African food system and biodiversity mainly affected by urbanization via dietary shifts

Koen De Vos [1,2,3] ✉, **Charlotte Janssens** [1,2,3], **Liesbet Jacobs**[1,4], **Benjamin Campforts**[5], **Esther Boere**[3,6], **Marta Kozicka** [3], **David Leclère** [3], **Petr Havlík** [3], **Lisa-Marie Hemerijckx** [1,2], **Anton Van Rompaey** [1], **Miet Maertens** [1] & **Gerard Govers** [1]

The rapid urbanization in Africa profoundly affects local food and ecological systems. According to earlier research, urbanization may cause food production and biodiversity losses as agricultural or natural lands are absorbed by expanding cities. Land-use displacement effects may buffer agricultural production losses or may lead to additional biodiversity losses but are often overlooked. Moreover, impacts of dietary changes associated with urbanization are rarely considered. To address this, we combined spatially explicit projections of African urban area expansion with observed rice consumption shifts to inform a partial equilibrium model (the Global Biosphere Management Model). We demonstrate the importance of displacement effects to identify potential food production or biodiversity issues until 2050 and argue for their integration in land-use planning and policymaking across spatial scales. We identify that because of agricultural displacement, the impact of urban area expansion on food production losses is probably limited (<1%)—at the cost of additional losses of natural lands by 2050 (up to 2 Mt). We also show that considering dietary shifts associated with urbanization increases rice consumption, production (+8.0%), trade (up to +2 Mt of required import) and agricultural methane emissions (up to +12 MtCO$_2$-equivalent yr^{-1}), thereby underscoring the need for a systems approach in future sustainability studies.

Since the early 2000s, Africa's urban population has more than doubled, reaching over 600 million in 2020. If current growth continues, this urban population is expected to double again by 2050. Annual rates of urban area expansion in Africa, estimated at around 5% per year between 1970 and 2000[1], exceed the urban population growth rate (estimated at 4% (our own calculation based on Food and Agriculture Organization (FAO) data)). This urban area expansion results in important local effects on biodiversity and food systems through ensuing land-use changes (LUCs)[1–4]. At a global scale, future urban area expansion is predicted to lead to substantial food production losses (−2.5% by 2100 for rice), a reduction in biodiversity and elevated annual LUC emissions (+0.05 PgC yr^{-1}) (refs. 3–6), thereby potentially compromising human livelihoods and the natural environment. As Africa is urbanizing the fastest, it is also the most food-insecure region in the world[7]. This stresses the importance of assessing the impacts of future urbanization on African food system transformations.

[1]Department of Earth and Environmental Sciences, KU Leuven, Leuven, Belgium. [2]Research Foundation Flanders (FWO), Brussels, Belgium. [3]Biodiversity and Natural Resources Program, International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria. [4]Institute for Biodiversity and Ecosystem Dynamics, University of Amsterdam, Amsterdam, the Netherlands. [5]Department of Earth Sciences, VU University Amsterdam, Amsterdam, the Netherlands. [6]Environmental Geography Group, Institute for Environmental Studies (IVM), VU University Amsterdam, Amsterdam, the Netherlands. ✉e-mail: koen.devos@kuleuven.be
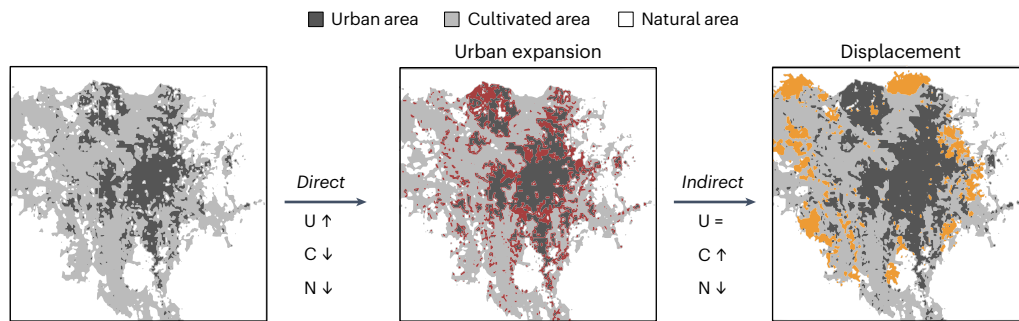
◼ Urban area ▢ Cultivated area ▢ Natural area

Fig. 1 | Conceptual representation of the direct and indirect displacement effects of urban expansion on urban, cultivated and natural lands. Indirect displacement effects can occur in different types of land use because compensation of direct loss in cultivated area can also occur in multiple LUCs. Here we particularly highlight compensation of cultivated area to meet the demand in crops (cropland compensation), in livestock (grassland compensation) and for wood (forest compensation). Urban pattern is modelled after Antananarivo, Madagascar. Cultivated area includes any land used to meet demand in crops (croplands), livestock (grasslands) or wood (forests). C, cultivated lands; N, natural lands; U, urban lands. Red indicates expansion of urban area, orange indicates displacement of cultivated area.

Many studies assessing the environmental footprint of urban area expansion treat it as a conversion of any other land cover to urban land and are thereby focusing solely on direct effects (for example, refs. [3],[8]). Meanwhile, the complexity of urbanization and its indirect consequences are increasingly being recognized[9],[10]. Urban area expansion may trigger displacement effects, with agricultural land being expanded elsewhere. This potentially attenuates food production losses but may also increase the loss of natural lands (Fig. 1)[11],[12]. In addition, urban expansion may induce changes in comparative advantages for agricultural products, leading to a shift in peri-urban production patterns often characterized by an increase in higher-value products[13]. While local-scale studies accounting for LUC complexity are emerging[14],[15], assessments at a larger scale are still very sparse[11]. Therefore, our current understanding of potential impacts of urbanization and its junction with sustainability is incomplete[16].

Apart from general dietary shifts due to changes in income or education, which may also occur in a rural setting, the unique sociocultural food environment in urban centres contributes to specific dietary shifts associated with urbanization. This food environment is shaped by (1) a higher opportunity cost for traditional cooking practices due to structural employment in the industry or services sector[17],[18] and (2) the emergence of supermarkets, which increases access to diverse foods[19]. Globally, urbanization is associated with increased consumption of animal-based products and a decrease in the share of cereals[2]. In Africa, urbanization stands out as a driver of the rising per capita demand for rice over recent decades[20],[21]. This surge in rice demand is linked not only to a growing income or the growing presence of supermarkets, but also to the convenience of storing and preparing rice compared with other cereals[21]. A rapidly changing food environment in African cities has been identified as a driver for other development issues such as health or poverty[22], making it important to identify substantial effects to direct the food system towards a sustainable future.

Within the shared socioeconomic pathways (SSP) framework, demand trajectories are based on projections by ref. [23], which suggest a deceleration in the future growth of rice demand for developing countries, which is contradicting the elevated growth in African rice demand anticipated under continued urbanization trends. This implies that the impact of urbanization may not be well captured. As rice cultivation has a considerable environmental footprint, requiring a vast amount of water for irrigation[24] and being an important source of agricultural methane (CH_4) emissions[25], current projections of the environmental footprint of future rice cultivation may also be underestimated. Future environment and food systems analyses thus require integration of urbanization in a holistic manner where land-use displacement effects and dietary shifts associated with urbanization are accounted for and are analysed against a background of changes in yield and/or total population already considered in existing scenarios (for example, ref. [26] for rice).

In this Article, we integrate the effects of land-use displacement and dietary shifts associated with urbanization to develop a more holistic understanding of the impact of future urbanization on the African environment and African food demand. We assess both direct and indirect LUC effects from urban expansion as well as the increase in rice demand driven by urbanization. We estimate their individual and combined effects on LUC, environmental degradation, the availability of rice, methane emissions and water use. We used the Biodiversity Intactness Index (BII) as defined by ref. [27] to assess biodiversity impacts. Data on future urban expansion is derived from ref. [5], which provides spatially explicit information on urban expansion based on a panel regression method and urban population estimates that are in line with the SSP framework[28]. We used micro-level data from household surveys in the World Bank's Living Standards Measurements Study (LSMS) to parameterize the difference in rice demand in a global economic model (the Global Biosphere Management Model (GLOBIOM)) that was adapted to account for urban displacement effects[29],[30]. See Methods for further details.

Results

Urban expansion and land-use displacement effects

By 2050, 3.28 Mha of land is projected to be converted into urban area following the SSP2 middle-of-the-road narrative for Africa (Fig. 2a). Most of this land is converted from cropland (50.4%), while the rest stems from grasslands (12.7%), forests (primary: 12.0%; managed: 10.0%) or 'other natural lands' (12.2%). Only 2.7% of the additional urban land is converted from wetlands. Differences between SSP2 and other SSP narratives are minor, both in terms of total land converted to urban area (3.38 Mha for SSP1, sustainability, and 3.07 Mha for SSP3, regional rivalry) and in terms of order of magnitude of each converted land-use class (Supplementary Table 1).

Land-use displacement affects the resulting LUC pattern substantially, indicating that urban expansion is not a one-to-one land conversion (Fig. 2b). We projected a partial buffering of direct effects for (1) cropland to accommodate for agricultural demand through an expansion into grasslands and other natural lands (1.05 Mha), (2) grassland to accommodate for livestock demand through an expansion into primary forest and other natural land (0.54 Mha) and (3) managed forest to accommodate for wood demand through an expansion into primary forest (0.28 Mha). In particular, primary forest and other natural lands are affected by LUC displacement effects, which exceed direct LUC effects in terms of magnitude. Interestingly, the net conversion of primary forest to croplands is lower under an urban expansion scenario as compared with no urban expansion (visible as
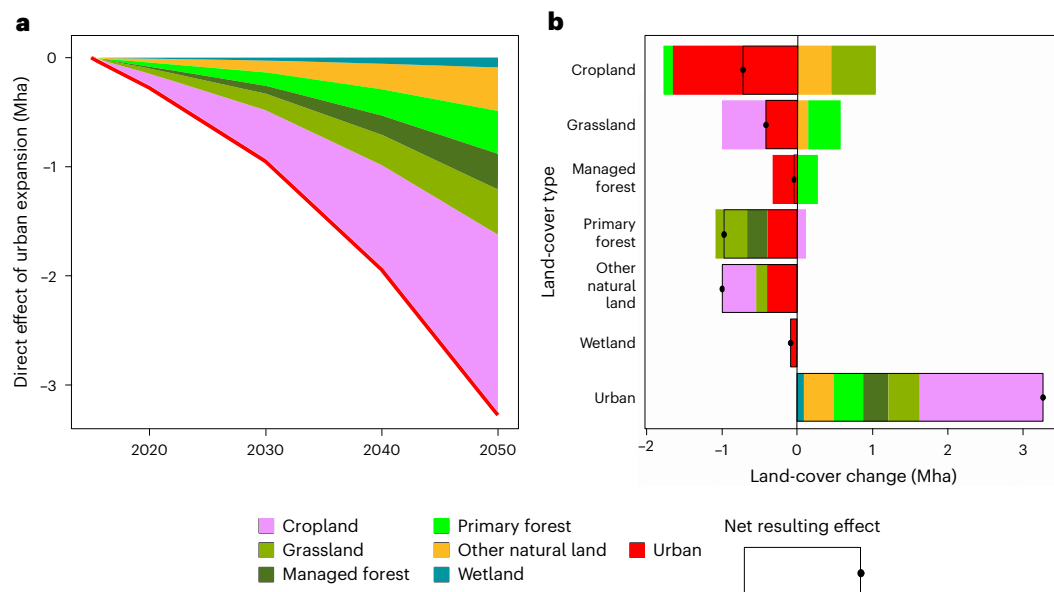
Fig. 2 | Estimated LUCs induced by urbanization on the African continent by 2050 under SSP2, middle of the road. a, Considering only direct effects of urban expansion. **b**, Also considering land-use displacement effects. For SSP1, sustainability, and SSP3, regional rivalry, see Supplementary Fig. 2. For figures separated for Northern Africa and sub-Saharan Africa, see Supplementary Figs. 3 and 4.

a net negative LUC in Fig. 2b) because there is less primary forest left to cultivate in the former (as more is already converted into managed forest and grassland).

The area of cropland directly converted to urban land is projected to be limited (0.63% of the continental cropland under SSP2). This results in minor net production losses (<0.7%) for all key staple crops at the continental scale (Fig. 3). If only direct land uses are accounted for, production losses at the continental scale are overestimated. There is, however, an important difference between Northern Africa and sub-Saharan Africa. In Northern Africa, expected production losses from direct effects are substantial for rice (−1.88%), millet (−2.07%) and wheat (−4.53%). Displacement effects, however, mostly compensate these production losses. For maize, we project a substantial production loss that further increases when indirect LUCs are considered (−7.29%; Fig. 3). In sub-Saharan Africa, direct effects on modelled production losses are much smaller (<1%) for all key staple crops, and these minor losses are almost entirely compensated by displacement effects (Fig. 3).

Impact of demand

On the basis of the LSMS data, we observed a substantial difference in rice consumption between urban and rural households in several African regions. Urban households tend to consume on average 1.5 times as much rice as rural households (Supplementary Fig. 4). This leads to a substantial increase in projected rice demand compared with a baseline scenario that does not account for this dietary shift (+9.2%−SSP1; Fig. 4a)).

To meet this elevated demand, future urbanization is projected to increase both imports and production of rice across all considered SSP scenarios. The largest part of the net increase in rice demand is met through increased production in Africa rather than through imports (between 70% and 80%, depending on SSP). Under SSP1, relative urban effects are substantially higher than under SSP2 or SSP3 (Fig. 4).

Environmental footprint

Total agricultural CH_4 emissions (including rice-specific methane emissions, enteric fermentation and manure management effects) are projected to increase by 2.4% or 12.2 $MtCO_2$-equivalent (CO_2e) under SSP2 mainly because of increased emissions from rice fields (Supplementary Table 8). According to our projections, total agricultural water use is affected only slightly by urbanization. Urban area expansion slightly reduces agricultural water use through abandonment of cropland. Urban demand impacts on water use are minor (<0.5%) for SSP2 and SSP3 and slightly positive under SSP1.

Although the relative decrease in natural lands (primary forest and other natural lands) is minor (<0.5%) (Fig. 4), mainly because of the large baseline values at the continental scale, the impact of LUCs on local biodiversity can be considerable (Fig. 5). While the major differences in our projections of the evolution of BII are determined by the SSP narrative, our estimations also indicate that urbanization (both expansion and demand effects) could decrease future biodiversity levels considerably. This is particularly true for areas where considerable urban expansion and subsequent LUCs are expected. For the Lagos–Ibadan area, for example, it reduces biodiversity intactness up to 4.5% under SSP1, resulting in an even lower BII value than under SSP3, which has the lowest BII under a baseline scenario. This effect is largely cancelled out at the continental and regional scales.

Discussion

We demonstrate that the expected production losses due to urban expansion in Africa by 2050 stay well below 1% for all major staple crops. This is because (1) the minimal share of agricultural land that is directly converted to urban area compared with the continental scale (−0.63% under SSP2)) and (2) land-use displacement effects compensate for the direct impacts on production losses. If displacement is not considered, food production losses are overestimated. Although there are considerable differences between Northern Africa and sub-Saharan Africa in terms of magnitude of production losses due to direct LUCs, displacement effects attenuate these losses for almost all staple crops in both regions. Maize in Northern Africa is an exception; we project an additional loss of cropland due to displacement. This is induced by the response (displacement) of other crops, for which a comparative advantage exists over maize and the limited possibilities for cropland to expand into natural land in this region.

Similarly, we observe that the direct effects of urban area expansion on the extent of natural lands (primary forest and other natural lands) are also minor relative to the continental extent of natural lands (−0.09% under SSP2). When accounting for displacement effects of cropland (for agricultural demand), grassland (for livestock demand)
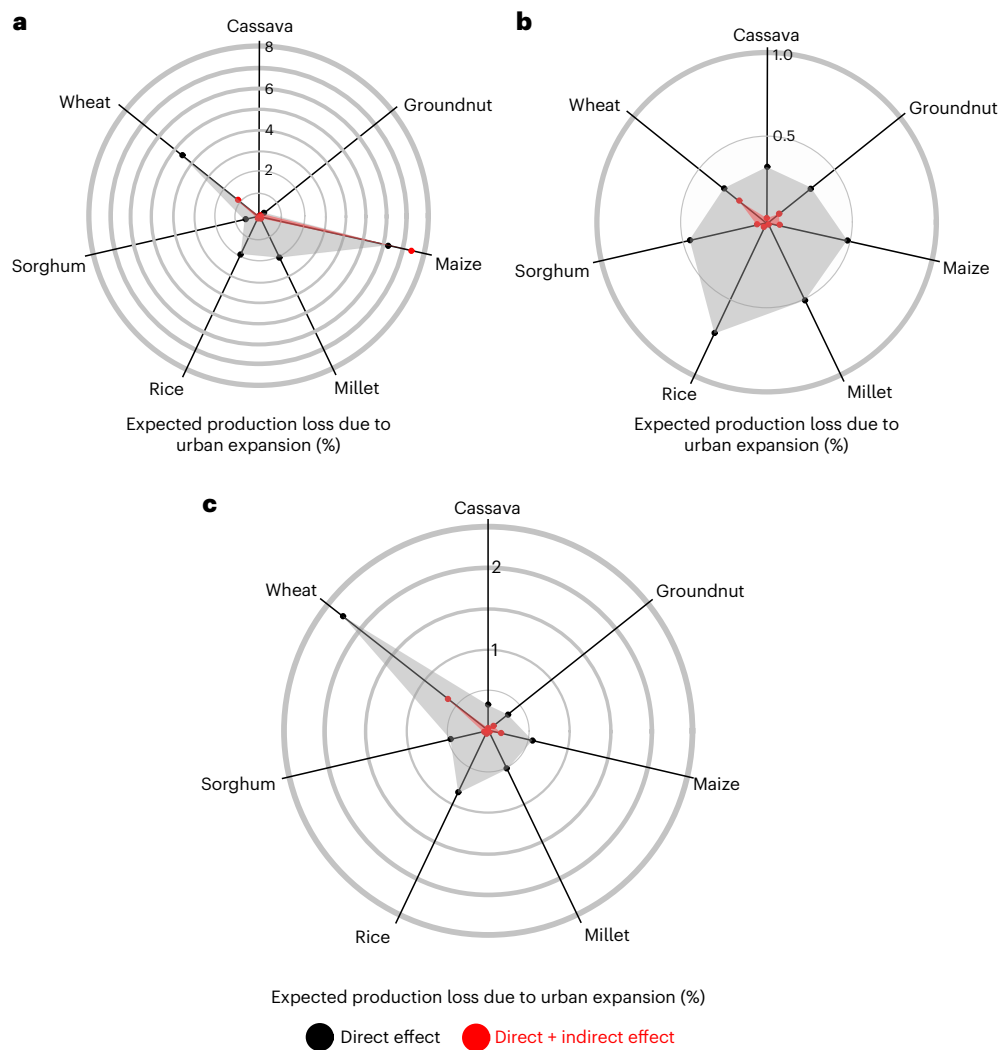
Fig. 3 | Estimated expected production losses for key staple crops in Africa following the SSP2 middle-of-the-road narrative when accounting only for direct urban expansion effects and when also accounting for displacement effects. a, For Northern Africa. **b**, For sub-Saharan Africa. **c**, For the total African continent. Note that the scale differs between panels. See Methods for the estimation of the production losses. For a comparison with other SSP scenarios, see Supplementary Fig. 5.

or managed forest (for wood demand), this impact increases (−0.25% under SSP2). Similar to ref. 11, indirect effects outweigh direct effects in our projections, which means that accounting for displacement effects is key in developing credible projections of the environmental footprint of future urbanization in Africa. We therefore advocate the explicit integration of indirect land-use dynamics in urban spatial planning efforts at various spatial levels. In this study, we presented a methodological benchmark for this purpose by adjusting the GLOBIOM model to explicitly simulate potential direct and indirect effects of urbanization.

Our findings also indicate that while future challenges of food production losses and of natural land conservation due to urbanization seem manageable at the continental scale, this is not necessarily true at the local scale. Earlier work already demonstrated the importance of local food production within African cities and in their close surroundings for food security[31,32] as well as the inclination towards higher-value production within or close to the city perimeter[13]. Changes to food production in these areas may therefore be relatively more important than changes in land-use area suggest. In addition, while we project displacement effects, the capacity of African agricultural and food supply chains to respond to the projected urban area expansion remains uncertain, particularly given the financial and institutional constraints faced by smallholder farmers in accessing land[33].

Effects on biodiversity also transcend direct habitat loss caused by LUCs as effects of habitat fragmentation or degradation can also be considerable[6]. The latter two are not captured by the indicator that was used in this study[34,35]. Habitat fragmentation also depends on the spatial form of urban sprawl, particularly for African cities that are already dispersed over relatively large areas[36,37].

Furthermore, we show the critical role of accounting for dietary patterns and their drivers in global-scale modelling assessments. While frequently used food demand trajectories often lack explicit consideration of commodity-specific dietary contexts, our study emphasizes such granularity for projections of global food distribution, trade dynamics and environmental impacts. As urbanization continues to reshape the food system, it is also important to consider it into projections of food security and/or caloric availability or when prioritizing for investments.

The demand effect of urbanization for rice, which was modelled here, leads to increased estimates of rice production, consumption per capita, imports and producer price at the continental scale. In our projections, the additional increase in continental demand (+8.4%−SSP2) is met largely by African rice production (+8.0%−SSP2). This in turn forces local production to expand into less-productive areas, which results in higher producer prices (+1.05%−SSP2). This result is based
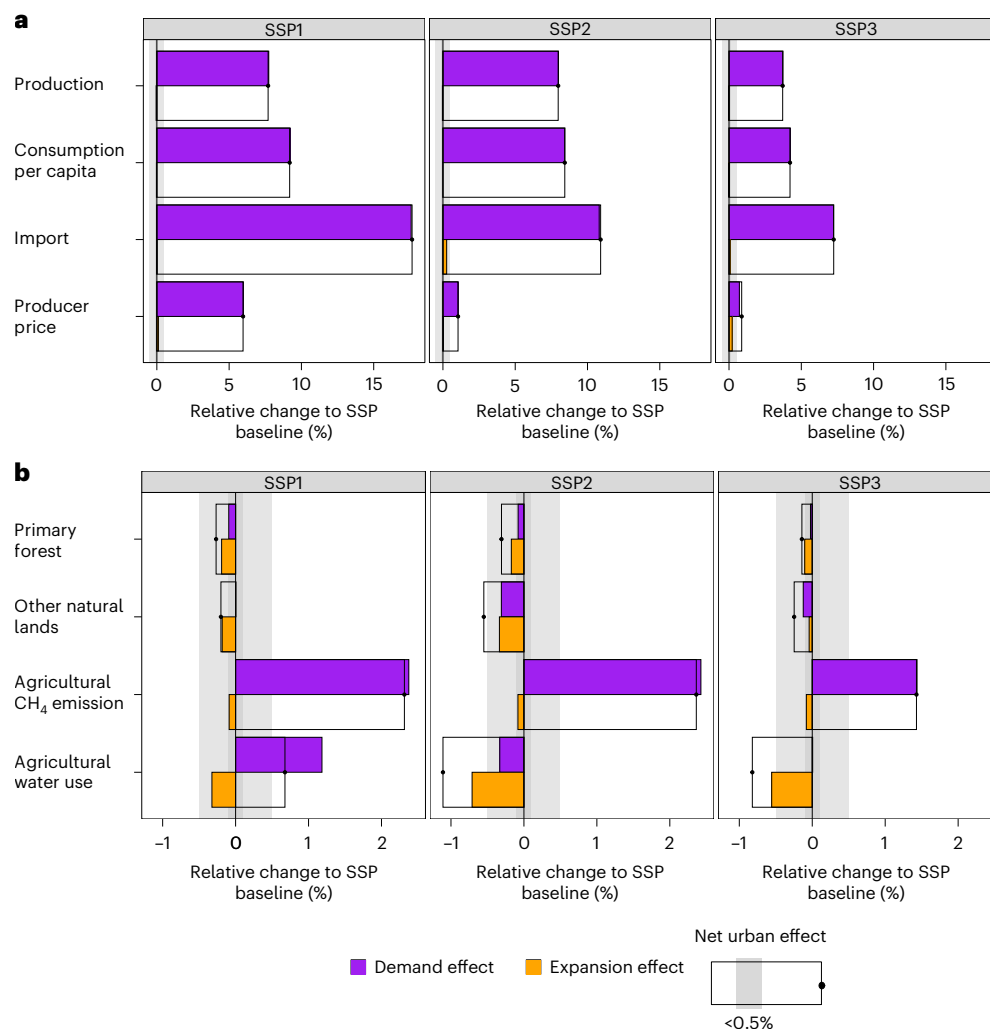
Fig. 4 | Estimated effects of African urbanization by 2050 when compared with different SSP baseline scenarios. a, Rice-specific parameters. **b**, General parameters. Purple bars indicate demand effect; orange bars indicate expansion effect. Grey shading indicates a relative net urban impact smaller than 0.5%. For a detailed description of these effects and how they were quantified, see Methods.

on the assumption that rice is a homogeneous good, and hence we do not account for possible preferences for imported rice. Particularly in Africa, however, urban consumers are known to prefer imported over locally produced rice, such that they cannot be considered perfect substitutes[38,39]. We may therefore assume that our projections overestimate the impact of demand on local production and underestimate its effect on rice imports. Another uncertainty is in the magnitude of change in dietary pattern associated with urbanization. Our analysis is based on the LSMS data, which has good coverage over the Economic Community of West African States and the East African Community regions. They are projected to jointly contribute to around 73% of the African rice demand by 2050 (following SSP2), and we can therefore estimate the magnitude of change in these regions with reasonable confidence. However, for the Rest of Central-Eastern Africa (RCEAf) and Rest of Southern Africa (RSouthAf) regions, data are available from only a single country (respectively, Ethiopia and Malawi), and it is unclear how representative these countries are for their respective regions' dietary patterns. Further research and data collection are required to improve survey coverage in other regions and to identify the effects of different levels of (perceived) goods heterogeneity on rice demand to assess the impact of demand changes on local production versus imports more accurately.

We also show that urbanization leads to important environmental spillover effects. Agricultural CH$_4$ emissions increase substantially

(+2.4%−SSP2), mainly because of the increase in rice demand, which is met by an increase in African rice production[26]. Agricultural water is the limiting factor under SSP2 and SSP3; therefore, almost all additional water required for rice production increase is sourced from other crops' irrigation, resulting in an almost net-zero demand effect on agricultural water use and a larger importance of urban area expansion effects. Under SSP1, agricultural water is not a limiting factor (because of a higher water efficiency), resulting in a larger importance of demand effects. It is, however, still unclear how these changes interact with the expected increase in water demand for other purposes (for example, industrial or household use) that is also often linked to urbanization[40,41]. Depending on the location and the spatial scale, urbanization also substantially decreases the intactness of biodiversity or the extent of natural areas. In general, effects of urbanization (both demand and expansion effects) are more pronounced under SSP1 than under SSP2 or SSP3 because the SSP1 narrative assumes (1) a more urbanized future than the others[28] and (2) lower baseline values for rice production and demand[26].

Earlier research has shown the importance of meat and dairy demand for environmental conservation[42–45], and while there are clear correlations between urbanization and the consumption of meat and dairy[46,47], we indicate that dietary shifts in other (staple) foods can also lead to considerable impacts. This important aspect has not been well captured in future food trajectories up until now.
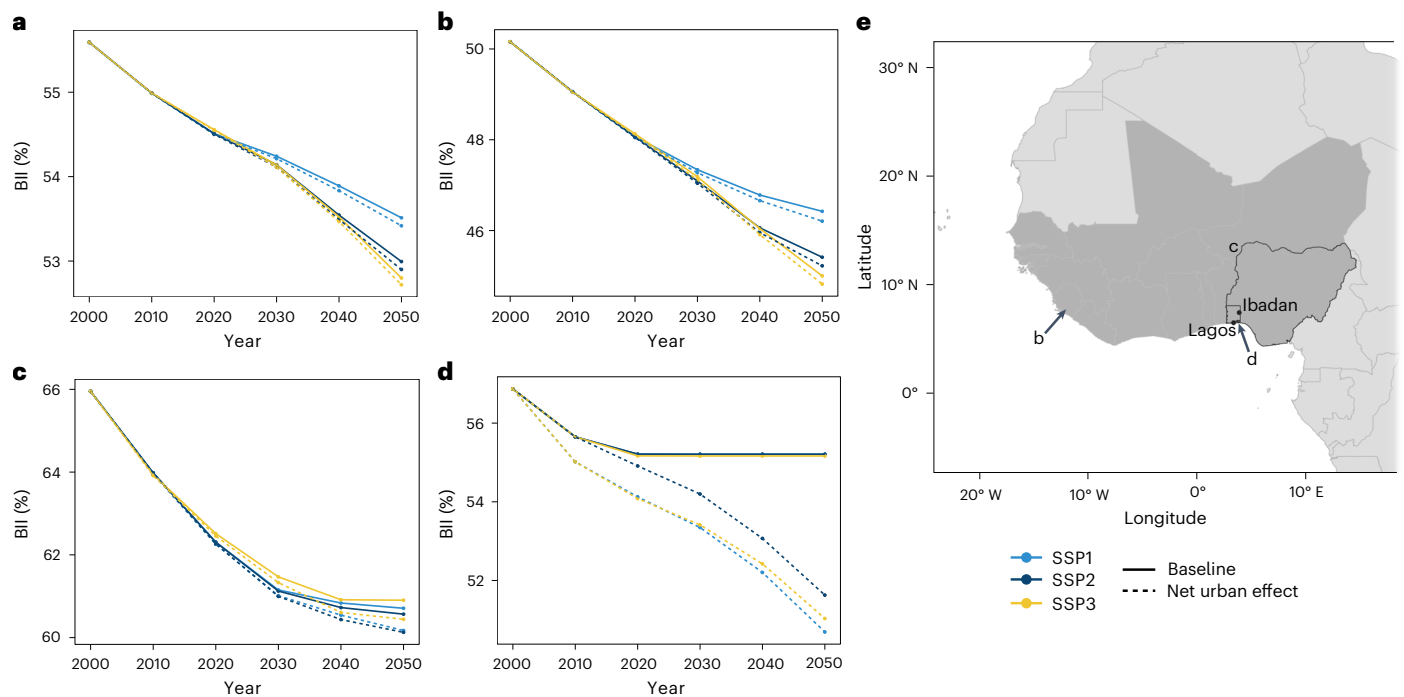
Fig. 5 | BII projections under different SSP narratives for 2050. a, Africa. **b**, Economic Community of West African States. **c**, Nigeria. **d**, The Lagos–Ibadan region. **e**, Overview of the different spatial scales used in **b**–**d**. Dashed lines indicate projections considering net urban effect (demand effect + expansion effect). For the calculation of the BII, see Methods.

Our simulations show that observed differences in preferences for rice between urban and rural households can lead to considerable effects on rice-specific (for example, production, imports, producer price) as well as non-rice-specific (for example, biodiversity intactness or agricultural water use) variables. This underscores the need to improve the representation of heterogeneity of dietary patterns and their respective drivers in global assessment models. This would reduce potential bias resulting from the assumption of a representative consumer in the estimates of future land allocation, production and trade dynamics and their environmental impacts. It might be even more important to consider different food types, crop varieties and cross-price effects or to disentangle the observed effects into effects of income, education, sociocultural environment and other socioeconomic drivers instead of using urbanization as a single driver. Our approach enables the introduction of consumer heterogeneity in global integrated modelling studies and is thereby an important tool in identifying and reducing consumer aggregation bias in global-scale assessments. In this research, we used urbanization as a complex driver of socioeconomic changes (for example, income, education), which results in dietary changes. This approach could be further refined by explicitly considering dynamics in the drivers of dietary patterns rather than considering exogenous scenarios in dietary patterns. This is an important step in improving the application of impact modelling assessments to enable effective policymaking.

Methods
Model design
The GLOBIOM is a spatially explicit partial equilibrium model of the agricultural, forestry and bioenergy sectors at a global scale. In each time step, it distributes production, consumption and trade to optimize the sum of consumer and producer surplus. Land management is delineated by altitude, slope, soil, agro-ecological classes, country borders and a 5 arcmin spatial resolution grid, resulting in 212,707 global simulation units (SU). Each of these units has its own yield, shadow price and input requirements for different crops, agricultural

intensity levels (for example, irrigated versus rainfed) and land-cover classes. Demand for food (Q) is adjusted exogenous to the model and is based on projected changes in population (Pop), gross domestic product per capita (GDP^{pc}) and income elasticity of demand (equation (1)). Changes in producer price (P) affect demand endogenously through own-price elasticity of demand (ε^p) (equation (2)), while cross-price effects between food types are not explicitly considered. Notably, these equations incorporate the dynamic nature of population and GDP per capita through income elasticity of demand (ε^y) across different SSP scenarios, thereby influencing the trajectories of commodity demand and resulting in diverse dietary conditions across SSP scenarios.

$$\overline{Q_T} = \left(\frac{Pop_T}{Pop_{2000}}\right)\left(\frac{GDP_T^{pc}}{GDP_{2000}^{pc}}\right)^{\varepsilon_T^y} \overline{Q_{2000}} \qquad (1)$$

$$\frac{Q_T}{\overline{Q_T}} = \left(\frac{P_T}{P_{2000}}\right)^{\varepsilon_T^p} \qquad (2)$$

Base year (2000) demand values ($\overline{Q_{2000}}$) are calibrated using available FAO data, allowing for independent validation of model results for the year 2010 and 2020. A wide variety of staple crops for food and feed (barley, cassava, chickpea, dry beans, groundnut, maize, millet, potato, rapeseed, rice, soybean, sorghum, sweet potato, wheat), livestock products (bovine, goat, pig, poultry, sheep) and other agricultural products (cotton, oil palm, sugarcane, sunflower) are explicitly modelled at a global scale. Fruit and vegetable systems are not explicitly modelled. One-way bilateral trade was modelled by assuming nonlinear trade costs and homogeneous goods between regions. Detailed information on the structure of parameters used to calibrate the standard version of GLOBIOM can be found in ref. 29, and further specifications for the version used here that is adapted to better represent the African agricultural context can be found in ref. 30. Model bias for the African rice system (production, consumption and trade) is described in ref. 26.

Urban expansion and displacement effects

We use estimates of future urban expansion from ref. 5, who constructed global spatially explicit expansion maps for each urbanization projection following the corresponding SSP narrative[28] until 2100 at a spatial resolution of 1 km. For this, they estimated future urban land demand for each SSP scenario using a panel data regression model that established the relationships between several socioeconomic parameters and historical urban land-use demand for different macroeconomic regions. These estimations were used by the future land use simulation model (which is established under the framework of a cellular automata model combined with an artificial neural network classifier) to allocate the urban expansion. More information on the methodology and a validation of their results can be found in ref. 5.

Using the Google Earth Engine application programming interface in Python, we used an overlay of these spatially explicit urban expansion maps for different SSP narratives and global land-cover maps from the Copernicus Global Land Service (CGLS-LC100) available in Google Earth Engine[48] to estimate which percentage of land cover within each SU (from the GLOBIOM model) is being converted into urban land at each future time step. For simplicity, we assumed that the proportion of land being converted into urban land is independent of any future land-cover changes. In this analysis, we considered only expansion on the African continent.

This information is then introduced in the GLOBIOM model as an exogenous land-cover change occurring within each SU at each recursive time step. This exogenous land-cover change is introduced before land allocation is calculated so displacement can be accounted for within the same time step. If, due to the assumption we made earlier about urban expansion being independent of future land-cover changes, the extent of expansion into a specific land-cover class exceeds the remaining extent of that land cover, we adapt the exogenous land-cover change to match the remaining extent. For example, using the Google Earth Engine analysis where we assumed the land cover to be constant, we identified that for a specific SU, 20 ha of grasslands will be converted to urban land in 2030, but that because of projected land-cover changes there is only 10 ha of grasslands remaining in that SU in 2030. In this case, the exogenous land-cover change from grasslands to urban is converted to 10 ha to not end up with negative extents. This resulting exogenous land-cover change is used to quantify the direct effects and the difference in projected land-cover changes between a model run with urban expansion (LUC_urban and a standard model run without (LUC_base) are used to quantify direct + displacement effects for each land-cover class (LC) at each time step (T).

$$\text{Direct effect}_{LC,T} = \sum_{t=2000}^{T} \sum_{SU} \text{exogenous LUC}_{LC,t,SU} \quad (3)$$

$$\text{Direct + displacement}_{LC,T} = \sum_{t=2000}^{T} (\text{LUC}_{urban} - \text{LUC}_{standard}) \quad (4)$$

Estimates of production loss (PL) are made in a similar way. For the production losses because of direct effects, we multiplied the expected area converted to urban for each crop (c) with the respective predicted yield (Y_c), and for the direct + displacement effects, we compared the production estimates (P_c) from the model run with urban expansion and the standard model run without.

$$\text{PL}_{direct,c,T} = \sum_{SU} (\text{Exogenous LUC}_{c,T,SU} \times Y_{c,T,SU}) \quad (5)$$

$$\text{PL}_{direct+displacement,c,T} = \sum_{SU} (P_{urban,c,T,SU} - P_{standard,c,T,SU}) \quad (6)$$

Effects of biodiversity are estimated by using the BII as defined by ref. 27. The index provides an indication of the percentage of pre-industrial biodiversity still intact. Effects of land use on the BII

were modelled using the PREDICTS database[49] and adapted to the GLOBIOM framework by ref. 50. The index quantifies effects of biodiversity through land-use dynamics by considering a fixed BII value for each land use (LU) and simulation unit (SU) combination and changes in area (A). The BII does not consider degradation of biodiversity within the same land cover.

$$\text{BII}_T = \frac{\sum_{LU} \sum_{SU} \text{BII}_{LU,SU,T} \times A_{LU,SU,T}}{\sum_{LU} \sum_{SU} A_{LU,SU,T}} \quad (7)$$

Household survey analysis

To identify dietary differences between urban and rural households, we used several household surveys from the LSMS for African countries that are accessible through the World Bank's microdata library (https://microdata.worldbank.org/). The LSMS consists of a series of household surveys conducted by the World Bank to collect data on various socioeconomic indicators, including household consumption patterns. The surveys ensure a representative sample of households through a well-thought sampling design and employ a standardized questionnaire, which makes it accessible to compare across countries. This makes the LSMS surveys particularly suitable to assess consumption patterns in African countries, as is also exemplified by previous research (for example, ref. 51 for meat and fish consumption). Typically, the surveys question households on their food consumption pattern of the past week (7 days) before the survey date, which is more feasible to remember than asking for longer periods. Although this covers only a small window in time, the dedicated sampling scheme, in principle, should counter any issues of representation. Existing seasonal patterns in food consumption are thus not explicitly considered, although they can be considerate[52]. Based on national definitions, the surveys also distinguish between urban and rural households, thus allowing comparison between urban and rural dietary patterns.

In our analysis, we combined the rice consumption (or rice demand) of the past 7 days for each household (hh) with the household size (N_{hh}) to make an estimation of the annual rice consumption per capita ($\tilde{Q}$) (equation (8)). It is important to note that this is an estimated value, hence why we included the ~, and is subject to uncertainties regarding granularity and seasonality. These estimated values are calculated for urban and rural households separately and are used to identify the relative difference in rice consumption between urban and rural households (equation (9)). These values are calculated for each survey wave (sw) and each country (cou) and are aggregated to the regional level (reg) using the population of that country in the year the survey was conducted (Pop$_t$) (equation (10)). Annual population values are taken from FAOSTAT. A similar approach is used to calculate this at the continental level.

$$\tilde{Q} = \frac{\sum_{hh} Q_{7d,hh} \times 52}{\sum_{hh} N_{hh}} \quad (8)$$

$$U/R = \frac{\tilde{Q}_{urban}}{\tilde{Q}_{rural}} = a \quad (9)$$

$$a_{reg} = \frac{\sum_{cou} \sum_{sw} a_{t,cou,sw}}{\sum_{cou} \text{Pop}_{t,cou}} \text{ where cou} \in \text{reg} \quad (10)$$

Disaggregation framework

The observed regional difference in rice consumption between urban and rural households (a_{reg}) is used to disaggregate the representative consumer considered in the GLOBIOM demand framework (equations (1) and (2)). For regions that were not covered by the LSMS surveys (Arab Maghreb Union (AMU), Economic Community of Central African

States (ECCAS), Egypt and Southern African Customs Union (SACU); Supplementary Fig. 6), we assumed the continental value.

In our disaggregation framework, we consider the total exogenous demand at a certain time step ($\overline{Q_t}$) equal to the sum of urban ($\overline{Q_{t,urban}}$) and rural ($\overline{Q_{t,rural}}$) demand within a region (equation (11)). By doing so, we assume that each demand region is characterized by a single market and thus that there are no differences in price or own-price elasticity of demand between rural and urban environments. In a similar manner, we have disaggregated the exogenous demand function (equation (1)) in terms of urban (U) and rural (R) population share and initial demand in an urban ($\overline{Q_{2000,u}}$) or rural ($\overline{Q_{2000,r}}$) environment (equation (12)). Accordingly, we made a second assumption by not considering any differences in income growth or income elasticity of demand between an urban and rural environment. Although this assumption is certainly not valid in an African context as the difference in employment opportunities and wages has been identified as an important driver of rural–urban migration by previous research[53], the particularly low values for income elasticity of demand for rice[54] probably cancel out any differences in income growth. This was also verified by a sensitivity analysis we performed (not included here) by comparing the differences between total expenditure trends between urban and rural households using the LSMS surveys for Tanzania. Since the temporal coverage of the LSMS surveys is limited (Supplementary Table 9), this information was not included in this analysis.

$$\overline{Q_t} = \overline{Q_{t,urban}} + \overline{Q_{t,rural}} \tag{11}$$

$$\overline{Q_t} = \left(\frac{Pop_t}{Pop_{2000}}\right)\left(\frac{GDP_t^{pc}}{GDP_{2000}^{pc}}\right)^{\varepsilon_t^{GDP}}\left(\frac{U_t}{U_{2000}}\overline{Q_{2000,u}} + \frac{R_t}{R_{2000}}\overline{Q_{2000,r}}\right) \tag{12}$$

Simultaneously, the initial exogenous demand can be considered the weighted average of the urban initial demand and the rural initial demand, where weighting is done using respective population shares (equation (13)). By combining the observed difference between urban and rural demand for rice (equation (10)) and available information on total rice demand and population shares (from FAOSTAT), we were able to disaggregate the initial demand (equations (14) and (15)).

$$\overline{Q_{2000}} = U_{2000}\overline{Q_{2000,u}} + R_{2000}\overline{Q_{2000,r}} \tag{13}$$

$$\overline{Q_{2000,r}} = \frac{\overline{Q_{2000}}}{a - aR_{2000} + R_{2000}} \tag{14}$$

$$\overline{Q_{2000,u}} = \frac{a\overline{Q_{2000}}}{1 + aU_{2000} - U_{2000}} \tag{15}$$

To quantify the potential demand effect, we used projections on urban and rural population shares for the different SSP narratives from ref. 28 in the updated exogenous demand function (equation (12)). Although we applied our framework only to rice demand and urbanization in Africa, it could also be easily expanded to other food types, regions and socioeconomic indicators, as it requires only a reasonable spatial coverage of standardized household surveys, for which we identify the LSMS surveys to be particularly suitable.

Net urban effect
For each SSP narrative, we did four model runs: (1) an SSP baseline run without urban expansion or urban demand effects, (2) a model run where we accounted only for urban expansion (expansion effect), (3) a model run where we accounted only for dietary differences (potential demand effect) and (4) a model run where we considered both for urban expansion and for dietary differences (net urban effect). The results from model runs 2–4 are compared with the SSP baseline run to quantify the respective effects.

Data availability
The model output data generated by the GLOBIOM model that was used to visualize the results have been deposited on the Zenodo online repository: https://doi.org/10.5281/zenodo.10899595 (ref. 55). Source data are provided with this paper.

Code availability
The code used for the analyses and visualization is available from the corresponding author on request.

References
1. Seto, K. C., Fragkias, M., Güneralp, B. & Reilly, M. K. A meta-analysis of global urban land expansion. *PLoS ONE* **6**, e23777 (2011).
2. Seto, K. C. & Ramankutty, N. Hidden linkages between urbanization and food systems. *Science* **352**, 943–945 (2016).
3. Seto, K. C., Güneralp, B. & Hutyra, L. R. Global forecasts of urban expansion to 2030 and direct impacts on biodiversity and carbon pools. *Proc. Natl Acad. Sci. USA* **109**, 16083–16088 (2012).
4. Güneralp, B., Lwasa, S., Masundire, H., Parnell, S. & Seto, K. C. Urbanization in Africa: challenges and opportunities for conservation. *Environ. Res. Lett.* **13**, 15002 (2017).
5. Chen, G. et al. Global projections of future urban land expansion under shared socioeconomic pathways. *Nat. Commun.* **11**, 537 (2020).
6. Li, G. et al. Global impacts of future urban expansion on terrestrial vertebrate diversity. *Nat. Commun.* **13**, 1628 (2022).
7. *The State of Food Security and Nutrition in the World 2023: Urbanization, Agrifood Systems Transformation and Healthy Diets Across the Rural–Urban Continuum* (FAO, IFAD, UNICEF, WFP and WHO, 2023); https://doi.org/10.4060/cc3017en
8. Bren d'Amour, C. et al. Future urban land expansion and implications for global croplands. *Proc. Natl Acad. Sci. USA* **114**, 8939–8944 (2017).
9. McDonald, R. I. et al. Research gaps in knowledge of the impact of urban growth on biodiversity. *Nat. Sustain.* **3**, 16–24 (2020).
10. Meyfroidt, P. et al. Focus on leakage and spillovers: informing land-use governance in a tele-coupled world. *Environ. Res. Lett.* **15**, 90202 (2020).
11. van Vliet, J. Direct and indirect loss of natural area from urban expansion. *Nat. Sustain.* **2**, 755–763 (2019).
12. van Vliet, J., Eitelberg, D. A. & Verburg, P. H. A global analysis of land take in cropland areas and production displacement from urbanization. *Glob. Environ. Change* **43**, 107–115 (2017).
13. Follmann, A., Willkomm, M. & Dannenberg, P. As the city grows, what do farmers do? A systematic review of urban and peri-urban agriculture under rapid urban growth across the Global South. *Landsc. Urban Plan.* **215**, 104186 (2021).
14. Wang, B., Liang, Y. & Peng, S. Harnessing the indirect effect of urban expansion for mitigating agriculture–environment trade-offs in the Loess Plateau. *Land Use Policy* **122**, 106395 (2022).
15. Du, S., Shi, P. & van Rompaey, A. The relationship between urban sprawl and farmland displacement in the Pearl River delta, China. *Land* **3**, 34–51 (2014).
16. Yussif, K., Dompreh, E. B. & Gasparatos, A. Sustainability of urban expansion in Africa: a systematic literature review using the Drivers–Pressures–State–Impact–Responses (DPSIR) framework. *Sustain. Sci.* https://doi.org/10.1007/s11625-022-01260-6 (2023).
17. Cockx, L., Colen, L., De Weerdt, J. & Gomez-y-Paloma, S. *Urbanization as a Driver of Changing Food Demand in Africa* (European Commission, 2019); https://doi.org/10.2760/515064 (2019).

18. Casari, S. et al. Changing dietary habits: the impact of urbanization and rising socio-economic status in families from Burkina Faso in sub-Saharan Africa. *Nutrients* **14**, 1782 (2022).

19. Wanyama, R., Gödecke, T., Chege, C. G. K. & Qaim, M. How important are supermarkets for the diets of the urban poor in Africa? *Food Sec.* **11**, 1339–1353 (2019).

20. Herrero, M., Havlík, P., McIntire, J., Palazzo, A. & Valin, H. *African Livestock Futures: Realizing the Potential of Livestock for Food Security, Poverty Reduction and the Environment in Sub-Saharan Africa* (UNSIC, 2014); https://doi.org/10.13140/2.1.1176.7681

21. Seck, P. A., Touré, A. A., Coulibaly, J. Y., Diagne, A. & Wopereis, M. C. S. in *Realizing Africa's Rice Promise* (eds Wopereis, M. C. S. et al.) 24–34 (CABI, 2013); https://doi.org/10.1079/9781845938123.0024

22. Battersby, J. & Watson, V. Addressing food security in African cities. *Nat. Sustain.* **1**, 153–155 (2018).

23. Alexandratos, N. & Bruinsma, J. *World Agriculture Towards 2030/2050: The 2012 Revision* (FAO, 2012).

24. Qin, Y. et al. Flexibility and intensity of global water use. *Nat. Sustain.* **2**, 515–523 (2019).

25. Karakurt, I., Aydin, G. & Aydiner, K. Sources and mitigation of methane emissions by sectors: a critical review. *Renew. Energy* **39**, 40–48 (2012).

26. De Vos, K. et al. Rice availability and stability in Africa under future socio-economic development and climatic change. *Nat. Food* **4**, 518–527 (2023).

27. Scholes, R. J. & Biggs, R. A biodiversity intactness index. *Nature* **434**, 45–49 (2005).

28. Jiang, L. & O'Neill, B. C. Global urbanization projections for the shared socioeconomic pathways. *Glob. Environ. Change* **42**, 193–199 (2017).

29. IBF-IIASA, Global Biosphere Management Model (GLOBIOM) Documentation 2023—Version 1.0 (IIAS, 2023); https://iiasa.github.io/GLOBIOM/

30. Janssens, C. et al. A sustainable future for Africa through continental free trade and agricultural development. *Nat. Food* **3**, 608–618 (2022).

31. Karg, H. et al. Foodsheds and city region food systems in two West African cities. *Sustainability* **8**, 1175 (2016).

32. Hemerijckx, L.-M. et al. Mapping the consumer foodshed of the Kampala city region shows the importance of urban agriculture. *NPJ Urban Sustain.* **3**, 11 (2023).

33. Deininger, K., Savastano, S. & Xia, F. Smallholders' land access in sub-Saharan Africa: a new landscape? *Food Policy* **67**, 78–92 (2017).

34. Martin, P. A., Green, R. E. & Balmford, A. The biodiversity intactness index may underestimate losses. *Nat. Ecol. Evol.* **3**, 862–863 (2019).

35. Newbold, T., Sanchez-Ortiz, K., De Palma, A., Hill, S. L. L. & Purvis, A. Reply to 'The biodiversity intactness index may underestimate losses'. *Nat. Ecol. Evol.* **3**, 864–865 (2019).

36. Concepción, E. D. et al. Impacts of urban sprawl on species richness of plants, butterflies, gastropods and birds: not only built-up area matters. *Urban Ecosyst.* **19**, 225–242 (2016).

37. Xu, G. et al. Urban expansion and form changes across African cities with a global outlook: spatiotemporal analysis of urban land densities. *J. Clean. Prod.* **224**, 802–810 (2019).

38. Rutsaert, P., Demont, M. & Verbeke, W. in *Realizing Africa's Rice Promise* (eds Wopereis, M. C. S. et al.) 294–302 (CABI, 2013); https://doi.org/10.1079/9781845938123.0294

39. Tomlins, K. I., Manful, J. T., Larwer, P. & Hammond, L. Urban consumer preferences and sensory evaluation of locally produced and imported rice in West Africa. *Food Qual. Prefer.* **16**, 79–89 (2005).

40. Molden, D. Water responses to urbanization. *Paddy Water Environ.* **5**, 207–209 (2007).

41. Savelli, E., Mazzoleni, M., Di Baldassarre, G., Cloke, H. & Rusca, M. Urban water crises driven by elites' unsustainable consumption. *Nat. Sustain.* https://doi.org/10.1038/s41893-023-01100-0 (2023).

42. Springmann, M. et al. Options for keeping the food system within environmental limits. *Nature* **562**, 519–525 (2018).

43. Scarborough, P. et al. Vegans, vegetarians, fish-eaters and meat-eaters in the UK show discrepant environmental impacts. *Nat. Food* **4**, 565–574 (2023).

44. Enahoro, D. et al. Linking ecosystem services provisioning with demand for animal-sourced food: an integrated modeling study for Tanzania. *Reg. Environ. Change* **23**, 48 (2023).

45. Havlík, P. et al. Climate change mitigation through livestock system transitions. *Proc. Natl Acad. Sci. USA* **111**, 3709–3714 (2014).

46. Komarek, A. M. et al. Income, consumer preferences, and the future of livestock-derived food demand. *Glob. Environ. Change* **70**, 102343 (2021).

47. Milford, A. B., Le Mouël, C., Bodirsky, B. L. & Rolinski, S. Drivers of meat consumption. *Appetite* **141**, 104313 (2019).

48. Buchhorn, M. et al. Copernicus global land cover layers—collection 2. *Remote Sens.* https://doi.org/10.3390/rs12061044 (2020).

49. Hudson, L. N. et al. The database of the PREDICTS (Projecting Responses of Ecological Diversity In Changing Terrestrial Systems) project. *Ecol. Evol.* **7**, 145–188 (2017).

50. Leclère, D. et al. Bending the curve of terrestrial biodiversity needs an integrated strategy. *Nature* **585**, 551–556 (2020).

51. Desiere, S., Hung, Y., Verbeke, W. & D'Haese, M. Assessing current and future meat and fish consumption in sub-Sahara Africa: learnings from FAO Food Balance Sheets and LSMS household survey data. *Glob. Food Sec.* **16**, 116–126 (2018).

52. Cedrez, C. B., Chamberlin, J. & Hijmans, R. J. Seasonal, annual, and spatial variation in cereal prices in sub-Saharan Africa. *Glob. Food Sec.* **26**, 100438 (2020).

53. Tumwesigye, S. et al. Who and why? Understanding rural out-migration in Uganda. *Geographies* **1**, 104–123 (2021).

54. Colen, L. et al. Income elasticities for food, calories and nutrients across Africa: a meta-analysis. *Food Policy* **77**, 116–132 (2018).

55. De Vos, K. et al. Data for 'African food system and biodiversity mainly affected by urbanization via dietary shifts'. *Zenodo* https://doi.org/10.5281/zenodo.10899595 (2024).

Author contributions

All authors contributed substantially to this research. K.D.V., C.J., L.J., B.C., M.M. and G.G. developed the conceptual framework. K.D.V., E.B., M.K. and P.H. developed the scenarios and methodological framework. K.D.V., C.J., E.B., M.K., D.L. and P.H. developed the models and adaptations. K.D.V. conducted the model runs. K.D.V. analysed the data. K.D.V., C.J., L.J., B.C., E.B., M.K., P.H., L.-M.H., M.M. and G.G. interpreted the data. K.D.V. wrote the initial manuscript. C.J., L.J., B.C., E.B., M.K., D.L., P.H., L.-M.H., A.V.R., M.M. and G.G. edited and commented on the manuscript. L.J., B.C., M.M. and G.G. supervised the project.

Competing interests

The authors declare no competing interests

Additional information

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Correspondence and requests for materials should be addressed to Koen De Vos.

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Corresponding author(s): Koen De Vos

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Software and code

Policy information about availability of computer code

Data collection	Data was collected from the LSMS library for survey data, and through modeling in GAMS (GAMS Distribution 31.2.0) for the GLOBIOM model.
Data analysis	Analysis of the LSMS data and post-processing of GLOBIOM modeling outputs were performed in R using RStudio (version 2022.02.2 Build 485).

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The model output data generated by the GLOBIOM model that was used to visualize the results, have been deposited on the Zenodo online repository: https://doi.org/10.5281/zenodo.10899595

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Reporting on sex and gender	For the reporting on sex and gender in data used within this research, we refer to the specific guidelines provided by the WorldBank in constructing and disseminating the LSMS datasets in their Microdata catalog.
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Ethics oversight	Before disseminated, the surveys in the LSMS collection are ethically overseen independent of our research. More information can be found in the terms and agreements or the specific ethical guidelines accompanying the various LSMS datasets.

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All studies must disclose on these points even when the disclosure is negative.

Study description	Our study combined information existing in micro-level household surveys existing in the Living Standards Measurements Study (LSMS) collection on rice consumption with spatially-explicit projections of future urbanization in the GLOBIOM partial-equilibrium model to identify future effects of urbanization on the African food system and the environment. We found that, despite urban expansion is often referred to as an imminent issue for both food security and biodiversity - particularly dietary shifts related to urbanization pose issues for the African continent.
Research sample	We combined all available datasets in the LSMS collection that reported on urban/rural households' consumption of rice. This resulted in a set of 38 surveys which included 289.309 African households.
Sampling strategy	For the specific sampling strategy of the different LSMS surveys, we refer to their metadata. The selection of surveys to include in our research was based on their inclusion of 1) a distinction between rural/urban households, and 2) a variable providing information on rice consumption. Households that did not report consumption in standardized metric units (such as kg, g, or tonnes) were also excluded. A list of all surveys in the LSMS catalog and their reason for inclusion/exclusion can be found in the Supplementary Material.
Data collection	LSMS microdata was downloaded from the LSMS Microdata Catalog.
Timing and spatial scale	Surveys cover a total of 12 countries between 2008-2020 (varies between countries). The research covers the continental scale and provides projections up to the year 2050.
Data exclusions	Household data that did not report on rice consumption in metric units were excluded from the sample.
Reproducibility	LSMS data is available on the catalog and processing code is available upon request.
Randomization	For further information on randomization in the LSMS surveys, we refer to their respective metadata.
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