Reimagining Sustainable Intensification of Agriculture:

A Novel Application of Modern Portfolio Theory within a General Equilibrium Framework

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Abstract:

The challenge of feeding a growing global population while conserving natural resources is central to the sustainable intensification of agriculture. Despite decades of accumulated global knowledge and widespread implementation of sustainable intensification strategies, the expansion of global cropland through deforestation in developing countries has been increasing over the past decades. This study proposes a novel approach to promote sustainable intensification by perceiving farming as an investment activity and utilizing optimal portfolio analysis to enhance efficiency at the economy-wide system level. Using Senegal as a case study, we demonstrate that adopting optimal diversification strategies could potentially reduce new cropland demand by 68% by 2030. This strategy not only helps mitigate emissions and reduce water footprint but also enhances crop biodiversity. Socio-economic and environmental benefits are found to be greater when the country promotes high-value crops in the portfolio, such as fruits and vegetables, compared to grain crops. The analysis also sheds light on the intense discussions regarding land-sparing and land-sharing approaches, as well as the reasons behind rampant cropland expansion, considering the typical global cropland portfolio profile.

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Introduction

Feeding the growing global population while preserving the environment stands as one of our most urgent challenges today (Godfray et al. 2010). Although agriculture intensification strategies promoted by the Green Revolution had shown the remarkable success in feeding the global population and alleviating millions from hunger and poverty (McArthur and McCord, 2017; Gollin, Hansen, and Wingender, 2018; Spielman and Pandaya-Lorch, 2010), unfortunately they came at a high environmental cost, marked by the overuse of natural resources and the development of unsustainable production systems (Pingali, 2012; Ramankutty et al. 2018). Sustainable Intensification (SI) has been envisioned as the new green revolution, aiming to increase food production to meet future demand while minimizing or even eliminating harm to the environment (The Royal Society, 2009; Foley et al., 2011; Garnett, 2014, Pretty 2018).

The premise of SI is commonly perceived as a general guiding principle or process of inquiry to promote agricultural development through diverse approaches (Garnett and Godfray, 2012; Struik and Kuyper, 2017). Extensive research on SI has explored various avenues, including closing the yield gap and improving agricultural management practices to reach production potentials (Cassman et al., 2003; Tilman, 2011; Jain et al., 2023). Others have proposed a paradigm shift by allowing the production frontier to operate within the limits of planetary boundaries (Steffen et al., 2015; Rockstrom, 2016). The scope of impact from SI has also been widened by incorporating social and economic aspects such as poverty reduction and improved nutrition as part of the targeted goals (Pretty and Bharucha, 2014; Rockstrom, 2016). Many commissions, focus groups, and donors worldwide have collaborated to promote initiatives aimed at achieving the globally committed sustainable development goals (da Silva 2012; USAID 2012; FAO 2011; Levidow 2018; Foresight, 2011).

Despite decades of accumulated global knowledge and widespread implementation of SI strategies, recent data shows real progress observed on the ground is still lacking. Alarmingly, we are still witnessing a significant loss of our natural ecosystems due to the accelerating expansion of cropland. Global satellite imagery studies reveal that the annual rate of cropland expansion has surged from 5.1 million hectares per year in the first decade of this century to 9 million hectares per year in recent years (Craig et al., 2022; Potapov et al., 2022). This expansion is predominantly observed in developing countries, particularly in Africa, where 79 percent of the cropland is generated by the destruction of natural ecosystems in areas with low yield potential. This trend aligns with findings by

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Cassman and Grassini (2020), who also emphasize the accelerating rate of global cropland expansion, primarily driven by staple crops.

If we still commit to this trajectory, not only will our environment suffer irreparable damage, but we will also continue to witness impoverished farmers struggling to escape poverty due to the low economic returns from the crops they cultivate. Additionally, access to a healthy diet will remain elusive for the global majority, given the prevailing production bias towards grains. Despite promising outcomes from hundreds of SI initiatives worldwide, with approximately 163 million farmers implementing recommended practices across nearly half a billion hectares, the potential for scaling up these initiatives remains limited (Pretty et al., 2018). There is a pressing need to redesign and further integrate SI with agricultural knowledge economies and policy measures to overcome these challenges (Pretty 2018).

Motivated by these findings, this study proposes a novel approach to exploring pathways toward SI using financial and economic theory as the guiding principles. Unlike the prevailing strategy of SI, which primarily focuses on the adoption of high yield enhancing technologies, our analytical approach utilizes economic and financial tools to optimize farming activities. It aims to maximize returns from all cultivated crops while considering potential production and market risks. At the core of our analytical framework, we perceive farming as an investment activity that generates economic return through the use of natural resources, such as cropland. We analyze the cropland allocation across different crops as an investment portfolio and examine its impacts on both socioeconomic and environmental factors. We conduct the analysis by taking into account the uncertainty factors exposed to the agricultural system that determine the risk and return profiles of each crop, which ultimately drive the outcome of different portfolio options. The SI strategy is then reflected in the adoption of optimal portfolio options that offer ways to increase economic return while reducing environmental costs.

We pursue this analytical process by developing an integrated assessment model based on financial and economic theories, supported by modern portfolio analysis and Computable General Equilibrium (CGE) models. This integration allows for a comprehensive assessment of agricultural investment or land use allocation performance in an economy-wide setting under uncertain conditions. The modeling approach involves stochastic simulations by running tens of thousands of scenarios to properly capture the production and market risk factors that influence agricultural investment outcomes. Portfolio analysis is then used to find the optimum diversification strategy for promoting SI that offers a better return given the associated risk.

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All analyses are conducted in a general equilibrium setting, capturing the importance of sectoral interlinkages across different commodity and input markets, as well as the interactions among different economic agents. We found that this unique integrated investment portfolio assessment framework has received relatively little attention in the literature on SI. Building on this premise, we believe our study makes a significant contribution to the existing body of literature and has the potential to stimulate further discussion about evaluating ongoing efforts and promoting the application of SI. To our knowledge, this is the first research study that explores the idea of achieving SI by adopting the optimal portfolio of cropland allocation evaluated at an economy-wide system level.

Considering the rapid increase of cropland expansion in Africa, we applied this analytical framework to the Senegalese economy by evaluating investment return generated from different cropland allocations across six crop groups: rice, other cereals, groundnuts, root crops, fruits and vegetables, and other crops. We measure the impact of different investment portfolios on various socioeconomic and environmental indicators to reflect the achievement of SI strategy through the reallocation of cropland following the optimal portfolio analysis. The core of our analysis involved comparing the current land allocation with the optimal portfolio allocation using the integrated model and assessing various impacts on socioeconomic and environmental outcomes. We conduct the analysis by specifically evaluating three optimal investment portfolio options, representing low, medium, and high-risk/return profiles, derived from the optimal portfolio allocation model. We then measure these alternative portfolios against the current land allocation to explore potential pathways for achieving a sustainable intensification strategy.

We show in this study that the current cropland allocation in Senegal is less efficient compared to all three alternatives land allocation portfolios. It is estimated that the socioeconomic gains generated by reallocating cropland following the optimal land allocation portfolios would result in higher GDP, reduced poverty, and improved diet diversity as the country shifts from low to high-risk/high-return land allocation portfolios. This implies that the country needs to gradually reallocate new cropland area away from grain toward fruits and vegetable crops that offers better returns and even lower relative risk level against the current cropland portfolio structure. We also show that by using the least amount of land to produce a comparable return on investment under a high-risk/high-return portfolio profile, the country could not only save around two-thirds of newly cultivated cropland but also improve biodiversity levels and reduce environmental footprint. The economic return on cropland shows a diminishing rate

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following land availability, which suggests that the incentive to expand land could be suppressed as production (efficiency) increase. This also means that the potential rebound effect is somehow restrained under the high-risk/high-return portfolio profile. The finding opens new avenues for achieving SI through the adoption of optimal cropland reallocation. It also underscores the urgency of shifting natural resources toward high-valued and health-promoting crops, which not only benefit the environment and human health but also yield higher investment returns to farmers.

Results

Optimal Cropland Portfolio Analysis

Like in many Sub-Saharan African countries, agricultural production in Senegal relies on a rainfed system that is prone to erratic rainfall, creating uncertainty in farming activities. This condition leaves Senegal's farming sector particularly vulnerable to weather fluctuations, which can result in crop failures, leading to income instability, increased poverty, and food insecurity. Senegal also relies on imports to meet the growing country's food demand, further exposing the economy to uncertainty stemming from global market fluctuations. Both production and market uncertainty are considered key risk components that influence farmers' decisions (Komarek, De Pinto, and Smith, 2020). Therefore, it is essential to comprehensively grasp the decision-making mechanisms of farmers in allocating input resources under uncertainty conditions by considering the risk and reward factors that influence the overall agricultural system and market performance.

We utilize a general equilibrium framework to comprehensively capture farmer's decision-making process in allocating various input factors across different commodities and potential repercussion from overall market adjustments influenced by both production and market uncertainties. We first evaluate farming activities in Senegal using Stochastic CGE (S-CGE) model by measuring cropland allocation across crops as an investment portfolio under uncertainty driven by both production and market fluctuations (see methodology). To measure portfolio performance, we derive investment profile for all six crops analyzed in this study by estimating the expected investment return with its associated risk using the S-CGE model. This process is undertaken by considering the uncertainty conditions generated by production and global market uncertainties within an economywide framework.

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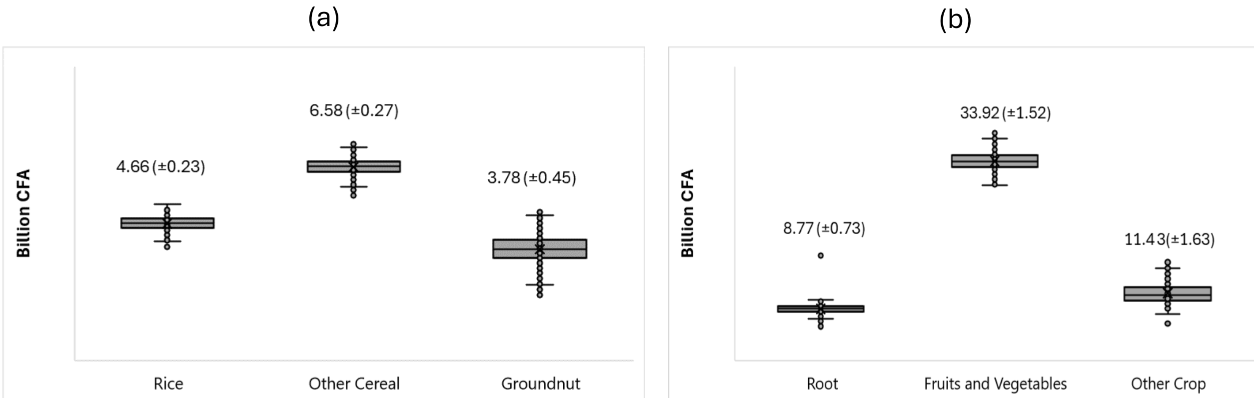
Figure 1. Expected investment return and risk by crop



Source: S-CGE Model results

Figure 1c and 1d shows investment return and uncertainty results for each crop measured in total crops value added estimated by mean and standard deviation values. The results illustrate the varying degrees of investment return and uncertainty resulting from the same investment of 50 thousand hectare of cultivated area in each crop. The return on investment is measured by changes in agriculture's crop sub-sector value added, which encompasses all income generated from agriculture crop production. The number shown on top of each boxplot shows the average investment return and the associated standard deviation value from cropland expansion inside the bracket. The results suggest that expanding cropland area has a positive impact on agriculture income. The lowest investment return of investing 50 thousand hectare of cropland is generated by groundnut, which gives around CFA 3.78 (±0.45) billion, while the highest investment return and risk is generated by fruits and vegetables crops with expected return of CFA 33.9 (±1.52) billion. The rice and other cereal crops generate decent amounts of return with lowest risk values ranging from 4.66 (±0.23) billion to 6.58 (±0.27). Overall, it shows that the higher the investment return generated by the crop, the higher the risk associated with it. The results are in line with past research showing higher investment return is generated by fruits and vegetables crop than the grain crops (See Rivera-Padila 2020 and Zhang et. al 2022).

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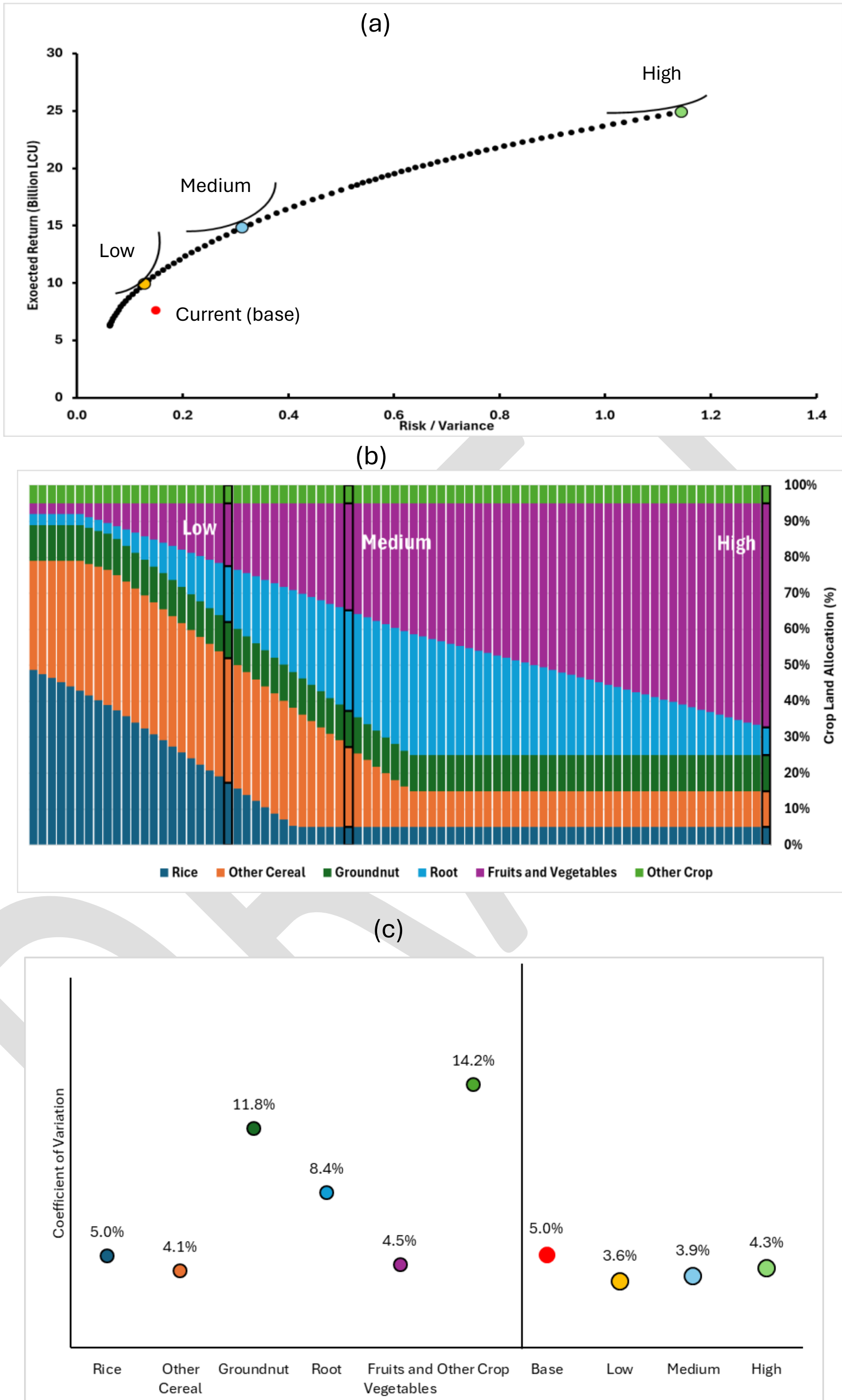
Figure 2. Efficient frontier and portfolio options



Source: Modern Portfolio Analysis simulation results

The investment performance results for each crop serve as the key input data for running the financial model following Modern Portfolio Theory principles to help identify the optimal combination of land allocation across six crops considering the return and risk values associated with each crop (see methodology). By leveraging information on average return, variance, and covariance values, the financial model generates combination of cropland allocations that offer optimal returns based on risk tolerance levels, depicted as an efficient frontier. Figure2a shows the output results from the model, where the top diagram shows the efficient frontier curve reflecting the optimal portfolio options available. Each dotted line on the frontier curve provides information on how much return and risk are associated with each investment option. The positive slope of the efficient frontier suggests that higher return is associated with higher risk across all investment option. This aligns with the indifference curve characteristic that is tangent to the efficient frontier at the top of the curve. The steeper the indifference curve, the higher additional return required for adding a certain amount of risk (risk-averse), while the flatter the curve, the less additional return is required for an additional certain amount of risk (risk-neutral).

Figure 2b illustrates the breakdown of portfolio options, reflecting the distribution of land allocated to each crop, with a total allocation of 100 percent in each portfolio option. This bar chart provides a visual translation of the portfolio profiles depicted in the top diagram (Figure 2a). Each bar chart in Figure 2b is associated with a point along the efficient frontier, reflecting a specific land allocation configuration that offers the optimal return given the associated risk. Similar to the efficient frontier, when we look at the bar chart from the left side, we find the low risk and low return investment profile, while further right of the bar chart shows high risk and high return profile. The low-risk investment option indicates that most land is allocated to grow staple crops like rice and other cereal crops. As we shift slightly to the right, the optimal allocation indicates a greater proportion of cropland allocated to root and fruit crops. Moving towards the far-right area indicates the higher-risk investment options reflecting a significant portion of new cropland area is allocated mainly to fruit crops. Investment options in this area essentially offer the highest return but are also associated with the highest risk.

In this analysis, we select three points from the efficient frontier that represent low, medium, and high-risk investment profiles, marked by the yellow, blue and green dots respectively as shown on Figure 2a. These three dots on the efficient frontier correspond to the highlighted bars in Figure 3b, indicating how the new crop land area can be optimally allocated across all six crops. Figure 2c shows coefficient of variation values to compare risk-return tradeoff across investment portfolios. To show that the three portfolio options from the efficient frontier actually offer the optimal investment allocation, we first compare the risk and return profile from individual crop investment results. The left panel in figure 2c shows investment profile on individual crops as measured by coefficient variation calculated by dividing standard deviation value with the expected return on each crop. The right-hand side on the other hand, displays the relative risk for the three optimal investment portfolio options including the base or current scenario cropland allocation. The base scenario is set following the current cropland distribution with more than 70 percent of cropland allocated towards grain and groundnut crops.

Comparing the relative risk (coefficient variation) generated by each individual crop with base scenario suggests that diversification strategy under base scenario provides lower relative risks compared to investing in individual crops such as rice, roots and other crops. However, when we compare base scenario with the alternative three optimal portfolios, it becomes obvious that all the alternative portfolio options provide lower risk-return tradeoff. This suggests that cropland allocation following the optimal portfolio offers the optimal return given the associated risk or minimal risk given the associated return. The next sessions elaborate the socioeconomic and environmental impacts of each alternative cropland allocation portfolios and illustrate how Senegal could achieve sustainable intensification by adopting the optimal cropland allocation strategy.

Cropland Reallocation and Socioeconomic Impacts

To measure the socio-economic impact of cropland reallocation, we employ Dynamic Computable General Equilibrium (D-CGE) model to simulate several cropland expansion scenarios based on the optimal portfolio options. The model allows us to scrutinize the complex interactions between input markets, representing land use change dynamics, and commodity markets across different sectors, as well as income levels among various economic agents, which ultimately drive the outcomes of various socio-economic factors. We run three simulation scenarios following different portfolio allocation from the year 2024 to 2030 and compare the results to baseline scenario to measure impacts. The results are then used to determine the investment performance of each cropland portfolio option.

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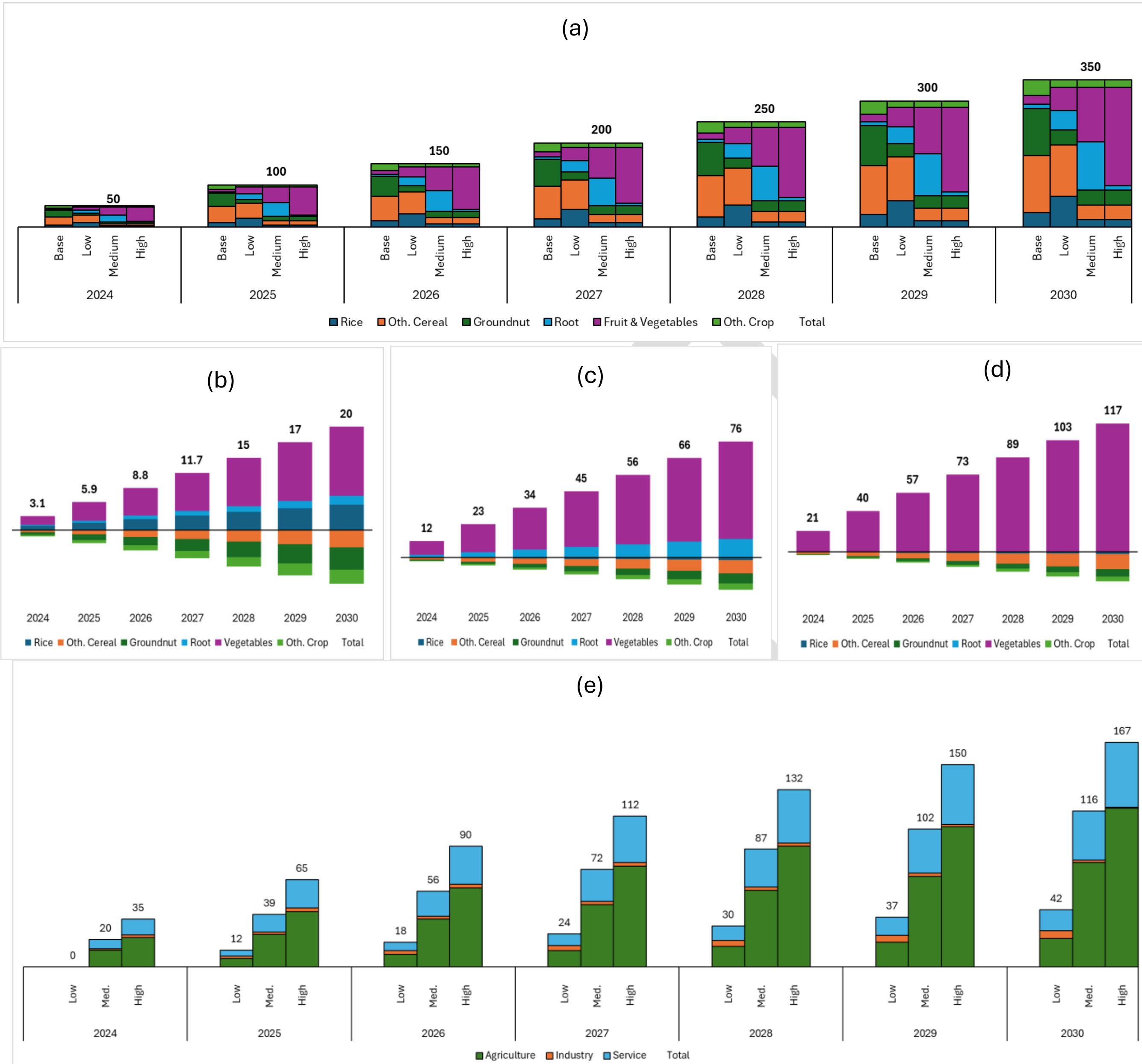
Figure 3. Impact on Sectoral and Total Value Added



Source: D-CGE Model simulation results

Figure 3a illustrates the trend of cropland expansion and its allocation across different crops for all the scenarios. We assume the cropland expansion in the country increases by 50 thousand hectares per year, which equals to 350 thousand hectares of cropland expansion in 2030 under all scenarios including the baseline. The only differing factor between baseline and the three alternative portfolio options is how the new cropland is allocated across the six crops, which is driven by portfolio analysis results elaborated in the previous section. Given the total cultivated area in year 2030 is 3.85 million, the adjustment on cropland allocation only applies to small part of the total cropland area (9 percent of total cultivated area). Figure 3a shows how cropland is allocated under the baseline scenario with around half of the area used to grow grain and about one-third to grow groundnut. However, this allocation changes under the three optimal portfolio scenarios, where the new cropland allocation shifts more toward root and fruit crops. While under the high-risk portfolio, most new cropland area allocated towards fruit crops considering the high risk and high return returns investment characteristic of the portfolio.

The direct impact of cropland allocation on crops value added is shown by the middle panels (Figure 3b to 3d) showing positive investment return across all three scenarios against the baseline. This suggests that there is a significant room to increase economic efficiency in the crop sector by reallocating cropland towards optimal portfolio options. The lowest gain the country could achieve is by shifting cropland allocation following low-risk portfolio as depicted in Figure 3b. The crop value added under this portfolio could generate a net positive investment return of CFA 20 billion in 2030 compared to the baseline. This net gain stems from increased production of root as well as fruit and vegetable crop, while production of other cereal, groundnut and other crops decreases following the optimal cropland allocation. The medium and high-risk portfolios, however, offer larger investment returns because the new cropland area is allocated more towards fruit and vegetable crop that generate higher return compared to other crops, with increased in investment return by CFA 76 and CFA 117 billion in 2030 under medium and high-risk portfolio, respectively.

Figure 3e demonstrates that the positive impact of cropland reallocation extends beyond the agricultural sector, creating positive spillover effects across the broader economy. These spillover effects increase as the portfolio offers higher return and risk profile. It primarily stems from the increased demand for trade and transport services needed to support the rising demand of the associated crops promoted in each portfolio. As a result, total GDP increases by CFA 42, 116 and 167 billion, which are equal to an increase of 0.2%, 0.6% and 0.8% of GDP in 2030 for low, medium and high-risk portfolio respectively. It's important to note that all these positive economic gains are based on the assumption that the annual increase in cropland area is only equal to half of what has been observed historically. This suggests that the results provide a conservative estimate of the potential gains from each portfolio in contrast to the potential land expansion that the country could have as in the past. Furthermore, the analysis only considers the marginal increase in cropland area, which amounts to less than 10 percent of the total cropland area in 2030. Potential larger impacts could be realized if the

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portfolio allocation were applied to the larger share of total cropland area, resulting in a more significant shift in land use allocation.

To illustrate how much economic gain that each hectare of additional cropland provides to the crop sector, we divide the crop value added with total new cropland area for each scenario. The top diagram in Figure 4a shows the total crop value added for each scenario overtime, while the bars at the bottom show how much economic gain generated by each hectare of land every year under all three cropland allocation scenarios. Given the total new cropland area are the same across scenarios, the high-risk portfolio provides the largest marginal return for land with annual gain of 333 thousand per hectare of land in 2030 compared to the baseline. On the other hand, the low-risk portfolio could only generate economic benefit of 82 thousand per hectare of land at the end of simulation period compared to the baseline. This implies that crop choice matters in determining income to farmers as reflected by rate of marginal return on land. The more land allocated towards low-valued crops, the less potential revenue could be generated from farming activities and the lower income earned by farmer. Even after considering the risk factor, we have shown in section 2 that the relative risk under the three alternative cropland portfolio options is still lower than the relative risk under the baseline. This again suggests the rationale to adopt the optimal portfolios to achieve economic efficiency using the same amount of resources. This is the key requirement to promote sustainable agriculture intensification from economic gain perspective.

Figure 4b shows how poverty rate decreases over time with increase in income as reflected by increase in value added across sectors. The highest poverty reduction is observed under high-risk portfolio scenario given the higher return generated from this cropland portfolio option. However, we still observe a reduction in poverty rate under low and medium-risk portfolio. Simulation results show that the optimal cropland allocations could reduce the number of poor people in 2030 by 20, 51 and 122 thousand in 2030 under low, medium and high-risk portfolio, respectively. Positive impact on diet diversity is reflected in Figure 3c, showing the reduction in diet deprivation. The diet indicator is based on the Reference Diet Deprivation (ReDD) index built by Pauw et. al (2023) showing the changes in household's diet quality based on household food consumption across a distinct number of food groups. The shift in diet towards healthier food stems from both an increase in income as well as more production of nutritious food compared to the baseline. Obviously, the high-risk portfolio option produces more fruits and vegetable commodities which generate more positive impact on diet diversity

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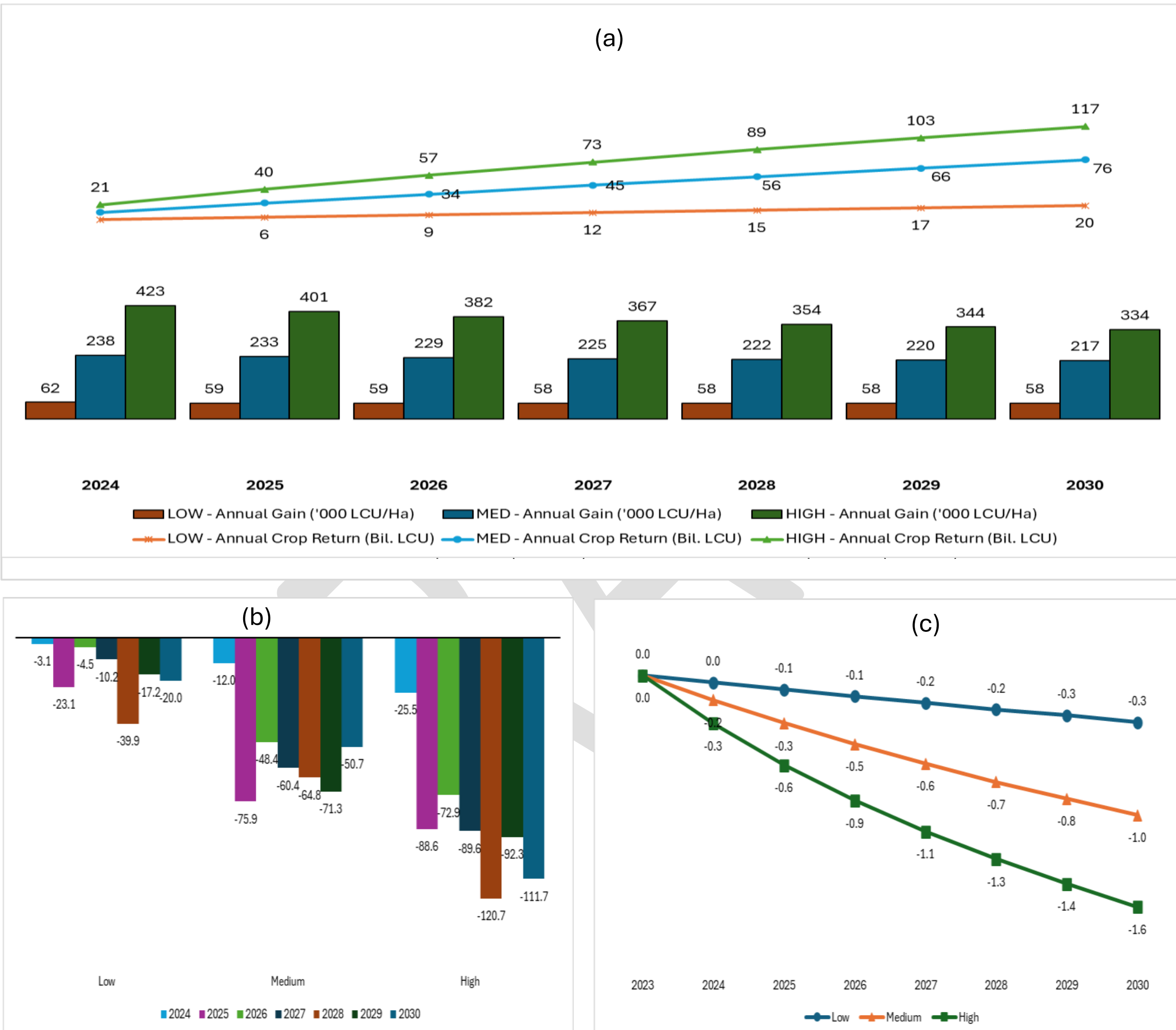
and consequently reduce diet deprivation status. Overall, we can argue that the three optimal cropland portfolios explored in this study are superior in generating socio-economic benefits compared to the current crop portfolio allocation (baseline).

Figure 4. Return on Cropland and Socioeconomic Factors



Source: D-CGE model simulation results

Impacts on the Environment

Improvement in production and economic efficiency achieved through cropland reallocation strategy following the optimal portfolio analysis also implies that total crop production in Senegal could actually be generated by using less land. This means that on the other side of the coin there is potential for land saving benefit by reallocating the new cropland area following optimal portfolio allocation. In this section, we particularly explore the environmental benefit by estimating how much land that the country could save under the three optimal cropland portfolio allocations. We also calculate changes in emission, water footprint and crop biodiversity following the alternative cropland portfolio allocation against the baseline (see methodology).

We conduct the analysis by targeting the minimum amount of new cropland area needed to generate the same economic return as in the baseline scenario. The crop value added serves as the investment or economic return indicator, given the direct income effects generated from an increase in new cropland supply. This means that in all three alternative scenarios, we gradually reduce the amount of land until the crop value added in each scenario matches that of the baseline by the year 2030. To further explore the opportunity cost between land expansion and economic gains, we run some simulation scenarios to develop production possibility frontier showing the optimal points of generating both economic and environmental (land savings) gains.

Figure 5a shows the amount of land needed to generate the same economic return across all cropland portfolio scenarios. As observed, the amount of cropland area used under the optimal scenarios is much less than what is needed under the baseline scenario. This means that there is a potential amount of land that could be saved when the country adopts any of the alternative or optimal cropland portfolio options. Even if the country only adopts the low-risk portfolio option, the potential of land that could be spared for nature in 2030 is 78 thousand hectares. This land savings number increases as the portfolio moves toward a riskier profile considering that each hectare of land could generate higher investment return as discussed in the previous section. The largest land savings potential could be achieved by adopting high-risk portfolio with 238 thousand of land can be saved for nature in year 2030 instead of being converted to grow crops.

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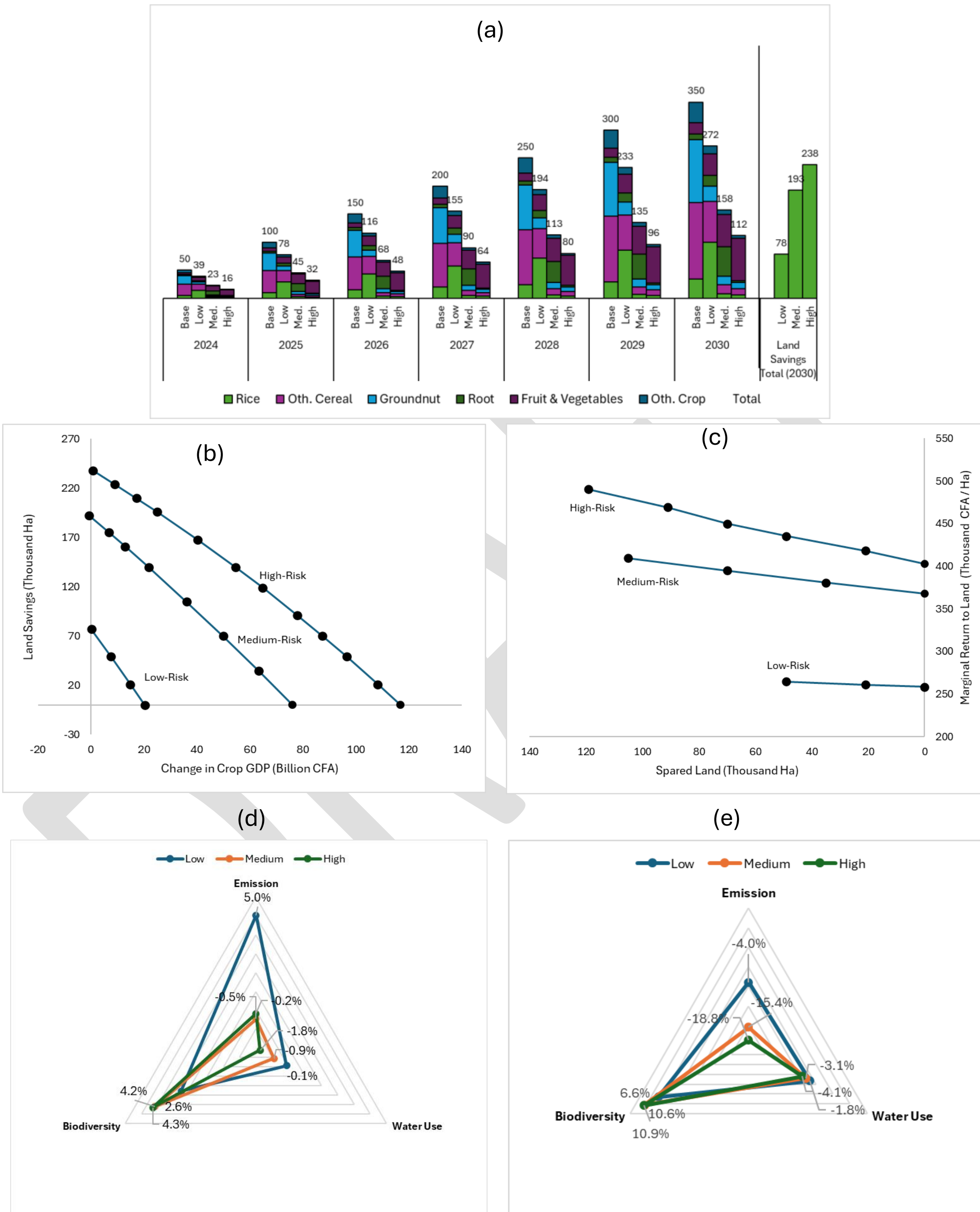
Figure 5. Potential Land Savings on Economy and Environment



Source: Fig. 1a-e (D-CGE model simulation results); Fig. 1d-e (Authors' own calculation derived from D-CGE model simulation results)

So far, we have provided figures on the maximum amount of investment return and the minimum amount of land needed (potential land savings) to generate the same economic return as in the baseline. Figure 5b shows the range of trade-off in attaining economic return and land savings benefit. We can perceive the graph as the production possibility frontier that allows the economy to produce environmental benefits (land savings) as well as economic gains (higher income) by the year 2030. The production point located on the horizontal line shows the maximum economic gains the country could get by using all new cropland supply. On the other hand, the production point lays on the vertical line provides information on the maximum land that the country could save by using the least amount of new cropland to generate the same economic return as in the baseline. Points in between show the production possibility of producing or generating both economic and environmental gains as reflected by positive value in crop value added and total land savings in year 2030. Relating this graph to SI strategy, we have demonstrated that all three alternatives portfolio options offer the possibility of increasing both land savings as well as economic gain at the same time.

Comparing the three production possibility frontiers from each optimal cropland portfolio options (Figure 5b), it is clear that the high-risk portfolio profile offers the highest potential in attaining both environmental as well as economic return at the same time. This is because all points on the production frontier generated by high-risk high-return profile is higher compared to the other two portfolio profiles. However, at the marginal level, the high-risk portfolio provides the highest opportunity cost of expanding cropland compared to other portfolio options. Figure 5c provides a relationship between marginal (economic) return on land with the potential amount of land saved in 2030. The graph shows that the less amount of land being saved (higher cropland expansion), the lower the marginal return of land per hectare can be generated. This means that the potential earnings that the country could generate from each hectare of new cropland actually decreasing as the cropland expansion continues under the high-risk profile.

This is also reflected from the slope of each portfolio option, where the reduction in marginal return to land is actually much higher under high-risk portfolio option as reflected by the steeper slope. This implies that there is less incentive for farmers to cultivate new cropland when they adopt the high-risk portfolio option, which in the long run could act as a locking mechanism to avoid any potential deforestation caused by cropland expansion. On the other hand, the low-risk portfolio option shows flatter slope, which means that there is little trade-off for the farmer to expand cropland given the minimal reduction in marginal return to land. This is one of the reasons why we observed rampant cropland expansion over the last decades, given that most new cropland areas are used to cultivate grains that is associated with low-risk portfolio profile. As shown in the graph, the reduction in marginal return to land under the low-risk portfolio profile is actually very small, which creates less (economic) barrier for farmer to expand cropland area.

Finally, figure 5d and 5e show how the alternative portfolio options also provide benefit in mitigating environmental footprint by reducing the amount of emission and water use in farming activities compared to the baseline. Futhremore, the optimal portfolio option also increases biodiversity index at the farm level as more diverse crops are promoted under all three portfolio options. Figure 5d shows changes in emission, water use and biodiversity index when the country uses all the new cropland area to maximize economic return. The results are associated with points on the horizontal line shown in Figure 5b. On the other hand, figure 5e shows environmental indicator results that are associated with points on the vertical line shown in Figure 5b, which reflects the maximum land savings amount that the country could save in 2030. Both figures show the overall benefits generated by optimal portfolio options. The only portfolio that generates larger emission is under the low-risk profile when the country uses most of new cropland to grow rice that generates larger emission compared to the baseline. The other two portfolios, however, generate environmental benefits for all indicators under the two spectrums of maximizing land savings and economic gains. The impact is obviously larger when the country adopts the high-risk high-return portfolio option.

Discussion

Achieving SI in crop production does not have to be limited by focusing the intervention on specific crops or the adoption of certain high-yield technologies. The key factor in promoting SI is basically to find ways to improve efficiency in farming activities to help optimize the use of scarce natural resources. This effort is important in order to meet the increasing food demand which over the last decades has been associated with deforestation and wildlife loss globally despite the fact that crop yield was still showing increasing trend (Cassman and Grassini 2020). In this study, we have demonstrated using the modern portfolio analysis and general equilibrium framework applied on Senegal economy that sustainable intensification could be strategically achieved by mainly reallocating new cropland following the optimal portfolio options. By allocating new cropland more towards root and fruits and vegetables crops in Senegal, the country could increase agriculture investment return that leads to higher

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GDP and improved socio-economic conditions as reflected by the reduction in poverty and diet deprivation rate. More importantly, we also observe the potential of saving land together with improvement in economic gain over time. Various environmental indicators like emissions and water footprint as well as biodiversity index also show positive impact from the adoption of optimal cropland portfolio allocation, especially when the cropland portfolio promotes cultivation of high-valued crops.

It is important to reemphasize that the cropland portfolio reallocation strategy proposed in this study does not involve or need any application of certain agricultural technologies as commonly perceived in the SI approach. This contrasts with the land sparing concept to promote SI by using high-yielding agriculture technologies or practices that could potentially harm the soil or environment, despite its limited ability to save land for ecosystem services (Techen, Robinson and Helming 2019). On the other hand, the land sharing strategy promoted as another approach to attain SI involved significant trade-off in lowering the yield which reduce overall country's food production and consequently drives food imports, thereby passing on the negative impact on wildlife overseas (Bateman and Balmford 2023).

We believe that our approach could bridge the contention between promoting land sparing or land sharing in attaining SI. This is because our optimal portfolio strategy not only offers land savings benefit but also increases the agriculture productivity as measured by investment return without the need of applying any high-yielding technologies or farming practices that could still harm the environment. Instead, the recommendation from our analysis is to gradually move away from grain toward more profitable, healthier and environmentally friendly crop, like fruits and vegetables. Our study also broadly addresses issues on rebound effect or Jevon's paradox (Rudel et al. 2009; Lambin and Meyfroidt 2011; Maxwell et al. 2011; Bernard et al. 2023) under the land sparing concept that has been characterized by the increase in deforestation with improvement in productivity (efficiency). The trend in marginal return across difference cropland portfolio shown in Figure 5c provides one of the reasons. It indicates that the under low-risk low-return portfolio option, there is only small trade-off to expand cropland area as observed by the flatter line. In contrast, reduction in marginal return under high-risk high-return portfolio shows steeper slope, which implies higher cost (less incentive) for farmers to cultivate new cropland when they adopt high-risk portfolio option.

We think that this finding offers a new perspective in understanding why we observe the rebound effect globally despite the improvement in crop productivity over time. We argue that it is because of the domination of grain crop in agriculture farming globally that closely match to low-risk low-return portfolio profile. Given the low reduction in marginal return to land under the low-risk profile, the barrier to increase production through cropland expansion is much less compared to agricultural farming dominated by high-risk high return profile. This does not mean that the high-risk portfolio profile is bullet proof to the rebound effect, instead we argue that the rebound effect could be highly suppressed when the distribution of cropland follows the high-risk high-return portfolio profile.

Improvement in biodiversity index shown from this study through the increase in forest area as well as the more variety of crops also add more weight on the benefits of adopting the alternative portfolio options, especially the high-risk profile that offers larger positive impacts. Abundant research has shown the positive externalities that emerged by diversifying farming activities leading to not only increase in yield but also improvement in ecosystem services (Snapp et al., 2010; Beillouin 2021, Zhao et al., 2022). Recent global study using five decades of time series data shows that the greater the crop diversity at national level could actually increase resiliency in maintaining national food supply (Renard and Tilman 2019). One potential real application to implement our optimal cropland portfolio approach is by promoting a diversified farming system that has been found to be profitable and feasible to be adopted in almost half of the world including in Africa (Kamau, Roman and Freudenberger 2023). More encouragingly, the implementation of optimal crop allocation on diversified farming system is not only limited to the developing world only but it also offers the same potential benefits both economically and environmentally to the developed nations, which could further boost the global agenda in promoting SI.

Considering the analysis demonstrated in this study only looked at the country level impacts, we believe there is more room to broaden and expand the analysis at regional or even global level to capture the important repercussions effects generated from international trade transactions. The analysis in this study also limits the simulation scenarios by using annual change of cropland expansion instead of total land allocation in the country. Further studies may be needed to explore the scaling up effect by looking at total cropland reallocations at national level following certain policy incentives promoted by the government to achieve various feasible policy targets. Testing the resiliency of the optimal cropland portfolio system against long-term climate change effects or extreme weather events could also be another avenue to explore. We believe there are still rooms to further test and extend the application this analytical framework to better understand how SI could be more optimally achieved under various circumstances and challenges faced at different economic scale from sub-national to global level.

Methods

Analytical foundations

The analytical framework developed in this study is fundamentally grounded in economic and financial principles, centering the analysis on farmers' decision-making processes to evaluate farming as investment activities. We capture farmers' behavior by tracking their economic decisions in allocating limited economic and natural resources based on rational agent assumptions following various economic transactions within a complex and interlinked market system. This approach allows us to measure farmers' decision comprehensively as part of the whole economic system by taking into account the economic interlinkages between agriculture and non-agriculture sectors as well as any potential policy interventions. Thus, the analytical framework facilitates us to capture the interconnectedness of the system from micro to macro level, where farmer's decision in allocating their resources to grow any crops at national scale would affect not only other agriculture commodity markets but also overall economic system through market mechanisms which could then generate a feedback loop effect on agriculture sector and farmer's income.

Based on this foundational analytical setup, we specifically evaluate farming activities at national level by perceiving cropland allocation across different crops as an investment portfolio. We measure the cropland portfolio investment performance by incorporating the uncertainty factors affecting individual crops driven by both production and market fluctuations. We then utilize financial principles to conduct investment portfolio evaluation, examining the expected return and associated risk generated by the portfolio. This portfolio assessment stands as the key feature of the analyses that offers insight on the importance of diversification and portfolio options based on risk factors in order to promote sustainable intensification strategy. The primary objective of this financial assessment is to identify the optimal investment return given the associated risk following farmer's risk behavior. To measure the investment performance overtime, we impose the optimal portfolio allocations on the economy reflected by farmer's decision in allocating cropland and assess the potential impacts on both economic and environmental outcomes.

We developed the framework by utilizing an economy-wide modeling approach given its ability to capture and track down market interlinkages across different sectors, along with the influence of production and market uncertainty on the entire economic system concurrently. This general equilibrium framework serves as the ideal tool for comprehensively measuring investment and risk performance required by the optimal portfolio analysis. In our context, capturing the link between natural resource allocation and market performance is essential for understanding the trade-off between economic gains and environmental outcomes. By integrating portfolio analysis into a general equilibrium framework, we have established an ideal method for evaluating agriculture investment performance. This approach enables us to capture how natural resources are allocated across different crops under uncertainty conditions affecting not only agriculture but also the entire economy, which then drives impacts on socioeconomic and environmental outcomes. The simulation results demonstrate the potential pathways of achieving SI through the reallocation of cropland following the optimal portfolio analysis. Both socio-economic and environmental indicators are used to assess the feasibility and effectiveness of attaining the SI strategy. The next section provides more detailed information about the models employed and the simulation designs used in the analysis.

Models and Simulation designs

We run series of models to demonstrate how investment reallocation in agriculture represented by different cropland distribution following the optimal portfolio analysis could help improve agriculture production efficiency and increase farmer’s income to achieve the sustainable agriculture intensification goals. Figure 6 shows the models used in the analysis and the linkages to measure impacts of cropland reallocation on socioeconomic and environmental outcomes as main indicators of SI. We set up the models and introduce simulation scenarios by passing on the selected parameter results from one model to the others to develop the model linkages. We adopt the dual approach of maximizing economic return and minimizing input use to measure the potential space of attaining both economic and environmental gains simultaneously. We measure changes in various socioeconomic and environmental indicators to evaluate the achievement of sustainable agricultural intensification.

The economy-wide model of Computable General Equilibrium (CGE) is developed based on extension of Rural Investment and Policy Analysis (RIAPA) model built by Diao and Thurlow (2012) following Lofgren, Harris and Robinson (2002) in the spirit of Dervis, de Melo and Robinson (1989). The model is calibrated to capture Senegal economy using the latest Social Accounting Matrix (SAM) data with more detailed illustration and model explanation provided in Supplementary note 1. The extension of the standard CGE model is designed to capture uncertainty in the crop production and international agriculture commodity market prices that influence farmer’s decision in allocating input resources. The model extension is called Stochastic Computable General Equilibrium (S-CGE) model

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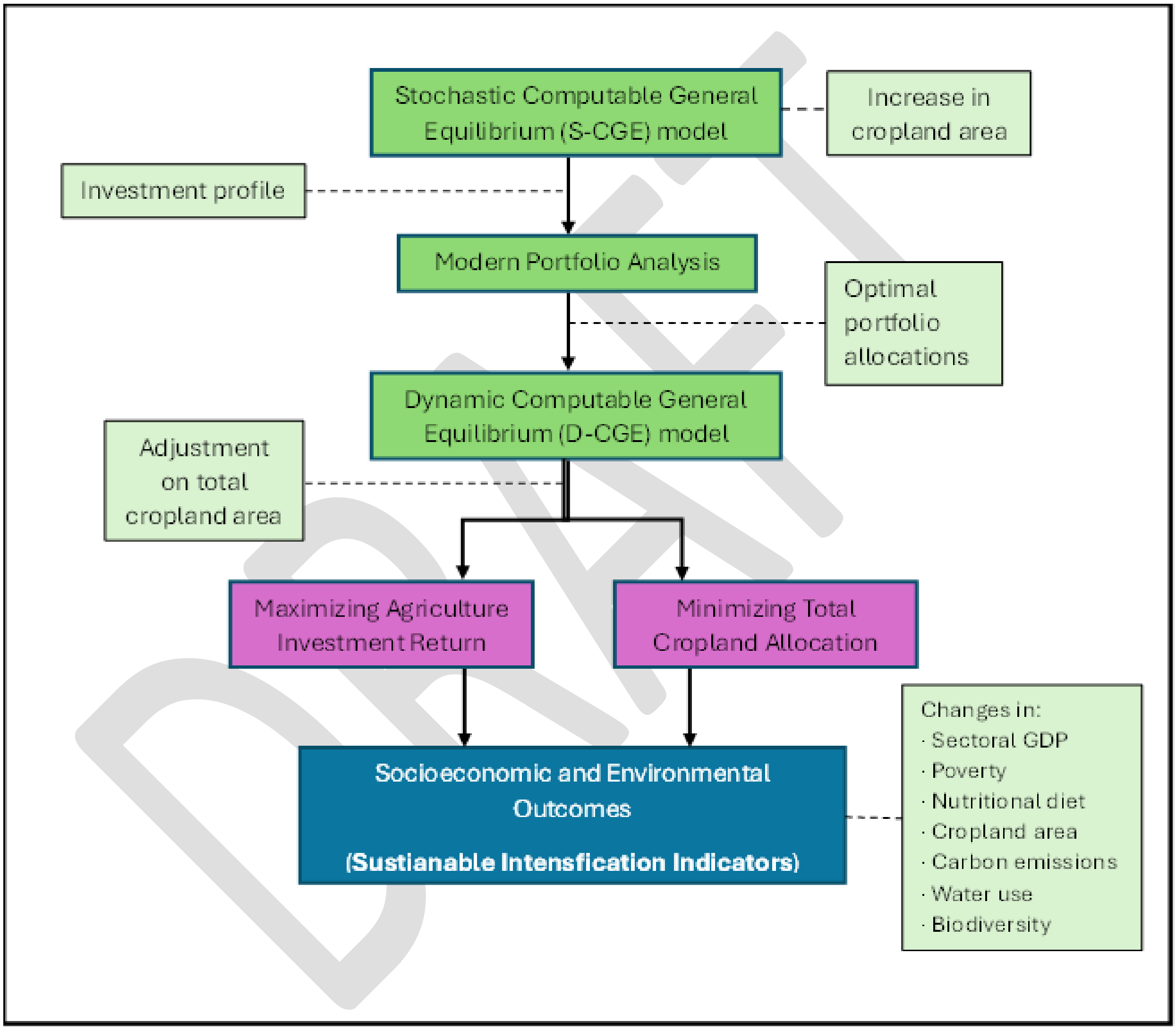
which is operated by imposing stochastic (random) shocks capturing the uncertainty stemming from production and global agriculture price fluctuations. We use historical productivity data for Senegal published by FAO (2023) and the global commodity prices published by the World Bank (2023) to derive both production and international market uncertainty by crops.

Figure 6. Modeling Framework and Sustainability Measurement



Source: Authors

The time series data from 1985 to 2019 are used to estimate the production and international market fluctuations separately for each crop using polynomial regression technique. This approach allows us to capture the fluctuations in production and global commodity market price over the years using polynomial regression technique. One of the reasons we use polynomial regression is to help better fit the estimated trendline on the non-linear data with potential vast range of curvatures. Given our interest is to measure uncertainty factors affecting each crop, we capture it by measuring the distance of observed data with its estimated trendline generated by the polynomial regression. The polynomial regression is run by making sure each model generates at least 70 percent value of R^2 to capture the model fitness in explaining the uncertainty.

Supplementary Fig. 1 shows the projected trendline results generated by each polynomial regression against the observation data. The uncertainty factors are measured by generating random dataset derived from deviation value of observed data away from the projected trendline. The further away the observed data from the trendline would suggest the higher the shock or the unexpected event took place along the trendline. We derive the mean and variance value of the deviation points from the trendline for each crop to generate 1000 random data by maintaining covariance value across crops on production and world price (Supplementary Table S1). The reason of maintaining the covariance value in the random data generation process is because there is potential systematic risk that inherent across crops originated from country's production as well as global market fluctuations affecting the agriculture production system.

We then use the generated random data as input to shock the productivity and international commodity price parameters in the S-CGE model and set it as the baseline values of the model (Supplementary note 1). Both stochastic (random) shocks on production and global agricultural prices represent uncertainty factors within agriculture production and global commodity market transactions that determine the risk factors associated with each crop. We use total crop value added as an indicator of agriculture income to evaluate changes in investment return. Supplementary Fig. 2 shows the distribution of the random shocks on production and global market prices as well as the baseline results reflected by changes in agriculture income generated by the S-CGE model following the random shocks. The mean and standard deviation value on each crop reflect the uncertainty factors driving the risk and investment return. The investment return is centered around zero with standard deviations of CFA 63.8 billion.

After setting up the model baseline, the next step is to develop agriculture investment scenarios to capture investment results in a new cropland area measured by each crop. We refer to historical cropland data expansion in the country to estimate how much the potential cropland area to be invested. Figure 7a shows the total area in Senegal allocated into six major crop groups from 2005 to 2020 in five years period. In Senegal, we observe that total cropland area allocated has increased by around 1.5

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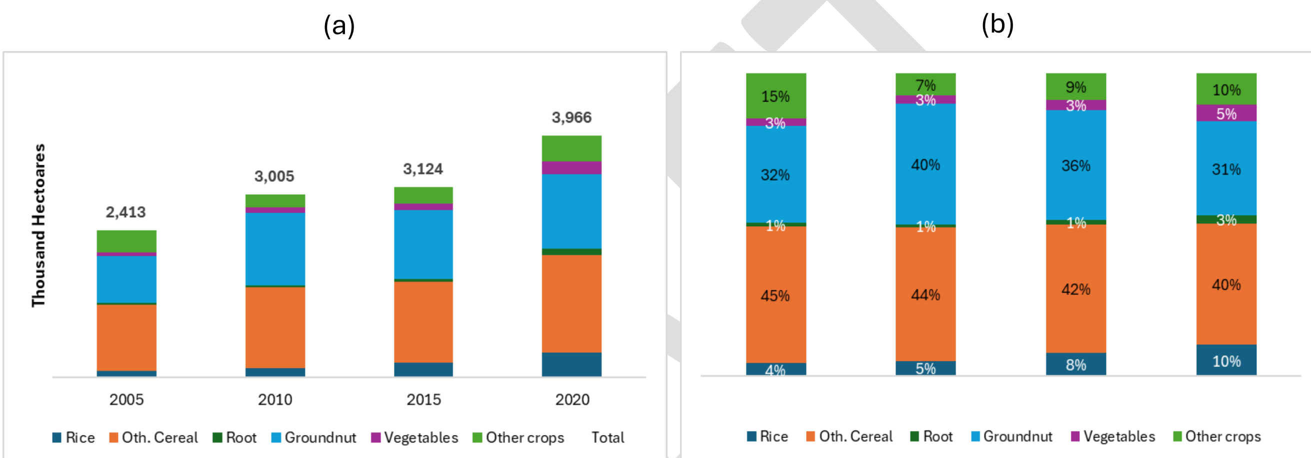
million hectares in the last 15 years from 2005 to 2020. This on average set the country's annual cropland expansion or natural capital investment to be around 100 thousand hectares per year. Looking at the share of cropland allocation overtime (Figure 7b), we do not observe significant structural shift, which implies that the allocation of new cropland follows the total land allocation share. Based on that, we allocated half of the new cropland expansion towards grain crops and about one third to groundnut crops. The remaining share goes to root, fruits and vegetables, and other crops, with the combined shares of about one fifth of total new cropland area.

Figure 7. Historical cropland expansion in Senegal



Source: FAOSTAT 2023

This information becomes our main guidelines to set the simulation scenarios of cropland investment following the current total land distribution with most of the new cropland are used to grow grains and groundnut. However, we set the annual cropland expansion at only 50 thousand instead of 100 thousand hectares to capture the potential lower bound in promoting SI. It is important to note that we conduct the cropland expansion assessment on individual crop to evaluate crop investment performance. We do this by running a separate scenario for each individual crop using the stochastic model by increasing land supply of the investigated crop by 50 thousand hectares. These scenarios capture the counterfactual analysis of investing cropland expansion in a single crop to estimate the expected return and risk associated with each crop. We evaluate the investment performance using agriculture crop value added as investment return indicator which also reflects potential impact on farmer's income. We believe this modeling approach offers an ideal instrument in measuring return from cropland expansion at national level, given there is no empirical data could provide information on how much investment return generated by individual crop investment, measured under the controlled market and production uncertainties. Results from this experiment are provided in Figure 1(c-d) showing how much potential risk and return generated by each crop reflected by the mean and standard deviation values.

The investment profile data generated by the S-CGE model are then used as input data in the optimal portfolio analysis as shown in Figure 6. The analysis is based on Modern Portfolio Theory (MPT) that has been used as the foundational method for selecting investment portfolio that offers the highest return given the associated risk. The method was developed by Markowitz (1952, 1991) to design an optimal portfolio from diversified investment options that gives the maximum return with the quantifiable amount of risk. The method has been widely applied in the finance industry to help investors and portfolio managers to craft the optimal investment allocation by diversifying investment allocation following the expected return and risk information. In this study, we apply the same method to find the optimal cropland allocation using the crop investment profile generated by the S-CGE model as explained earlier. The main goal is to find the optimal diversification strategy that not only helps increase investment but also to reduce the risk associated with each portfolio options.

$$EP = \sum_i^n X_i \, . \, \mu_i \qquad (1)$$

$$VP = \sum_i^n \sum_j^n X_i \, . \, Cov_{ij} \, . \, X_j \qquad (2)$$

$$\sum_i^n X_i = 1 \qquad (3)$$

$$X_i \geq 0 \qquad (4)$$

Where:

EP	is the portfolio expected return
VP	is the portfolio variance
X*i*	is share of new cultivated area allocated to crop *i*
μ_i	is the expected investment return of crop *i*
$Cov_{i,j}$	is the variance and covariance matrix across crops

The mathematical model is presented by equation (1) to (5), which is simply founded based on two statistical measures of mean that represent expected return of the portfolio (EP), and variance (VP)

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that represents risk associated with the portfolio. Sometime the model is also called "Mean-Variance" model given the core components of the model are based on these two statistical measures. The objective set in the model is to find the optimal portfolio allocation by maximizing return measured by portfolio mean value and minimizing risk as measured by variance. Given there is trade-off between risk and return, the solutions for optimal portfolio are given as an efficient frontier that provides series of optimal portfolio allocation that are attainable following investor's risk tolerance. Thus, the model solutions are given by varying the risk tolerance level (λ) of the investor reflecting the changes from risk averse to risk neutral behavior.

$$\text{Maximize } [\ (1-\lambda).\ EP] - [\ \lambda^*\ VP] \qquad (5)$$

$$\text{s.t} \quad \sum_i^n X_i = 1\ ; \quad X_i \geq 0$$

$$\text{Where: } 0 \leq \lambda \leq 1$$

The risk tolerance value is set to vary from 0 to 1 to capture all range of optimal portfolio options from low to high return given the associated risk. When the risk behavior value is set to zero, the objective function is set to only maximize expected portfolio return. However, as the risk tolerance value increases, the total portfolio risk starts to emerge until it reaches maximum negative value where the objective function is turned to mathematically minimize the total portfolio risk. All the solutions are displayed as an efficient frontier to reflect the varying degree of risk tolerance level of the investor from risk averse to risk neutral as presented in figure 2. Based on all the optimal portfolios, we choose three portfolio allocations that represent low, medium and high-risk profile as alternative cropland allocation against the baseline. To demonstrate the superiority of diversification solutions generated by portfolio analysis, Supplementary Fig. 3 compared the baseline cropland portfolio against two portfolios in the efficient frontier. It is clear that all the points on the efficient frontier are superior in improving investment return or reducing risk compared to baseline. This implies that reallocating cropland following the optimal portfolio profile could generate positive gain by either increasing investment return while maintaining the risk level or reducing risk while maintaining investment return.

As pointed out in Figure 6, we adopted optimal cropland portfolio allocation results following Modern Portfolio Analysis in the Dynamic Computable General Equilibrium (D-CGE) model to evaluate how the cropland expansion following optimal portfolio allocation affects both socioeconomic and environmental outcomes. We run the model over seven-year period from 2024 to 2030 to observe the impact of land reallocation by adjusting the cropland reallocation following the three optimal

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portfolio profile (i.e. low, medium and high) and compared the results against the cropland allocation adopted in the baseline.

We also extend the analysis by running some additional scenarios by varying land supply to capture both economic and environmental benefits at the same time. As shown in Figure 6, we design the scenario assessments using two separate approaches by: (1) targeting a higher investment return using the same amount of land (maximizing economic gains) and (2) using the least amount of land necessary to generate a comparable return on investment (minimizing use of cropland). The first approach is basically designed to maximize the return on investment from cropland reallocation on agricultural income while maintaining the same amount of land. On the other hand, the second approach aims to identify the minimum amount of land required to generate an equivalent agricultural income. This means that at one extreme we use all the available cropland expansion area in all simulation scenarios to reach the objective of maximizing the economic gains. At the other extreme, we set the model to generate economic gain across all simulations to be the same as in the baseline to meet the objective of minimizing (maximizing) the use of new cropland area (land savings). Based on these results, we run some additional scenarios in between by adjusting total cropland expansion to construct a graphical curve illustrating the relationship between economic and environmental outcomes. The results help to quantify the potential trade-off between economic returns and environment cost under SI pathways. The results are also used to develop the production possibility frontier to show the optimal points of production in generating both economic and environmental gains as shown in Figure 5b.

To demonstrate our approach in achieving SI through cropland reallocation, we calculate the impact of different cropland portfolio allocation on both socioeconomic and environmental indicators as listed at the bottom of Figure 6. The pass the bar, we need to demonstrate positive impact on both various socioeconomic outcomes and environmental factors at the same time. Most of the indicators are calculated directly in D-CGE model, such as changes in sectoral GDP and cropland area. However, other indicators like poverty and nutritional diet are computed by linking D-CGE model with microsimulation module to measure distributional effects by linking model results with national household survey data (ANSD 2013). The nutritional diet measure follows Pauw et al. (2023), where changes in diet is measured by the incidence of diet deprivation across multiple food as reflected in the Reference Diet Deprivation (ReDD) index. The lower the index means the more (less) diet improvement (deprivation) observed among households. The changes in carbon emissions are measured by crop at farm level by adopting emission intensity from Poore and Nemecek (2018), while the changes in water use are calculated using water intensity data from Mekonnen and Hoekstra (2010). Finally, the biodiversity index is calculated based on changes in cultivated area by crop using Shannon Diversity Index (Shannon and Weaver 1949).

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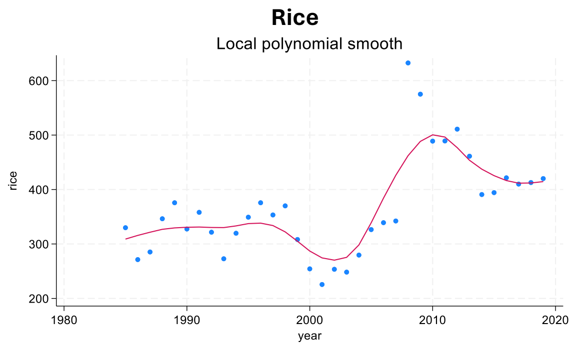
Supplementary Information

Supplementary Fig. 1 Observed versus predicted production and global price trendlines.

Supplementary Fig. 1a Crop Production Trendlines

Supplementary Fig. 1b Global Crop Price Trendlines



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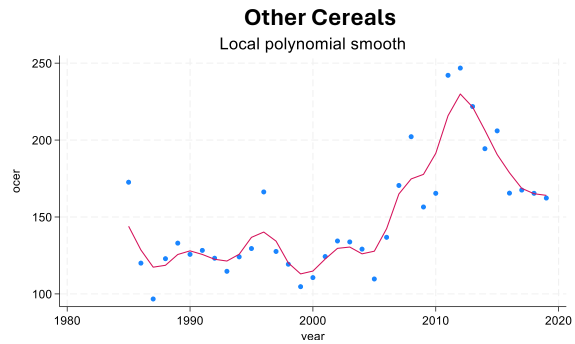

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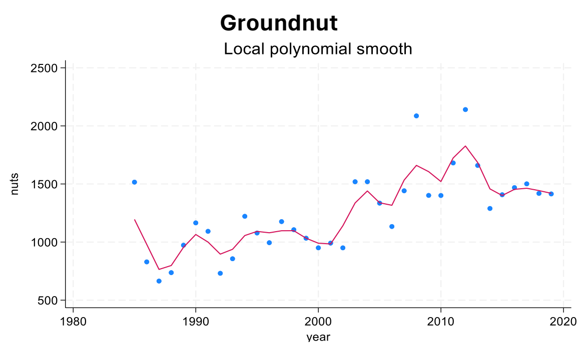

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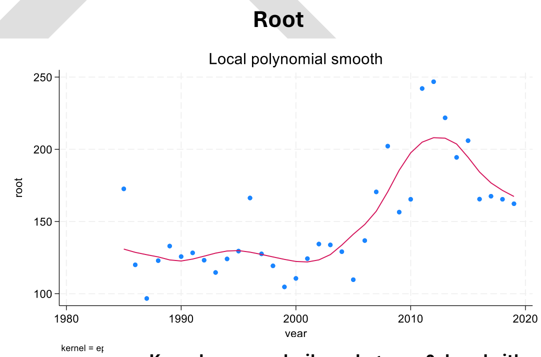

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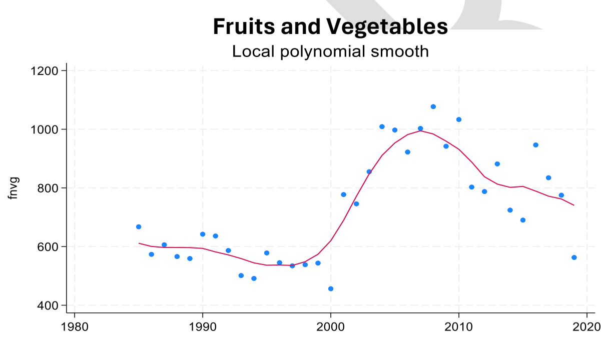

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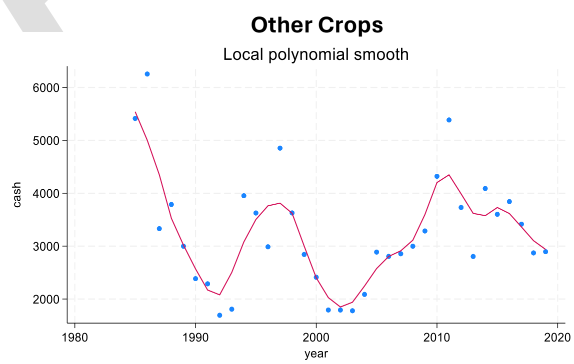

Kernel – epanechnikov, degree = 0, bandwith = 1, R^2 = 0.793

Supplementary Table S1. Covariance Matrix comparisons

Supplementary Table S1a. Covariance Matrix on Crop Production (Observation)

	Rice	Root	Fruit	Groundnut	Other Crop	Other Cereal
Rice	0.0073					
Root	0.0058	0.0234				
Fruit	0.0002	-0.0013	0.0016			
Groundnut	0.0026	0.0048	0.0016	0.0076		
Oth. Crop	0.0010	0.0023	0.0018	0.0033	0.0105	
Oth. Cereal	0.0025	0.0046	0.0018	0.0062	0.0039	0.0071

Supplementary Table S1b. Covariance Matrix on Crop Production (Random sample)

	Rice	Root	Fruit	Groundnut	Other Crop	Other Cereal
Rice	0.0071					
Root	0.0052	0.0222				
Fruit	0.0003	-0.0014	0.0016			
Groundnut	0.0028	0.0042	0.0016	0.0077		
Oth. Crop	0.0014	0.0020	0.0018	0.0036	0.0107	
Oth. Cereal	0.0027	0.0043	0.0018	0.0063	0.0042	0.0073

Supplementary Table S1c. Covariance Matrix on Global Prices (Observation)

	Rice	Root	Fruit	Groundnut	Other Crop	Other Cereal
Rice	0.0130					
Root	0.0050	0.0164				
Fruit	0.0024	0.0009	0.0101			
Groundnut	0.0056	0.0068	0.0027	0.0124		
Oth. Crop	0.0004	-0.0009	-0.0021	0.0022	0.0187	
Oth. Cereal	0.0035	0.0104	0.0000	0.0046	-0.0009	0.0073

Table S1c. Covariance Matrix on Global Prices (Random sample)

	Rice	Root	Fruit	Groundnut	Other Crop	Other Cereal
Rice	0.0136					
Root	0.0053	0.0175				
Fruit	0.0017	0.0007	0.0098			
Groundnut	0.0061	0.0068	0.0023	0.0121		
Oth. Crop	0.0004	-0.0004	-0.0017	0.0023	0.0175	
Oth. Cereal	0.0038	0.0112	0.0000	0.0048	-0.0006	0.0080

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Supplementary Fig. 2 Crop GDP under production and global market uncertainty (Baseline from S-CGE model)

Fig. 2a Distribution of random shock on crop productivity

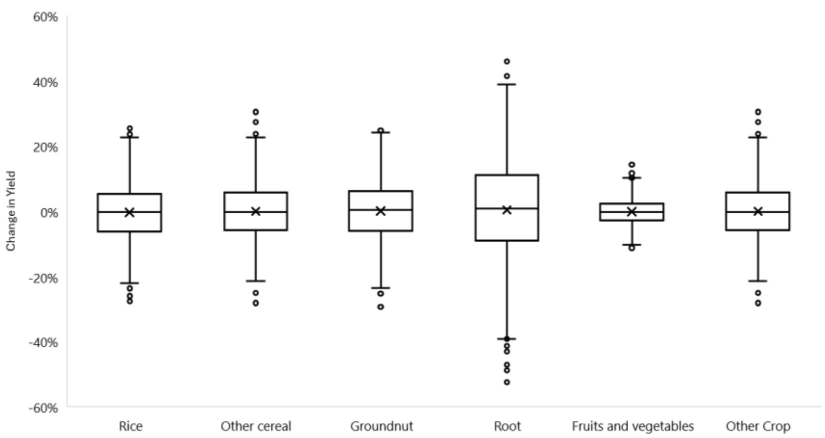


Fig. 2b Distribution of random shock on world prices

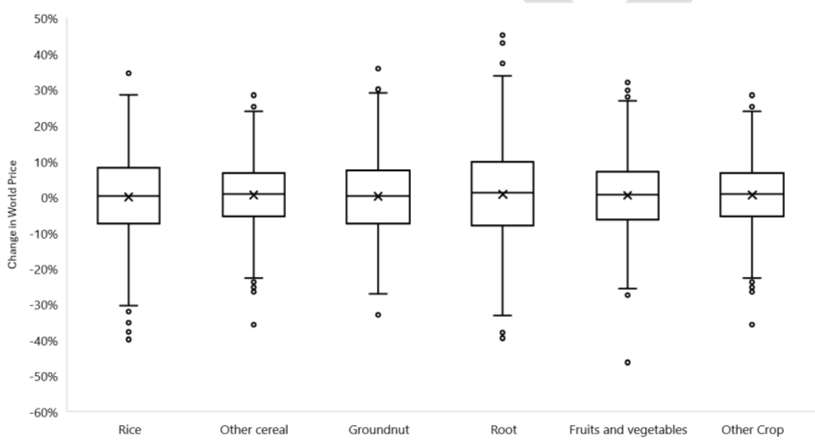
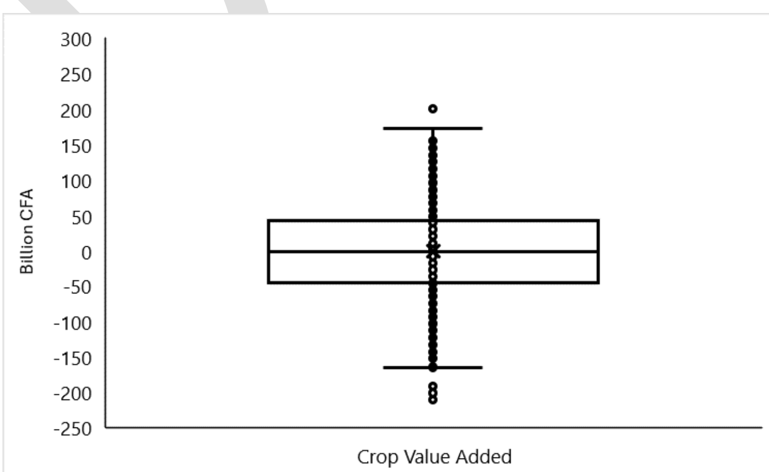
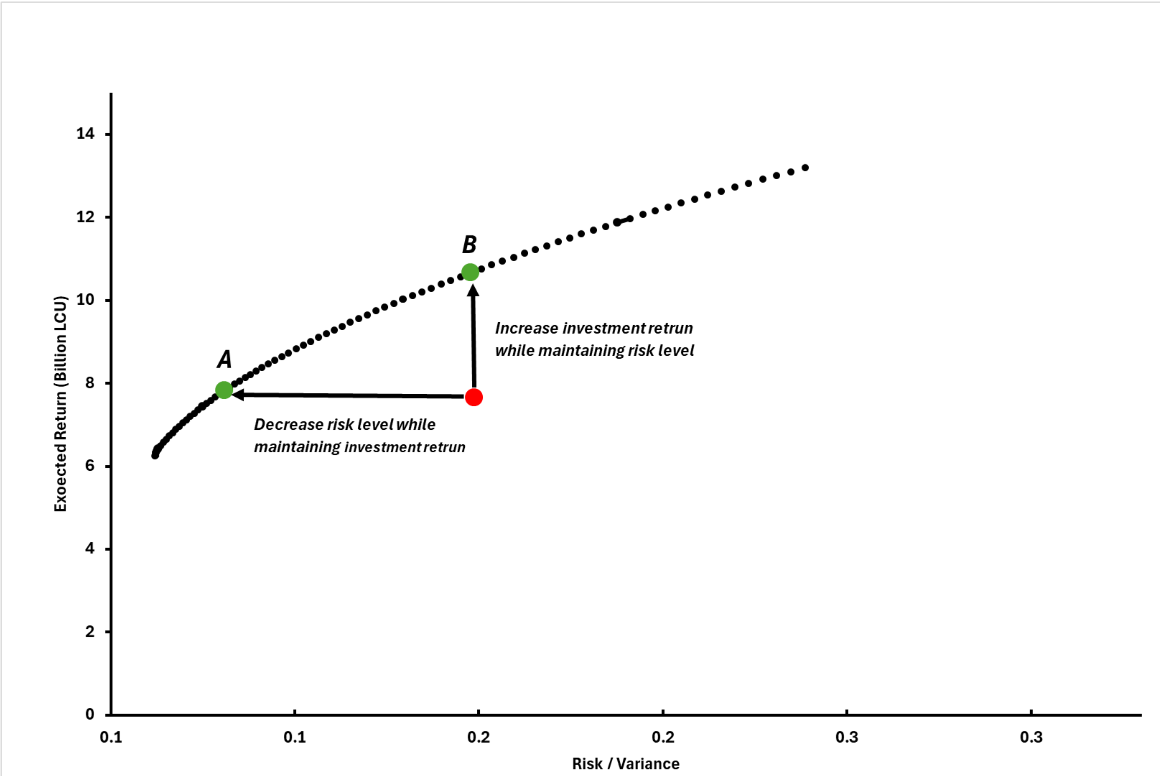


Fig. 2c Distribution of crop value added from S-CGE model simulation result given the production and global market uncertainty.



Supplementary Fig. 3 Comparison between current land allocation and optimal portfolio options



Red dot represents cropland allocation under the baseline with expected investment return of CFA 7.98 billion and risk/variance of 0.24 billion. The green dots on the efficient frontiers offer higher return (B) or lower risk (A) level compared to the baseline (red dot).

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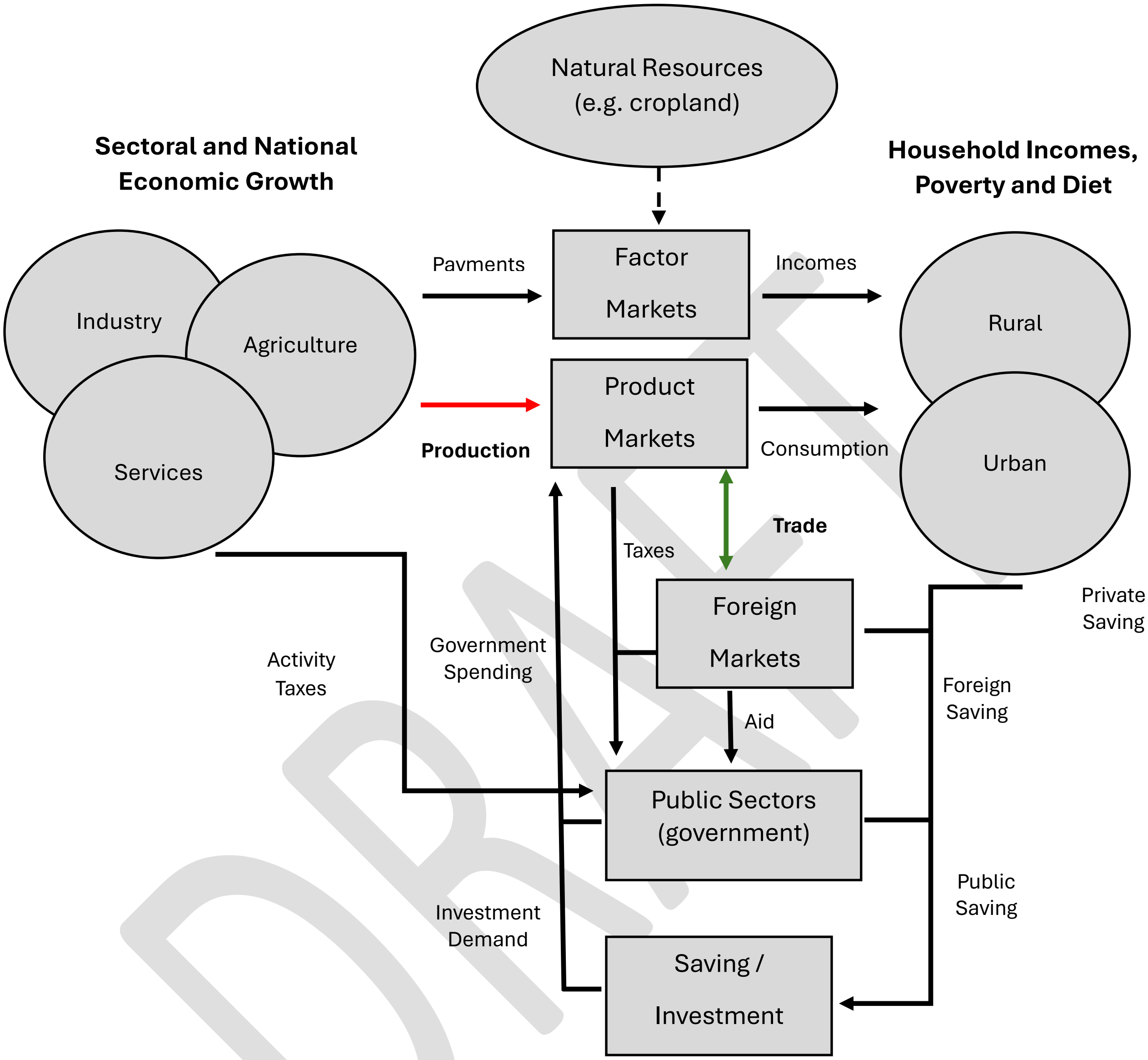
Supplementary Note 1. Computable General Equilibrium (CGE) Model Framework



Source: Authors (adapted from Diao and Thurlow 2012)

The above diagram illustrates how economywide modeling framework captures the sectoral interlinkages by linking production and consumption activities through economic interactions taking place in both factor and product markets that are operated following the basic economic principles. In this study, the model is calibrated into Senegal economy using 2019 Social Accounting Matrix (SAM) database adapted from Randriamamonjy (2021). We disaggregated production activity into 55 sectors with 10 agriculture sectors categorized under agriculture, 33 under industry and 12 under services. The household is distinguished not only based on rural and urban location but also their income level and whether the rural household receives income from agriculture activities. The factor markets are disaggregated into 3 major factors of land, labor and capital with labor and capital are further disaggregated into 8 and 4 types respectively (Supplementary Table 2). The supply of land (cropland) is determined exogenously from natural resources, which in this study is assumed to be associated with deforestation. Therefore, if the economy uses less cropland in the equilibrium, it translates into increase in land savings or less deforestation rate. In this study, both total cropland supply as well as its allocation across different crops are used as the main levers to design the simulation scenarios as elaborated in the methodology section.

We assume labor is mobile across sectors, while land and capital are fixed by sector specific to capture the short to medium term impact changes. The land allocation scenarios adopted in this study are reflected by the changes in the amount of land used in producing each crop. If the share of land allocated to certain crop goes down, this obviously leads to lower production of that particular crop. Similarly, when the share of land to certain crop increases, this means more land allocated to produce that crop leading to an increase in its production. The production value and land area for each crop is provided in Supplementary Table 3. The land value per hectare reflects the shadow price of land generated by dividing the land return recorded in the SAM database with the cultivated land used by each crop. The value is in line with past research showing the higher return of land for high valued crops like fruits and vegetables compared to grain crops (See Rivera-Padila 2020 and Zhang et. al 2022).

The key function that reflects the behavior of producer or farmer in the model is the production function (Supplementary eq.1). This function demonstrates how farmer optimally allocates the limited supply of resources by combining different input factors to produce certain output at sectoral level (red arrow). The mathematical relationship between input factors (V) and output (X) is provided in Supplementary eq.1. The quantity demand of each input factor f (land, labor, capital) is shown by variable V with α acts as the share parameter of factor f employed in producing good i. Since we adopt the Constant Elasticity of Substitution (CES) function in the production system, we allow substitution between factors that is determined by ρ value. The λ represents total productivity (TFP) that determines efficiency level of production system. The higher the λ means the higher the production system efficiency.

$$X_i = \theta_i . \lambda_i \left(\sum_f \alpha_{if} . V_{if}^{-\rho_i} \right)^{-1/\rho_i} \quad (1)$$

In the Stochastic Computable General Equilibrium (S-CGE), we add a new parameter of θ which acts as a shift parameter to drive production fluctuation through changing in TFP. By default, the value of θ equals to 1 in the standard model, but in the S-CGE model the value is determined by random shocks data generated from historical crop production data as measured by deviation value between the estimated trendline with the observed data (Supplementary Fig. 1a). The random shift parameters for each crop are generated by drawing 1000 random sample from multivariate distribution by maintaining the mean and covariance values as explained in the methodology section. The same approach is also applied in generating random shocks to capture uncertainty in the global crop markets.

$$PP_i.X_i = PD_i.D_i + \delta_i.pwe_i\,(1 - te_i).E_i \tag{2}$$

$$(1 - tc_i)P_i.Q_i = PD_i.D_i + \mu_i.pwm_i\,(1 - tm_i).M_i \tag{3}$$

In the S-CGE model, the global market uncertainty is captured by introducing random shocks on both export and import prices (green arrow). Supplementary equation 2 and 3 show the relationship between global commodity prices with domestic economy and how fluctuation in global price affects both production and consumption activities. The random shocks introduced to export price (*pwe*) are driven by shift parameter of δ that is unique by each crop. Similar condition applies to import price (*pwm*), where the random shocks are driven by shift parameter of μ that also different across crops. In the standard model the values for both δ and μ are unity, but in the S-CGE model the value fluctuates around one. When the value of δ is larger than one it means an increase in export price relative to domestic price. This change in relative price between export and output price (PP_i) drives the producer or farmer to sell more of their product into the export market. Similarly, when the value of μ is larger than one, this drives the consumer to purchase more of their consumption from domestic market and reduce imports. Tariff are introduced on international transaction on both import (te) and export (te), while for the domestic goods (Q_i) the government imposes commodity tax (tc) apply on domestic price (P_i).

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Supplementary Table 2. Model disaggregation by production sector, household, and input factors.

Table 2a. Sectoral disaggregation

No.	Code	Sector Description
		Agriculture
1	arice	Rice
2	aocer	Other cereals
3	aroot	Other roots
4	agnut	Groundnuts
5	afrui	Other fruits
6	aocrp	Other crops
7	acatt	Cattle
8	afore	Forestry
9	aaqua	Aquaculture
10	afish	Capture fisheries
		Industry
11	aomin	Other mining
12	ameat	Meat processing
13	afsea	Fish and seafood processing
14	afveg	Fruit and vegetable processing
15	afoil	Fats and oils
16	adair	Dairy
17	ammll	Maize milling
18	asmll	Sorghum and millet milling
19	armll	Rice milling
20	agmll	Other grain milling
21	asref	Sugar refining
22	afood	Other foods
23	afeed	Animal feed
24	abeve	Beverages
25	aptob	Tobacco processing

No.	Code	Sector Description
		Industry
26	ayarn	Cotton yarn
27	atext	Textiles
28	aclth	Clothing
29	aleat	Leather and footwear
30	awood	Wood products
31	apapr	Paper products and printing
32	apetr	Petroleum products
33	afert	Fertilizers and herbicides
34	achem	Other chemicals
35	anmet	Non-metal minerals
36	ametl	Basic metals
37	aequi	Electrical equipment
38	amach	Machinery and other equipment
39	avehi	Motor vehicles
40	aoman	Other manufacturing
41	aelec	Electricity, gas and steam
42	awatr	Water supply and sewage
43	acons	Construction
		Service
44	atrad	Wholesale and retail trade
45	atran	Transportation and storage
46	ahotl	Accommodation
47	arest	Restaurants and food services
48	acomm	Information and communication
49	afsrv	Finance and insurance
50	areal	Real estate activities
51	absrv	Business services
52	apadm	Public administration
53	aeduc	Education
54	aheal	Health and social work
55	aosrv	Other services

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Table 2b. Household disaggregation

Code	Household Description
hhd-f1	Rural farm - quintile 1
hhd-f2	Rural farm - quintile 2
hhd-f3	Rural farm - quintile 3
hhd-f4	Rural farm - quintile 4
hhd-f5	Rural farm - quintile 5
hhd-n1	Rural nonfarm - quintile 1
hhd-n2	Rural nonfarm - quintile 2
hhd-n3	Rural nonfarm - quintile 3
hhd-n4	Rural nonfarm - quintile 4
hhd-n5	Rural nonfarm - quintile 5
hhd-u1	Urban - quintile 1
hhd-u2	Urban - quintile 2
hhd-u3	Urban - quintile 3
hhd-u4	Urban - quintile 4
hhd-u5	Urban - quintile 5

Table 2c. Sectoral disaggregation

Code	Labor Description
flab-rn	Labor - rural uneducated
flab-rp	Labor - rural primary
flab-rs	Labor - rural secondary
flab-rt	Labor - rural tertiary
flab-un	Labor - urban uneducated
flab-up	Labor - urban primary
flab-us	Labor - urban secondary
flab-ut	Labor - urban tertiary
flnd	Land - agricultural crops
fcap-c	Capital - crops
fcap-l	Capital - livestock
fcap-m	Capital - mining
fcap-o	Capital - other

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Supplementary Table 3. Production and Cultivated Area by Crops

Crop	Production (Thousand Tons)	Cultivated area (Thousand Ha)	Yield	Production Value (Billion CFA)	Land Return (Billion CFA)	Land Value per Ha (Thousand CFA)
Rice	1,156	346	3.34	156.8	38.0	109.9
Other cereals	1,613	1,384	1.17	347.8	188.9	136.5
Other roots	1,338	204	6.54	117.0	39.7	194.3
Groundnuts	1,433	1,032	1.39	298.3	58.3	56.4
Fruit and vegetables	2,487	202	12.32	559.1	138.3	685.2
Other crops	1,770	378	4.69	383.0	91.0	241.0

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