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LETTER

Regional trade and sustainable intensification advance rice self-sufficiency in East Africa

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Abstract

Many global regions, including East Africa, implement policy goals advocating increased agricultural self-sufficiency to promote economic development and food security. Required increases in production can, however, negatively impact the environment. We assessed upscaling sustainable rice intensification in East Africa, comparing regional trade and environmental policy scenarios using a novel hydro-economic modeling framework that optimizes farmer profit subject to technical and resource constraints. Allocating rice production to current croplands, where rainfed rice production is economically competitive with other crops, can achieve regional rice self-sufficiency in 2050 with limited environmental impacts. Regionally integrated trade further increases rice production (+14%), improves resilience to climate shocks (−46% production losses), and reduces water use (−81%) and greenhouse gas emissions (−7%). Negative impacts of climate shocks could be avoided by expanding irrigated rice production. To realize these benefits, East African countries need moderate productivity upgrading, investment in infrastructure, especially for irrigation, and enhanced regional cooperation, including trade agreements and benefit-sharing mechanisms, as well as joint planning and access to production inputs, land and water resources.

1. Introduction

East Africa (EA) will face increasing pressures on food security due to population growth, economic development, and climate change. Population will more than double (up to +140%) by 2050, compared to 2010 (Tramberend *et al* 2021), contributing to expanding food demand. The demand for rice, a major staple crop in EA, is estimated to increase by 72%–104% depending on socioeconomic development (authors' calculations based on population and GDP growth projections and assumptions on income elasticities). Climate shocks on regional and international production, transmitted through trade, could increase food security risks. EA imports up to 30% of its rice from Southeast Asia and India. Currently (2019–2023), almost two thirds of rice imports to Tanzania and Rwanda are from Southern Asia (authors' calculations based on FAOSTAT). We analyze where and how intensified production in EA can meet local demand and assess associated environmental impacts. Achieving rice self-sufficiency in the medium to long term through a more regional supply of rice will reduce dependence on world markets and enhance resilience to geopolitical and climate shocks (van Oort *et al* 2015, Yuan *et al* 2024).

The East African Community's (EAC) vision for 2050 aims at enhancing and diversifying local production and significantly increasing intra-regional trade (East African Community 2015). Policies in the EAC member countries explicitly set the target to achieve self-sufficient rice production by 2030 and beyond (State Department for Crop Development and Agricultural Research 2020, Ministry of Agriculture and Natural Resources 2021, Ministry of Agriculture, Animal Industry

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and Fisheries (MAAIF) 2012). Research addressed some aspects of rice self-sufficiency, but production allocation, environmental sustainability and trade remain less understood (Arouna *et al* 2021b, van Oort 2023, van Ittersum *et al* 2025). In this study we examine the biophysical and economic feasibility and environmental implications of achieving regional rice self-sufficiency. Meeting regional rice demand sustainably requires an optimal allocation of agricultural production, good agricultural practices, and regional trade and cooperation (Janssens *et al* 2022).

Research finds that rice productivity in Africa has improved in recent decades, yet significant yield gaps remain, especially for rainfed rice (Rodenburg and Saito 2022). Most studies focused on agronomic opportunities for upgrading yields or improved management practices. Yet decision-makers also need insights on the optimal spatial allocation of rice production to leverage agronomic practices for closing yield gaps and minimizing environmental impacts (van Oort 2023). Some studies identified suitable locations such as inland valleys in EA (Rodenburg *et al* 2014). However, detailed spatially explicit information on production allocation for improving production and sustainability of rice is limited. Central questions for agriculture, especially rice production, are whether closing yield gaps will be sufficient to meet the demand of a growing population or whether additional area expansion and policy interventions would be needed (van Ittersum *et al* 2016, Rodenburg and Saito 2022).

Our study goes beyond previous studies (De Vos *et al* 2023, De Vos *et al* 2024, Yuan *et al* 2024) by using a multi-scale modeling approach including economic optimization and water availability in EA. The benefits of our sub-national regional analysis accrue in comparison to the previous country-level focus (De Vos *et al* 2023, 2024), as we incorporate land suitability and area allocation in a spatially explicitly manner using agronomic information obtained from biophysical models. While previous studies using economic models also include consumer surplus and trade with regions outside of Africa, we explicitly focus on the production potential and sustainability ramifications of an entirely self-sufficient rice supply. This addresses the impacts of trade and environmental sustainability policies as well as future self-sufficiency and resource use by using a hydro-economic framework that includes previously unexplored linkages between the economic and biophysical aspects of rice production (Rodenburg and Saito 2022). Rice production's sustainability is commonly studied separately, but it accounts for 4.6 million tons of CO_2e greenhouse gas (GHG) emissions in our five EA study countries, 1.8% of their total GHG emissions (FAOSTAT 2023), among the highest rice shares of total global emissions (Wang *et al* 2023). Emissions rise, with methane emissions from rice contributing 31% of Africa's increased methane emissions (Chen *et al* 2024). Limiting GHG emissions requires an integrated approach to rice production and emissions.

Our study area is the extended Lake Victoria Basin (eLVB), defined by the headwaters of the Nile River (Tramberend *et al* 2021) including areas in five countries (Burundi, Kenya, Rwanda, Uganda, and United Republic of Tanzania). The eLVB covers only the parts of Kenya and Tanzania within the Lake Victoria watershed's hydrological boundaries, aligned with our integrated hydro-economic model, which needs consistent water data and hydrological links across the study area. The eLVB includes large rice-producing regions, important water sources, biodiversity hotspots, and major economic and densely populated centers. These characteristics make it ideal for assessing trade-offs between agricultural intensification, conservation efforts, and regional trade. Less than a quarter of the 303 000 hectares of rice cropland in the eLVB are under irrigation (International Food Policy Research Institute 2020). While irrigation enhances resilience to droughts and ensures stable production, rainfed production can reduce water use and assure profitable yields under good agricultural practices in the lowlands of EA countries (van Oort and Zwart 2018). In some parts of the eLVB, two rainy seasons enable rainfed double-cropping.

The eLVB includes internationally important wetlands, vital for biodiversity, ecosystem functions, and water quality regulation in Lake Victoria. Protecting wetlands, especially those not covered by a protection designation, can help reduce the biodiversity loss (van Soesbergen *et al* 2017). Sustainable intensification in this study thus considers 14.45 million ha of current non-protected cropland as potential area for rice production. Currently, some wetlands that are not legally protected are already used as croplands. We explore a scenario with strict environmental conservation policies that exclude current cropland on wetlands from future rice production, thereby reducing the available cropland to 13.96 million hectares. The sustainability scenario additionally incorporates policies targeted at reducing water use and GHG emissions.

2. Methods

Using an integrated spatially explicit hydro-economic optimization modeling framework (figure 1), we show how future demand for rice can be met and how environmental and trade policies influence the supply and spatial allocation of production. The objective function of the optimization is to maximize farmers' total profit subject to water availability and land conservation constraints. Profits are composed of revenues from sales of rice minus production costs. Farmers endogenously choose to grow rice in rainfed or irrigated systems, once or twice a year, and using conventional or mixed improved inputs. Production

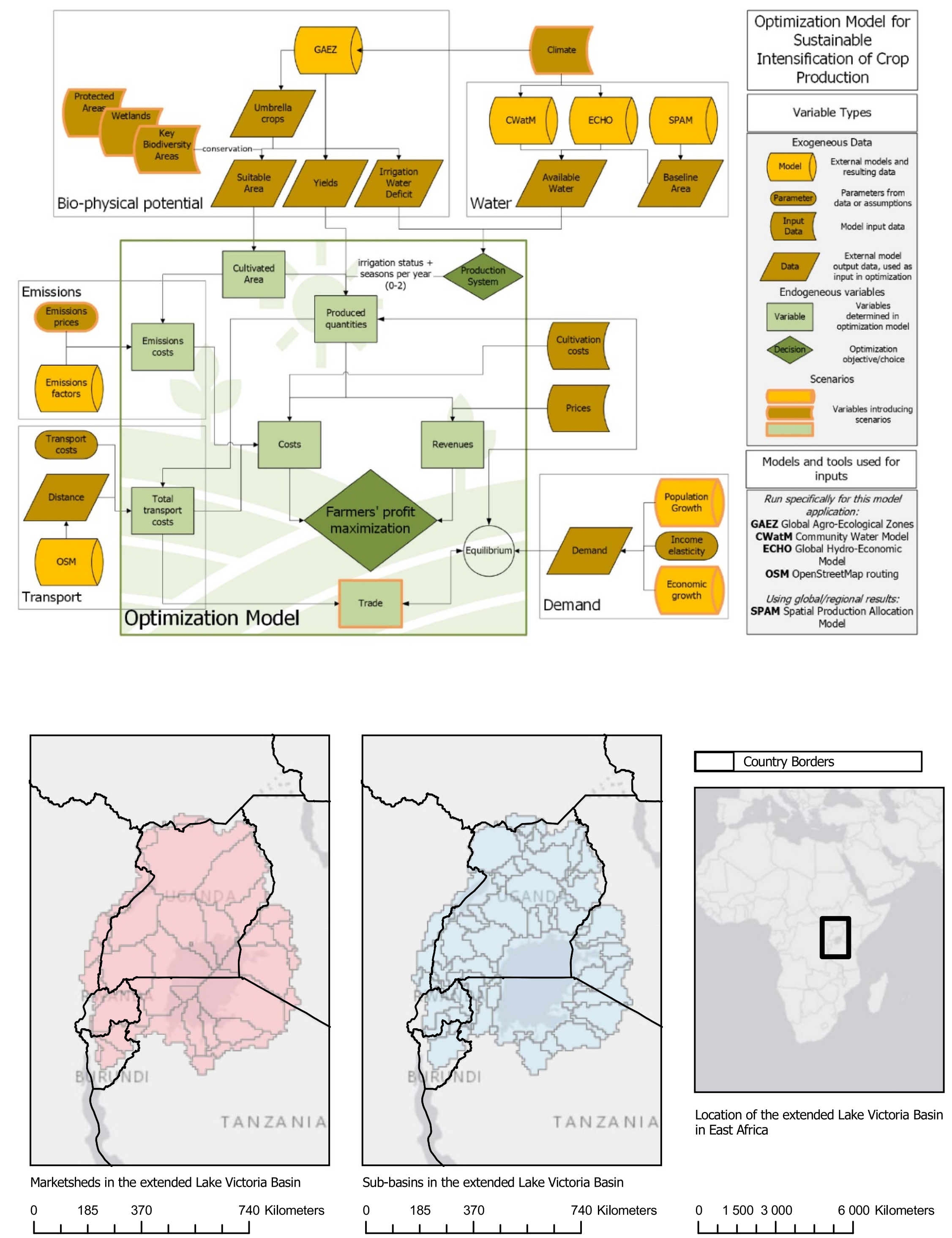

Figure 1. Schematic overview of the hydro-economic optimization framework (top) and overview of spatial scale of the study area: extended Lake Victoria Basin (bottom).

costs are composed of input costs including irrigation costs, transportation costs, and GHG emission costs.

Required input data are obtained from a set of specialized models adapted specifically to the eLVB. Water available for rice irrigation in each subbasin is set to current agricultural surface- and ground-water irrigation withdrawals from the hydro-economic model ECHO (Kahil *et al* 2018, 2025) and rescaled to 2050 using projected changes in irrigation infrastructure from ECHO and subbasin-level changes in discharge from the hydrological model CWatM (Burek *et al* 2020) following the REF and EA-RVS scenarios of Tramberend *et al* (2021). We inform land suitability for biophysical crop production potentials under specified agronomic management conditions using a customized version of the Global Agroecological Zones model GAEZ (Fischer 2021). We consider GAEZ's intermediate inputs using limited mechanization, a mix of manual labor or animal traction, with improved varieties and partial fertilizer and agrochemical use. We compiled the current rice production area from the SPAM database (International Food Policy Research Institute 2020).

Price parameters use producer price data per country from FAOSTAT. We compute methane and nitrous oxide emissions using FAOSTAT data alongside national statistics compilation techniques (Calvo Buendia *et al* 2019, Smith *et al* 2021). Rice production costs were compiled from publications documenting regional rice production practices (Kikuchi *et al* 2013, Ndiiri *et al* 2013, Kadigi *et al* 2020). The summarized costs for each type of production system include items for labor costs, input costs for seeds, fertilizers, and pesticides, as well as irrigation costs. We used a simple projection technique based on population and economic growth projection scenarios to estimate rice demand (Bijl *et al* 2017). An equilibrium constraint ensures no significant overproduction that would lead to exports outside the region. Our spatially explicit modeling framework operates at the level of subbasins of the eLVB for rice production, water and land availability, and spatial allocation of production. Demand is aggregated at the marketshed level, defined as major trading centers and their surroundings (HarvestChoice 2014). Competition between rice and other crops is accounted for by rice having a comparative economic advantage over other major crops in GAEZ grid-cell level calculations. The comparative advantage of rice is determined by the condition that the rice value of output is at least 80% of the highest value of maize, sorghum, pearl millet, wheat, rice, dry bean, groundnut, soybean, sunflower, sweet potato, and white potato. The goal of the economic optimization model is to assess regional trade and self-sufficiency; therefore imports from outside the eLVB are not considered.

We implement business-as-usual (BAU) and environmental sustainability (SUST) scenarios that combine trade and environmental policy interventions, yield shocks, and future demand assumptions (table 1). The SUST policy includes land and water use restrictions and emissions pricing based on a recent estimate of the social cost of carbon of 122 US\$/tCO_2e (Tol 2023). Different yield scenarios for shocks to rainfed production (average, 25th, and 5th yield percentiles) are applied across the entire eLVB, implying different magnitudes of yield loss. While droughts may affect the entire region or only specific subbasins, this approach provides a useful estimate of rice production's resilience to yield shocks when the entire region is affected. The rainfed yield scenarios are aligned with climate scenarios that affect water availability for irrigated production. We assume constant irrigated yields but reduced water availability, applying the same 25th and 5th percentiles to CWatM-derived water availability. The supplementary information reports results for additional climate and policy scenarios, such as different levels of emissions pricing, and a sensitivity analysis conducted for alternative demand projections based on varied income elasticities. The main results of this study remain valid under these alternative specifications.

3. Results

The East African eLVB can produce sufficient rice to meet local demand by 2050 under all policy and demand scenarios, assuming reference climate conditions. Only during dry years and when trade is not regionally integrated do local farmers struggle to meet demand, emphasizing the importance of regional trade in simultaneously achieving rice self-sufficiency and environmental protection goals.

3.1. Biophysical potential of rice production

Average potential rainfed rice yields are close to irrigated yields for average climate (figure 2, Panel (A)). However, rainfed yields decrease by 55% in the driest years (p05), while irrigation can prevent yield losses in those years if sufficient irrigation water is available. Agro-ecological conditions and the competitiveness of rice (figure 2, Panel (B)) determine the rice area. Conserving wetlands reduces the overall suitable cropland area by only 4.5% (figure 2, Panel (C)), from 4.3 to 4.1 million ha. Wetlands are suitable for high-yielding double-cropping rice cultivation, but are banned for rice production under sustainability policy scenarios. In some subbasins, notably in western eLVB, where absolute production potential is marginal, the potential for rice production declines significantly when wetland areas are not used (SUST policy).

3.2. Production allocation with and without regional trade

Regional trade results in a concentrated rice production in eLVB. When trade restrictions are in place, production drops, primarily because of the limited possibility to shift production towards more suitable cropland. (figure 3). Climate shocks increase these production gaps. In the sustainability policy scenarios under reference yields restricting trade reduces rice production (−13.8%) to a level only marginally below the rice quantities needed to cover local demand even without regional trade. However, yield shocks cause a sharp decline in rice production, up to 45.9% under 5th percentile yields.

Rice export revenues in subbasins with abundant cropland surpass transportation costs. This results in higher profits in the most productive subbasins, causing rice production to concentrate there. Overall, trade increases total production across all subbasins, as regions with high yields and ample suitable land can produce more for export. Compared to localized

Table 1. Scenarios of trade and environmental policies, rice yields, and rice demands.

Policy scenarios			
Trade policies	**No trade**	**Basin trade**	
Trade policies	*No trade between local markets (i.e. marketsheds)*	*Allowing trade between local markets, considering transportation costs*	
Environmental policies	**BAU**	**SUST**	
Land conservation	*Mid conservation: potential rice area on current unprotected cropland and current cropland in wetlands, but not in any other protected areas*	*High conservation: potential rice area only on current unprotected cropland and non-wetlands (i.e. not in wetlands or any other protected areas)*	
Emissions price	*No emissions pricing*	*122 $/tCO_2e$*	
Water use	*100% of projected yearly discharge*	*40% of projected yearly discharge (i.e. assuring sustainable water use)*[a]	
Climate scenarios			
Yield percentiles	**Reference yields**	**25th percentile**	**5th percentile**
Percentile yield in GAEZ	*Rice yields in average years from GAEZ*	*Yields in dry years*	*Yields in extremely dry years*
Water availability	**REF**	**EA-RVS**	
Water available for irrigation	*Reference scenario*	*East Africa Regional Vision for Sustainability*	
	Derived using irrigation infrastructure upgrade scenarios and changes in discharge from Tramberend *et al* (2021)		
Demand scenarios			
Rice demand scenarios	**REF**	**EA-RVS**	
Aligned to population growth in Tramberend *et al* (2021)	*Reference middle-of-the-road scenario*	*East Africa Regional Vision for Sustainability with reduced population growth*	
eLVB population scenario in 2050 (baseline: ∼73 million in 2010)	*181 million*	*153 million*	

[a]The 40% threshold is widely recognized as a threshold for water stress (Raskin *et al* 1996, Gleick and Cooley 2021).

production (no trade), trade leads to only a modest expansion of rice areas (<5% in reference scenarios, see next sub-section *Cropland use and multi-cropping*). When trade is possible, a high fraction of rice production is allocated to central Uganda's fertile White Nile subbasin (figure 4). A more distributed production emerges in the trade scenario only when shocks decrease yields, caused mainly by yields decline in GAEZ classes that have less than optimal suitability. In these classes, farmers previously had small margins due to favorable climate conditions, but these margins become unprofitable after yield shocks. An example here is central Uganda. Without trade, rice production is distributed more evenly across the eLVB, but demand is not always met. Sustainability policies do not significantly alter production allocation unless rice farmers experience extreme yield shocks, which may require expanding rice area or reducing rice production.

3.3. Cropland use and multi-cropping

The total rice area is 7.1% lower without trade than with trade (ref. yields, EA-RVS demand, BAU policies, figure 5). With trade, the eLVB produces 15% more rice than demanded, while the marketshed self-sufficiency (no trade) scenarios only cover demand. Without trade, the rice production intensity increases shifting to more frequent production, namely, growing rice twice per year. Without trade, rice production area allocation shifts from a single rainfed season (−38.5%) to two rainfed seasons (+12.9% compared to trade scenario) and one rainfed and one irrigated season per year (+129%). Severe climate shocks and less trade lead to rice production under multi-cropping irrigated systems, but the allocated area cannot cover local demand entirely, and increases water use.

High rice demand in the REF scenario caused by increasing population, is largely met by expanding

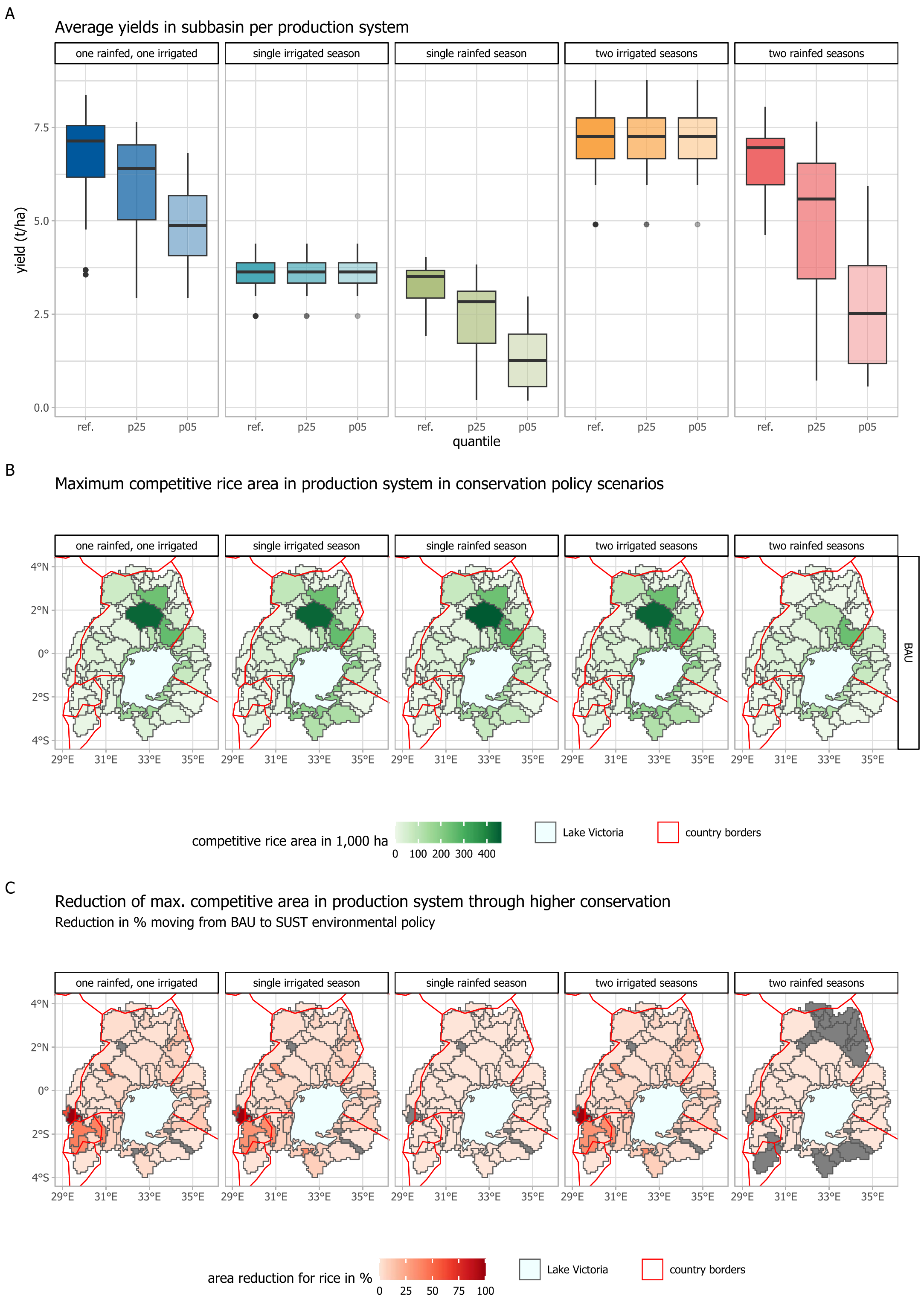

Figure 2. Biophysical potential of rice production under varying conservation and production systems. Panel (A) Average yields in rainfed/irrigated production systems under reference (ref), 25th percentile (p25) and 5th percentile (p05) yield respectively resemble those of an average, dry, and extremely dry climate (under the SUST environmental policy). Panel (B) Biophysically suitable and economically competitive rice area in subbasins of the eLVB in (i) unprotected cropland areas (BAU) and with (ii) stricter environmental policy, excluding protected and wetland areas (SUST). Panel (C) Reduction in suitable and economically competitive rice area under SUST compared to BAU environmental policy. In subbasins where no percentage change is shown (gray) the change due to land conservation (transition from BAU to SUST policy) is less than 0.5%. Results from GAEZ under BAU and SUST policies. As defined in the GAEZ methodology, suitability classes are: very suitable, suitable, and moderately suitable. Economically competitive means that the value of rice production is competitive with a set of crops that are also suitable for the same area (details provided in the Methods section).

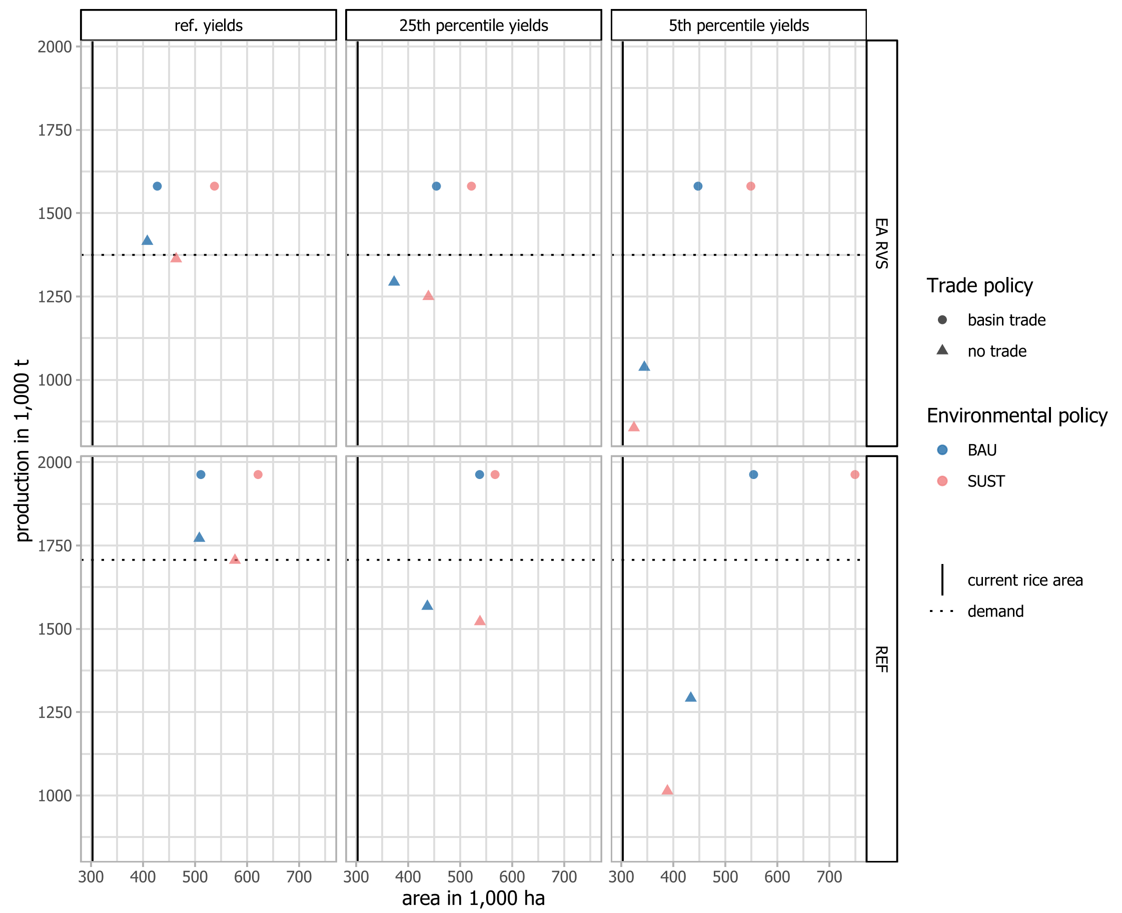

Figure 3. Optimized production quantity and area for rice production in eLVB under trade and environmental policies, and yield and demand scenarios. Datapoints under the dashed line indicate the scenarios where rice demand cannot be fulfilled.

areas harvested twice a year. This compares to lower population in EA RVS resulting in higher area allocation only for the two rainfed season production systems. Additional area is allocated to the two irrigated seasons class only if extreme yield shocks (5th percentile) occur.

3.4. Irrigation water use

Water use for rice production in scenarios with trade is only a fraction of that in non-trade scenarios, as trade reduces irrigation by shifting to productive rainfed systems. Under regional trade, irrigation water use amounts to 0.04 km^3 of the 0.30 km^3 available (REF demand, SUST policies, and reference yields, figure 6). Without trade, water use increases to 0.19 km^3, if all other scenarios remain constant. While in some no-trade scenarios additional water is available in some marketsheds, its use is not economically feasible. In the reference case for yields and demand, water use as a share of water availability amounts to 14.5%, using BAU environmental restrictions, and 12.1%, when enforcing SUST policies. However, limiting trade increases this percentage to up to 76.2% of available water in the BAU scenario. SUST policies limit this drastically higher water use to 63.0%.

Trade scenarios require less irrigation, but when yield shocks occur at the 5th yield percentile, more than half of the total rice production area is irrigated in trade scenarios (62.5%), compared to less than 5% under reference yields and trade (2.2%).

3.5. GHG emissions

To reduce GHG emissions from rice production, farmers can switch to a mix of conventional and organic inputs, releasing less GHGs per hectare. The SUST policy includes a high price on GHG emissions of 122 US$/tCO2e to incentivize reductions in methane and nitrous oxide emissions. The switch to more climate friendly production would therefore reduce their tax payments for a given level of rice output. Diversification can also increase soil fertility and nutrient cycling (He *et al* 2023). In a sensitivity analysis, we tested two additional lower levels of emissions pricing (50 and 80 US$/t$CO_2$e, results in supplementary).

Emissions pricing under SUST policy reduces absolute GHG emissions by 11.5% with trade to 19.8% without trade (REF demand, ref. yields). However, the emission-pricing costs for farmers reduce profits under REF demand by 19.8% under reference yields with trade and to up to 47.7% under

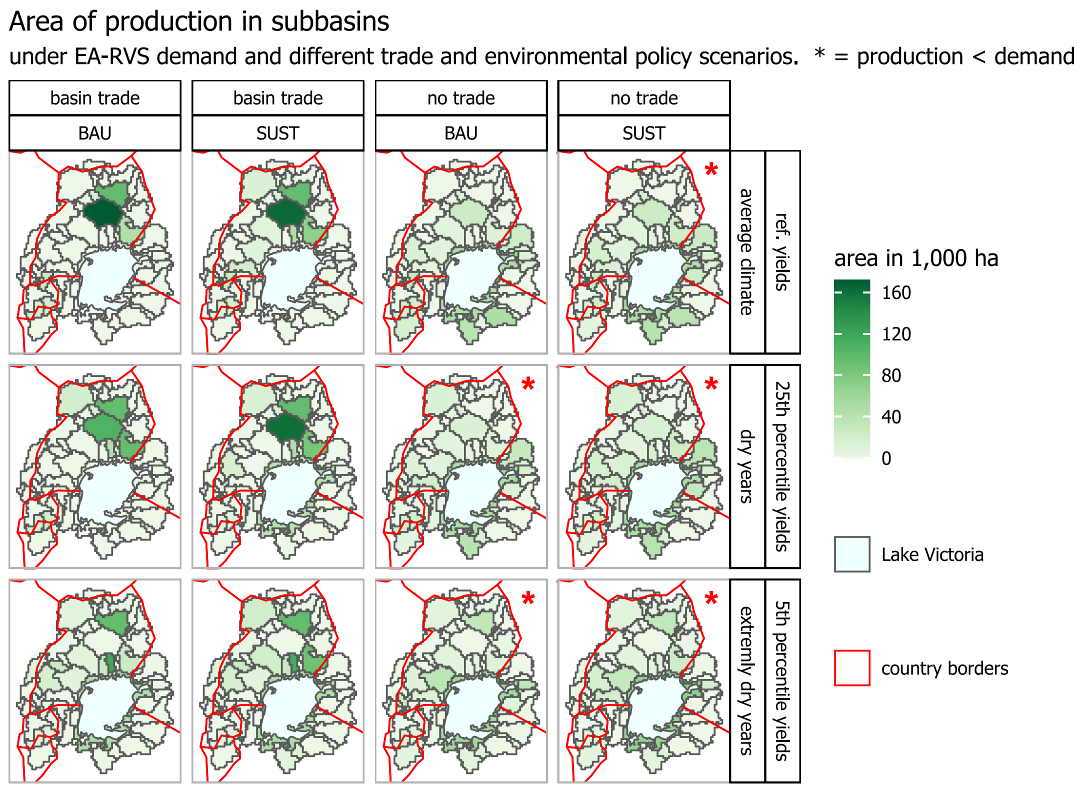

Figure 4. Area for rice cultivation in optimized use under trade and environmental policies and in yield scenarios under EA-RVS demand.

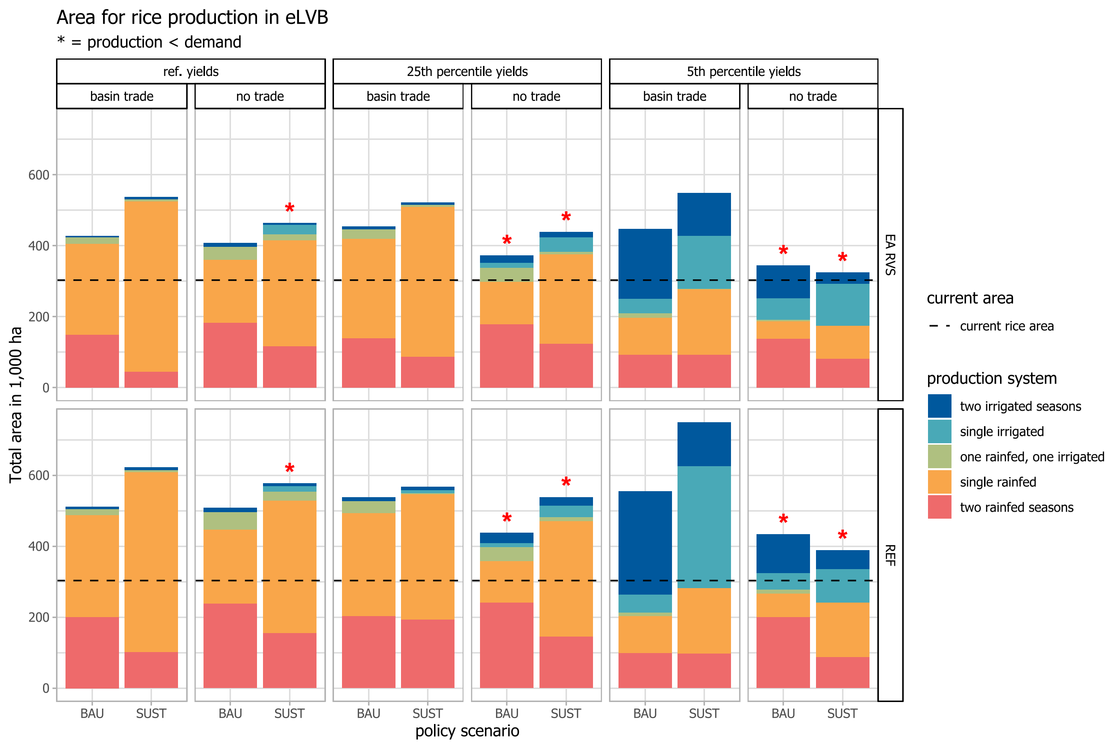

Figure 5. Areas optimizing farmers' profits in each multi-cropping production system in the eLVB under trade, conservation, demand, and yield scenarios compared to the current rice area.

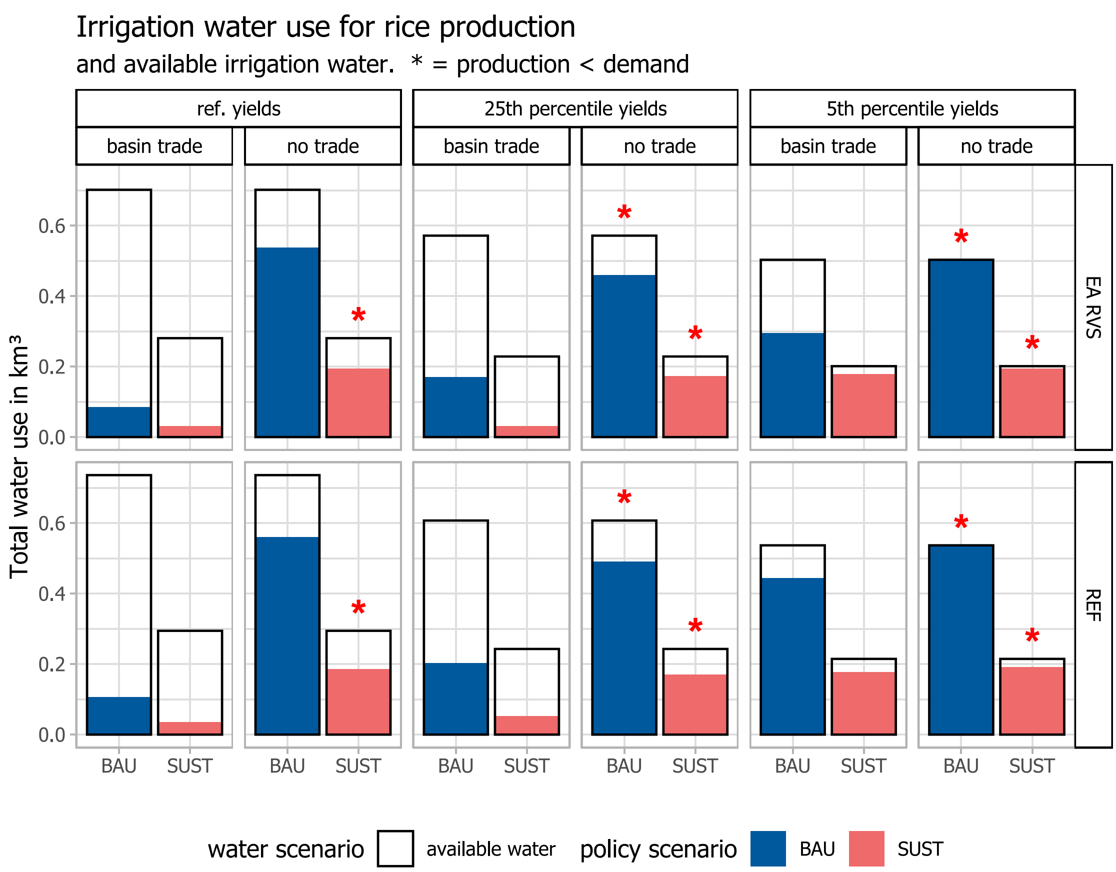

Figure 6. Irrigation water use for rice in the eLVB under policy, trade, demand, and yield scenarios compared to water availability in 2050. Water available estimated in CWatM and ECHO. The SUST scenario makes available only 40% of the water discharge in BAU.

5th percentile yields and no trade (profits across scenarios are reported in supplementary figure 3 and supplementary table 2). Because SUST policies also affect the optimal rice area allocation, relative emissions per ton of rice produced are reduced by a smaller magnitude of 7% to 11% under reference yields (figure 7). Tax schemes should consider smallholder farmers by weighing the trade-offs between emission reductions, practicability, and economic viability. While production does not fall under reference yield conditions when pricing is introduced, it does drop when climatic shocks diminish yields. Setting emission prices too high could harm food security without trade options, and if offsetting mechanisms are not established to compensate farmers for forgone income.

4. Discussion

Sustainable rice self-sufficiency is possible in the eLVB by 2050. Recent trends confirm that yield gaps in East Africa have slowly started to decrease and already implemented area expansions may be sufficient for future cereal self-sufficiency (van Ittersum *et al* 2025). Under average climate conditions, high local production concentration, followed by regional trade, and low irrigation levels, are economically optimal in the eLVB. In contrast, more spatially distributed production and some irrigation can help build resilience to climate shocks, but this can also reduce farmers' profits and increase water use.

Regional trade supports self-sufficient local rice systems and can enhance food security even in years with unfavorable agroclimatic conditions and under climate change (Brenton *et al* 2022) while also reducing irrigation expansion. Such optimal allocation of production patterns can prevent excessive agricultural water use, as seen in other world regions (Shi *et al* 2024). The self-sufficiency results of our main analysis, which uses negative income elasticities to project future rice demand, also hold for substantially higher demands using positive income elasticities. Such higher demands can be met through trading within the region, but not when restricting trade between marketsheds. Similar area allocations and production systems emerge for both model runs. A notable difference between the different demand projections occurs for water use, which is substantially higher when the eLVB rice producers aim to meet increased demands (see supplementary for all sensitivity checks).

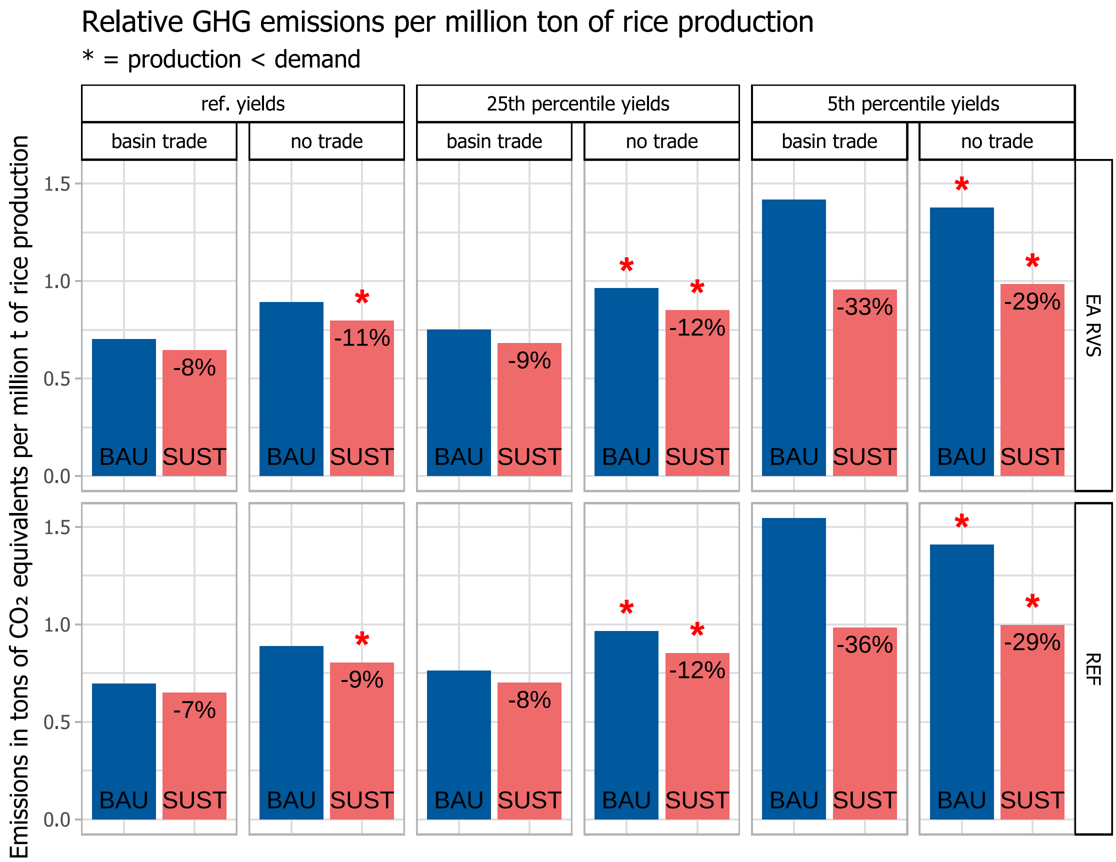

Figure 7. Relative greenhouse gas emissions as tons of CO2-equivalents per ton of rice produced in eLVB.

4.1. Regional integration

The current tariff-free trade already helps create an enabling environment for rice trade. However, further barriers, including nontariff trade barriers and occasional bilateral reinstatements of rice tariffs, still exist (Bouët and Nimenya 2023). While global food trade provides the largest opportunities for buffering yield shocks, major producer countries often target short-term food security by imposing trade restrictions (Smith and Glauber 2020). Regional trade could balance these benefits and trade-offs. A regional trade regime could alter price dynamics and profits for producers (Headey and Hirvonen 2023) and consumer prices and welfare, though specific poverty impacts require further socioeconomic analysis and appropriate economic, social, and environmental policies. While our analysis focuses on achieving regional self-sufficiency, sensitivity analyses suggest potential for export production if infrastructure and policy constraints were addressed.

Regional trade could offer advantages beyond policy compliance, including focusing production on rice varieties matching local consumer preferences in EA (Twine *et al* 2023) and reduced transportation distances compared to imports from Asia, which could lower both costs and GHG emissions. Regionally integrated trade could create job opportunities throughout the rice value chain and enhance resilience to global trade shocks.

4.2. Sustainable intensification and farmer adoption

Policies of sustainable intensification to boost agricultural productivity are most effective when coupled with investment in infrastructure to improve access to input and output markets (Gebresilasse 2023). Our model assumes current infrastructure and calculates transport distances based on the existing road network. Infrastructure upgrades will enhance benefits, equitable distribution, and productivity. Because the optimization maximizes farmers' profits and accounts for rice's comparative advantage over other crops, the spatial allocation identifies areas where rice production is economically viable for farmers while meeting environmental goals. To realize these benefits, policymakers should focus on creating enabling conditions through extension services, infrastructure development, and market access.

Farmers and other stakeholders are likely to accept sustainable intensification and regional trade when policies and informal institutions guarantee their land tenure, ensure environmental conservation, facilitate access to appropriate production inputs, such as seeds and fertilizers, and enable benefit sharing and reallocation (Yami and Van Asten 2017, Yami and van Asten 2018). Increased trade commonly leads to increased economic inequality, especially in developing countries (Artuc et al 2019). Trade adjustment policies, funded by recycled emissions-pricing revenue, can support farmers reducing rice production under land conservation or emissions pricing through training and crop diversification.

Under SUST policies some areas expand due to lower land suitability for double cropping. However, we specifically allow these increases only on current cropland. These areas may still be intensified but cultivating different crops. To reach intermediate input and output levels, we assume at least partially closed yield gaps. Research shows significant potential for this type of intensification and resulting production (Yuan et al 2021, Arouna et al 2021a, Johnson et al 2023, Kamau et al 2023, Joseph et al 2025). Such intensification strategies are most likely to succeed when coupled with appropriate extension services that address good agricultural practices, such as nutrient, water, and weed management (Nhamo et al 2014, Jayne et al 2019, Senthilkumar 2022). Future research could investigate how nutrient cycling in a dynamic setting as compared to our comparative-static analysis for a single representative year may alter rice production systems.

4.3. Environmental policy implementation and trade-offs

GHG emission taxes are best implemented gradually. Smallholders in informal markets are less likely to comply with taxes than larger producers. For larger producers, taxes could be based on estimated emissions at seed purchase or rice sale. A progressive tax with lower rates for small producers can ensure compliance and reduce the inequality impacts of increased trade.

To compete with world market prices, African farmers will need to reduce their production costs (Adjao and Staatz 2015) and aim to upgrade productivity, for example, by concentrating rice production in the high-yielding areas identified in this analysis, where greater productivity allows for lower per-unit costs through improved resource efficiency. Under the intermediate input regimes which this analysis assumes, rice cropland expansion ranges from 15.5% (basin trade, 5th percentile yields, ref. demand, BAU) to 82.9% (no trade, 5th percentile yields, ref. demand, BAU). If agricultural development is ambitious, involving high levels of input, the area required for self-sufficiency would decrease (GAEZ high-input regime; see Methods).

High conservation in the SUST scenario reflects Uganda's ban on rice cultivation in wetlands (Twine 2023). Anecdotal evidence indicates rice cropland is often in wetlands, as assumed in the BAU scenario. While conserving protected areas is insufficient to conserve biodiversity (Kehoe et al 2017), strict wetland conservation can lead to setbacks in food security (Henry et al 2022) and increase overall cropland use because production must shift to lower-yielding non-protected areas. Optimized strategies like ours to concurrently preserve biodiversity, prevent GHG emissions, and reduce water use are promising ways to balance conservation and land availability for agriculture (Jung et al 2021). However, environmental policies involve trade-offs among environmental outcomes. While the SUST combination of policies reduces emissions and water use, it also increases land use, mainly caused by a shift from double rainfed and irrigation to single rainfed systems resulting from excluding high-yield wetland areas and water analyses suggest potential for limits.

5. Conclusion

Our modeling results show future rice production potential and are valuable for policy planning based on realistic future scenarios. Additional policies are needed, however, to ensure enabling conditions for agricultural transformations to achieve this potential. Our macro-level research needs to be complemented with analysis at the farm or plot level (Kruseman et al 2020). Nevertheless, this approach advances on previous similar studies (Yuan et al 2024), in that it implicitly accounts for agricultural economic profitability, water availability, and GHG emissions and identifies the food security and environmental benefits of trade in a spatially explicit optimization framework.

Our modeling approach has broader applications beyond EA. By combining hydrological modeling, economic optimization, and spatial analysis, this framework can help policymakers evaluate trade-offs between conservation and intensification while accounting for climate risks. Regional trade, enhancing sustainability and resilience, may be relevant for other developing regions seeking to reduce dependence on global markets.

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Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://doi.org/10.5281/zenodo.18328137.

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Conflict of interest

The authors declare no conflicts of interest.

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References

Adjao R T and Staatz J M 2015 Asian rice economy changes and implications for sub-Saharan Africa *Glob. Food Secur.* **5** 50–55

Arouna A *et al* 2021a Assessing rice production sustainability performance indicators and their gaps in twelve sub-Saharan African countries *Field Crops Res.* **271** 108263

Arouna A, Fatognon I A, Saito K and Futakuchi K 2021b Moving toward rice self-sufficiency in sub-Saharan Africa by 2030: lessons learned from 10 years of the coalition for African rice development *World Dev. Perspect.* **21** 100291

Artuc E, Porto G and Rijkers B 2019 Trading off the income gains and the inequality costs of trade policy *J. Int. Econ.* **120** 1–45

Bijl D L, Bogaart P W, Dekker S C, Stehfest E, de Vries B J M and van Vuuren D P 2017 A physically-based model of long-term food demand *Glob. Environ. Change* **45** 47–62

Bouët A and Nimenya N 2023 Agricultural trade and trade integration in the East African community *Africa Agriculture Trade Monitor 2023* (AKADEMIYA2063 and International Food Policy Research Institute (IFPRI)) (available at: https://hdl.handle.net/10568/140061)

Brenton P, Chemutai V and Pangestu M 2022 Trade and food security in a climate change-impacted world *Agric. Econ.* **53** 580–91

Burek P, Satoh Y, Kahil T, Tang T, Greve P, Smilovic M, Guillaumot L, Zhao F and Wada Y 2020 Development of the community water model (CWatM v1.04)—a high-resolution hydrological model for global and regional assessment of integrated water resources management *Geosci. Model Dev.* **13** 3267–98

Calvo Buendia E, Tanabe K, Kranjc A, Baasansuren J, Fukuda M, Ngarize S, Osako A, Pyrozhenko Y, Shermanau P and Federici S 2019 *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC)

Chen Z, Balasus N, Lin H, Nesser H and Jacob D J 2024 African rice cultivation linked to rising methane *Nat. Clim. Change* **14** 148–51

De Vos K *et al* 2024 African food system and biodiversity mainly affected by urbanization via dietary shifts *Nat. Sustain.* **7** 869–78

East African Community 2015 *East African Community Vision 2050: Regional vision for socio-economic transformation and development* EAC Secretariat

FAOSTAT 2023 Climate change: agrifood systems emissions/emissions totals (available at: www.fao.org/faostat/en/#data/GT)

Fischer G 2021 Global agro-ecological zones v4—Model documentation (FAO) (available at: www.fao.org/documents/card/en/c/cb4744en)

Gebresilasse M 2023 Rural roads, agricultural extension, and productivity *J. Dev. Econ.* **162** 103048

Gleick P H and Cooley H 2021 Freshwater scarcity *Annu. Rev. Environ. Resour.* **46** 319–48

HarvestChoice 2014 Market Sheds *International Food Policy Research Institute and University of Minnesota* (available at: https://hdl.handle.net/10568/149819)

He X *et al* 2023 Agricultural diversification promotes sustainable and resilient global rice production *Nat. Food* **4** 788–96

Headey D and Hirvonen K 2023 Higher food prices can reduce poverty and stimulate growth in food production *Nat. Food* **4** 699–706

Henry R C, Arneth A, Jung M, Rabin S S, Rounsevell M D, Warren F and Alexander P 2022 Global and regional health and food security under strict conservation scenarios *Nat. Sustain.* **5** 303–10

International Food Policy Research Institute 2020 Spatially-disaggregated crop production statistics data in Africa South of the Sahara for 2017 (available at: https://dataverse.harvard.edu/dataset.xhtml?persistentId=doi:10.7910/DVN/FSSKBW)

Janssens C, Havlík P, Boere E, Palazzo A, Mosnier A, Leclère D, Balkovič J and Maertens M 2022 A sustainable future for Africa through continental free trade and agricultural development *Nat. Food* **3** 608–18

Jayne T S, Snapp S, Place F and Sitko N 2019 Sustainable agricultural intensification in an era of rural transformation in Africa *Glob. Food Secur.* **20** 105–13

Johnson J-M, Ibrahim A, Dossou-Yovo E R, Senthilkumar K, Tsujimoto Y, Asai H and Saito K 2023 Inorganic fertilizer use and its association with rice yield gaps in sub-Saharan Africa *Glob. Food Secur.* **38** 100708

Joseph J, Tramberend S, Kabi F, Fischer G and Kahil T 2025 Sustainable intensification of fodder crop production can mitigate feed shortage and seasonality in East Africa *Environ. Dev.* **54** 101158

Jung M *et al* 2021 Areas of global importance for conserving terrestrial biodiversity, carbon and water *Nat. Ecol. Evol.* **5** 1499–509

Kadigi I L, Mutabazi K D, Philip D, Richardson J W, Bizimana J-C, Mbungu W, Mahoo H F and Sieber S 2020 An economic comparison between alternative rice farming systems in Tanzania using a Monte Carlo simulation approach *Sustainability* **12** 6528

Kahil T *et al* 2018 A continental-scale hydroeconomic model for integrating water-energy-land nexus solutions *Water Resour. Res.* **54** 7511–33

Kahil T *et al* 2025 Development of the global hydro-economic model (ECHO-global version 1.0) for assessing the performance of water management options *Geosci. Model Dev.* **18** 7987–8015

Kamau H, Roman S and Biber-Freudenberger L 2023 Nearly half of the world is suitable for diversified farming for sustainable intensification *Commun. Earth Environ.* **4** 1–9

Kehoe L, Romero-Muñoz A, Polaina E, Estes L, Kreft H and Kuemmerle T 2017 Biodiversity at risk under future cropland expansion and intensification *Nat. Ecol. Evol.* **1** 1129–35

Kikuchi M, Tokida K, Haneishi Y, Miyamoto N, Tsuboi T and Asea G 2013 *Rice in Uganda: Viewed from Various Market Channels* Japan International Cooperation Agency Survey Report

Kruseman G, Mottaleb K A, Tesfaye K, Bairagi S, Robertson R, Mandiaye D, Frija A, Gbegbelegbe S, Alene A and Prager S 2020 Rural transformation and the future of cereal-based agri-food systems *Glob. Food Secur.* **26** 100441

Ministry of Agriculture and Natural Resources 2021 Rwanda Rice development strategy (2021–2030) (Kigali, Rwanda)

Ministry of Agriculture, Animal Industry and Fisheries (MAAIF) 2012 *Uganda National Rice Development Strategy, 2008-2018* Ministry of Agriculture, Animal Industry and Fisheries of Uganda

Ndiiri J A, Mati B M, Home P G, Odongo B and Uphoff N 2013 Adoption, constraints and economic returns of paddy rice under the system of rice intensification in Mwea, Kenya *Agric. Water Manage.* **129** 44–55

Nhamo N, Rodenburg J, Zenna N, Makombe G and Luzi-Kihupi A 2014 Narrowing the rice yield gap in East and Southern Africa: using and adapting existing technologies *Agric. Syst.* **131** 45–55

Raskin P D, Hansen E and Margolis R M 1996 Water and sustainability *Nat. Resour. Forum* **20** 1–15

Rodenburg J and Saito K 2022 Towards sustainable productivity enhancement of rice-based farming systems in sub-Saharan Africa *Field Crops Res.* **287** 108670

Rodenburg J, Zwart S J, Kiepe P, Narteh L T, Dogbe W and Wopereis M C S 2014 Sustainable rice production in African inland valleys: seizing regional potentials through local approaches *Agric. Syst.* **123** 1–11

Senthilkumar K 2022 Closing rice yield gaps in Africa requires integration of good agricultural practices *Field Crops Res.* **285** 108591

Shi W *et al* 2024 Wheat redistribution in Huang-Huai-Hai, China, could reduce groundwater depletion and environmental footprints without compromising production *Commun. Earth Environ.* **5** 1–14

De Vos K *et al* 2023 Rice availability and stability in Africa under future socio-economic development and climatic change *Nat. Food* **4** 518–27

Smith C *et al* 2021 The Earth's energy budget, climate feedbacks, and climate sensitivity supplementary material *Climate Change 2021—The Physical Science Basis: Working Group I Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* ed V Masson-Delmotte *et al* (available at: www.ipcc.ch/)

Smith V H and Glauber J W 2020 Trade, policy, and food security *Agric. Econ.* **51** 159–71

State Department for Crop Development and Agricultural Research 2020 *Kenya National Rice Development Strategy 2 (2019–2030)* (Ministry of Agriculture, Livestock, Fisheries and Cooperatives)

Tol R S J 2023 Social cost of carbon estimates have increased over time *Nat. Clim. Change* **13** 532–6

Tramberend S *et al* 2021 Co-development of East African regional water scenarios for 2050 *One Earth* **4** 434–47

Twine E E 2023 *Implications of the ban on rice cultivation in Uganda's wetlands for breeding and seed systems programing* Market Intelligence Brief Series 4 CGIAR (available at: https://hdl.handle.net/10568/129733)

Twine E E, Ndindeng S A, Mujawamariya G, Adur-Okello S E and Kilongosi C 2023 Consumer preferences for rice in East Africa *Br. Food J.* **125** 316–29

van Ittersum M K *et al* 2016 Can sub-Saharan Africa feed itself? *Proc. Natl Acad. Sci.* **113** 14964–9

van Ittersum M K *et al* 2025 Prospects for cereal self-sufficiency in sub-Saharan Africa *Proc. Natl Acad. Sci.* **122** e2423669122

van Oort P A J and Zwart S J 2018 Impacts of climate change on rice production in Africa and causes of simulated yield changes *Glob. Change Biol.* **24** 1029–45

van Oort P A, Saito K, Tanaka A, Amovin-Assagba E, Van Bussel L G J, van Wart J, de Groot H, van Ittersum M K, Cassman K G and Wopereis M C S 2015 Assessment of rice self-sufficiency in 2025 in eight African countries *Glob. Food Secur.* **5** 39–49

van Oort P 2023 Balancing rice supply and demand in Africa *Nat. Food* **4** 460–1

van Soesbergen A, Arnell A P, Sassen M, Stuch B, Schaldach R, Göpel J, Vervoort J, Mason-D'Croz D, Islam S and Palazzo A 2017 Exploring future agricultural development and biodiversity in Uganda, Rwanda and Burundi: a spatially explicit scenario-based assessment *Reg. Environ. Change* **17** 1409–20

Wang X, Chang X, Ma L, Bai J, Liang M and Yan S 2023 Global and regional trends in greenhouse gas emissions from rice production, trade, and consumption *Environ. Impact Assess. Rev.* **101** 107141

Yami M and van Asten P 2017 Policy support for sustainable crop intensification in Eastern Africa *J. Rural Stud.* **55** 216–26

Yami M and van Asten P 2018 Relevance of informal institutions for achieving sustainable crop intensification in Uganda *Food Secur.* **10** 141–50

Yuan S *et al* 2021 Sustainable intensification for a larger global rice bowl *Nat. Commun.* **12** 7163

Yuan S, Saito K, van Oort P A J, van Ittersum M K, Peng S and Grassini P 2024 Intensifying rice production to reduce imports and land conversion in Africa *Nat. Commun.* **15** 835