A Framework for Measuring African Ecosystem Services Impacts from Land-Related Policies

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Abstract. This paper presents an integrated modeling framework that links a computable general equilibrium (CGE) model with spatially explicit ecosystem service models to assess the economic and ecological consequences of land use change in Kenya. Using the SSP2-RCP4.5 scenario as a baseline, we simulate land allocations and ecosystem service outcomes through 2075. Preliminary outputs indicate substantial conversion of forests and grasslands in high-growth zones, leading to declines in carbon storage and pollination services. These results highlight the importance of spatially targeted restoration and protection policies to mitigate natural capital loss. The integration of DEMETRA and SEALS with InVEST allows for the evaluation of alternative policy scenarios aligned with Kenya's climate and biodiversity commitments. While early findings underscore the potential for feedbacks between ecological change and economic performance, future work will focus on full model coupling and improved representation of ecosystem dynamics. This approach offers a novel pathway for evaluating land use and environmental policy in a spatially explicit, economy-wide framework.

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1. Introduction

Sustainable development requires jointly achieving economic growth, necessary to reduce poverty and improve human well-being, and environmental sustainability, critical for maintaining the life-support systems provided by nature. Striking this balance is one of the defining policy challenges of the 21st century, particularly in sub-Saharan Africa, where rapid development is creating both opportunities and mounting pressures on ecosystems. This tension is especially pronounced in land use, where expanding agricultural and infrastructure investments can drive economic transformation but also risk long-term environmental degradation.

Addressing this challenge requires tools that can assess potential trade-offs between economic and environmental goals. Computable General Equilibrium (CGE) models are commonly used to evaluate national policy scenarios and their macroeconomic consequences. However, CGE models typically represent land in highly aggregated terms, limiting their ability to capture spatial or ecological heterogeneity. On the other hand, ecosystem service models like InVEST (Integrated Valuation of Ecosystem Services and Tradeoffs) offer spatially explicit estimates of environmental outcomes such as carbon sequestration, water purification, and pollination, but generally operate outside of an economic framework.

Recent efforts, such as the GTAP–InVEST model, have begun integrating economic and environmental models at global scales, showing that investing in nature can simultaneously boost GDP and improve environmental outcomes (Johnson et al., 2023). Yet these integrated models are often oriented toward global trade analysis, lacking the flexibility needed for country-specific policy applications in Africa. Moreover, such approaches tend to overlook local dynamics, institutional settings, and the policy experimentation capacities that are essential for national planning.

This paper presents a new framework designed to bridge that gap: linking a national CGE model with a spatially explicit land-use downscaling tool and ecosystem service models. We apply this framework in the Kenyan context, evaluating how different socioeconomic development pathways and land-related policies influence ecosystem services at a fine spatial resolution. Our approach enables feedback between economic activity and environmental change, allowing policymakers to explore how market dynamics, policy incentives, and natural capital interact over time.

By combining national economic modeling with high-resolution environmental valuation, this framework enables more grounded assessments of sustainable development strategies. It builds on existing global approaches but prioritizes flexibility, national relevance, and scenario-based planning. Ultimately, this work contributes a replicable model for other African countries seeking to chart development pathways that preserve vital ecosystem services while promoting economic growth.

2. Modeling Framework

2.1 Economic Model: DEMETRA

The Dynamic Equilibrium Model for Economic development Resources and Agriculture (DEMETRA) is a recursive dynamic CGE model designed for single-country applications. Developed by the Joint Research Centre of the European Commission and implemented in GAMS, DEMETRA builds on the STAGE_DEV framework described by Aragie et al. (2017). STAGE_DEV itself is an extension of the STAGE_2 model (McDonald, 2015), enhanced to better reflect economic structures in developing countries. These enhancements include modeling the dual role of semi-subsistence agricultural households, introducing a nested consumption function, allowing for an endogenous functional income distribution, and incorporating domestic migration and segmented factor markets. The model is calibrated to the 2017 Social Accounting Matrix (SAM) for Kenya, developed by Mainar Causapé et al. (2018). The SAM captures annual economic flows across 53 productive sectors—including 11 representing household home production—alongside 55 marketed commodities, 18 home-produced commodities, and 22 distinct household groups.

This model has been enhanced to include an expanded representation of heterogeneous land use, allowing for endogenous calculations of land-use changes at the Kenya-AEZ (Agro-Ecological Zone) scale. In contrast to earlier CGE approaches that assume a fixed land supply within each AEZ, DEMETRA introduces land supply functions that endogenize land availability, making it responsive to economic signals such as changes in land rental rates. Land supply in each AEZ is specified as a function of the real land rental rate and an asymptote representing the maximum arable land available for conversion. The parameters governing these land supply curves are calibrated using historical land-use change, following approaches used in models like MAGNET and GTAP-InVEST.

To calculate the total available land in each AEZ, we combine high-resolution (10 arc-second, ~300m) spatial data on biophysical land suitability. Specifically, we incorporate a range of soil and agronomic constraints including nutrient retention, nutrient availability, oxygen availability, rooting conditions, soil toxicity, excess salts, land workability, and topographic roughness. Land is excluded from potential conversion if it exceeds biophysical thresholds (e.g., soils worse than class 4 based on the Harmonized World Soil Database, or roughness index above 20). Additional criteria include minimum crop caloric yields within a local neighborhood (e.g., ≥20 billion kilocalories within 5 km) and overall crop suitability (≥30%). Urban areas, permanent water bodies, barren land, ice, and rocky surfaces are excluded from the land base.

This process ensures that the land supply curves used in DEMETRA reflect both physical and agronomic constraints, producing more realistic estimates of potential cropland expansion. Once these constraints are imposed and the land supply functions are calibrated, policy simulations in DEMETRA can generate estimates of land-use conversion at the Kenya-AEZ level. This allows for a more spatially and biophysically grounded representation of land expansion in response to economic shocks or interventions.

2.2 Environmental and Spatial Modeling: SEALS + InVEST

To analyze ecosystem services effectively, it is essential to identify land-use at a sufficiently high spatial resolution. To enable this, we downscale the regional projections of land-use change generated by DEMETRA to a fine spatial resolution (10 arc-seconds, approximately 300 meters) using the Spatial Econometric Allocation and Land-use Simulator (SEALS), originally published in Suh et al. (2020) and extended in Johnson et al. (2020). To ensure that our high-resolution downscaled results are credible and aligned with existing global datasets, we calibrated them to be consistent with the Land-Use Harmonization 2 (LUH2) dataset (Riahi et al., 2017). LUH2 provides annual estimates of land-use transitions for 13 land-cover categories under five Shared Socioeconomic Pathway (SSP) scenarios used by IPBES, at a medium resolution of approximately 30 kilometers. SEALS integrates both land-use projections to create a high resolution landscape, based on observed relationships present in timeseries input data. SEALS uses a spatial allocation approach that has been calibrated on the European Space Agency Climate Change Initiative (ESA CCI) LULC 1992-2015 dataset using an iterative Gaussian L1-loss function minimization approach (ESA, 2017).

Two key enhancements have increased the flexibility and adaptability of the SEALS framework. First, the model now supports alternative basemaps, enabling users to initialize projections with a range of land-use datasets. Second, the integration of sub-national administrative boundaries allows for more granular modeling of land-use change within countries, aligning spatial dynamics with single-country CGE analyses.

After SEALS has generated fine-scale land use landscapes, Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) is used to calculate the projected change in ecosystem service provision, including pollination sufficiency, carbon storage, and biodiversity. Each of these InVEST models is thoroughly documented in its user guide (Sharp et al., 2021).

For the pollination model in our Kenya application, we assumed that pollinators are fully abundant in areas classified as natural land cover—specifically, land cover types corresponding to classes 50 to 180 in the underlying ESA CCI Land Cover (LULC) dataset. Following the global version of the InVEST model, we applied uniform assumptions about pollinator efficacy and distance decay parameters. We then calculated the proportion of natural habitat surrounding each plot of pollination-dependent agricultural land (classified as classes 10–20) to estimate the availability of nesting and foraging resources. In essence, the model estimates pollination sufficiency based on the presence of these two key landscape features: nesting habitat (natural land cover) and nectar sources (crop types requiring pollination). We implemented this methodology across Kenya, adapting the global approach used in (Chaplin-Kramer et al., 2019), which produced a worldwide map of pollination sufficiency.

The InVEST Carbon Storage and Sequestration model quantifies the amount of carbon currently stored in a landscape and estimates future carbon sequestration based on projected land-use change. It calculates total carbon stocks by summing contributions from four key carbon pools: aboveground biomass, belowground biomass, soil organic carbon, and dead organic matter. These estimates are derived from the downscaled land-use maps, yielding the estimated change in carbon storage over time.

2.3 Model Linkages

Figure 1 shows the linkages between DEMETA, SEALS, and InVEST. Following a policy experiment, economically driven endogenous land-use change from DEMETRA is integrated with exogenous land-use change from the SSP-RCP projections. SEALS downscales these land-use changes to a fine resolution that can be used by InVEST. Ecosystem service provision is estimated for pollination, carbon storage and sequestration, and biodiversity.

The pollination ecosystem service creates an output that can be used as an economic feedback shock to DEMETRA. Following Johnson et al. (2023), this is implemented as a factor-neutral productivity shock, which changes the efficiency coefficient in each impacted production function. This approach uses spatially detailed data to identify land areas projected to lose pollinator habitat and quantifies the resulting declines in crop pollination services, linking these losses directly to specific economic growth scenarios.

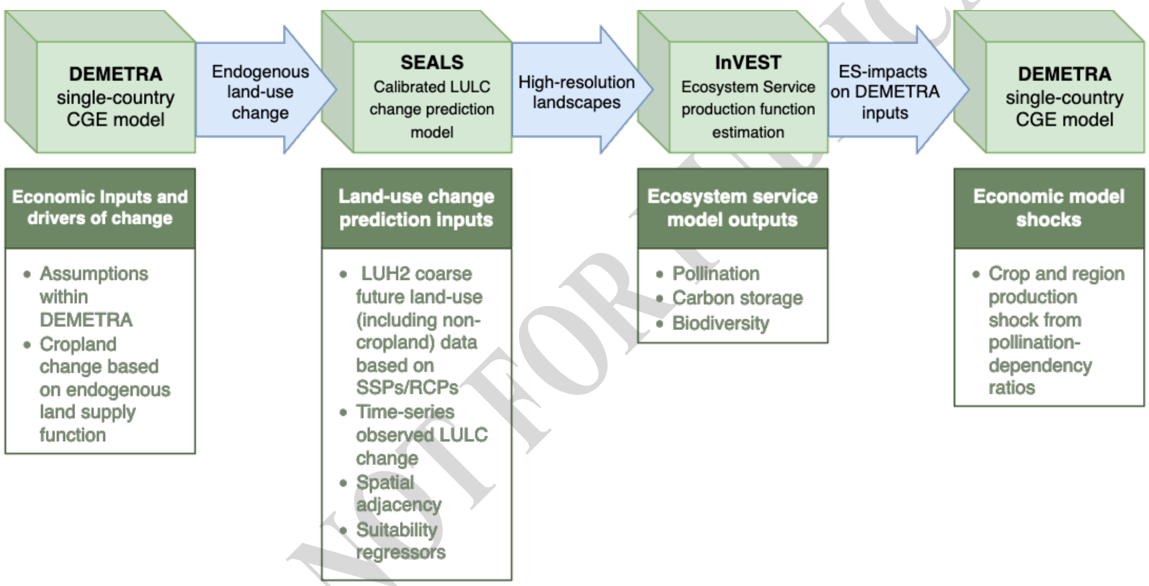

Figure 1. Overall model linkages between DEMETRA and InVEST/SEALS

3. Scenario Design and Policy Experiments

Scenario development is ongoing, but initial modeling results have been completed for a baseline trajectory consistent with SSP2-RCP4.5. This pathway reflects a middle-of-the-road development trajectory with moderate climate mitigation, incorporating assumptions about land supply elasticities, demographic trends, and sectoral growth aligned with this global scenario.

In addition to the baseline, we are considering a set of policy-relevant scenarios to explore how Kenya's land use could evolve under alternative policy choices. These include a scenario focused on achieving Kenya's forest restoration targets, which would involve the protection or expansion of forested areas in select agro-ecological zones (AEZs), and a scenario centered on responding to ongoing land degradation pressures. The forest restoration scenario aligns with Kenya's national climate and biodiversity commitments, while the degradation scenario aims to capture the economic and environmental consequences of unsustainable land management practices.

These scenarios are being developed in close coordination with national policy priorities and will be evaluated for their impacts on both economic outcomes and ecosystem services in future work.

4. Preliminary Results

Initial outputs from the SEALS model under the SSP2-RCP4.5 baseline scenario suggest substantial land-use change through mid- and late-century. As shown in Figure 2, projections for 2045 and 2075 reveal significant conversion of natural land covers, particularly forest loss and cropland expansion to accommodate the pressures of population growth. These trends reflect rising demand for agricultural land and settlement expansion under moderate development and climate trajectories.

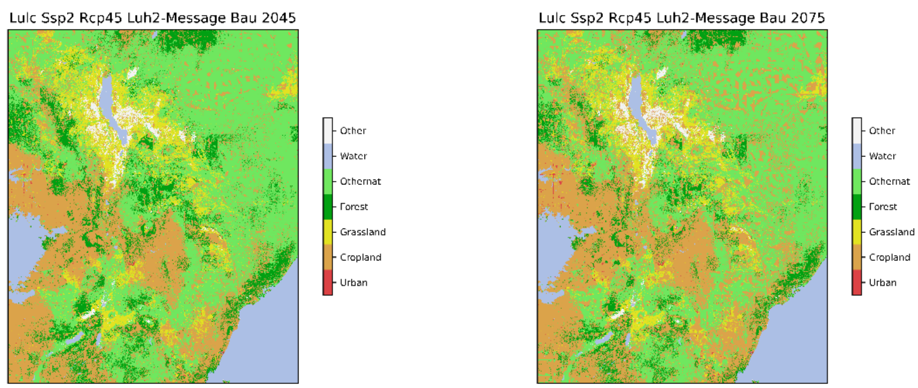

Figure 2. Land Use/Land Cover projections for Kenya using SEALS

Associated ecosystem service impacts are evident in early InVEST model runs. Figure 3 displays projected changes in carbon storage, highlighting declines in areas experiencing agricultural encroachment and forest loss. These losses are most pronounced in western and central Kenya, where pressure on remaining forest patches intensifies under the baseline scenario. Similarly, Figure 4 presents changes in pollination abundance, which fall in regions of intensified cultivation. The decline in pollination services is particularly evident in zones transitioning from mixed-use or semi-natural systems to high-input croplands, raising potential concerns about long-term agricultural productivity and landscape resilience.

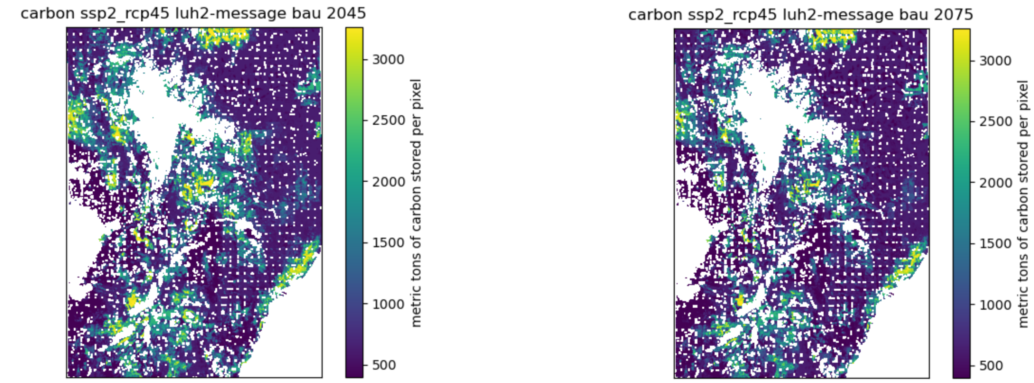

Figure 3. Carbon Storage based on LULC Projections using InVEST

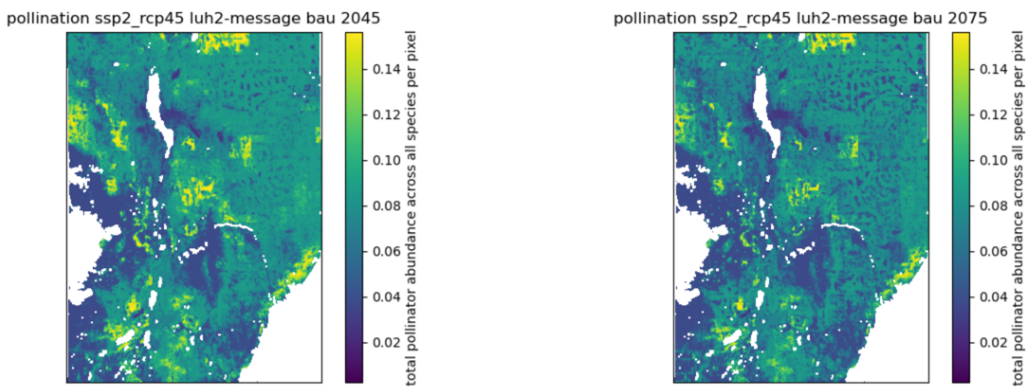

Figure 4. Pollination Abundance based on LULC Projections using InVEST

While still preliminary, these results highlight both limitations in the current modeling approach and opportunities for refinement. Ongoing improvements will introduce more realistic constraints on land transitions and incorporate spatially targeted policies aligned with Kenya's restoration and conservation goals. These refinements are expected to enhance the credibility of projected outcomes and support more policy-relevant scenario comparisons.

Additional outputs, currently in progress, will include spatial projections of biodiversity retention and Kenya-AEZ-specific pollination shocks, enabling a more comprehensive evaluation of trade-offs between land use change and ecosystem service provision. Subsequent scenario runs will also assess how policy interventions, such as restoration targets or improved land management in degraded areas, may alter the spatial distribution and magnitude of ecosystem service flows and their feedbacks on agricultural productivity.

5. Discussion

This work represents an important step toward integrating general equilibrium modeling with spatially explicit ecosystem service analysis at a national scale. Preliminary results from SEALS highlight substantial land conversion in certain agroecological zones (AEZs), especially in areas with high projected population growth. These trends result in measurable declines in forest cover, which in turn drive down carbon storage and pollination potential—key natural capital assets in Kenya's landscapes.

While still early, these findings underscore both the potential and the complexity of integrating economic and ecological models. Initial results point to a general decline in natural capital driven by land use change, highlighting the need for spatially explicit policy layers. Future model iterations will incorporate richer ecological feedbacks, including the full pollination feedback mechanism in DEMETRA, additional scenario layers, and alignment with Kenya's NDC and land degradation neutrality commitments.

This hybrid modeling approach opens new avenues for policy-relevant analysis. Unlike conventional economic models that treat land supply as fixed, or ecological assessments that often remain decoupled from economic behavior, this framework enables evaluation of specific land use policies, such as restoration, conservation incentives, or input subsidies, within a broader system of market interactions and land competition. It provides a foundation for assessing potential trade-offs and cooperative gains across development and environmental goals, with particular relevance for countries rich in natural capital navigating structural transformation.

More broadly, this work contributes to a growing literature demonstrating that investing in nature can yield substantial economic returns, particularly in lower-income settings. By explicitly modeling ecosystem services as economic inputs, this project reinforces findings from global GTAP–InVEST applications that show nature-positive policies are not only environmentally beneficial but also equitable, increasing regional welfare and long-term productivity. However, realizing these benefits will require strong institutions, accurate ecological measurement, and careful attention to implementation challenges—especially in contexts with weak property rights or high transaction costs.

The scenarios explored here are not forecasts but plausible trajectories designed to test the relative impacts of alternative land use and conservation strategies. Results should thus be interpreted as comparative outcomes rather than predictions. A key frontier for future work is dynamic feedback modeling, which would allow for the co-evolution of ecological and economic systems over time and better reflect the cumulative impacts of land management decisions.

In sum, this integrated modeling approach offers a promising platform for informing policy decisions at the interface of environment and development. While challenges remain, continued refinement—including validation against observed land change, expansion of ecosystem service metrics, and incorporation of full ecological feedbacks—will enhance its utility as a decision-support tool for Kenya and beyond.

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