/ton	5	Empirically assumed

mm). Due to insufficient information, annual average temperature is used instead of temperatures during the maize growing season in Mozambique.

Parameters for Equation 1 are obtained from different sources as shown in Table 1. FAO provides default K_c and K_y values for different crops (including maize). Y_x is based on each country's specific context (e.g., edaphoclimatic conditions, crop variety used, and so on). In the case of maize in Mozambique, Brito and Holman (2012) suggest about 2 ton/ha as the potential yield for farmers matching the profile of the many small-scale farmers from the Central and Northern regions of the country, that often rely on low use of agricultural inputs.

Given yields obtained from Equation 1, total production is computed assuming a constant compound annual growth rate for harvested areas (Equation 5). This rate is computed from data over the period 2000–2017, which overall suggests a constant growth rate for harvested areas. Given that the majority of maize farmers are small-scale and subsistence-oriented – and only a small fraction of farmers commercially trades their produce (MASA 2011) – it is assumed that the decision on the area of land to grow maize is not influenced by the dynamics created by the market. The exogenous assumption on the growing area of land also seems reasonable given that only about 10 percent of the arable land is currently being used in Mozambique (MASA 2011).

$$Prod = A \times Y_a \tag{5}$$

Where

$$A_t = (1 + r)A_{t-1} \tag{6}$$

A = the area of land used to grow maize in year t;

r = annual growth rate of land expansion.

Climate conditions are also assumed to explain part of the PHL observed at the farm level (PHL1, pre-storage PHL), either from its direct impacts or through the creation of favourable conditions to the upsurge of agricultural pests and diseases. In general, warmer temperatures and adequate soil moisture may increase insects' reproduction (Savopoulou-Soultani et al. 2012), which are the major agricultural pests of maize.

There are no empirical studies found assessing the relationship between climate and PHL in maize (or any other agricultural commodity) in Mozambique. Therefore, Equation 7 is defined as a proxy to represent that relationship. This equation assumes the ratio between *ETa* and *ETo* as a proxy for soil moisture that favours pest attacks. The higher the ratio, the higher the expected soil moisture and PHL. Other components of the overall system, i.e., management and marketing related issues, are also responsible for part of the overall PHL observed (denoted as PHL2 below).

$$PHL1 = f(ETa, ETo) \tag{7}$$

2.2.2 Management and marketing subsystems

Implications of management practices on total PHL can implicitly be accounted for in PHL due to climate conditions (PHL1) as well as explicitly in the way they are related to with marketing issues (PHL2). The management subsystem in this case comprises all farmers' decisions and actions that result in PHL. These include postharvest management practices, storage facilities used and trading decisions. This subsystem is the most difficult to model in this study due to insufficient information on farmers' attitudes to postharvest handling practices. Nonetheless, farmers' attitudes towards storage (e.g., the decision to use or not the private storage services provided by the Mozambique's Commodity Exchange, BMM[2]), can be empirically modelled under particular assumptions as represented in Equation 8.

Equation 8 is proposed to describe farmers' decisions on using private storage services. This equation assumes that the decision to store maize in private warehouses is influenced by the storage fees relative to the market value of the product, along with other barriers to access these services. Equation 8 acknowledges the fee (Z parameter) and non-fee (B parameter) barriers that impact on farmers' reliance on private storage services. This equation highlights key aspects that may impact on farmers' attitudes towards the use of private storage services available in the country. Equation 8 could be refined (or redefined) through interviews or experiments with key stakeholders in this value chain.

Farmers' postharvest decision making is a complex topic on which there are not many studies available, particularly in the context of small-scale farmers from developing countries (Ruhinduka et al. 2020). However, Equation 8 is broadly defined to take into account some of the variables (e.g., price and access costs) described in the experiment by Ruhinduka et al. (2020) with small-scale rice farmers from Tanzania.

$$BMM = (1 - B) \times NS \times \left(1 - \frac{Z}{p_{dom2}}\right) \tag{8}$$

Where,

BMM = amount of maize stored in private warehouses (e.g., BMM);
B = barriers to access private storage services other than fees ($0 \leqq B \leqq 1$);
NS = net surplus (after trade);
Z = fee charged for the services provided by BMM;
P_{dom2} = domestic price of maize in the surplus market (where most of the production occurs).

The resulting PHL caused by marketing (and management) issues (PHL2) is obtained as the difference between the net surplus (NS) and the amount of maize stored (BMM) (Equation 9). Marketing aspects such as (domestic and international) price changes are assumed to impact on net surplus due to dynamics created on domestic, export and import demand. In this model, domestic markets are distinguished in surplus (Centre and North) and deficit (South) markets. South Africa and Malawi are used to represent the import and export markets, respectively. South African prices for maize are modelled as an exogeneous process, but spot prices for maize in Malawi are assumed to be determined by the total domestic supply of maize in Mozambique. These assumptions derive from the findings by Popat et al. (2021) that point to mutual price transmission effects between maize markets in Malawi and in the surplus region of Mozambique; and the no apparent price transmission between South Africa and the deficit market. Therefore, the relationship between Malawian prices and maize production in Mozambique is needed to establish the endogenous price relationship between Malawi and the surplus market in Mozambique.

$$PHL2 = NS - BMM \tag{9}$$

Where,

$$NS = Prod + BMM_{t-1} - PHL1 - Cons - Exports \tag{10}$$

$$Cons = (Cons_1 + Cons_2)Pop - Imports \tag{11}$$

$$Cons_i = f(Pdom_i) \tag{12}$$

$$Pdom_1 = \alpha_0 + \beta_0 Pdom_{1,t-1} + \delta_0 Pdom_{2,t-1} \tag{13}$$

$$Pdom_2 = \alpha_1 + \beta_1 Pdom_{2,t-1} + \delta_1 Px_{t-1} \tag{14}$$

$$Px = f(Q_t) \tag{15}$$

$$Q_t = Prod_t + BMM_{t-1} - PHL1 \tag{16}$$

$$Pop_t = (1 + r_{pop})Pop_{t-1} \tag{17}$$

$$Imports = \alpha_2 + \beta_2 Pdom_1 + \delta_2 Pm \tag{18}$$

$$Exports = \alpha_3 + \beta_3 Pdom_2 + \delta_3 Px \tag{19}$$

Cons = domestic consumption of maize in market *i* (*i* = 1 and 2, for the deficit and surplus markets respectively);

Pdom = price of maize in the domestic market;

Px = price of maize in the export market;

Q_t = total domestic supply of maize;

Pop = population size;

r_{pop} = population annual grow rate;

Pm = price of maize in the import market;

Imports = import volume of maize;

Exports = export volume of maize;

$\alpha, \ \beta, \ \delta \ =$ parameters.

Some of the parameters used in the overall system dynamics model are summarised in Table 1.

The only exceptions are parameters for domestic prices and import and export quantity equations, given that their values are adjusted in the model and, therefore, are not necessarily the same as found in the original sources. The initial values for the parameters on the domestic price equations (estimated as natural log) derive from Popat et al. (2021). For import and export quantities, parameters were obtained from linear regression models as described in Equations 18 and 19.

Despite lagged values not being explicitly accounted for in some equations[3] (e.g., import and export equations), in some cases lagged values are intrinsically accounted for by the delays introduced in the model. In system dynamics models, delays are important to mediate behaviour in prediction (Hamza and Rich 2015). There are also exceptional cases where adjustment parameters are introduced in order to improve estimates. Adjustment parameters are introduced in the yield equation (Equation 1), to account for the rapid decline in yield observed in 2012 (which seems an outlier in the dataset), as well as in the export equation (Equation 18) to improve the overall estimates from that equation. These adjustment parameters are not shown in Table 1 (see Appendix B for information on values for the full set of parameters).

In general, the three subsystems are interrelated as the following: the biophysical subsystem is important to determine production, whilst the management and marketing subsystems influence each other in a circular loop. The biophysical subsystem impacts on the model by affecting the production process, as well as by causing part of the PHL that could be avoided (or minimised) if some management actions could be improved. Part of PHL will also be caused by the dynamic relationship between management and market forces in determining the amount of maize traded.

Figure 1 shows the model detail. Apart from the maize prices in South Africa, the exogeneity assumption is also extended to other variables such as temperature and rainfall. These three exogenous processes are modelled using Markov Chain Monte Carlo Simulation.

As defined by Barreto and Howland (2006, 216), "*Monte Carlo simulation* is a method of analysis based on artificially recreating a chance process (usually with a computer), running it many times, and directly observing the results". Uses of this method are well established in a wide diversity of fields. The Markov Chain Monte Carlo method consists of generating proxy samples of a random variable whose distribution matches with a target distribution (Rubinstein and Kroese 2008). In this study, the method is used to generate random samples on minimum and maximum temperatures, rainfall and maize prices in South Africa, all assuming a normal probability distribution function.

The use of Monte Carlo to simulate changes in climate related variables is well known (Baldini et al. 2019; Garijo and Mediero 2019). There are also examples of past studies on system dynamics models applying Monte Carlo simulations (Dizyee, Baker, and Rich 2017).

2.3 Data

Overall, data is a major limitation on this study, mainly hampered by the budgetary limitations for primary collection and the limited number of observations on secondary data for many of the

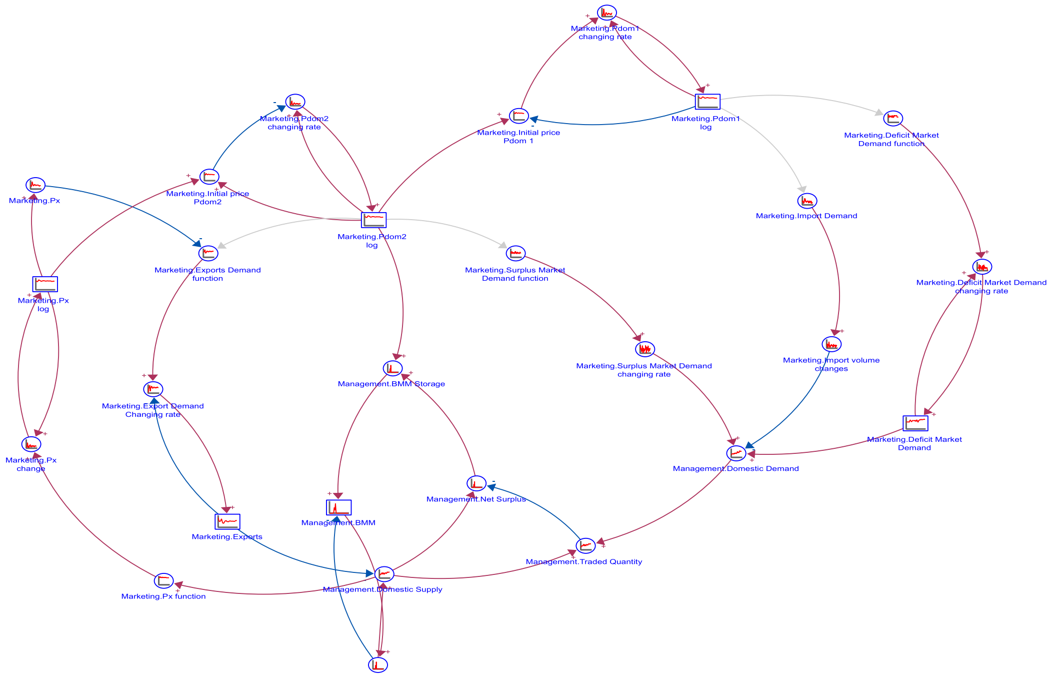


Figure 1. Complete system dynamics model for PHL in maize in Mozambique.

variables used. The datasets used come from different sources covering different periods as shown in Table 2. In general, these data are also at different levels of aggregation and frequency. To effectively model the overall process, yearly data is used, which is the widest frequency across the variables collected.

With regard to balance sheet elements, available information is aggregate at a national level. To account for the asymmetries between the deficit and surplus regions, data on consumption is disaggregated for these two regions based on the overall consumption per capita. Annual maize consumption for each region is estimated from estimates of annual population size based on disaggregated data from the last three population census. Multiple sources are also considered for balance sheet elements due to some inconsistencies found and highlighted in Popat et al. (2020).

For price and climate data, proxy regions are used to represent the different regions domestically as well as the exports and imports markets. For prices, Maputo and Chimoio are considered as the reference markets for the deficit and surplus regions, and Malawi and South Africa as the reference markets for exports and imports, respectively.

Climate data, which is collected from the National Oceanic and Atmospheric Administration (NOAA) (from the U.S. Department of Commerce) and Popat (2010), were collected for specific locations. Where available, climate data from Chimoio – a district in Manica province (Centre of Mozambique) – is used. This province is ranked in the top three major producers of maize in Mozambique. Alternatively, for variables such as *ETo*[4] and *ETa*, whose data from Chimoio could not be accessed, information from Beira (a district located relatively close to Chimoio) is used.

2.4 Further assumptions

Apart from the assumptions mentioned earlier, several additional assumptions are required to understand the modelling process and for interpretation of the results:

Table 2. Variables and their respective sources.

Variable	Description	Unit[a]	Frequency: Aggregation level	Source	Data availability/Period collected
Area	Harvested area	(x 1,000) ha	Yearly: national	(USDA 2018)	2000–2017
Ya	Maize yield	ton/ha	Yearly: national	(USDA 2018)	2000–2017
Prod	Maize production	(x 1,000) ton	Yearly: national	(USDA 2018)	2000–2017
Cons	Consumption	(x 1,000) ton	Yearly: national	(FAO 2018a)	2000–2013
M	Imports	(x 1,000) ton	Yearly: national	(UN COMTRADE 2018)	2001–2015
X	Exports	(x 1,000) ton	Yearly: national	(FEWSNET 2018)	2005–2015
PHL	Postharvest losses	(x 1,000) ton	Yearly: national	(FAO 2018a)	2000–2013
Pdom1[a, b]	Maize price in Maputo	USD/ton	Monthly: district	(MASA, spreadsheet)	2007–2015
Pdom2	Maize price in Chimoio	USD/ton	Monthly: district	(MASA, spreadsheet)	2007–2015
Pm[c]	Maize price in South Africa	USD/ton	Monthly: district	(FAO 2018c)	2007–2015
Px	Maize price in Malawi	USD/ton	Monthly: district	(FAO 2018c)	2007–2015
Pop	Population	people	Yearly [d]: province	(INE 2018)	1997, 2007 and 2017
Temp	Temperature	° F (converted to ° C)	Daily [e]: district	(NOAA 2020)	2005–2019
Rain	Rainfall	Inches (converted to mm)	Daily: district	(NOAA 2020)	2005–2019
ETx		Mm	Yearly: district	(Popat 2010)	2000–2009
ETa[f]		Mm	Yearly: district	(Popat 2010)	2000–2009

[a]Domestic prices are converted from their original units (MZN/Kg) to USD/ton using exchange rate data gathered from the Mozambique's Central Bank.
[b]All prices are converted from monthly to annual basis and to real terms using Mozambique's CPI gathered from the World Bank (2020).
[c]Except for prices from the imports market, which is at wholesale level, all other prices are at retail level.
[d]Available for specific years (1997, 2007 and 2017) only.
[e]Dataset with gaps, not covering every day of a normal calendar.
[f]Estimated from Equation 1, based on past realisation of other variables.

- Population growth is used to account for the increased domestic demand over time due to factors other than price. This assumption is also important to balance increased production from exogenous growth in harvested areas;
- Other uses of maize are negligible, so the difference between net surplus and storage is assumed to result in PHL. Nonetheless, the model assumes that up to 25 percent of the net surplus ($B = 0.75$) can be stored for future trade, which may vary slightly according to market prices as suggested in Equation 8;
- Imports are the preferred source by the deficit market. This assumption captures, in part, the preference in quality attributes for imported maize. Nonetheless, the volume of imports is defined to be dependent on price changes;
- Similar to imports, exports will respond to price incentives.

2.5 Model validation

Results from the model are validated using the structure-verification test approach. These are described as core tests for system dynamics models (Forrester and Senge 1979). In this case, the structure-verification test consists of assessing the model's behaviour against the real observations using visual and statistical approaches. The model is initiated with data from 2003, and the period 2004–2013 is used for the structure-verification test.

In general, standard statistical approaches are described as inappropriate to assess system dynamics models (Barlas 1989). Barlas (1989) suggest that an effective assessment of system dynamics models should centre on patterns over time. Apart from visual inspection to compare patterns over time between fitted and actual values, descriptive statistics of the two series are also compared. Mean average percentage error (MAPE) is used to assess the model's goodness-of-fit. MAPE gives the overall ability of a model in prediction.

2.6 Scenarios

The model is used to test different intervention scenarios and their economic implications over the decade 2020–2030. The scenarios tested are described in Table 3. Scenario 1 is the business-as-usual case. Scenarios 2–9 represent suggested improvements along various stages in the supply chain (B–E), both individually and as packages.

In Scenario 2, the model is used to test the impact of increased production which is a specific policy of the government. In this scenario, increased production alone is tested, given the lack of other policies explicitly related to promoting trade (domestically or regionally) or reducing PHL in Mozambique. Scenario 3 assumes that the only intervention is on reducing PHL due to climate related issues. The underpinning assumption under this scenario is the apparently less costly approach (in financial terms) for reducing part of the overall PHL. Reducing PHL due to climate related issues would be dependent, in part, on changes in postharvest management practices by farmers.

Scenarios 4 and 5 assume improvements in transportation that reduce domestic prices and increase the volume of maize stored by private storage service providers (e.g., BMM) respectively. The last four scenarios represent combinations of the increased production scenario with other scenarios as detailed in Table 3.

3. Results and discussion

3.1 Model adequacy

The observed (solid lines) and fitted values for key variables in the system dynamics model are shown in Figure 2. Overall, a visual inspection suggests that the model adequately fits the observed data in most cases. Under or over prediction of the values for some variables is due to the errors associated with any modelling process as well as to the limited amount of information available for this study. Overall, the model is run with yearly data, for which less than 30 observations per variable are available. In a few instances, such as with imports and exports, the datasets seemed insufficient (around 13 observations for each) to describe the true relationship between different variables.

In the latter cases (imports and exports), linear regressions between quantities and domestic and regional prices return coefficients describing seemingly spurious relationships. For instance, a linear

Table 3. Scenarios tested for PHL over the period 2020–2030.

Intervention	Scenarios									Changes to the model
	1	2	3	4	5	6	7	8	9	
A. Base	X									None
B. Increase production (7%)		X				X	X	X	X	Equation 1: Potential yield[a] (Yx) increased by 5% a year
C. Reduce climate-related PHL (50%)			X			X			X	Equation 6: 0.5 adjustment factor multiplying PHL1
D. Increase transport efficiency (10%)				X			X		X	Equation 14: 0.1 absolute increase in the (negative) intercept[b] (α1)
E. Increase access to private storage					X			X	X	Equation 8: Barriers to private storage access (B) reduced from 0.75 to 0.5

[a]A change is introduced to the potential yield in order to not ignore the impact of climate on actual yield and production. This results in a net increase in production of about 7%, due to the exogenous growth assumed in the production area. That is the increased production level planned by the government for the period 2010–2020 (MASA 2011).

[b]The most significant coefficient on infrastructure investments obtained from Popat et al. (2021) is −0.09, which is embedded in the intercept of Equation 14.

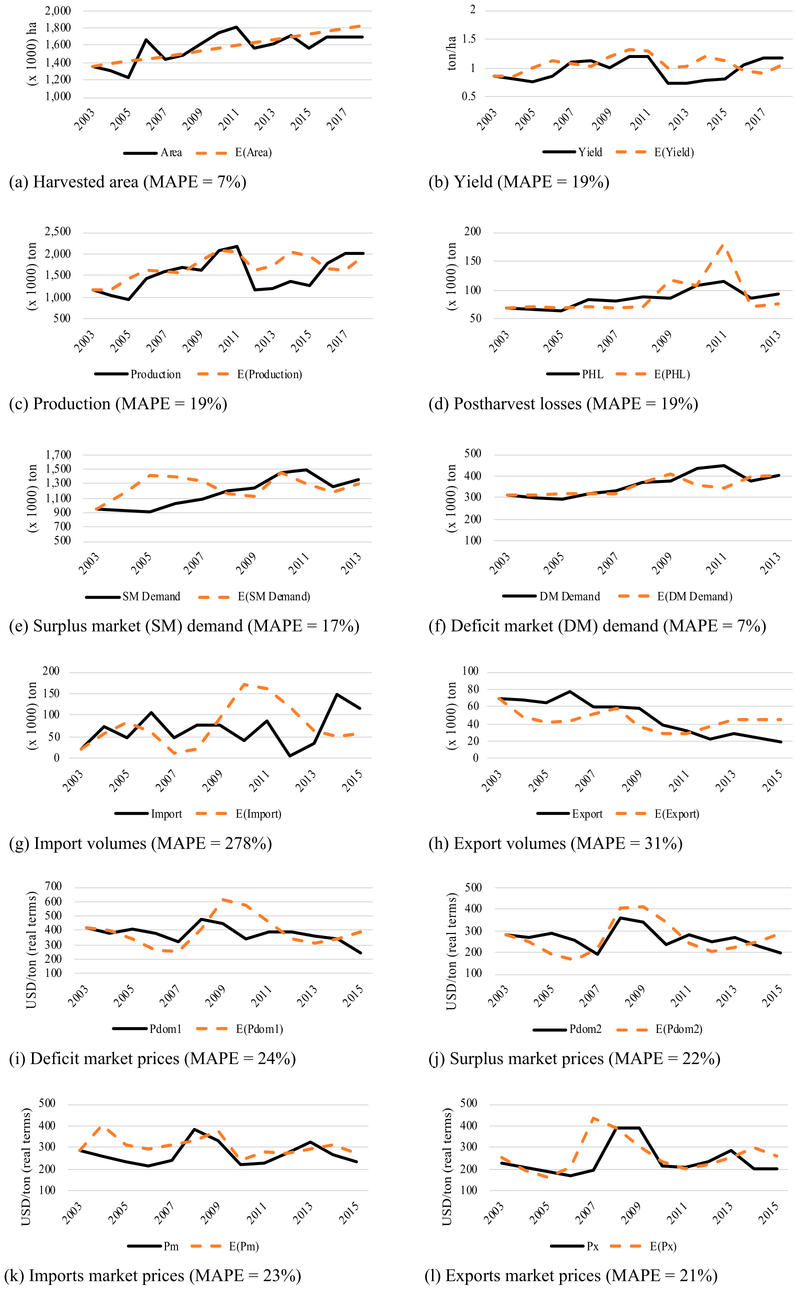


Figure 2. Fitted vs observed values.

regression on import volumes and maize prices in Maputo and South Africa returns coefficients with a negative sign to domestic prices and a positive sign to imports market prices. Similar outcomes are found when lagged prices are used. From a theoretical point of view, this is an unexpected outcome. Thus, due to a lack of published information to adequately model these two processes, coefficients to describe the relationship between (import and export) quantities and prices were adjusted to take signs with some economic meaning[5] and up to a point where fitted values reasonably mimic (from a visual perspective) the observed data. In fact, the ability to model a real-world problem in situations

Table 4. Descriptive statistics for the observed and fitted values (2004–2013).

	Mean	Stdev	Min	Max	CV
Area	1,547.00	182.86	1,230.00	1,813.00	0.12
E(Area)	1,518.95	91.04	1,387.20	1,657.83	0.06
Yield	0.96	0.19	0.75	1.20	0.20
E(Yield)	1.10	0.14	0.86	1.33	0.13
Production	1,494.30	416.46	942.00	2,179.00	0.28
E(Production)	1,670.80	269.40	1,187.58	2,077.72	0.16
PHL	87.60	15.83	65.00	116.00	0.18
E(PHL)	90.75	35.78	70.09	179.88	0.39
SM consumption	1,190.90	205.14	912.04	1,483.59	0.17
E(SM consumption)	1,278.63	115.57	1,129.31	1,444.85	0.09
DM consumption	365.20	54.83	289.96	446.41	0.15
E(DM consumption)	355.08	38.24	313.35	410.06	0.11
Imports	60.19	29.80	5.74	107.44	0.50
E(Imports)	84.69	53.16	13.16	171.14	0.63
Exports	51.05	18.97	21.80	77.52	0.37
E(Exports)	42.03	9.04	29.55	57.66	0.22
Pdom1	390.77	44.59	324.00	474.48	0.11
E(Pdom1)	396.03	121.85	251.63	614.03	0.31
Pdom2	272.83	49.39	187.53	357.44	0.18
E(Pdom2)	264.97	88.83	161.50	412.18	0.34
Pm	270.90	56.43	212.54	380.60	0.21
E(Pm)	311.63	48.99	239.09	401.15	0.16
Px	249.25	79.03	172.55	388.29	0.32
E(Px)	261.13	87.78	166.70	432.56	0.34

like this of limited access to information is one of the major advantages of using system dynamics models.

Apart from estimates related to the import and export markets, MAPE estimates for the overall domestic market components of the model concur with the visual inspection in suggesting the adequacy of the system dynamics model in describing the problem. The highest MAPE estimate (except for import and export volumes) is below 25 percent (Figure 2). MAPE at about 10–20 percent suggest good forecasting and up to 50 percent a reasonable forecasting ability from a model (Moreno et al. 2013). In average terms (Table 4), the model seems also to replicate the behaviour shown in the observed data.

3.2 Valuation of postharvest losses

The overall adequacy of the model allows the economic impact of PHL to be assessed. A strength of the model is its ability to distinguish between postharvest losses due mainly to climate related issues and those due to marketing dynamics. Overall, the value of total PHL is high (Figure 3) On average (2003–2013), PHL in maize account for about $USD 30.8 million annually at the average nominal price. This is close to the findings by Popat et al. (2020) using a different methodology (about $USD 28 million annually). Using average historical prices over the two markets results in similar estimates (nearly $USD 28.5 million annually). However, this simplistic arithmetic exercise on past observations is of limited use from a policy analysis perspective, as it does not allow for assessment of causal-effect, long-term projections, or the distribution of PHL impacts across different actors (this last assessed in the study by Popat et al. (2020)).

Disaggregated results point to climate as the major driver of PHL of maize in Mozambique, particularly in years with low production. Over the period 2003–2019, the model suggests that climate related issues were consistently linked to PHL at about 70,000 tons per year. This outcome suggests that, over that period, farmers did not improve their postharvest handling techniques and therefore the amount of PHL due solely to climate related issues remained about the same. Issues with handling techniques immediately after harvest are not a specific problem to Mozambique. Sheahan and

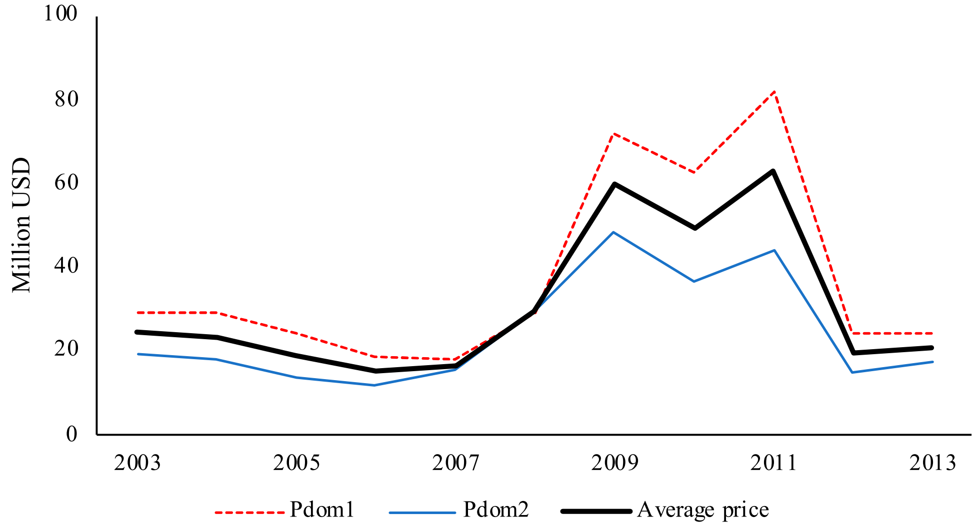


Figure 3. Annual cost of total PHL in maize assuming prices in the deficit (Pdom1) and surplus (Pdom2) markets, and the average price between the two.

Barrett (2017) highlight these as amongst the major causes of PHL in SSA; due mostly to farmers' drying techniques that are strongly reliant on direct exposure to the sun and other factors that accelerate biodeterioration.

In average terms (2003–2019), results from this study point to PHL due to management issues (i.e., PHL due to climate related issues) at about 4 percent of the estimated production. That is close to the relative amount (2.9 percent) of PHL in maize before storage reported for neighbouring countries such as Tanzania (Chegere 2018) and it mirrors the overall picture of the Sub-Saharan region. Aggregate estimates in SSA point to drying processes as the cause of up to 2 percent of PHL in maize, with an additional loss of up to 3 percent from threshing and winnowing (Swai et al. 2019).

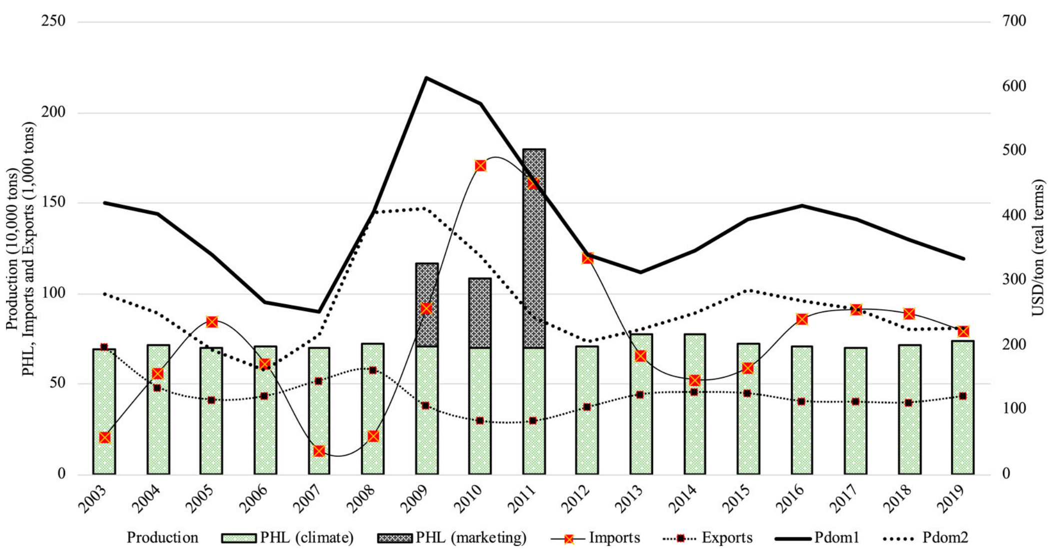


Figure 4. Model estimates on maize quantities (production, PHL, imports and exports) and domestic prices (2003–2019).

In years of increased production, however, marketing barriers are also important drivers for PHL due to excessive supply (Figure 4). The highest PHL depicted (2008–2011) matches the period when observed domestic production increased sharply and more rapidly than domestic consumption. This also corresponds to the period when the highest PHL was reported (Figure 2). The impact of marketing barriers seems to be linked as well to poor storage conditions at the farm level that characterises many other countries in SSA. It is well known that the typical traditional warehouses at the farm level are amongst the causes of deterioration of grains over time in the SSA region (Sheahan and Barrett 2017; Swai et al. 2019), but estimates of these losses are highly variable across countries in the region, ranging from as low as 2 percent to around two-thirds of the overall PHL (Chegere 2018; Swai et al. 2019).

In Mozambique, however, the results shown in Figure 4 suggest that marketing related issues are not always a cause of the overall PHL. For instance, the sharp increase in production observed between 2015 and 2017 (Figure 2) are not necessarily linked to estimates of PHL due to market related issues. With lack of information about the overall PHL and domestic consumption of maize after 2013 it is difficult to judge the accuracy of the estimates of losses due to market related issues in more recent years. Nevertheless, the data and a linear trend (see Figure in the Appendix C) suggest that the overall domestic demand for maize has been higher and increasing at a faster rate than the domestic supply in years beyond 2011. That is a plausible explanation of why climate related issues have been the dominant cause of PHL since then.

The faster increase in demand for domestic maize has been apparently driven by the rapid increase in the domestic poultry industry. Between 2003–2007 and 2014–2018 the average quantity of chicken meat produced in Mozambique rose from about 21,700 tons to nearly 78,000 tons (FAO 2018a). With maize being a key component for poultry feed in the country and the overall domestic demand for maize being higher and increasing faster than the domestic supply, it is unlikely that marketing related issues would be a major cause of PHL.

In Figure 4, an inverse correlation between domestic prices and production is suggested, as expected, but a positive correlation between production and imports is apparent. This positive relationship is confirmed in the correlation matrix for observed data (see Table in Appendix C). There are three possible reasons for this result: (i) there are built-in lags in import orders as shown by a late response in imports from previous changes in domestic prices (e.g., in some instances in Figure 4 increases in domestic prices are followed by increased imports the following year); (ii) inefficiencies in the maize value chain limit domestic trade, therefore domestic production and imports do not show a consistent relationship, and imports and prices in the import market are weakly correlated, or; (iii) the representation of the existing relationship between production and imports is inaccurate given the insufficient information available as highlighted previously. The latter option seems unlikely given the overall adequacy of the model to describe PHL, which is the main subject in this study.

3.3. Future trends

Figure 4 is constructed under the business as usual (or base) scenario, which assumes no changes in the parameters of the model. Under this base scenario, over the period 2020–2030 it is projected that PHL will cost on average nearly $20 million a year. This relatively decrease compared to the period 2003–2013 can be attributed to the inverse relationship between quantity and prices. Table 5 shows the summary of the expected cost of PHL under the different scenarios at the average price between the deficit and surplus markets (see Appendix D for full details on the expected yearly changes in domestic production and prices).

As shown in Table 5, the worst-case scenario is when increased production occurs in combination with reduced climate related PHL (scenario 6). The combined effect of scenarios 2 and 3 (i.e., scenario 6) imply a much larger quantity supplied than scenario 2 alone, which could result in increased PHL due to marketing related issues. If increased production – at about 7 percent a year as targeted by

Table 5. Projected cost of PHL ($USD million) under different scenarios (2020–2030).

Scenarios	Description	Mean	Min	Max	Stdev
Scenario 1	Base	19.59	16.42	21.45	2.06
Scenario 2	Increase production (7%)	79.76	19.27	195.81	61.93
Scenario 3	Reduce climate-related PHL (50%)	10.25	7.99	13.85	1.73
Scenario 4	Increase transport efficiency (10%)	17.60	14.59	20.12	2.02
Scenario 5	Increased access to private storage	19.59	16.42	21.45	2.06
Scenario 6	Increase production and reduce PHL	86.63	9.15	219.42	81.56
Scenario 7	Increase production and transport efficiency	80.80	18.30	165.86	51.34
Scenario 8	Increase production and access to private storage	70.91	19.27	174.68	55.80
Scenario 9	Increase production, transport efficiency, access to private storage, and reduce PHL	47.01	9.24	95.81	30.05

the government over the period 2010–2020 (MASA 2011) – is the only intervention (scenario 2), the cost of PHL is expected to be also very high compared to the base scenario, at almost $80 million a year on average. This amount is about four times the annual cost of PHL projected under the base scenario. Overall, higher costs of PHL compared to the base scenario are projected in all scenarios linked with increased production. This is due mostly to marketing related issues (Figures 5(a,b)).

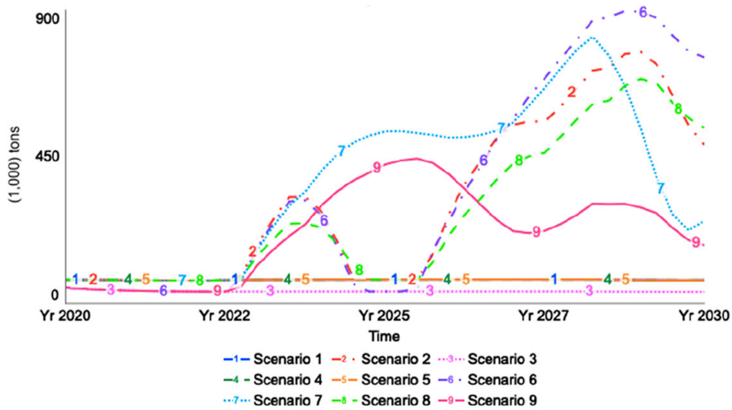
Increasing agricultural production has been the focus not only of Mozambique, but of many countries in SSA. Over the past few years increasing production has been seen as a strategy to compensate for increased demand for food in the region (Chegere 2018). Nevertheless, for some authors, reducing PHL seems the most sustainable strategy given the resource limitations (e.g., land and water) associated with increased production (Chegere 2018; Swai et al. 2019). In the case of Mozambique, however, land is not currently a major limitation and it would unlikely be at least in the mid-run.

In all scenarios with increased production of maize in Mozambique (scenarios 2, 6, 7, 8 and 9), the variability in the estimates of the cost of PHL is high overall. That, apart from being a consequence of the magnitude of the total PHL projected, is likely influenced by the relationship between prices and quantities. Domestic production of maize is weakly correlated with spot prices for maize in the export market (correlation coefficient of about 0.15), which is assumed to impact on domestic prices. Domestic production is also weakly correlated with prices in the domestic market. So, if spot prices for maize are strongly influenced by factors other than domestic supply, increased production is unlikely to significantly increase consumption considerably in the short-term; in which case high PHL can be expected due to increased production levels combined with lack of increased and adequate storage.

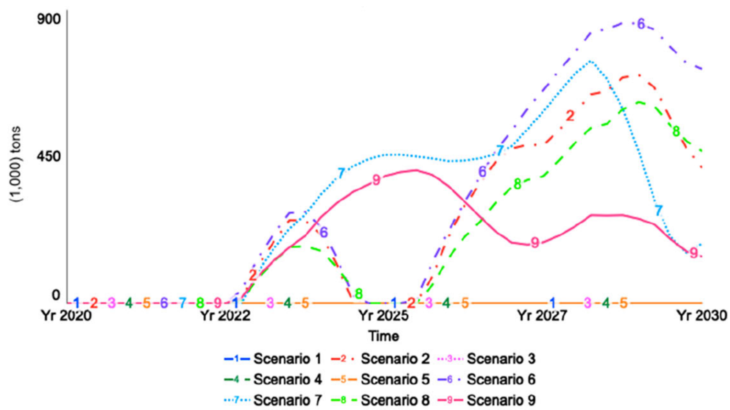
PHL due to climate related issues, on the other hand, are likely to continuously be a systematic problem over the period 2020–2030. That is evident from Figure 5(c). If PHL due to climate related issues can be halved (scenario 3), the expected cost of PHL is estimated at about $9 million less than what is projected under the base scenario. Although apparently less costly to implement compared to other scenarios, interventions required to successfully achieve the goal from scenario 3 may be complex. It can be hindered, for instance, by a lack of economic incentives and social barriers at the farmer level to reduce PHL (Chegere 2018). Limited access to credit by farmers may also represent an important barrier given that a significant reduction in pre-storage PHL may imply substantial investments in improved technologies such as machinery for appropriate drying of grains (Chegere, 18; Sheahan and Barrett 2017).

Another potential strategy to reduce PHL could be through improving farmers' access to private storage services (scenario 5). As shown in Table 5, however, that strategy alone may not produce fruitful results if domestic supply is less or equivalent to domestic demand. That, in fact, is the main reason why outcomes from scenarios 1 and 5 are exactly the same in Table 5. (See Appendix E with the estimated balance sheet based on results from the model for the base scenario).

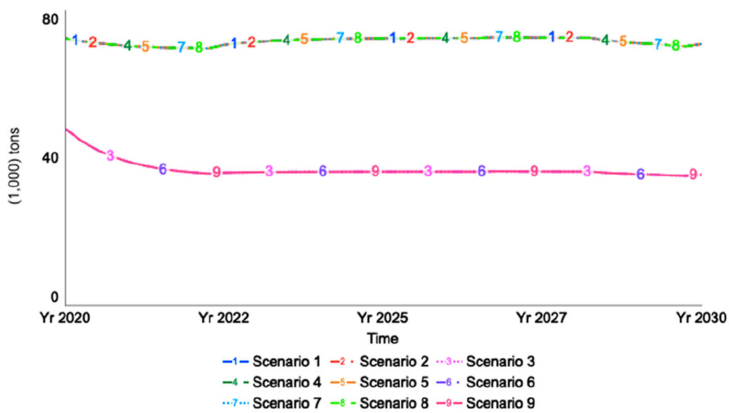
Despite the excessive costs of PHL expected from increased production, that seems to be the most attractive strategy to decision-makers. There are recent examples where increased production



(a) Total PHL



(b) PHL due to marketing related issues



(c) PHL due to climate related issues

Figure 5. Projections for (a) Total PHL, (b) PHL due to marketing and (c) PHL due to climate related issues under different scenarios (2020–2030).

Table 6. Projected changes in average returns from production and consumption ($USD million) (2020–2030).

Scenarios	Description	$USD (million) Revenue	Value of PHL	Gross margin	Value of domestic consumption
(a) Compared with the base scenario (scenario 1)					
Scenario 1	Base	–	–	–	–
Scenario 2	Increase production (7%)	206.13	60.17	145.96	126.61
Scenario 3	Reduce climate-related PHL (50%)	0.60	(9.34)	9.94	9.93
Scenario 4	Increase transport efficiency (10%)	(62.02)	(1.99)	(60.02)	(59.54)
Scenario 5	Increased access to private storage	–	–	–	–
Scenario 6	Increase production and reduce PHL	190.96	67.03	123.93	99.57
Scenario 7	Increase production and transport efficiency	126.58	61.21	65.37	45.65
Scenario 8	Increase production and access to private storage	229.10	51.32	177.78	128.66
Scenario 9	Increase production, transport efficiency, access to private storage, and reduce PHL	124.16	27.41	96.75	61.57
(b) Compared at with the scenario with only increased production (scenario 2)					
Scenario 2	Increase production (7%)	–	–	–	–
Scenario 6	Increase production and reduce PHL	(15.17)	6.87	(22.03)	(27.04)
Scenario 7	Increase production and transport efficiency	(79.55)	1.04	(80.59)	(80.96)
Scenario 8	Increase production and access to private storage	22.97	(8.85)	31.82	2.06
Scenario 9	Increase production, transport efficiency, access to private storage, and reduce PHL	(81.96)	(32.75)	(49.21)	(65.04)

has been successfully achieved over a consecutive couple of years. One is evident from Figure 2. Between 2005 and 2011 yield and production areas increased considerably, which resulted in increased maize production at about 13 percent a year as well as in increased overall PHL. If similar efforts are put in place again, outcomes like that in scenario 2 can be expected in future.

Despite higher costs of PHL being linked with the scenarios of increased production, those scenarios result in very high returns (or gross margin) from domestic supply – calculated as the difference between the gross value of total domestic supply[6] and the cost of PHL – compared with the base scenario (Table 6a). Table 6 shows the changes in revenue, total PHL cost, gross margin and value of consumption for each scenario against the selected reference scenarios. In Table 6a the base scenario is used as the reference scenario for comparisons. The higher returns for most of the alternative scenarios in Table 6a against the base scenario could explain why in the past and currently increased production has been the major goal to improve agricultural performance in Mozambique, despite the potential implications for a high volume (and value) of PHL. A reduction in PHL due to climate-related issues is likely to result in marginal gains in revenue (compared to other scenarios) due to its relatively low contribution to overall supply.

Overall, Table 6a suggests that all alternative scenarios result in higher value of consumption compared to the base scenario, which is linked to increased availability of maize. The only exception is the scenario of increased transport efficiency. Apart from reduced prices, increased transport efficiency is expected to result as well in increased volume of exports, which slightly reduces the quantity supplied domestically.

In Table 6b all scenarios combined with increased production are compared against a reference scenario of only increased production. Results suggest that other interventions combined with increased production may result in lower average net returns and value of consumption compared to increasing production alone. The only exception is scenario 8, where increased production is combined with increased access to private storage. Unlike the other scenarios (6, 7 and 9), increased access to private storage adds value to the surplus produced, which exceeds the negative impact of lower current prices. For consumers, scenarios 6, 7 and 9 impact positively by reducing the cost of maize sourced domestically.

Table 6b also suggests that scenarios 6 and 7 may result in higher costs of PHL and lower revenue compared to increased production alone. In scenario 6 a reduction in climate related PHL increases the overall PHL due to higher supply and the consequent increase in PHL due to marketing issues.

With increased transport efficiency (scenario 7) an increase in PHL is evident although very low. This occurs because increased transport efficiency results in a relative increase in maize exports. With exports increasing less is stored domestically and, overtime, domestic prices increase, which results in lower domestic consumption of local maize. That might also be an indication as well that, at a certain level of increased quantity supplied, demand becomes more inelastic.

The overall results from Table 6 highlight the fact that increasing production alone, may not necessarily be the best policy to maximise returns in the maize production sector. Also, any of the other interventions alone, may not necessarily offset the gains from increasing production. Rather, a combination between increased production and other forms of interventions results in higher returns.

Outcomes from Table 6 should not be regarded as an accurate assessment of the net benefits from each of the scenarios tested. A more detailed assessment would take into account all the direct and indirect benefits and costs associated with each of these scenarios. One important indirect benefit from reducing PHL that should be taken into account is related to food security in the country; which, in the mid and long run, could potentially offset benefits from other stand-alone forms of interventions in the maize value chain as well as the direct costs associated with the implementation of some of the strategies aimed at reducing the levels of PHL.

3.4 Potential improvements

Although the results from this study are consistent with previous findings about the short run costs of PHL in maize in Mozambique (Popat et al. 2020), some improvements to the model are possible with additional data. Firstly, a more precise relationship between postharvest losses and climate conditions is desirable. The function established in this study is driven by historical data on temperature and rainfall, combined with information on overall PHL, not derived from direct measurements. Also, access to seasonal instead of annual average values of climate data could have improved the overall estimates from the model, in particular for yield and PHL1.

Aligned to the previous point, model projections could be improved by obtaining seasonal climate data and considering future climate variability. Climate projections are based on a stochastic modelling approach using annual data. This means the model does not currently capture the most likely (based on the most recent climate trend scenarios) future trends due to climate change, including the potentially damaging effects of seasonal changes in climate (such as shortened seasons or delayed rains). Therefore, projections from this study should be interpreted cautiously.

Nevertheless, given the purpose for which the model was constructed and its overall adequacy in describing past observations, including PHL and prices, the findings from this study provide useful insights for policy. Results clearly show that the full value chain must be considered in agricultural policy rather than focusing only on interventions to increase production at the farm level.

In future, apart from improvements with the use of more adequate climate data series, the model can be extended to include more experiments such as the role of BMM and trade policies in reducing PHL, or the impacts of climate change or other major events (e.g., the COVID-19 pandemic) on the overall supply chain. With the current model, although the impact of reduced barriers to access private storage services is tested, the effective role of BMM is not explicitly tested. That is a consequence of the behavioural assumptions made in Equation 8. Equation 8 could be redefined based on information from experiments or interviews with key stakeholders. With regard to regional trade policies, impacts of trade policy on regional price transmission between Mozambique and its main exports and imports markets for maize were found to be insignificant (Popat et al. 2021). Thus, regional trade policies in place became irrelevant for this study.

4. Conclusions and recommendations

This study found that the annual average value of PHL in Mozambique for the period 2003 -2013 to be over $USD 30 million - in line with similar studies. Climate related issues were consistently responsible for most PHL at about 70,000 tons a year over that period. Over the next decade (2020–2030), the cost of PHL is projected to remain high if no changes are introduced. If government initiatives to support farmers focus only on increasing production, the cost of PHL is likely to increase significantly, unless other actions along the supply chain are taken simultaneously. In the past, increased production has been associated with high levels of PHL. Increasing production is an appealing strategy to improve the net returns from production, at least at the farm level perspective. However, combining increased production with other forms of intervention aiming at reducing PHL are more likely to improve net returns, particularly if indirect benefits such as to food security are accounted for.

Notes

1. All equations not explicitly shown throughout the methodology have been estimated using the graphical function from Stella.
2. The use of private storage facilities is still incipient. In 2012 the government of Mozambique launched the Mozambique's Commodity Exchange (BMM), whose role include linking sellers and buyers of agricultural commodities (including maize) through the provision of services such as storage and quality assurance (BMM 2016). The effectiveness of BMM in engaging particularly smallholder farmers, however, is not yet evident.
3. Lagged values on import and export equations were tested in the linear regression models, however, they did not provide substantial improvements in the models' estimates.
4. Data on evapotranspiration is not readily available from official statistics in Mozambique or from NOAA. Popat (2010) estimated reference evapotranspiration for Beira was based on the Penman-Monteith equation.
5. e.g. in the case of imports, a positive sign for the coefficient on domestic prices and a negative sign for the coefficient on the imports market prices are assumed. The opposite is assumed in the case of exports.
6. Gross value of domestic supply (or revenue) is defined as the product between the (average) domestic prices and the value of domestic production and previous year stocks.

Disclosure statement

No potential conflict of interest was reported by the authors.

ORCID

Meizal Popat http://orcid.org/0000-0003-2669-6870

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