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Enhancing Governance Performance in Sub-Saharan Africa Can Bolster Climate Mitigation and Food Security

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The sub-Saharan Africa (SSA) region has experienced substantial population growth over the past decades, accompanied by severe hunger and environmental degradation. Underperforming governance is a major driver of unsustainable agricultural production and land use in SSA. The impacts of governance performance on food security and the environment in SSA require better understanding by considering socioeconomic and biophysical dynamics. Using an agro-economic dynamic optimization model, we investigate the impacts of governance performance on land use, greenhouse gas (GHG) emissions, and food security in the SSA region by 2050. Our findings indicate that strong governance could lead to less deforestation, thus reducing GHG emissions in the agriculture, forestry, and other land use (AFOLU) sector. Strong governance could also improve food security, with higher agricultural productivity, lower food prices and food expenditure share, as well as higher self-sufficiency. These findings highlight that those efforts should extend beyond specific agricultural and environmental measures and promote integrated governance to achieve long-term synergies between food and environmental security in SSA.

Introduction

The sub-Saharan Africa (SSA) region is currently confronted with severe food insecurity [1] and rising greenhouse gas (GHG) emissions [2,3]. With the highest Global Hunger Index score in the world at 27.0, the food security challenge in SSA remains alarming [1]. Rapid population growth, low crop yields and production, lack of credit and investment in infrastructure, and corruption [4,5] are major driving factors of the severe hunger problem. The population of SSA grew from 154.5 million in 1950 to 1,122.4 million in 2021 and is projected to reach 2,111.2 million by 2050 [6]. To meet the surging food demand resulting from population growth, agricultural land in SSA has expanded by 165.7 million hectares (Mhm^2) over the past 2 decades, including 90.8 Mhm^2 of cropland and 74.9 Mhm^2 of pasture areas. In contrast, forests have declined by 76.9 Mhm^2 [7]. Forests play a crucial role in carbon sequestration, containing larger carbon pools than agricultural land [3]. Deforestation is a major source of emissions in the agriculture, forestry, and other land use (AFOLU) sector [8], particularly in the SSA region [2]. Carbon emissions resulting from the conversion of forest to cropland account for approximately 45% of the total carbon emissions from land use in SSA on an annual average between 1980 and 2009 [2].

The coexistence of food insecurity and environmental pressures reinforces the need to meet the growing food demand without sacrificing the environmental benefits, particularly facing agricultural expansion and deforestation [7]. Institutions, which are dynamic and complex [9], have been found to play a pivotal role in determining land-use behaviors [10,11]. The complexity and dynamics of institutions arise from the diverse interests of various stakeholders and the ongoing interactions between formal and informal rules [9]. Institutional performance can affect agents' decision-making regarding land-use patterns through property rights [12], particularly in terms of land tenure and ownership [13,14]. Well-enforced property rights generate incentives altering agents' cost-benefit assessments, whereas the absence of secure property rights increases costs for technological investments due to the associated risks, prompting unregulated deforestation to expand agricultural land [15,16].

Governance performance in SSA falls far behind other regions [17]. Its governance grapples with challenges, including weak institutions, social and economic instability, poverty issues, and emerging infectious diseases [18–20]. According to the International

Monetary Fund (IMF), only Ghana, Botswana, and Namibia score above the average of the rest of the world on the governance indicator, accounting for political, economic, and financial risks [18]. Empirical research suggests that underperforming governance performance in SSA leads to higher discount rates, discouraging long-term capital investments in agricultural technology [21,22]. Instead, it favors short-term expansion of cropland to compensate for low crop yields due to a lack of research and development (R&D) investment [21,22]. This expansion encroaches on forests and other natural areas [14], with negative impacts on GHG emissions [2]. In contrast, improved governance performance leads to lower discount rates, encouraging long-term capital investments in agricultural technology [21,22]. This in turn increases crop yields, reduces cropland expansion, mitigates GHG emissions in the AFOLU sector, and improves food security by increasing agricultural production [11,16,23]. While these empirical findings based on historical data are informative, they lack the ability to reflect long-term dynamics. Given that SSA plays a crucial role in achieving the global Sustainable Development Goals (SDGs) by 2030, it is imperative to explore future prospects in SSA in terms of food and environmental security. Taking into account various governance performance trajectories can provide insights into how unstable governance in SSA impacts the outcomes. Such forward-looking analyses could inform the formulation of future global and local actions aimed at poverty reduction, livelihood improvement, climate change mitigation, and ecosystem conservation in SSA.

Existing studies have delved into the long-term projection of governance impacts on land-use changes (LUCs), food security, and GHG emissions [12,24]. While these global analyses offer valuable insights, an understanding that takes into account SSA-specific contextual factors is still lacking. Built upon the quantification framework of governance impacts introduced by Wang et al. [12], this study incorporates dynamic interest rates, which are used as discount rates in a recursive agro-economic land system model, Model of Agricultural Production and its Impact on the Environment (MAgPIE) [25,26]. This study aims to address the following key questions concerning the SSA region: (a) How do changes in governance performance affect LUCs, specifically concerning agricultural land expansion and deforestation? (b) What are the impacts on GHG emissions under various governance performance scenarios? (c) How do changes in governance performance affect food security in terms of food self-sufficiency, prices, and expenditure share?

This study makes 3 contributions to the existing literature. First, instead of using static interest rates over time for specific regions [12], we incorporate dynamic interest rates associated with the regional development status. By employing these interest rates linked to gross domestic product (GDP) projections from the shared socioeconomic pathways (SSPs), we establish a relationship between interest rates and socioeconomic development indicators to reflect the dynamic nature of governance [9]. Second, we use an experimental and control setup to improve the understanding of how changes in governance performance within SSA affect the region. By holding conditions constant in other regions at baseline levels, this study can control for the impacts of changes in governance performance in these regions on climate mitigation and food security in SSA through international trade. Third, we conduct a relatively comprehensive analysis of the impacts of governance performance on environmental and food security in the SSA region, considering outcome indicators including LUCs, AFOLU GHG emissions, food self-sufficiency, prices, and expenditure share. Our model results shed light on how changes in governance performance of SSA influence its progress toward SDG 2 (Zero Hunger) and SDG 13 (Climate Action).

The remainder of this study is structured as follows. In the "Methods" section, we introduce the model used to simulate the effects of governance performance and the scenario design. In the "Results" section, we present the results related to the impacts of governance performance on the environmental and food security. The findings are discussed in the "Discussion" section, and conclusions are drawn in the "Conclusion" section.

Methods

Agro-economic land system model

MAgPIE, an agro-economic optimization model, combines economic and biophysical information to analyze spatial-explicit dynamics of land use and associated economic and environmental outcomes on multiple scales [27]. The primary objective of MAgPIE is to minimize the global production costs associated with meeting the demand for food, feed, materials, etc., considering both socioeconomic and biophysical constraints [26]. In this study, we employ MAgPIE version 4.6.11, featuring 12 world regions and 200 clusters aggregated [25]. At the biophysical level, constraints such as land and water availability, crop yields, and terrestrial carbon are specified at the 0.5-degree grid level sourced from the global crop, hydrology, and vegetation model named Lund-Potsdam-Jena model with managed land (LPJmL) [28]. The model operates dynamically in a recursive mode from 1995 to 2050 at 5-year intervals. Model results from 1995 to 2020 are calibrated according to historical data.

In the agricultural sector, MAgPIE encompasses the production activities of 24 main commodities, including 19 crop commodities and 5 livestock commodities (Table S1). Food demand is determined by future population and income growth. Both factors are projected exogenously under the SSPs [29]. Regions can meet demand by increasing yields, expanding agricultural land, and agricultural trade. Technical changes incentivized by investments in technology and infrastructure increase land-use intensity which is key to driving yield improvements [30,31]. Expanding irrigated areas to enhance crop yields requires blue water, available in limited quantities per cluster [32]. International trade is integrated into the MAgPIE based on historical trade patterns and comparative advantage [33].

MAgPIE accounts for various land types, including cropland, pasture, forest, other land (including nonforest natural vegetation, abandoned agricultural land, and deserts), and settlements. While changes in cropland, pasture, forest, and other land areas are modeled endogenously, settlement areas are projected exogenously, following socioeconomic pathways. The forest in MAgPIE also incorporates afforestation for carbon dioxide removal (CDR) and timber production. The afforestation target is driven by the National Determined Contributions. MAgPIE includes the production of wood and wood fuel from plantation forests, establishing new plantations to meet future timber demands [25]. LUCs and agricultural production activities result in GHG emissions (CO_2, CH_4, and N_2O) from the AFOLU sector. CO_2 emissions mainly occur during the conversion of nonagricultural land to cropland, which affects terrestrial carbon stocks [34]. CH_4 emissions are associated with enteric fermentation of livestock, animal waste management, and rice cultivation [26]. N_2O emissions result from sources such as manure, inorganic fertilizers, crop

Table 1. Attributes of governance scenarios in this study

Scenarios	Population growth	Economy growth	Governance performance	Interest rates (2050)
Business-as-usual (BAU)	SSP2 (Medium)	SSP2 (Medium)	SSP2 (Medium)	SSP2 (6.9%)
Governance improvement (InstImp)	SSP2 (Medium)	SSP2 (Medium)	SSP1 (Improvement)	SSP1 (5.2%)
Governance deterioration (InstDet)	SSP2 (Medium)	SSP2 (Medium)	SSP3 (Deterioration)	SSP3 (8.2%)

residues, and indirect emissions [34,35]. Freshwater resources are critical for agricultural production. Irrigation water demand is endogenously determined based on irrigated cropland area and livestock production, whereas water demand from other sectors is prescribed exogenously.

The minimized costs in MAgPIE include production input factors (i.e., labor and capital), land conversion, domestic transport, fertilizer, irrigation, trade, and technological investments [26,27,35]. MAgPIE employs an annuity approach that evenly distributes the costs that occurred in the current time step over six 5-year simulation periods by adopting an annuity factor [12]. This annuity factor is designed to be affected by regional governance performance, represented as the discount rates in MAgPIE. Specifically, governance performance leverages land-use decisions concerning costs related to R&D investments for yield enhancement and expenses associated with converting forests or natural vegetation to cropland through discount rates.

Scenario design

We parameterized our scenarios based on the middle-of-the-road socioeconomic pathway (SSP2), reflecting a continuation of existing development trends [36]. In SSP2, there are no remarkable departures from historical social, economic, and technological patterns. However, notable disparities persist among and within countries. Built upon the quantification framework of governance impacts introduced by Wang et al. [12], this study uses lending interest rates as a proxy for discount rates and integrates them into the model to capture the risk-related factors associated with governance performance. Lending interest rates are often used as a proxy for discount rates to approximate governance performance [12,37,38]. Lending interest rates set by banks are typically designed to meet the short- and medium-term financial needs of the private sector [39]. They are influenced by economic development and political stability, thereby reflecting the investment risks. Weak governance is usually associated with high investment risks, which in turn lead to higher lending interest rates. Notably, existing research suggests a negative correlation between lending rates and the aggregate governance indicator, which comprises governance accountability, political stability, government effectiveness, regulatory quality, rule of law, and control of corruption [12]. Governance performance could substantially impact agricultural R&D investments, which promote technological innovation to achieve yield growth [23]. Deterioration in governance performance results in high risks and uncertainties associated with investments, making investing in agricultural technologies less appealing to decision-makers [13,14]. To assess the impacts of governance performance, we employ the interest rates of a sustainability pathway (SSP1) and a regional rivalry pathway (SSP3) (Fig. S1A) to represent governance improvement (InstImp) and governance deterioration (InstDet) in SSA (see Table 1), respectively. We assume that the interest rates of other regions remain at SSP2 level (see Fig. S2 for the methodological framework).

Given that the challenges of food and environmental security in SSA are largely driven by population growth [3,4,6], we further conduct a sensitivity analysis with a higher population growth following the SSP3 scenario.

Dynamic interest rates under different governance scenarios

In our study, interest rates are contingent on a region's development status, which is associated with the GDP per capita [12,27]. Consequently, interest rates are dynamically driven by GDP per capita but remain exogenous to the model optimization (see Fig. S1B for the GDP per capita values in the SSA region in the scenarios). The following equations illustrate the methodology employed to calculate the interest rate of region i in year t.

$$dev\_sta_{i,t} = \begin{cases} 0, \; income_{i,t} < a \\ \dfrac{income_{i,t} - a}{b - a}, \quad a \le income_{i,t} < b \\ 1, \; income_{i,t} \ge b \end{cases} \qquad (1)$$

where i is the set of regions, t denotes the year, $income_{i,t}$ represents the GDP per capita of region i in year t, and $dev\_sta_{i,t}$ represents the development status of region i in year t. The development status interpolates between 0 and 1, with 0 corresponding to a low-income region, and 1 refers to a high-income region. a and b represent the lowest income levels of middle-income and high-income regions estimated by the World Bank, respectively. For middle-income regions with an income between a and b USD per capita per year, a higher GDP per capita reflects a higher development status.

$$int_{i,t} = int\_lic - (int\_lic - int\_hic) * dev\_sta_{i,t} \qquad (2)$$

The interest rate in region i at year t, represented by $int_{i,t}$, is interpolated based on the region's development status according to Eq. 2. int_lic indicates the initial interest rate in low-income regions, which is set to 10%; int_hic stands for the initial interest rate in high-income regions, which is set to 4%. The calculated interest rates of the SSA between 1995 and 2050 under the 3 scenarios are presented in Fig. S1A.

Results

Impacts of governance performance on LUCs

Cropland and pasture areas are projected to increase over time along with population growth, while strong governance could help mitigate their expansions. In the BAU (business-as-usual) scenario, cropland and pasture areas in SSA are projected to increase by 67.9 and 15.5 Mhm^2 in 2050 compared to the levels in 2020 (Fig. 1A). Conversely, other land and forest areas are expected to decrease by 33.9 and 54.8 Mhm^2, respectively. The expanded cropland is used for cultivating cereals, roots, vegetables, and fruits (Fig. S3). If the governance performance of SSA deteriorates, cropland and pasture areas could increase by 11.4 and 4.1 Mhm^2, respectively, in 2050 compared to the BAU scenario (Fig. 1B). Forest area would further reduce by 19.6 Mhm^2, while area of other land would expand by 4.1 Mhm^2. In contrast, 4.2 and 0.9 Mhm^2 of cropland and pasture expansions could be avoided in 2050 with improved governance performance compared to BAU. Forest area would decrease by 3.6 Mhm^2, while area of other land could expand by 8.7 Mhm^2.

The differences in land-use patterns among scenarios are mainly attributed to the varying growth rates of land-use intensity [30,31,40]. Land-use intensity is an indicator of agricultural productivity, reflecting the degree of yield amplification caused by human activities, such as investments in agricultural R&D. These investments, in turn, are strongly influenced by governance performance. The SSA region in 2020 has the same level of land-use intensity in all 3 scenarios (Table 2). By 2050, the increase in land-use intensity in the InstImp scenario would be 6.7% higher than the BAU scenario and 29.7% higher than the InstDet scenario. If we look at the technological change (TC) costs per se without taking risks into account, the weak governance scenario results in 10% less costs than the strong governance scenario (Table 2). However, the TC costs including investment risk premium in the weak governance scenario would become 17.7% higher than those in the strong governance scenario. Due to the insufficient growth of land-use intensity in the InstDet scenario, additional cropland and pasture areas are needed to increase production to meet the demand for agricultural products.

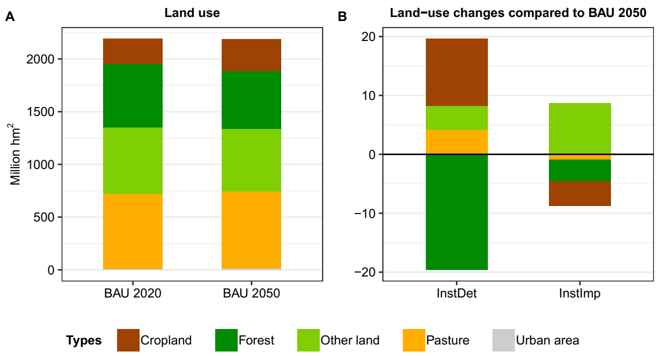

Fig. 1. Land use and LUCs in SSA in different governance scenarios. (A) Areas of different land-use types in 2020 and 2050 in the BAU scenario. (B) Changes in areas of different land-use types in 2050 in the InstDet and InstImp scenarios compared to the BAU scenario in 2050.

Impacts of governance performance on GHG emissions in the AFOLU sector

Cumulative GHG emissions from the AFOLU sector between 2020 and 2050 in the BAU scenario amount to 69.6 Gt CO_2eq (Fig. 2A). CH_4, whose cumulative emissions account for 50% of the total, is the biggest pollutant, followed by CO_2 and N_2O, whose cumulative emissions account for 39% and 11%, respectively. Enteric fermentation is the predominant source of CH_4 emissions (86.2%), followed by animal waste management (9.9%) and rice cultivation (3.5%). 97.8% of the CO_2 emissions primarily stem from LUCs. N_2O emissions mainly originate from agricultural soil and animal waste management. These 2 sources account for 81.6% and 17.3% of N_2O emissions, respectively.

Improving governance performance leads to a larger reduction in cumulative AFOLU GHG emissions by 2.2% compared with the BAU scenario from 2020 to 2050 in SSA. Cumulative CO_2 emissions register a reduction of 6.3% compared to those in the BAU scenario between 2020 and 2050. The primary contributor to the reduction in CO_2 emissions is the diminished agricultural land expansion and deforestation, along with a larger area of natural vegetation (part of other land). Meanwhile, cumulative CH_4 and N_2O emissions experience slight increases of 0.3% and 0.8%, respectively. The increase in CH_4 emissions can be attributed to an expansion in the rice cultivation area between 2020 and 2050, in contrast to the BAU scenario. Concurrently, the increase in N_2O emissions primarily stems from a higher cumulative fertilizer application between 2020 and 2050.

It is worth noting that the deterioration of governance performance in SSA could result in a marginal decrease of 1.2% in

Table 2. Changes in land-use intensity and related TC costs in SSA in the BAU, InstImp, and InstDet scenarios

Scenarios	(τ)[a] 2020	(τ) 2050	($\Delta\tau$)	Annuity TC costs [b] (USD$_{05MER}$/t dm)	Total TC costs [c] (USD$_{05MER}$/t dm)
BAU	0.74	1.19	0.45	13.04	37.66
InstImp	0.74	1.22	0.48	11.56	39.08
InstDet	0.74	1.11	0.37	13.61	35.19

[a] τ represents land-use intensity.

[b] Refers to the average annuity TC costs with accounting for investment risks between 2020 and 2050.

[c] Refers to average total TC costs without accounting for risk premium between 2020 and 2050.

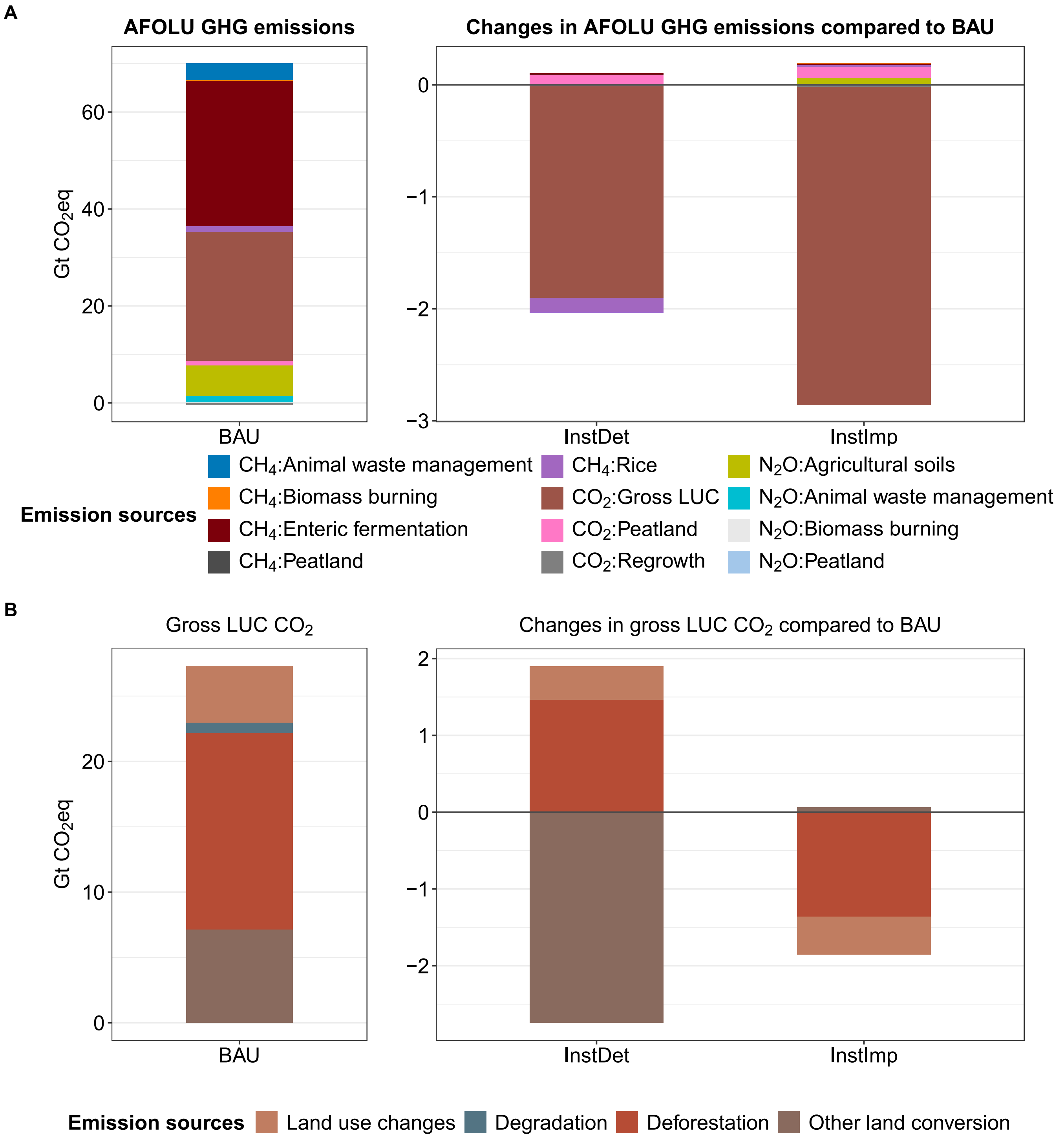

Fig. 2. Cumulative emissions of CO_2, N_2O, and CH_4 from the AFOLU sector in SSA between 2020 and 2050 in different governance scenarios. (A) Cumulative emissions in the BAU scenario and changes in the InstDet and InstImp scenarios compared to the BAU scenario. (B) Cumulative emissions in LUC CO_2 emissions in the BAU scenario and changes in the InstImp and InstDet scenarios compared to the BAU scenario.

the cumulative AFOLU GHG emissions between 2020 and 2050 compared to the BAU scenario, mainly from gross LUC. The CO_2 emissions from gross LUC in the InstDet scenario amount to 48 Gt CO_2eq, 1.9 Gt CO_2eq less than the BAU scenario. The deforestation contributes to an increase in CO_2 emissions by 1.5 Gt CO_2eq, while the expansion of other land leads to a reduction by 2.7 Gt CO_2eq compared to BAU (Fig. 2B). The conversion of other land mainly occurs in tropical areas with high carbon density, while the deforestation mainly occurs in highland area with low carbon density (Fig. S4). Cumulative CH_4 emissions in the InstDet scenario are 0.2% lower than those in the BAU scenario, mainly because of a 7.3% shrinkage of the rice cultivation area in the InstDet scenario compared to the BAU scenario between 2020 and 2050.

Impacts of governance performance on food security

In the BAU scenario, food self-sufficiency index in SSA would decrease by 3.4 percentage points by 2050 compared to 2020 (Fig. 3A). This decline is attributed to increased demand for food and reduced trade barriers. Concurrently, the food price index would decrease by 15% between 2020 and 2050, while the food expenditure share would decrease by 4.9 percentage points over the same period, both of which indicate an improvement in food affordability (Fig. 3B and C). This is driven by the intricate interplay of increased agricultural productivity, domestic demand dynamics, trade liberalization, and economic development in the SSA region.

For the impacts of governance performance on food security with respect to food groups, we further classified food products in the MAgPIE into 14 groups: cereals, roots, pulses, oil seeds, vegetable oils, vegetables and fruits, sugar, alcohol, bovine meat, pig meat, poultry meat, milk, eggs, and fish. Except for sugar and fish, all food groups exhibit a decline in self-sufficiency in the BAU scenario between 2020 and 2050. Notably, the self-sufficiency indices of cereals, oil seeds, and pulses substantially decrease by 5.6, 16.3, and 10.6 percentage points, respectively (Fig. 3A). The primary factor contributing to this reduction is the accelerated growth in demand for these food groups compared with their limited production capacities (Fig. S5). Consequently, increasing reliance on imports to fulfil this demand results in a diminishing level of self-sufficiency (Fig. S5). Concurrently, the increasing demand also contributes to increases in food price index for most food groups, ranging from 4% to 27%, except for milk, bovine meat, sugar, and fish, whose price indices are projected to decrease by 46%, 48%, 21%, and 1% by 2050, respectively, compared to 2020 (Fig. 3B). For these 4 food groups, more flexible fulfilment of demand through both domestic production and imports leads to lower food prices. Furthermore, despite the rising demand, economic progress and dietary shifts contribute to lower food expenditure share in the SSA region for most food groups (Fig. 3C). Specifically, among the groups experiencing a decline in the share of food expenditure, cereals, roots, oil seeds, pulses, milk, and bovine meat show relatively large reductions in their proportion of food demand, ranging from 0.05 to 2.5 percentage points. In contrast, poultry meat, pig meat, eggs, and fish show an increase in the food expenditure share, which is attributed to their doubled demand shares between 2020 and 2050 (Fig. S5).

As shown by our model results, governance performance plays a crucial role in boosting agricultural productivity by promoting R&D investment. This in turn contributes to improved self-sufficiency, lower food prices, and thus a reduction in the share of food expenditure in SSA (Fig. 3). By 2050, the self-sufficiency index of food in the InstImp scenario slightly surpasses that of the BAU scenario by 0.2 percentage points. In contrast, the InstDet scenario shows a decrease in self-sufficiency index by 1.8 percentage points compared to the BAU scenario. Improved governance performance leads to a more pronounced reduction in food price index and food expenditure share by 13% and 0.7 percentage points in 2050 compared to the BAU scenario, respectively. Conversely, in the InstDet scenario, the food price index and food expenditure share in 2050 increase by 7% and 0.4 percentage points, indicating lower food affordability.

The influence of governance performance on self-sufficiency index varies across food groups. These variations mainly stem from the impacts of governance performance on the production of specific food groups. Notably, the deterioration of governance performance has a more pronounced impact on cereals, showing a decrease in its self-sufficiency index by 4.2 percentage points, compared with the BAU scenario in 2050. Weak governance widens the disparities between the production and demand for cereals (Fig. S5). The deterioration in governance performance triggers an increase in food price index, particularly for cereals, roots, pulses, and oil seeds, which experience an increase of 9%, 9%, 13%, and 11% in 2050 compared to the BAU scenario, respectively. The production of these crops is largely decreased in InstDet, leading to a shortage of food supplies for these categories. The increase in food prices resulting from weak governance also leads to an increase in the food expenditure share for each food group compared with the BAU scenario in 2050. By contrast, the enhancement of governance performance results in the decline in the price indices of crop foods, with pulses, oil seeds, and cereals experiencing reductions in food prices exceeding 20% compared to BAU in 2050. In the InstImp scenario, the production of these crops experiences the most substantial increase, thereby augmenting the overall food supply (Fig. S5). In addition, the enhancement of governance performance results in a decrease in the food expenditure share for each food group compared to BAU. Specifically, in the InstImp scenario, the reduction in the food expenditure share from 2020 to 2050 for oil seeds, pulses, vegetable oils, and vegetables and fruits exceeds that of the BAU scenario by more than 20%.

Impacts of governance performance with higher population growth

We further consider alternative scenarios with a higher population growth (HighPop) in SSA to estimate the impacts of governance performance if agricultural demand becomes even higher. Other socioeconomic conditions are assumed to follow SSP2. In 2050, agricultural demand under the HighPop scenario is 3.8% higher than under the BAU scenario (Fig. S6). Driven by demand growth, most indicators related to the environment and food security in SSA show worse performance (Fig. 4).

With a higher population growth, improved governance performance could also positively impact both the environmental and food security indicators, while the deterioration of governance performance worsens them. Concerning the environment, the improved governance performance would restrain the expansion of agricultural land, facilitate efforts to nurture natural vegetation, and boost the reduction of AFOLU GHG emissions. However, the deterioration of governance performance would further exacerbate the expansion of agricultural land, thereby increasing deforestation and AFOLU GHG emissions. Specifically, under higher population growth, deterioration of governance performance would lead to an exacerbation for environmental indicators including cropland area (+2.7%), pasture area (+0.3%), forest area (−1.7%), other land area (−0.4%), and AFOLU GHG emissions (+7.2%), relative to the BAU scenario. In contrast, improved governance performance is expected to mitigate the deterioration of most environmental indicators. Concerning food security, with higher food demand in SSA, the deterioration of governance performance results in higher food prices (+7.1%), larger food expenditure share (+7.6%), and lower self-sufficiency (−2.1%), compared to the BAU scenario. An improvement of governance performance leads to lower food prices (−10.7%), smaller food expenditure

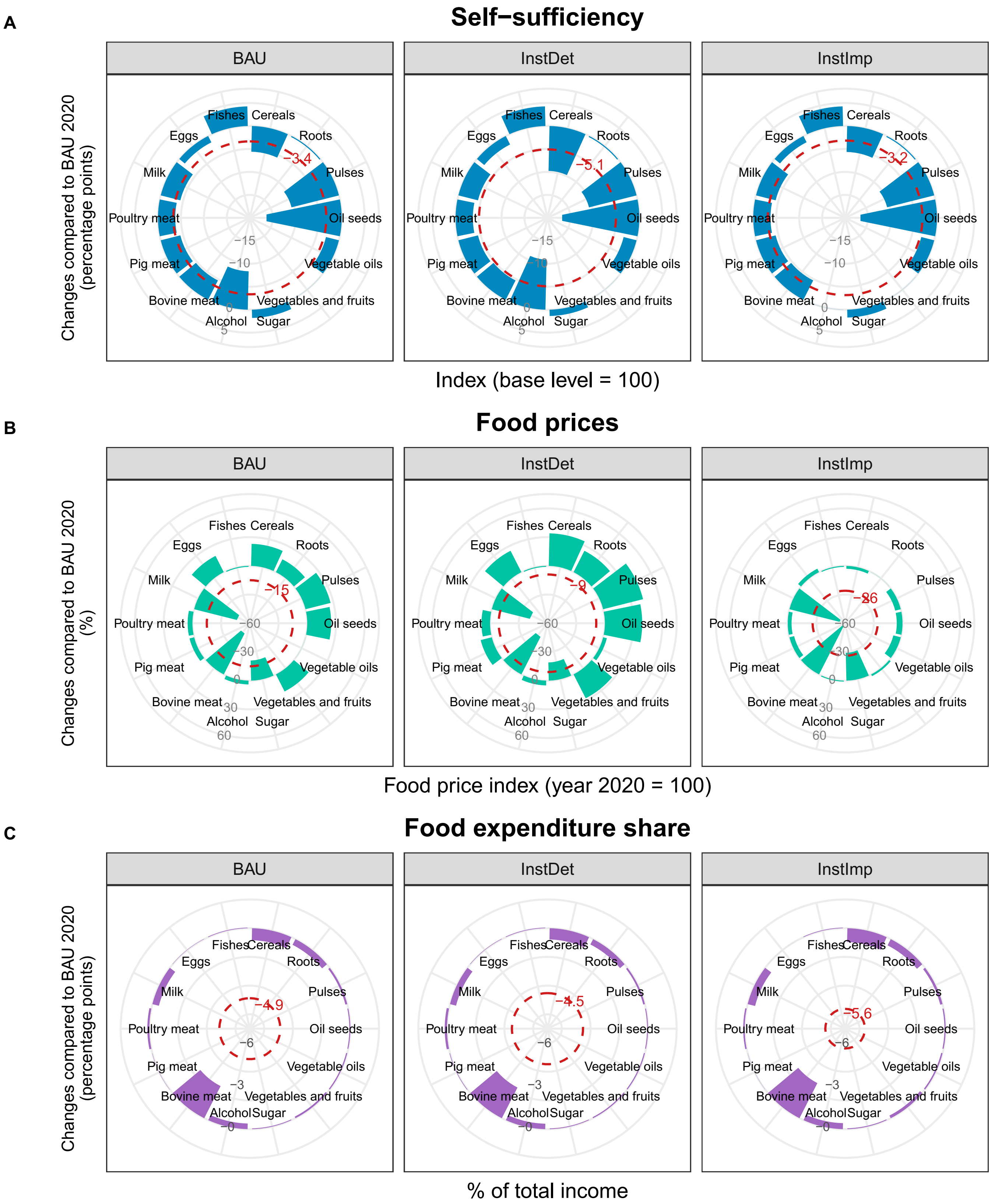

Fig. 3. Changes in food security in SSA in the BAU, InstDet, and InstImp scenarios in 2050 compared to the BAU scenario in 2020. (A) Changes of self-sufficiency index. (B) Changes of food price index. (C) Changes of food expenditure share. The red dashed line in each panel refers to the overall change in the respective scenario in 2050 compared to the BAU scenario in 2020. The number near the red dashed line represents the corresponding overall change. The base level of self-sufficiency index is 100, indicating a full self-sufficiency. The food price index is normalized to 100 for the base year of 2020. The food expenditure share is the proportion of food expenditure per capita per year of per capita income.

Fig. 4. Comparison of the impacts of governance performance on the environment and food security in the SSP2 and HighPop scenarios by 2050, which have different population trajectories. The point size varies with the scale of the relative changes of corresponding indicators in the respective scenario compared to the BAU scenario. The point color refers to the direction of the relative changes. Green color refers to an improvement in the respective scenario, while the red color represents a worse performance. The text in each box is the value of the respective indicators in each scenario.

share (−9.1%), and higher self-sufficiency (+0.1%), compared to the BAU scenario.

Discussion

Balancing the environment and food security through improved governance

Our results highlight that enhancing governance performance can effectively mitigate the negative impacts of agricultural production on land use, AFOLU GHG emissions, and food security in SSA, which corroborates previous research [12,41–43]. Specifically, our findings indicate that improved governance performance can reduce investment risks and promote investments in TC for agricultural productivity improvements. This is consistent with the findings of existing studies [13,15,19,20,22]. For instance, a well-established land tenure system in Ethiopia is found to increase the propensity to invest in soil and water conservation measures by 20 to 30 percentage points [21]. Another study, also focusing on Ethiopia, indicates that secured land tenure can lead to a 1.5% increase in crop yields [22]. These studies support our findings on the critical role of effective governance in fostering agricultural productivity, even within the context of other regions. [44] Our study further suggests that higher agricultural productivity resulting from technological investments could limit the expansion of cropland in the SSA region, thereby preserving more forest area and mitigating AFOLU GHG emissions. This finding is consistent with a previous research, which finds that controlling corruption reduces the expansion of cropland on forest by 9.4% in South American and Asian countries between 1990 and 2003 [11]. In addition, a study regarding environmental governance quality finds that improvements in environmental regulations lead to a reduction in the average annual loss of forest in Brazil [24]. The finding that improved governance performance can mitigate deforestation and GHG emissions in the SSA region is particularly important, given the observed patterns of forest deforestation and agricultural land expansion in the region. Between 1990 and 2018, the forest area in the region decreased from 31% to 27%, while cropland increased by 3.1% [45]. In SSA, deforestation was responsible for 94% of the carbon loss from 1850 to 2000 [3]. In addition to these findings, our results reveal that underperforming governance in SSA could simultaneously undermine efforts to conserve natural land and mitigate GHG emissions, underscoring the urgency of improving SSA's governance performance.

Our findings indicate that improved governance performance could ensure food affordability and accessibility in the SSA region by improving agricultural productivity. This aligns with findings from empirical studies, which find that governance performance plays a crucial role in ensuring food security by enhancing agricultural productivity and boosting agricultural production [16,23]. Unlike studies that use crop production value and agricultural productivity as indicators of food security [16,23], this study employs food self-sufficiency, food prices, and food expenditure share, which are more direct indicators related to food security, to measure the impacts of governance performance on food security. Our results demonstrate that improved governance performance is associated with increased self-sufficiency, lower food prices, and lower food expenditure shares, offering insights from a perspective that has been underexplored in the existing literature. The current status of governance in SSA negatively affects factors such as the transparency of financial process, the importance of informal sector, and the quality of public institutions, resulting in higher investment risks [46]. Therefore, enhancing governance quality is necessary to encourage both domestic and foreign investments in SSA [47][48]. Incentivizing technological investments in SSA could enhance agricultural productivity, thereby keeping production in pace with the growing demand and ensuring food security.

Tailoring institutional arrangements for more efficient land use

We find a marginal reduction of GHG emissions along with cropland expansion and deterioration of governance performance in SSA. This reduction stems from spatial heterogeneity of carbon density, a factor also highlighted in a prior study [47], which indicates that the impact of LUCs on GHG emissions is influenced not only by the area of land but also by its underlying carbon density. Cropland converted from areas with high carbon density releases more stored carbon, thereby leading to increased CO_2 emissions. Conversely, when cropland is converted from areas with low carbon density, the impact on carbon emissions is less pronounced. This finding hints at a limitation that this study does not consider the spatial heterogeneity of governance impacts on land conversion. This calls for more diverse institutional arrangements and governance structures in accordance with local biophysical and socioeconomic conditions [49,50].

This finding further reveals a requirement of additional efforts on designing institutional arrangements including property rights, regulations and public policies, and transformation of governance structure to ensure that the improvement of governance could synergistically incentivize agricultural production while conserving natural resources. Improved access to land and natural resources is essential for sustainable management and good governance, despite high costs of enforcing institutional arrangements. Good governance could provide the basis for mediating conflicts, issuing regulations, and imposing penalties on free-riding issues, thus alleviating environmental degradation. Building a polycentric governance structure is crucial to regulating the interaction between humans and the environment, thus promoting the sustainable management of natural resources [50]. This would require involving a diverse range of stakeholders while considering institutional diversity.

Conclusion

This study uses an agro-economic dynamic optimization model to analyze the impacts of governance performance on LUCs, AFOLU GHG emissions, and food security in SSA. Our study reveals that improved governance performance could encourage agricultural R&D investments by decreasing investment risks, thereby leading to an increase in agricultural productivity. As a consequence, cropland expansion and deforestation could be further reduced, leading to a reduction in AFOLU GHG emissions. Moreover, improved governance performance substantially increases food self-sufficiency, lowers food prices, and reduces food expenditure share, thus contributing to improved food security. Improvements in governance performance could play a crucial role in enhancing environmental sustainability and food security in the SSA region, which can contribute to addressing global issues such as climate change and hunger.

This study has several caveats. First, while we use dynamic interest rates to represent the dynamic nature of governance, these rates are calculated based on dynamic GDP per capita according to SSP narratives. This approach reflects the socioeconomic conditions influenced by governance performance, yet it may not capture the full spectrum. Future studies should consider improving this method for estimating interest rates based on a more comprehensive set of socioeconomic drivers. Second, interest rates can serve as a proxy of governance performance, but they are often influenced by monetary policy. Further research could consider directly incorporating governance performance indicators, such as regulatory quality, rule of law, and government effectiveness, into quantitative modeling frameworks. This might require careful consideration of whether to use a single composite indicator or an aggregate score from multiple indicators to represent governance performance.

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Author contributions: X.W. conceived and developed the study. X.W. designed the study methodology. X.W., R.D., and H.C. curated the data. R.D. and H.C. conducted the data analysis and visualization. R.D., H.C., and X.W. drafted the manuscript and created the illustrations. X.W., R.D., H.C., J.X., M.S., J.P.D., A.P., and H.L.-C. edited and reviewed the manuscript and agreed on the final version.

Competing interests: The authors declare that they have no competing interests.

Data Availability

Data and code can be provided upon reasonable request.

Supplementary Materials

Table S1
Figs. S1 to S6

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