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Parameter Uncertainty in Policy Planning Models: Using Portfolio Management Methods to Choose Optimal Policies under World Market Volatility

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Declarations of interest

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4 ABSTRACT

5 Even accurate and precisely specified models with excellent underlying data quality can be inhibited by parameter uncertainty that reflects uncertain factors. This paper suggests adopting 6 7 portfolio management methods from finance in policy planning models as a practical tool for 8 explicitly reckoning the parameter uncertainty when defining optimal policy. We demonstrate the 9 approach in an economywide model that aims to find an optimal pro-poor agricultural value chain 10 in Senegal under the world market uncertainty. We show that prioritizing the rice sector is the most 11 effective policy in terms of expected policy return, but this policy is also associated with the highest risk, increasing poverty under unfavorable yet realistic scenarios. However, like diversified 12 portfolios in finance, balancing rice promotion with support for other sectors can reduce risk at the 13 cost of reduced expected policy return. The suggested methodology allows for explicit risk-based 14 decision-making and can be used in policy prioritization models that cannot define robust optimal 15 policy under standard parameter sensitivity analysis tests. 16

18 1. Introduction

19 Modern evidence-based policy requires a model-based quantitative assessment of policy options considered by policymakers (Henning et al., 2017). However, policy analysis models often rest on 20 potentially influential assumptions and ad-hoc rules that can corrupt policy conclusions. The 21 sources of the modeling uncertainty can differ, ranging from underlying data quality describing 22 history or status quo to required assumptions/postulates about possible future developments. At 23 the same time, given the growing importance of evidence-based policy planning, there is also 24 certain progress in acknowledging the specific problems of modeling uncertainty and its impact 25 on modeling projections and conclusions (e. g. Manski, 2011, 2018; McKitrick, 1998; Hertel et 26 27 al., 2007; EPA, 2017; Chatzivasileiadis et al., 2018).

We focus on the problem of modeling uncertainty in one of the most famous tools used in 28 policy planning - Computable General Equilibrium (CGE) modeling (Dixon and Rimmer, 2016; 29 Taylor, 2016). Unlike partial equilibrium models, CGE models are completely specified and allow 30 estimating the economywide implications of potential policy interventions and exogenous shocks. 31 In various fields, they are used to compare policy options and define optimal interventions. For 32 example, Ojha et al. (2013) use a CGE model of India and compare the economic and distributional 33 34 consequences of policies that promote the growth of physical capital, human capital, and 35 technological progress. Liu et al. (2015) use China's financial CGE model to investigate the effectiveness of various monetary policy options in response to oil price shocks. Ge and Lei (2017) 36 37 use China's bioethanol CGE model and argue that demand incentives are better than supply 38 incentives for GDP growth, energy saving, and emission reduction. Benfica et al. (2019) use a 39 CGE model of Mozambique and show that the government should have reallocated resources

towards agricultural research and extension, as this is the most effective policy at raising growth 40 and reducing poverty in all regions of the country. 41

However, conclusions based on classic deterministic CGE analysis often are not robust, 42 and even the best-fitted and tailored models with excellent underlying data quality can be inhibited 43 by modeling uncertainty. Like other policy planning instruments, CGE models have been criticized 44 45 for intransparent results, lack of robustness checks, and publication bias (e. g., McKitrick, 1998; Domingues and Haddad, 2005; Taylor, 2016, Olekseyuk and Schürenberg-Frosch, 2016). In many 46 47 instances, simple model reparameterization can affect policy simulations' quantitative and even qualitative results (e.g., Domingues and Haddad, 2005; Olekseyuk and Schürenberg-Frosch, 2016; 48 Phimister and Roberts, 2017). In other words, even if higher-level modeling problems such as the 49 validity of selected functional forms or the quality of the macroeconomic data do not represent a 50 significant source of modeling uncertainty, a simple reassignment of influential exogenous 51 parameters can also significantly change policy simulation results. The necessity for several model 52 53 parametrizations depends on the study context, and can be driven, for example, by the lack of country-specific trade elasticity estimates (e.g., Olekseyuk and Schürenberg-Frosch, 2016) or 54 uncertainty regarding the world's future economic and demographic development (e.g. Webster 55 56 et al. 2008). Regardless of the reasons, when justified model reparametrization of a CGE model amends the ranking of considered policy options, standard deterministic policy comparison 57 58 methods become insufficient to define an optimal policy.

59

As a practical tool to address the problem, this paper proposes adopting portfolio management methods from finance. Unlike economic planning, which started acknowledging the 60 problem of uncertainty relatively recently¹, financial theory has focused on risk and uncertainty 61

¹To our knowledge, formal methodology of parameter uncertainty representation in CGE simulations was formalized only in 1996 by Arndt (1996).

for decades. Pioneer of Modern Portfolio Theory (MPT), Harry Markowitz developed his fundamental model in the 1950s (see Markowitz 1952, 1959), and to this day, its various extensions and elaborations are used in the financial markets (Gordon, 2009). The critical features of MPT are the explicit representation of the risk and return trade-offs associated with potential investment combinations and the exploration of risk diversification possibilities driven by the conventional wisdom of "never putting all your eggs in one basket" (Mangram, 2013).

In this context, we propose that in addition to the standard expected policy impact 68 estimates, policy options in CGE models should be analyzed from the risk perspective, with 69 70 indicators of policy impact variation caused by model reparameterization representing the risk dimension (e.g., represented by the standard deviation). Furthermore, we propose a method of 71 exploring various combinations of mixed policies to explore risk diversification possibilities and 72 argue that, like in MPT, policy choice should depend on policymakers' explicit risk/return 73 preferences. To our knowledge, this is the first paper to propose adopting MPT principles in 74 75 economic policy planning models.

We demonstrate the concept in CGE-based analysis of agricultural value chains that is 76 frequently used in practical policy advice in many low-income agrarian countries (e. g. Benfica 77 78 and Thurlow, 2017; Otchia, 2018; Wiebelt, Randriamamonjy, and Thurlow, 2020). We use Senegal as a case study country and focus on defining its pro-poor agricultural policy. Poverty 79 80 reduction and pro-poor growth are declared the most important goals of this nation (World Bank, 81 2020b; African Development Bank, 2010), and many studies demonstrate that on the macro level, agriculture remains the most efficient sector in achieving these goals (e. g., Diao et al., 2010; 82 83 Valdes and Foster, 2010; Klasen and Reimers, 2017). However, developing a country-specific 84 agricultural policy requires a rigorous comparative CGE-based analysis on a sub-sectoral level.

First, we perform a standard deterministic CGE simulation analysis. As a domain of policy 85 interventions, we consider the productivity growth of ten primary agricultural sectors, and as a 86 target outcome, we focus on the national poverty level. Our standard deterministic comparison of 87 agricultural sectors suggests that the promotion of the rice sector has the highest potential for 88 poverty reduction. As a next step, we question the standard assumption about constant world 89 90 market prices and model the uncertainty of the CGE parameters representing world markets. We demonstrate that promotion of the rice sector is not always the optimal policy, and, depending on 91 the world market scenario, other sectors can be more effective in poverty reduction. As a method 92 93 to define optimal policy under uncertain world markets, we refer to the MPT principles and consider the domain of diversified policies. Finally, we calculate the expected policy return and 94 risk metrics for all policy scenarios (standard non-diversified and diversified). 95

We find that a policy that exclusively promotes the rice sector is the most effective in 96 poverty reduction when only focusing on expected policy return. However, this policy is also 97 98 associated with the highest risk. Under the least favorable scenarios, the exclusive promotion of the rice sector can even lead to increased poverty. Mixed policies that assume policy diversification 99 can reduce risk at the cost of reducing the expected return. We show that mixing the promotion of 100 101 the rice sector with support for milk, vegetables, oilseeds, or the fishery sectors can mitigate the risks associated with rice. Given that Senegal prioritizes the rice sector (Liesbeth et al., 2013), our 102 103 findings thus could benefit its practical policymaking.

The rest of this paper proceeds as follows. Section 2 provides an overview of the CGE modeling literature that addresses the modeling uncertainty problem. Section 3 highlights the existing methodological gaps and describes how portfolio management methods can complement the arsenal of tools to address modeling uncertainty in CGE-based studies. Section 4 demonstrates

the application of portfolio management methods to the analysis of Senegalese pro-poor
agricultural value chains. Finally, section 5 highlights the potential implications for policy analysis
and concludes.

111

2. Uncertainty in policy planning models

Policy analysis models often rest on undisclosed modeling assumptions, and proper 112 communication of modeling uncertainty between researchers, policymakers, and the public 113 remains relatively rare in practical policymaking (Manski, 2011, 2018). One of the workhorses of 114 policy analysis - CGE models, besides underlying data quality, depend on a researcher's choice of 115 116 functional forms and subsequent model parameterization (for an overview of CGE specification stages, see e. g., Dervis et al., 1982; Annabi et al., 2006). Model misspecification at any stage can 117 significantly influence modeling results and affect policy conclusions. In this context, like other 118 119 policy planning instruments, CGE models have been criticized for intransparent results, lack of robustness checks, and publication bias (e. g., McKitrick, 1998; Domingues and Haddad, 2005; 120 121 Taylor, 2016, Olekseyuk and Schürenberg-Frosch, 2016).

In part, the critique can be explained by the increased complexity of the CGE models. Complex CGE models required in modern policy analysis are increasingly opaque, especially to outside observers (EPA, 2017), and sometimes advanced CGE models are even labeled as a 'black box' (Böhringer et al., 2003). Nevertheless, given the growing importance of CGE models for evidence-based policy planning, there has been a clear tendency to increase their transparency, and guidelines of good CGE modeling practice have been developed for various applications. Two focal points of relevant CGE literature can be distinguished. The first considers modeling uncertainty associated with a modeler's selection of the functional forms of core equations, and the second focuses on parameter uncertainty.

Strictly speaking, the literature focused on functional forms does not provide a formal 131 methodology but develops practical modeling advice. First and foremost, researchers are advised 132 133 to avoid building a complex model to answer all possible research questions. Instead, it is recommended to avoid universalism and build a specific CGE model that fits a specific context 134 and answers specific research questions (e. g., EPA, 2017; Taylor, 2016). At the same time, 135 researchers are advised to explicitly justify selected functional forms with underlying empirical 136 evidence, economic theory, or data availability. For instance, Bouët et al. (2014) and Ho et al. 137 (2021) compare the sensitivity of multi-regional trade-oriented CGE models to various 138 specifications of consumer demand functions and highlight simplicity-flexibility modeling trade-139 offs that researchers need to balance. Laborde and Traoré (2017) and Taylor (2016) investigate the 140 impact of endogenizing / exogenizing selected variables (also known as model closure rules²) in 141 single-country CGE models. The authors highlight the importance of properly selecting and 142 justifying macroeconomic closure rules that fit the study and country context. Agbahey et al. 143 144 (2020) investigate the importance of labor supply modeling in single-country CGE models and recommend functional specifications that depend on data availability. 145

At the same time, the literature focused on parameter uncertainty is more universal and has developed a formal methodology to reflect parameter uncertainty in modeling projections. Specified functional forms and closures require model parameterization, and even the best-fitted

² Mathematically, closure rules are necessary because they solve a model's underidentification problem (number of variables is more than the number of equations) by exogeneizing (fixing) selected variables that fit the country, study, or theory context the best. See Löfgren, Harris, and Robinson (2002) for a detailed overview.

and tailored models can be corrupted by parameter uncertainty. The sources of parameter uncertainty can differ, ranging from innocuous econometric estimation errors (e.g., Hertel et al., 2007) to outdated data and assumptions (e. g. Schürenberg-Frosch, 2015; Olekseyuk and Schürenberg-Frosch, 2016). In this context, several studies have demonstrated that the assignment of influential parameter values such as trade elasticities can affect both quantitative and qualitative results of policy scenario simulations (e. g., Domingues and Haddad, 2005, Olekseyuk and Schürenberg-Frosch, 2016).

As a method to represent the effects of parameter uncertainty on modeling results, the concept of Systematic Sensitivity Analysis (SSA) is increasingly used in CGE-based studies (Chatzivasileiadis et al., 2018).

Essentially, the SSA treats exogenous CGE parameters as random variables, thus converting the deterministic CGE model to a stochastic setting. Following Arndt (1996), who popularized the SSA, the method can be formally described as follows.

162 In a general deterministic form of a CGE

$$G(y, x) = 0 \tag{1}$$

163where164y is a vector of endogenous variables165x is a vector of exogenous parameters)166Let us denote167 $y^*(x)$ as a solution to (1)168 $H(x) \equiv y^*(x)$ as a vector of results of interest.

For simplicity's sake, we set aside discussion of the uncertainty associated with the status quo and assume the excellent quality of model data inputs³ - Social Accounting Matrix (SAM) and other corresponding data (e. g., sectoral employment, production quantities, factor use, etc.). In other words, let us assume high precision of the data and parameters that describe the status quo and focus on the model parameters that define the economy's response to potential shocks.

Then, the essence of the SSA is to treat *x* as a vector of *random variables* (instead of a vector of constants). Consequently, the 'classic' deterministic CGE modeling is transformed to a stochastic setting (if *x* is random, so is H(x)). Under this stochastic setting, researchers are not focused on a particular $H(x_i)$ (where x_i is a vector of a particular model parameterization) but are interested in estimating the distribution of H(x), its order statistic (e. g., min, median or specific percentiles) or its moments (e.g., mean, variance).

SSA is gaining momentum in modern CGE studies. For example, Hertel et al. (2007) use 180 the SSA in a free-trade-focused CGE to sample econometrically estimated import elasticities of 181 substitution and estimate 5th percentiles (95% confidence intervals) of the distribution of the 182 endogenous welfare outcomes. Valenzuela et al. (2007) use the SSA to validate the agricultural 183 CGE model of the Global Trade Analysis Project (GTAP) by sampling output shocks and 184 185 comparing simulated and historically observed price volatility in various world regions. Webster et al. (2008) use the SSA to address uncertainty in emissions projections and atmospheric 186 187 stabilization costs for five climate scenarios. Phimister and Roberts (2017) use the SSA to 188 investigate the implications of allowing uncertainty in exogenous shocks when modeling a new onshore wind sector in North East Scotland. Chatzivasileiadis et al. (2018) conduct SSA to address 189 190 parameter uncertainty when analyzing the effects of sea-level rise on the global economy.

³ For a detailed explanation of the data inputs and consequent CGE calibration, see Breisinger et al. (2009).

Mukashov et al. (2019) and Ziesmer et al. (2020) extend SSA's principles to policy parameters and use metamodeling methods to approximate a CGE model in analytic form and include it into the explicitly formulated utility function of a hypothetical social planner.

At the same time, it should be emphasized that, to our knowledge, to this date, the SSA methods are not adequately used in policy comparison CGE studies. At best, SSA is probably used in the background as a confirmatory robustness test of predefined policies and scenarios. However, probably because of the mentioned publication bias problem, none of the policy comparison CGE studies we could find highlight the problem of potentially unstable/nonrobust simulation results that invalidate defined optimal policy.

In this context, in the next section, we explain the problem of unstable/nonrobust optimal policy driven by parameter uncertainty and describe the application of MPT as a possible solution to the drawbacks of the existing CGE-SSA methods.

3. Introducing portfolio management methods to CGE modeling

Let us introduce to the general CGE form (1) k policy scenarios p_i . $(j = \{1, 2, ..., k\})$ 204 considered by policymakers. Let us assume that each policy's (budget) costs are equal, and thus 205 206 each policy is independently equally possible. Furthermore, let us assume that each p_i can be represented in a model via fully controlled parameters that are now excluded from x (x thus remains 207 a vector of randomly distributed exogenous variables/parameters). Finally, let us denote $H(p_i, x)$ 208 as a scalar (instead of a vector) and assume that a benevolent social planner is interested in its 209 210 maximization (*H* thus is a direct proxy for utility). For instance, *H* can be overall economic growth, p_i is funding for sector/policy *j*, and *x* is an uncertain economic environment (for example, volatile 211 world markets or varying elasticity parameters). 212

To define optimal policy under the SSA setting, one should 1. use estimated or assumed (multivariate) distribution of *x* and sample *n* economic uncertainty scenarios { $x_1, ..., x_n$ }; 2. simulate each policy scenario { $p_1, ..., p_k$ } for every sampled { $x_1, ..., x_n$ } and calculate vectors $H(p_j, x)$ (where $H(p_1, x), =$ { $H(p_1, x_1), ..., H(p_1, x_n)$ }, ..., $H(p_k, x) =$ { $H(p_k, x_1), ..., H(p_k, x_n)$ }; 3. estimate distributions of $H(p_1, x), ..., H(p_k, x)$ and/or (directly) compare means/minimums/medians/percentiles to find the best policy p_{opt} (opt $\in j$).

The last step can be non-trivial and involve advanced mathematical statistics. To estimate 219 distributions of $H(p_1, x)$, $H(p_2, x)$..., $H(p_k, x)$ random variables, one can use parametric or non-220 parametric density estimation methods, apply various probability distribution fitting methods, etc. 221 (for an overview, see Mittelhammer, 2013 (ch. 6-8); Härdle et al., 2004). Then, one can use 222 223 standard parametric tests to compare sample means or directly use distribution-free methods to compare sample minimums/medians/percentiles. Regardless of the comparison method, the best-224 225 case scenario would be if a researcher can find $H(p_{opt}, x)$ (opt $\in j$), which has the (statistically) highest mean/median/percentile. In other words, p_{opt} should be robustly superior regardless of 226 sampled uncertainty scenario x. However, identifying p_{opt} can be impossible if 227 means/medians/percentiles/minimums are not (statistically) different. In this case, there is no 228 229 robustly superior policy option (in the next chapter, we provide an example), meaning that the 230 existing CGE-SSA methods are insufficient to identify the optimal policy. As a solution to this common but so far hidden problem, we suggest referring to portfolio management methods from 231 finance. 232

To demonstrate the approach, we rely on the Modern Portfolio Theory (MPT) pioneered by Harry Markowitz (Markowitz, 1952, 1959). The theoretical foundations and extensions of the MPT involve the use of mathematical concepts and proofs that are beyond the scope of this paper

(for details, see Markowitz, 1952, 1959; Samuelson, 1963, 1967, and Sharpe, 1994). However, the
essential aspects of the MPT can be described as follows (based on Mangram, 2013 and Royal
Swedish Academy of Sciences, 1991):

First, in a setting where a price change over a given period measures the return, the risk 239 can be defined as a return variation (usually represented by the variance or standard deviation of a 240 241 price change). Second, diversification, a cornerstone of the MPT, is investment allocation among financial instruments that are not perfectly correlated. Therefore, instead of analyzing a financial 242 243 instrument's return and risk in isolation, investors focus on the risk and return of an aggregate portfolio. Finally, the Efficient Frontier (also known as Markowitz Efficient Frontier) represents 244 the best investment combinations of portfolios producing a maximum expected return for a given 245 risk (or portfolios producing minimum risk for a given return). In this context, 'Risk and return 246 trade-off relates to Markowitz's fundamental principle that riskier investment portfolios should 247 provide a higher expected return (and vice-versa). 248

249 We can use these basic portfolio management principles when CGE-SSA methods do not identify a robustly optimal policy. In particular, as a measure of return, we can use the expected 250 value of a policy impact (e.g., an average over $\{H(p_1, x_1), H(p_1, x_2), \dots, H(p_1, x_n)\}$ sample is the 251 252 expected policy return of p_l ; as a measure of risk, we can use dispersion metrics of a policy impact (e. g., the variance/standard deviation of $\{H(p_1, x_1), H(p_1, x_2), \dots, H(p_1, x_n)\}$ sample is the risk of p_1). 253 254 At the same time, a simple comparison of risk and return metrics of isolated (non-diversified) 255 policy options is insufficient as it reveals only part of the Efficient Frontier, with policy options having the highest return and the lowest risk constituting its two corners/extremes. However, 256 257 depending on risk/return preferences, diversified policy options on the Efficient Frontier can also 258 be optimal. In this regard, we use MPT to demonstrate the presence of multiple potential optimums.

We argue that selecting a specific policy, whether it is diversified or non-diversified, should 259 depend on explicitly formulated risk/return preferences (also known as risk appetite). Without 260 MPT diversification principles (only using standard SSA methods), only the Efficient Frontier's 261 corner optimums (non-diversified options with maximum expected return or minimum risk) would 262 be known. If making parallels to financial markets, consideration of individual (non-diversified) 263 264 policies with the standard SSA methods would be equivalent to making investment decisions based on the return/risk analysis of the individual financial instruments; assets having the highest return 265 (or lowest risk) would then receive 100% of the investment. While, in theory, extremes of the 266 267 Efficient Frontier might be sufficient to satisfy the risk/return preferences of specific investors (ultra conservative and ultra risky), in reality, most financial investors usually analyze the whole 268 spectrum of the potential optimums that constitute the Efficient Frontier and only then select a 269 270 portfolio that satisfies their risk appetite.

To realize the suggested approach in practice, determining the variation of CGE parameters 271 272 becomes the central part of the suggested concept. In a general equilibrium model where, strictly speaking, every parameter affects all endogenous variables, all model parameters should be treated 273 as uncertain random variables (especially if a CGE model is used to produce long-term 274 275 projections). However, given the opaqueness critique of classic deterministic CGE modeling results (EPA, 2017; Bohringer et al., 2003), we believe that the parsimony principle should be 276 prioritized. Like with the problem of functional forms, one should avoid universalism and focus 277 278 on the specifics of particular research questions. Depending on the nature of the considered policy interventions, some model parameters are significantly more influential than others. Thus, to 279 reduce the noisiness of the results caused by less influential uncertain parameters, it becomes 280

imperative to understand the major policy shock transmission mechanisms and focus on theuncertainty of the most important model parameters.

After defining policy and uncertain parameter sets, one needs to define their variation and 283 sample respective scenarios. Like in the SSA procedure described above, one can assume that 284 uncertainty scenarios are exogenous and sample them independently of the policy scenarios⁴. 285 Depending on data availability, the best-case scenario would be if $\{x_1, x_2, ..., x_n\}$ scenarios are 286 sampled from the estimated distribution of x such that the uncertainty environment is reflected in 287 return and risk calculations as realistically as possible. At the same time, if the data necessary for 288 289 estimation is missing, similar to the standard CGE-SSA methods, one can also use basic assumptions (e. g., use 'expert judgment' when assigning unknown correlations among uncertain 290 model parameters, see Webster et al., 2008). 291

Furthermore, considering diversified policy options requires a method to cover the spectrum of possible mixed policy scenarios. At the same time, defining diversified policy scenarios can be relatively straightforward.

In particular, if each government investment policy is (independently) equally possible, one can start with sampling solutions of the following underdetermined equation with linear equality constraints:

$$\sum_{j=1}^{k} share_{j} = 1 \quad \text{subject to } share_{j} \ge 0 \tag{2}$$

298 where *share*_j is an investment (budget) share of policy p_j .

In other words, of the infinitely many solutions to (2), one can sample a sufficiently large number of (jointly) uniformly distributed solutions that adequately represent the spectrum of

⁴ This does not have to be the case. For instance, it might be desirable/necessary to sample scenarios where policy and exogenous parameters are positively/negatively correlated (e.g. export/import policy depends on the world markets).

possible budget allocations (the higher the sample size, the better the coverage; for more details, see e. g., Van den Meersche, Soetaert, and Van Oevelen, 2009). Then, as a second step, sampled budget shares should be transformed into CGE policy parameters. This step might require additional information, such as the relationship between the budget for p_j (in monetary terms) and the values of corresponding CGE policy parameters.

Once all scenarios are defined, each policy scenario should be simulated under every sampled uncertainty scenario, and policy return and risk metrics should be calculated for all policy scenarios. Then, by ranking policy scenarios based on the expected return or risk characteristics, one can construct an Efficient Frontier (where, similar to MPT, higher expected policy return requires taking more risk, or lower risk requires lowering return expectations). As a result, like in MPT, policymakers who face a trade-off between expected return and risk must select an optimal policy based on their explicitly formulated risk/return preferences.

It should be emphasized that a topic of policymakers' risk/return preferences is beyond our 313 314 paper's scope. Potentially any policy on the Efficient Frontier can satisfy policymakers' risk/return preference and, thus, be optimal. In the financial markets, investors usually define their risk/return 315 preferences based on their fundamental characteristics. State-owned investment funds, central 316 317 banks, and pension funds are usually conservative and select their policies around less risky options; private investors and investment funds have a higher risk appetite and move towards 318 319 portfolios with higher returns. In this context, stakeholders' risk/return appetites depend on 320 country-specific national goals, political situation, cultural context, and other local aspects that are beyond our paper's scope. Our paper aims to demonstrate the presence of multiple optimums and 321 322 thus encourage policymakers to explicitly express their risk/return preferences in an environment 323 where higher expected policy return has a cost of accepting higher risk and uncertainty (and vice

versa). Although our method does not offer a universal remedy to uncertainty problems, the 324 suggested application of portfolio management methods contributes to practical policymaking by 325 offering widely-known diversification principles to communicate modeling uncertainty. In this 326 context, our framework can encourage policymakers to explicitly express their risk and return 327 preferences and, therefore, increase the transparency of their policy choices (for detailed 328 329 discussion, see Manski, 2011, 2018).

Finally, there is also a technical factor worth emphasizing. In particular, the movements 330 along risk/return dimensions of the Efficient Frontier largely depend on the study context. If a set 331 332 of considered policies is relatively heterogeneous (e. g., support of export-oriented versus domestically oriented sectors), similar to finance, the expected return reward for taking more risk 333 should be more pronounced. If, on the contrary, one compares highly similar/homogeneous policy 334 options (e. g., support of export-oriented sector a versus export-oriented sector b), movements 335 along risk/return dimensions of the Efficient Frontier can eventually become negligible, making a 336 selection of a particular optimal policy difficult. If making parallels to financial markets, the first 337 case would be equivalent to considering investment diversification among low or negatively 338 correlated assets (e. g. cyclical assets like stocks of industrial companies and counter-cyclical 339 340 assets like government bonds or gold); the latter would be equivalent to lower-level investment diversification performed within the limits of a specific market (where prices of financial assets 341 342 have a high positive correlation, e. g. stocks of tech companies).

343

In the next section, we provide a detailed example of MPT application to the CGE-based agricultural policy analysis in Senegal. 344

345 4. Agricultural policy in Senegal under the world market uncertainty

346 4.1. The standard approach

As our modeling basis, we use the CGE-based analysis of Senegalese agricultural value 347 chains conducted by Wiebelt, Randriamamonjy, and Thurlow (2020). The authors use the 348 regionalized 2015 SAM by Randriamamonjy and Thurlow (2019) and supply it as a data input to 349 the standard recursive-dynamic CGE model of the International Food Policy Research Institute 350 351 (IFPRI) developed by Löfgren, Harris, and Robinson (2002) and Diao and Thurlow (2012). The 352 authors conduct a 'classic' deterministic CGE-based analysis of how effective agricultural sectors 353 are in generating economic growth, reducing poverty, creating employment, and improving 354 nutrition (at the national and regional levels). This type of policy analysis is popular in practical 355 policymaking, and similar studies have been done for Uganda, Ethiopia, Mozambique, Egypt, and 356 many other countries (e. g., Pauw and Thurlow, 2015; Benfica and Thurlow, 2017; Benfica, Cunguara, and Thurlow, 2019; Breisinger et al., 2019). However, as we demonstrate in the example 357 of Senegal, these studies need new methods and approaches to addressing the parameter 358 359 uncertainty problem.

We begin our analysis by tailoring the CGE model to reflect specific adjustment possibilities of the Senegalese economy in the medium term of five years (see appendix A.1 and A.2 for more details) and assigning fixed parameter values (see appendix A.3 for more details). Next, we identify the model's most crucial shock transmission mechanisms and influential model parameters.

As a set of policy interventions *p*, we consider policy-induced Total Factor Productivity (TFP) growth of ten primary agriculture sectors (table 1, col. 1). Furthermore, given Senegal's prioritization of reducing poverty (World Bank, 2020b; African Development Bank, 2010), and

the size restrictions of our paper, we consider the national poverty headcount as the key endogenous variable *H* and disregard other endogenous variables⁵. The calculations of the poverty headcount are done through the IFPRI poverty microsimulation module that uses changes in the real consumption of the representative households as inputs from the primary CGE model and calculates the poverty headcount by comparing per capita consumption versus the poverty line (see Estrades, 2013 for more details).

Like Wiebelt, Randriamamonjy, and Thurlow (2020), we define TFP parameters for 374 sectoral scenarios based on the rule of thumb that +1% growth of total agriculture by 2024 is 375 376 achieved uniquely by a respective sector (table 1, col. 6). This approach allows us to account for differences in GDP sizes (e.g., the poultry sector is two times smaller than vegetables, see Table 377 1, col. 3) and directly compare sectors potential for poverty reduction. To operate with the term 378 'return' in a meaning similar to finance, we calculate policy impact as the percentage difference of 379 the national poverty headcount between the baseline (no-policy) and policy scenarios (in other 380 381 words, positive policy impact indicates national poverty reduction and vice-versa). Furthermore, because policy scenarios represent poverty reduction effect per 1 percent of agricultural growth, 382 we label obtained policy impact estimates as sectoral Poverty-Growth elasticities (PGE, Table 1, 383 384 col. 7). Finally, the obtained PGEs allow us to rank sectors from the most pro-poor to the least propoor agricultural value chain (Table 1, col. 8). 385

⁵ Considering multiple endogenous variables is possible by constructing the utility function that aggregates all outcomes (e.g., an average of outcomes, a weighted average of outcomes, Cobb-Douglas, CES, etc.)

Sector	Short	GDP, %	Export in output, %	Import in consumption, %
(1)	(2)	(3)	(4)	(5)
Sorghum, millet	sorg	1.46	-	0.0

1.15

1.01

rice

gnut

Table 1: Standard CGE analysis of pro-poor agricultural value chains in Senegal

53.6

0.0

TFP growth

1.49

2.94

2.70

per year (6) Standard

(7)

PGE

Rank

(8)

10

1

9

7

6

7

4

4

2 3

-1.04

0.84

-0.53

-0.40 Other oilseeds oils 1.48 4.3 1.2 1.91 Vegetables 4.6 1.49 -0.38 1.78 10.2 vege Fruits frui 1.55 7.4 3.9 1.30 -0.40 Cattle 0.2 -0.30 1.21 0.0 2.53 catt 2.99 -0.30 Poultry 0.85 0.1 0.3 poul Raw milk milk 1.20 2.04 0.02 Fishery fish 1.43 8.2 0.0 2.22 -0.29

19.4

6.0

387 Source: authors' calculations based on SAM 2015 and CGE simulations.

Like Wiebelt, Randriamamonjy, and Thurlow (2020), we conclude that rice and milk are the only sectors that can reduce the national poverty headcount (ranks #1 and #2), with the rice sector being more effective than milk. The primary shock transmission mechanism that explains the obtained results can be described as follows.

In general, the TFP increase means that the country can increase output with the same 392 available production factors (capital, labor, and land). As a result, households that own production 393 factors should receive a higher income and increase consumption. In Senegal, the effectiveness of 394 agricultural sectors in reducing national poverty mostly depends on income distribution among the 395 396 poorer rural households. Per-capita consumption of rural households is 3.7 times lower than that of urban residents, and even with that, poverty in rural areas is 57.1 percent compared to 26.1 397 percent in the capital Dakar and 41.2 percent in other cities (ANSD, 2013). In this context, our 398 399 model suggests that the rice sector is most effective in generating income for poor rural households 400 and thus reducing national poverty. At the same time, it is remarkable that productivity growth of 401 other agricultural sectors (except milk) increases the national poverty level, indicating that poorer 402 rural households under these scenarios lose income. These results can only be explained by the

Rice

Groundnuts

403 price effect that outweighs the increased production. Consequently, analyzing the factors 404 determining price responses is essential to understanding income distribution and poverty 405 reduction patterns.

The increased output of agricultural commodities should be absorbed by domestic or 406 external demand. At the same time, similar to other models of small developing countries, the CGE 407 408 model of Senegal assumes fixed (exogenous) world market prices (see appendix A.1 for details). Given relatively inelastic domestic food demand, the high effectiveness of the rice sector in 409 generating income and poverty reduction can be primarily attributed to its high trade intensity 410 411 (Table 1, col. 4 and 5). Under the standard assumption of constant world market prices, domestic rice producers benefit from import substitution and export expansion opportunities. Essentially, 412 domestic rice producers can increase production without decreasing output prices and therefore 413 enjoy higher income. On the other hand, less tradable sectors have fewer growth opportunities, 414 and their increased production quickly saturates domestic markets, leading to price reductions. 415 Eventually, the price effect in many sectors outweighs increased quantity, causing overall losses 416 for farmers. At the same time, the price reduction can benefit downstream agroprocessing sectors 417 (Table 2). In particular, agroprocessing sectors with a higher share of primary agriculture as 418 419 intermediates should benefit from decreased input prices. For example, meat processing can benefit from the fall in poultry and cattle prices. This spillover effect benefits wealthier urban and 420 421 rural non-farm households, while poor rural households engaged in primary agriculture remain net 422 losers.

Sector	Intermediate costs, %	of which primary agr., %
Meat	41.1	69.7
Fish and seafood	49.0	77.5
Dairy	52.2	32.1
Grain/cereal milling	70.9	81.5
Fruits, vegetables & other	68.4	62.0
Beverages	48.5	39.9
Other foods	41.1	42.6
Cotton yarn & other	58.0	2.2
Leather & other	63.5	6.8
Miscellaneous. non-food	68.5	10.0

Table 2: Linkages between agroprocessing and primary agriculture

424 Source: authors' calculations based on SAM 2015.

These estimates align with Senegal's actual agricultural policy, where domestic rice farming has been prioritized since the 1990s. The current national rice policies include trade liberalization and government investments to boost domestic production (Liesbeth et al., 2013).

428 4.2. Systematic Sensitivity Analysis

429 Our standard simulation results and sectoral rankings rely on the important assumption of 430 constant world market prices. CGE parameters of export and import prices and the (real) exchange 431 rate are assumed to be constant. Given the absence of reliable forecasts and projections about 432 future world markets, this assumption seems natural, and many CGE researchers impose it implicitly without explicit statement (e.g., Chhuor, 2017; Benfica and Thurlow, 2017; Otchia, 433 434 2018; Ferrari, 2018). However, it is known that world commodity markets (including agricultural commodities) follow global economic cycles (e.g., Baffes and Haniotis, 2016; Erten and Ocampo, 435 2012). In this context, it should be noted that the Senegalese government significantly increased 436 437 its investments to promote the domestic production of rice in response to the global commodity boom in the second half of the 2000s (Liesbeth et al., 2013). However, this trend reversed, and 438 with the global decline of commodity prices, agricultural prices fell from 2012 to 2019 (Figure 1). 439

With the most recent turbulence in the world markets caused by the COVID-19 pandemic,
developments in global markets have become unprecedently uncertain (World Bank, 2020c).
Given our simulation horizon of five years, the standard assumption of constant world markets
thus appears questionable. To test the robustness of obtained results, we employ Systematic
Sensitivity Analysis methods.

445

Figure 1: Price index of agricultural commodities



446

447 Source: authors' calculations based on the price index of agricultural commodities by the World Bank
448 (2020a). See appendix A.3 for details.

First, we define a set of uncertain model parameters x (Table 3). In particular, we expand 449 our focus beyond agricultural commodities and consider all uncertainties of external factors 450 relevant to the Senegalese economy. Besides agricultural prices, we consider price variation of all 451 other tradable sectors, including energy and fertilizer prices (both are 100% imported in Senegal). 452 453 This allows us to model possible external changes that create better or worse conditions for sectors more dependent on imported intermediates. Furthermore, as demonstrated in recent years, 454 455 developing countries like Senegal are exposed to volatility on international markets directly, through the prices of tradable commodities, and indirectly, via international capital flows that 456 affect the real exchange rate, investment, and growth (World Bank, 2020c; FAO, 2011). Therefore, 457

to fully reflect the uncertainty of the external economic environment, we also consider the variation

- 459 of the foreign capital inflows (represented in the CGE model as a change in the current account
- 460 deficit⁶).
- 461

Table 3: Uncertain model parameters

Original data	Mapping to CGE model	Short
Agriculture index (WB)	The world price of agricultural commodities	pw_agri
Manufactures Unit Value (WB)	The world price of manufacturing products	pw_MUVi
Energy index (WB)	The world price of energy commodities	pw_ener
Fertilizers index (WB)	The world price of fertilizers	pw_fert
Metals & Minerals index (WB)	The world price of metal or mineral commodities	pw_mtmn
CPI Services (France)	The proxy for the world price of services (France is a major trading partner)	pw_serv
Current account deficit (IMF)	foreign savings	fsav

462 Source: authors compilation (see appendix A.3 for sources and details).

463 To model the variation of the external economic environment, first, we use a historical sample of yearly growth rates from 1980-2019 and analyze the marginal distribution of each 464 variable. We find that individually, all variables except for services (pw serv) roughly follow 465 466 Gaussian distributions around zero means; services, however, are right-skewed with a mean value 467 of 1.26 (average yearly growth rate). Because by design, none of our variables can be assumed to be independent, we need to sample the external economic environment scenarios from an 468 469 analytically specified multivariate distribution. Given this restriction, despite pw serv not being normally distributed, we still assume that together variables representing world markets follow a 470 multivariate Gaussian distribution. 471

472 Table 4: Mean values, standard deviations, and correlations of yearly growth rates

pw agri pw MUVi pw ener pw fert pw mtmn pw serv fsav

⁶ Affects the real exchange rate, see functional forms and closures of the model presented in the appendix A.1

mean	0.00	0.00	0.00	0.00	0.00	1.26	0.00
STD	11.41	8.23	23.95	24.32	20.55	2.84	30.96
pw_agri	1.00	0.69	0.41	0.65	0.50	0.11	0.21
pw_MUVi	0.69	1.00	0.43	0.44	0.41	0.03	0.12
pw_ener	0.41	0.43	1.00	0.43	0.43	-0.09	0.40
pw_fert	0.65	0.44	0.43	1.00	0.38	0.05	0.61
pw_mtmn	0.50	0.41	0.43	0.38	1.00	-0.05	0.18
pw_serv	0.11	0.03	-0.09	0.05	-0.05	1.00	0.00
fsav	0.21	0.12	0.40	0.61	0.18	0.00	1.00

473 Source: authors compilation.

First, we calculate vectors of means, standard deviations (STD), and correlations among variables (Table 4). Then we use the Latin Hypercube Sampling algorithm implemented in the Rpackage 'EnvStats' by Millard (2013) and sample world market scenarios from specified multivariate Gaussian distribution (Table 5).

478

Table 5: Sampled external economic environment scenarios

Saanania	Yearly growth rates												
Scenario	pw_agri	pw_MUVi	pw_ener	pw_fert	pw_mtmn	pw_serv	fsav						
row1	4.89	2.58	7.78	0.67	-0.67	1.03	-6.94						
row2	0.42	1.02	3.05	7.39	-7.41	1.50	16.07						
row3	-3.11	-3.91	-11.54	-0.24	-5.73	0.11	-12.14						
row4	2.48	-3.12	-1.87	12.58	3.52	2.64	7.31						
row5	-5.46	-0.67	-5.99	-9.33	-10.37	2.29	1.59						
row6	-0.89	-2.16	6.39	-2.66	4.89	-0.06	11.06						
row7	-1.95	0.70	-8.96	-11.42	-3.70	2.07	-15.11						
row8	3.60	3.62	-3.03	9.03	10.36	0.80	4.99						
row9	2.29	1.86	12.19	3.23	0.10	0.47	-1.66						
row10	-3.91	-1.65	0.99	-6.00	7.17	1.59	-5.95						

479 Source: authors compilation.

480 Note: To avoid computational problems in the final years of model simulations, we truncate 0.1

481 percentiles from left and right.

To avoid unnecessary complexity, we do not focus on an extensive sampling size and only sample ten scenarios. A low number of scenarios allows us to analytically track possible changes in sectoral rankings while at the same time sufficiently representing realistic external environment scenarios. For each sampled scenario, we calculate sectoral PGEs and rank the sectors (Table 6). 486 This simple approach allows us to test the robustness of the rice sector optimality without referring

487 to sample-demanding statistical tests (e.g., to compare means or medians).

Scen	Rank1	Rank2	Rank3	Rank4	Rank5	Rank6	Rank7	Rank8	Rank9	Rank10
rowl	rice	vege	gnut	oils	frui	milk	catt	fish	poul	sorg
IOWI	0.58	0.38	0.35	0.32	0.32	0.31	0.29	0.29	0.05	0.02
mourt	rice	oils	vege	catt	fish	milk	poul	gnut	frui	sorg
TOWZ	0.78	0.36	0.36	0.24	0.24	0.23	0.05	0.05	0.05	-0.53
	gnut	fish	milk	poul	vege	oils	frui	rice	sorg	catt
row3	0.09	0.01	-0.01	-0.09	-0.13	-0.13	-0.13	-0.33	-0.36	-0.41
rout	rice	vege	fish	oils	frui	catt	poul	milk	gnut	sorg
10w4	0.31	-0.08	-0.10	-0.10	-0.10	-0.10	-0.14	-0.14	-0.37	-0.57
*ouv5	fish	milk	catt	vege	frui	oils	poul	gnut	sorg	rice
10w5	0.66	0.65	0.52	0.26	0.26	0.26	0.26	0.24	0.18	0.16
rowh	rice	milk	vege	oils	frui	fish	gnut	catt	poul	sorg
10w0	0.61	0.18	0.08	0.07	0.07	-0.11	-0.18	-0.21	-0.21	-0.69
* 011/7	fish	milk	gnut	rice	oils	frui	vege	poul	catt	sorg
10w /	0.04	-0.03	-0.13	-0.22	-0.24	-0.24	-0.29	-0.39	-0.41	-0.82
*011/9	rice	milk	oils	vege	fish	frui	catt	poul	gnut	sorg
10w8	0.71	0.00	-0.08	-0.08	-0.09	-0.14	-0.14	-0.14	-0.22	-0.36
row	vege	rice	milk	fish	catt	poul	frui	gnut	oils	sorg
10w9	0.38	0.31	0.27	0.27	0.25	0.20	-0.03	-0.03	-0.17	-0.32
row10	rice	milk	poul	oils	fish	catt	vege	gnut	frui	sorg
10w10	0.10	0.00	-0.02	-0.10	-0.16	-0.27	-0.29	-0.32	-0.34	-0.65

488 Table 6: Sectoral ranking and PGE under different external economic environment scenarios

489 Source: CGE simulations by the authors.

Rice is ranked the most effective in poverty reduction in six sampled scenarios. Under four 490 scenarios (#3, 5, 7, 9), the rice sector's promotion is a sub-optimal policy because other sectors are 491 more effective in generating income and reducing poverty. In particular, scenarios #3, 5, and 7 492 493 assume an overall decrease of world market prices, and under these external conditions, the promotion of rice is ranked as one of the worst policy options. Less tradable sectors with stronger 494 upward linkages tend to become more efficient under scenarios with suppressed world market 495 496 prices (the groundnut sector is the best option under scenario # 3, and fishery becomes the best option under scenarios #5 and 7). Furthermore, under scenario #9, which assumes high energy 497

498 prices, the rice sector is less effective than vegetables. The non-tradable milk sector, which has the 499 second-highest PGE under the standard approach (Table 1, col. 7-8), keeps its favorable position 500 and is ranked as a second or third best policy option under the majority of scenarios.

501 Depending on the external uncertainty scenario, different sectors are ranked as most 502 effective in poverty reduction, meaning that the standard CGE-SSA framework does not allow us 503 to define robustly optimal policy.

504 4.3. Portfolio management methods

Having established the presence of multiple potentially optimal policies, we now refer to portfoliomanagement methods.

To cover the spectrum of possible diversified policies, we use the R-package 'xsample' by Van den Meersche, Soetaert, and Van Oevelen (2009) and sample 1000 mixed policy scenarios that we assume to be sufficient for representing the parameter space of our policy options. For the sake of simplicity, instead of the 2-stage sampling algorithm described in section 3 (first, sample budget shares, then map budget to policy parameters), we directly sample TFP parameters. In particular, the Markov Chain Monte Carlo method of the 'xsample' package produces sampled solutions for the following underdetermined problem with linear equality constraints:

$$\sum_{j=1}^{10} share_j tfp_j = tfp_{tot} \text{ subject to } tfp_i > 0 \text{ where}$$
(3)

514

• share_i is share of sector i in total agricultural GDP;

515

• tfp_i is sampled TFP shock of sector *i*;

516 • tfp_{tot} is targeted TFP growth of the whole agriculture (1 percent by 2024).

517 The produced sample has a (jointly) uniform distribution, and the algorithm ensures that 518 the total (weighted average) TFP growth of the whole agriculture is still 1 percent by 2024 for all sampled scenarios. In other words, we directly sample TFP parameters because we extend the assumption of the standard approach that costs of productivity growth across all sectors of primary agriculture in Senegal are equal and depend only on sectors' size, i.e., sectors of the same size should receive the same TFP boost for the same money. This assumption is not unusual and can be met even in the literature strands that compare much more heterogeneous sectors (such as agriculture-led growth versus non-agriculture-led growth; for example, Valdes and Foster, 2010; Diao et al., 2010).

Due to computational limitations (including non-diversified options, there are 1010 526 527 scenarios in total), each policy scenario is simulated for ten exogenous scenarios considered above (10100 simulations in total). Similar to the standard comparative analysis of sectoral scenarios 528 (section 4.1), poverty reduction impacts of all policy scenarios are treated as PGE. Given sample 529 530 restrictions, similar to the SSA (section 4.2), we do not use advanced mathematical finance methods that involve analyzing return distributions. Instead, to represent risk/return trade-off, we 531 use straightforward metrics such as the average value of the PGE (represents expected return), 532 standard deviation of the PGE (represents the volatility of expected return), and the minimum 533 value of the PGE (represents the worst-case expected return). 534

Doliou		Weights/composition											Min
Toncy	sorg	rice	gnut	oils	vege	frui	catt	poul	milk	fish	Avg	Twg 51D	
rice		100.0									0.30	0.38	-0.33
D361	1.2	45.8	4.7	2.2	12.6	3.4	1.7	3.8	23.6	1.0	0.20	0.22	0.00
D831	0.6	46.6	2.4	14.6	17.6	4.3	4.4	3.9	3.4	2.2	0.19	0.21	-0.04
D923	5.1	67.4	1.5	4.1	0.7	1.3	11.3	3.9	2.0	2.7	0.18	0.22	-0.04
D896	5.2	43.7	1.5	2.5	7.3	0.1	1.2	5.1	22.8	10.6	0.18	0.20	0.00

Table 7: Top five policies based on expected return (avg[PGE])

536 Source: CGE simulations by the authors.

Table 7 shows the top five policies ranked based on expected return. The option with the 537 highest expected policy return is an exclusive promotion of the rice sector. However, this policy 538 option is associated with the highest risk (highest standard deviation, STD). Under the least 539 favorable external conditions, an exclusive promotion of the rice sector can even lead to negative 540 returns (min PGE is negative, which means poverty increases). Looking back at Tables 5 and 6, 541 we can see that min(PGE)=-0.33 of the non-diversified rice promotion scenario corresponds to 542 SSA sampled scenario #3, which assumes a strong downward trend in world market prices. In 543 544 other words, an exclusive promotion of a trade-intensive sector can be an extremely ineffective policy under a cheap import scenario. Consequently, policymakers might consider less risky 545 options with a lower expected return. The next four options with the highest return assume 546 547 diversified promotion of several sectors and have a much lower level of risk (≈ 60 percent less volatility), which comes at the cost of decreased poverty reduction (≈ 50 percent less expected 548 return). All four options are not significantly different in terms of expected return and risk and 549 550 assume the promotion of rice in combination with other sectors that demonstrate high returns under specific external scenarios (Table 6). In particular, sectors with high weights besides rice are milk, 551 vegetables, oilseeds, or fishery. 552

Table 8: Top five policies based on worst-case return (min[PGE])
---	-------

Doliou		Weights/composition											STD
roncy	sorg	rice	gnut	oils	vege	frui	catt	poul	milk	fish	IVIIII	1115	510
D361	1.2	45.8	4.7	2.2	12.6	3.4	1.7	3.8	23.6	1.0	0.00	0.20	0.22
D896	5.2	43.7	1.5	2.5	7.3	0.1	1.2	5.1	22.8	10.6	0.00	0.18	0.20
D767	1.0	55.7	7.5	0.2	3.6	5.8	3.6	8.2	3.4	11.1	0.00	0.18	0.22
D151	1.3	60.5	2.4	0.3	1.6	5.8	8.6	3.0	15.7	0.6	0.00	0.18	0.20
D766	4.9	50.0	5.0	3.3	4.7	10.2	1.2	5.3	4.8	10.7	0.00	0.17	0.20

554 Source: CGE simulations by the authors.

Another criterion used to rank policies is the worst-case return, which represents the 555 expected return of a policy option under the least favorable external scenarios (Table 8). This 556 557 criterion is a simplified version of the Value at Risk indicator used in finance to represent the risk of investment loss (see Jorion, 2007 for details). The top five policy options guarantee non-558 negative returns (all min=0), meaning that these policy scenarios ensure nonincreasing poverty 559 and do not significantly differ in expected return or volatility. Like previous criteria, all options 560 561 assume reliance on the rice sector in various combinations with other sectors such as milk, 562 vegetables, and fishery.

563

Table 9: Top five policies based on Sharpe ratio (avg[PGE] / STD[PGE])

Policy	Weights/composition											Δνα	STD
Toncy	sorg	rice	gnut	oils	vege	frui	catt	poul	milk	fish	Sharpe	Avg	510
D891	1.8	63.7	3.6	2.0	2.1	0.7	1.7	0.6	17.3	6.4	1.07	0.16	0.15
D896	5.2	43.7	1.5	2.5	7.3	0.1	1.2	5.1	22.8	10.6	0.94	0.18	0.20
D361	1.2	45.8	4.7	2.2	12.6	3.4	1.7	3.8	23.6	1.0	0.92	0.20	0.22
D831	0.6	46.6	2.4	14.6	17.6	4.3	4.4	3.9	3.4	2.2	0.91	0.19	0.21
D151	1.3	60.5	2.4	0.3	1.6	5.8	8.6	3.0	15.7	0.6	0.86	0.18	0.20

564 Source: CGE simulations by the authors.

The last criterion we consider is the Sharpe ratio (expected return / standard deviation, Table 9). This metric is used in finance to represent the reward-to-variability, with a higher ratio characterizing a better portfolio (Sharpe, 1994). Like the worst-case return criteria, an exclusive 568 promotion of rice does not perform well under this criterion, and the five best options are 569 diversified policies that assume a mix of rice with other 'balancing'/`hedging' sectors, the most 570 notable of which are milk, vegetables, and fishery.

The presented policy options reflect only a part of the Markowitz Efficient Frontier and do 571 not include all potentially optimal policies. Risk/return preferences of policymakers do not 572 573 necessarily concentrate in the extreme return/risk domains; for example, policymakers might have a particular appetite for a guaranteed positive outcome (for example, min[PGE] > 0.1) or volatility 574 (for example, STD[PGE] \in [0;0.1], and concrete portfolio selection processes require analysis of 575 the respective parts of the Efficient Frontier. This task, however, requires complementary 576 577 information on the risk/return preferences of the Senegalese policymakers. In this regard, the 578 demonstrated application of portfolio management methods paves the way for future work 579 investigating various potential optimums associated with the various risk and return preferences.

580 **5.** Conclusion

With the growing trends of increasing modeling transparency, in recent years, CGE-based studies 581 have developed the SSA methods to represent the impact of parameter uncertainty on modeling 582 583 projections. However, SSA has not been adequately used in policy comparison studies, and existing CGE-SSA methods cannot define optimal policy if none of the considered policies is 584 robustly superior. As a solution to this problem, we suggest adapting portfolio management 585 586 methods. Similar to finance, indicators representing the expected policy impacts are treated as expected policy returns, and indicators representing the dispersion of policy impacts due to model 587 reparameterization are used as risk metrics. Furthermore, much like diversified portfolios in 588 finance, it is particularly beneficial to explore diversified policy options that constitute the 589

590 Efficient Frontier (where higher expected policy returns have a cost of accepting higher risk and 591 uncertainty and vice-versa).

As a case study proof of concept, we investigate the pro-poor agricultural policy in Senegal. 592 We demonstrate that standard CGE-SSA methods do not define robustly optimal policy under 593 uncertain world markets. As a solution, we apply MPT and analyze the spectrum of agricultural 594 595 policy options from a risk and return perspective. We find that policy exclusively promoting the rice sector is the most effective in terms of expected poverty reduction, but this option is also 596 associated with the highest risk. Diversified policies that combine rice promotion with promotion 597 598 of other sectors can offer less risk at the cost of reduced expected policy return. While the exact policy choice depends on policymakers' risk/return preferences, it is possible to conclude that 599 promoting milk, vegetables, oilseeds, or the fishery sector can help mitigate the risks associated 600 601 with the country's current prioritization of the rice sector. At the same time, it should be emphasized that our proof of concept study is not aimed at suggesting optimal policy. Instead, it 602 demonstrates the spectrum of potentially optimal policies that would have remained hidden 603 without using the MPT methods. While rice sector prioritization might satisfy one policymaker's 604 risk and return preferences, the other policymaker might have a lower risk appetite/acceptance 605 606 level and opt for diversified, less risky policy options. In this regard, our work supports the most recent trends in increasing modeling transparency and suggests well-known financial 607 608 diversification principles for selecting and communicating policy choices in the environment of 609 explicitly formulated risk and return trade-offs.

The suggested concept can be used in other CGE-based studies that compare policy options. For example, a set of varying/uncertain model parameters and target outcome variables can be adjusted for specific research interests, and portfolio diversification principles can be used

to explore the whole spectrum of potentially optimal choices. For instance, many environmental and ecological CGE models are naturally characterized by high modeling uncertainty because they are used for long-term simulations and projections (e. g. Webster et al., 2008; Chatzivasileiadis et al., 2018). Consequently, our method can be particularly beneficial in such studies because it helps rationalize their policy choices by explicitly defining their risk appetite/risk acceptance level in an environment of extremely high uncertainty associated with long-term projections.

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- 862 A. Technical Appendix

863 A.1. Functional forms and closure rules

We define the Senegalese CGE model's equations based on the functional forms and closure rules defined in the standard IFPRI CGE model by Löfgren, Harris, and Robinson (2002) and Diao and

- 866 Thurlow (2012).
- 867

 Table A1: Functional forms and closures of the CGE

Block	Category	Form / closure (endogenous variables)
	Value-added	Constant Elasticity of Substitution (CES)
Production	Intermediate	Leontief
	Top of technology	Leontief
Trada	Import	CES
Trade	Export	Constant Elasticity of Transformation (CET) ⁷
Consumption	-	Linear Expenditure System (LES)
	Numeraire	The exchange rate is the model numeraire ⁸ ; Consumer Price Index and domestic producers' price levels are flexible;
Model closure rules	Rest of the World	the current account balance and world market prices are given exogenously (exogenous shocks)
	Government	Fixed government tax rates; (dis)savings adjust to available net revenues;
	Savings/Investment	Savings-driven
	Factors	Fully employed and mobile

⁷ Constant Elasticity of Transformation (CET) is a corollary CES function often used in CGE modeling to model producers' decision to supply goods to the export or domestic markets (unlike CES, in CET, markets with a higher relative price get a higher quantity).

⁸ The exchange rate of the CFA franc to the French franc (and later Euro) is fixed since 1994. See Boogaerde and Tsangarides (2005) for more details.

I. Prices

- 1) $PM_i = pwm_i(1 + tm_i)\overline{R}$ 2) $PE_i = pwe_i/(1 + te_i)\overline{R}$ 3) $PQ_i = f(PM_i, PD_i)$ 4) $PX_i = g(PE_i, PD_i)$ 5) $PV_i = PX_i - \sum_j a_{ij} PQ_i$
- 6) $CPI = \sum_{i} \Omega_i PQ_i$

7) **DPI** = $\sum_{i} \Psi_{i} PD_{i}$

II. Production, employment, and wage

8) $QX_i = f(\overline{K}_i, L_{fi})$ 9) $W_f = PV_i(\delta QX_i/\delta L_{fi})$ f= labor, land 10) $LD_f = \sum_{i} L_{fi}$ 11) $LD_f - \overline{LS_f} = 0$

III. Foreign trade

 $\begin{array}{l} 12) E_i = h(PE_i/PD_i) \\ 13) M_i = m(PM_i/PD_i) \\ 14) \sum_i pwm_i \, M_i - \sum_i pwe_i \, E_i - \, \bar{F} = \, 0 \end{array}$

IV. Income and flow of funds; endogenous variables

- 15) Y_h : income of households
- 16) $\mathbf{Y}_{\mathbf{G}}$: government revenues
- 17) S: total investment

V. Sectoral demand and product markets

 $\begin{array}{ll} 18) & I_i = \varphi_i S \\ 19) & Z_i = \sum_j b_{ij} \, I_j \\ 20) & V_i = \sum_j a_{ij} \, Q X_j \\ 21) & C_i = \sum_h q_{ih} \, (1-s_h) Y_h / P Q_i \quad j=g, \, G \\ 22) & D_i = d_i (V_i + C_i + Z_i) \\ 23) & d_i = 1 / f_i (M_i / D_i, 1) \\ 24) & X D_i = D_i + E_i \\ 25) & X D_i - Q X_i = 0 \end{array}$

VI. Dynamics

$$\begin{array}{ll} 26) & LS_{ft} = LS_{ft-1}(1+\phi_{f}) \\ 27) & LS_{ft} = LS_{ft-1}(1-\eta) + \sum_{i} \frac{PQ_{ft-1}I_{ft-1}}{\kappa}\phi_{f} \\ 28) & \alpha_{it} = \alpha_{it-1}(1+\gamma_{i}) \end{array}$$

<u>Subscripts</u>		Endogenous variables	
f	factor groups (labor, capital, and land)	PM	import price
h	household groups	PE	export price
i,j	sectors	PQ	commodity price
t	time periods	PX	output price
_		PV	unit value-added
Exogen	ous variables	CPI	consumer price index
R	nominal exchange rate	DPI	producer price index
F	foreign savings balance	QX	output quantity
pwm	world import prices	М	import quantity
pwe	world export prices	Е	export quantity
		L	labor and land demand quantity
Exogen	ous parameters	W	average factor return
α	factor productivity	L	factor demand quantity
Ω	consumer price index weights	Y	household income
Ψ	producer price index weights	YG	government revenue
φ	investment allocation shares	S	total investment
b	capital composition coefficients	Ι	investment by sector of destination
а	input-output coefficients	Ζ	investment by sector or origin
q	expenditure shares	V	intermediate demand
S	savings rates	С	consumption demand
tm	tariff rate	D	domestic demand
te	export subsidy rate	d	domestic demand ratio
ø	land and labor supply growth rate	XD	total demand for domestic output
η	capital depreciation rate	f(-)	CES cost function
γ	Hicks neutral rate of technical change	$\sigma(-)$	CET revenue function
κ	base price per unit of capital stock	0()	

869 A.2 SAM adjustments

870 The original SAM by Randriamamonjy and Thurlow (2019) has 462 accounts, including 262 (regionalized) production activities or sectors, 75 commodities, 45 (regionalized) factors of 871 production, 65 (regionalized) household types, and other institutional, tax, and savings or 872 investment accounts. However, some accounts in the SAM were incompatible with our theoretical, 873 empirical, or computational limitations. In particular: 874 • Certain commodities are reexported (export > domestic production); 875 Specific sectors, factors, or households are tiny and can cause computational 876 • problems for the GAMS solver; 877 Public goods and services are produced and consumed by both private and 878 • public entities. 879 • Due to these incompatibilities, we perform the following adjustments: 880 • we net out imports for those commodities that have the reexport problem; 881 882 • Sectors or commodities that are less than 0.5 percent of GDP or absorption are aggregated with the closest matching sectors or commodities; 883 • Household and factor accounts are aggregated within regions; 884 Public goods and services are consumed and produced only by the public sector. This 885

amendment emphasizes that public goods and services should be outside the consumers' demandfunction and that production costs only determine the prices of these specific goods.

The resulting SAM (available upon request) has 263 accounts, including 183 accounts representing (regionalized) activities, 48 accounts representing commodities, 12 accounts representing primary production factors, and 9 accounts representing households.

A.3 Fixed exogenous model parameters

892	•	We use approximations and assumptions when the necessary estimates are not available.
893		For example, we use Aguiar, Narayanan, and McDougall (2016) to define values of
894		elasticity parameters;
895	•	based on the observed productivity decline from 2006-2015 (see IMF (2017) for more
896		details), we assume zero productivity growth for all non-policy sectors;
897	•	given the peg of the Senegalese currency - CFA franc to French Franc/Euro (for details,
898		see Boogaerde and Tsangarides 2005), we use Euro as a trade currency and convert US
899		dollar prices to French Franc/Euro;
900	•	full parameter specification of all model simulations is available upon request.

Table A.3: Sources used to define model parameters

Parameter	Used sources
Non-policy TFP	Own assumption
Factor supply	ILO (2020) for labor; FAO (2020) for land; Feenstra et al. (2015) for economywide capital
Population	UN (2020)
World market prices	World Bank (2020a) and FRED (2020) for services
Current account deficit	IMF (2020)
Production and trade elasticities	Based on Aguiar et al. (2016)
Income elasticities	Own estimates based on the household survey and King and Byerlee (1978)
Frisch parameters	Own estimates based on the household survey, World Bank (2020d) and Ramprakash (1979)