Climate Change, Urban Expansion, and Food Production

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Abstract

Where and how cities grow will influence food production and the risks to food production. This paper estimates the overlap of future urban expansion in 2040 and 2100 with current crop and livestock production under different climate scenarios. First, it finds that urban areas will expand most into areas with fruits, vegetables, and chickens, and urban areas will expand most under a scenario with significant challenges to climate change mitigation. Second, the share of food producing areas that will overlap with urban expansion will be largest in Africa, particularly under a scenario of significant challenges to climate change adaptation. Third, across all scenarios, urban expansion is likely to take place in areas with higher crop or livestock production, but even more so when there are significant challenges to both mitigation and adaptation.

JEL Classifications: O13, O18, Q54, R14

Keywords: climate change, urban expansion, agriculture, crops, livestock

1. Introduction

Urbanization is intertwined with the opportunities to transform food systems. Because it gives rise to income growth, urbanization is associated with both a rising and changing demand for food.[1] Urbanization also leads to changes in land use that affect agriculture, as cities are pivotal in channeling finance, inputs, information, services, and off-farm employment opportunities to rural areas (Abu Hatab et al. 2019; de Bruin, Dengerink, and van Vliet 2021; World Bank 2009).[2] At the same time, how climate change is addressed will have important implications for land use, including for urbanization. And as such, there are important interactions across climate change, urban expansion, land use, and food production.[3]

Climate change adaptation and mitigation are, to an extent, determined by economic and demographic drivers such as population growth, the urban share of the population, and income per capita. One depiction of how changes in these underlying drivers relate to climate change is the five *Shared Socioeconomic Pathways (SSPs)* (Riahi et al. 2017). These SSPs trace the projected trajectories of various outcomes, including energy use, land use, greenhouse gas (GHG) emissions, and climate change. The five SSP narratives are: SSP1: Sustainability—Taking the Green Road (low challenges to adaptation and mitigation),[4] SSP2: Middle of the Road (medium challenges to mitigation and adaptation), SSP3: Regional Rivalry (high challenges to mitigation and adaptation), SSP4: Inequality (low challenges to mitigation, high challenges to adaptation), and SSP5: Fossil-fueled Development (high challenges to mitigation, low challenges to adaptation).

Of the five SSPs, SSP1 is considered a largely good scenario referred to as the "sustainability pathway," while SSP3 is a largely bad scenario called the "regional rivalry pathway". A look at the SSP projections reveals the following. First, total population will grow faster, and the illiterate proportion of the population will decline more slowly under SSP3 than under SSP1. Population will peak by around 2050 under SSP1, while it will continue to grow through 2100 under SSP3. The illiteracy rate will begin to grow by 2040 under SSP3. Second, the urban share of the population will increase under both scenarios, but it will do so much faster under SSP1 than SSP3

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[1] Urbanization not only affects food systems but can also be influenced by them. For instance, a more productive agriculture sector, leading to higher rural wages on the fringe of a city, could result in a smaller city (Krugman, 1991).
[2] DeFries et al. (2010) find that urbanization in India resulted in a reduction in agricultural land and changes in crop patterns. Gómez et al. (2013) show that unmanaged urbanization can negatively affect food security in Latin America.
[3] Food production also has significant negative impacts on climate. In 2015, GHG emissions from the global food system amounted to 18 gigatons of CO2 equivalent or one-third of total GHG emissions. The largest contribution, 71 percent, was by agriculture and land use or land use change activities, with the remainder by supply chain activities, including retail, transport, consumption, fuel production, waste management, industrial processes, and packaging (Crippa et al. 2021). Emissions associated with animal-based foods are twice as large as those of plant-based foods. Of the global GHG emissions from food production, 57 percent came from animal-based foods (including livestock feed), 29 percent from plant-based foods, and 14 percent from other uses (Xu et al. 2021). The two largest contributing plant- and animal-based commodities are rice (12 percent) and beef (25 percent).
[4] The narrative for SSP1 is that "the world shifts gradually, but pervasively, toward a more sustainable path, emphasizing more inclusive development that respects perceived environmental boundaries. Management of the global commons slowly improves, educational and health investments accelerate the demographic transition, and the emphasis on economic growth shifts toward a broader emphasis on human well-being. Driven by an increasing commitment to achieving development goals, inequality is reduced both across and within countries. Consumption is oriented toward low material growth and lower resource and energy intensity" (Riahi et al. 2017).

because urbanization is linked to better development outcomes. Third, GDP per capita grows exponentially under SSP1, while it remains stagnant under SSP3. Income inequality, referring to inter-household or inter-person income inequality within individual countries, declines much faster under SSP1 than SSP3.

The SSP projections define changes in land use (i.e. cropland, pasture, forests, urban land and other natural land, further described in Section 2), and these in turn have implications for food production. Chen et al. (2020) have shown that this loss of cropland could imply a decline in cereal and vegetable production across all pathways. There is a projected decline in production for the world's main cereals—rice, wheat, and maize—of about 2–3 percent, 1–3 percent, and 1-4 percent, respectively. The projected decline for vegetables is 2–4 percent and for potatoes 1–3 percent. These production declines are estimated to be equivalent to the food needs of up to 1.39 billion people, meaning that the reduced production could have sustained these many individuals under normal circumstances. Other estimates similarly project a total crop production loss of about 3.7 percent, rising to losses of 5.6 percent for Asia and 8.9 percent for Africa (d'Amour et al. 2017). D'Amour et al. (2017) also show that urban expansion is expected to take place on cropland that is 1.77 times more productive than the global average.

In this paper, we quantify the link between urban expansion and food production, under different SSP scenarios. That is, building on Chen et al. (2020) and d'Amour et al. (2017), we further describe the potential risks to food production driven by urbanization under different scenarios of climate change response. Our contributions are couched under the following data and analysis elaborations. First, we cover a more comprehensive list of food items, assessing seven crop groups (vegetables, fruits, roots, cereals, sugar, oils, and pulses), and eight types of livestock (chicken, duck, pig, buffalo, horse, goat, sheep, and cattle). Second, we disaggregate the results by regions of the world, and also present projections of potential risk at the city-level for select cities, offering valuable insights into regional and local analysis. Third, we estimate grid-level correlations between projected urban expansion and current food production, to better understand whether cities will expand in areas with higher crop and livestock production, and under which climate response scenarios. This analysis helps identify trends and potential challenges in the spatial distribution of urban growth and food production.

Like Chen et al. (2020), we provide projected urban overlap with food production under different SSPs, but here for a richer set of crop and livestock items and for different regions. Urban overlap, in this context, refers to the spatial extent to which urban expansion encroaches upon or coincides with areas designated for food production, including both crop and livestock farming. The work of d'Amour et al. (2017) assesses 16 major crops (including disaggregated analysis for four staples and three cash crops), looks into cropland and crop yields, and provides disaggregated regional analysis. Our work expands on this by looking at five SSP scenarios to 2100, as opposed to one projected probability of urban expansion to 2030, and by including livestock in our analysis.

We find the following three main results. First, globally the largest projected urban overlap is for vegetables and fruits among crop items, and for chickens among livestock. The urban overlap is initially larger under SSP1 (Sustainability Scenario) by 2040, but this then diminishes over time. By 2100, the largest urban overlap with food production is under SSP5 (Fossil-fueled Development Scenario), which is also the scenario where urban land expands the most by 2100.

Second, there are much larger overlaps in particular regions that are masked at the global level. We find that the overlaps are expected to be largest in Africa for both crops and for livestock, and particularly under SSP4 (Inequality Scenario). While Africa has smaller shares of global production, these regional dynamics have important implications for how we think about food trade, issues of perishability, and access to nutritious food for the most vulnerable. Moreover, the city-level examples in this paper highlight the importance of policy design and solutions at the local level, where the needs and risks would vary.

Third, for crops on aggregate and livestock on aggregate, urban expansion across all SSP scenarios will most likely occur under areas (i.e. grids) today that have higher levels of crop production and that have higher livestock density. This positive correlation between projected future urban expansion and current crop and livestock density is largest under SSP3 (Regional Rivalry Scenario) and smallest under SSP5 (Fossil-fueled Development Scenario). As such, while SSP5 impacts a lower food producing grid on average, it affects more grids in total so that the largest overlap of urban expansion with food production occurs under SSP5. In addition, while the estimated correlation is large and positive in both 2040 and 2100, it is smaller in 2100 than in 2040. That this correlation diminishes over time suggests that (in all SSP scenarios) suggests that urban expansion in the nearer-term (by 2040) will occur in higher food producing areas than the longer-term (by 2100).

The remainder of this paper is as follows. Section 2 discusses data and methodology, including SSPs, urban expansion, and crop and livestock data. Section 3 presents the extent of urban expansion on food production (globally and regionally), and grid-level correlations of urban expansion and food production. Section 4 concludes.

2.   Data and methodology

To estimate the relationship of climate-induced urbanization with crop and livestock production, we combine three distinct global spatial datasets— projected urban expansion, crop production, and livestock production— through the process of overlaying them at the grid-level using a mapping software. This allow us to delineate the locations and magnitude of potential urbanization overlap with land used for crop and livestock production, on both a global and regional level. In this case, the potential impact on crop and livestock production is defined as any production located in areas that overlap with future urban expansion.

2.1   Shared Socioeconomic Pathways (SSPs) and urban expansion

SSPs and land use change

The SSP scenarios depict how underlying determinants (i.e. population growth, urban share of population, and income per capita) affect land use (Riahi et al. 2017). First, under SSP1, cropland is projected to barely expand between 2010 and 2100, while pasture, suitable for livestock grazing, is expected to decrease. Meanwhile, forests and other natural land are projected to expand under SSP1. By contrast, under SSP3, cropland and pasture are projected to increase, while forests and other natural land are projected to dramatically decline. Under SSP5, the rapid economic growth

and conventional development focus will lead to a substantial increase in urban land demand, resulting in extensive urban expansion and greater conversion of cropland and pasture to urban land more than any other scenario. Under SSP1, therefore, sustainable food production implies the use of less land-intensive and more productive methods to feed a growing population. Under SSP3 and SSP5, the combination of population growth, deforestation, and unchecked livestock production will result in significantly increased risks, including a heightened risk for pandemics (Berthe et al., 2022).

The assumed growth in total population and in urban population share will lead to an increase in the demand for urban land to 2100 across all SSP pathways (Chen et al. 2020). Under SSP1, the demand for urban land will increase, but begin to decline after 2070, given the assumed eventual decline in population after 2050 under this scenario. Under SSP3, the demand for urban land will initially increase more slowly than under SSP1, given the assumed slow growth in the urban share of the population under SSP3. However, because of the continued population growth to 2100 under SSP3, urban land demand will continue to expand to 2100 and will approach the same level as SSP1 by 2100. Under SSP5, urban land demand is expected to increase significantly due to rapid economic growth, higher income levels, urban population growth, advancements in technology, and emphasis on globalization, leading to more extensive urban expansion and greater losses in crop production, more than other scenarios.

Across all pathways, it is projected that most urban expansion will entail the conversion of particularly productive cropland, followed by forests and then grassland (Chen et al. 2020). By 2100, 55 percent under SSP1 (63 percent under SSP3) of newly expanded urban land is expected to have displaced current cropland, 27 percent (21 percent) forests, and 12 percent (6 percent) grassland. Under SSP5, the land conversion proportions to urban expansion are expected to be 51 percent from cropland, 29 percent from forests, and 15 percent from grasslands. This projected conversion of cropland and grassland into urban land has important implications for crop and livestock production. Chen et al. (2020) show that urban expansion is projected to result in a 1.8–2.4 percent reduction in global cropland by 2030, and 80 percent of this loss is likely to take place in Asia and Africa. As mentioned above, d'Amour et al. (2017) show that urban expansion is expected to take place on cropland that is 1.77 times more productive than the global average. Under SSP5, the significant increase in urban land demand and the resulting land conversion may lead to the greatest amount of crop production losses among the scenarios, due to the rapid urban expansion and the potential displacement of highly productive cropland.

SSPs and projected urban expansion data

The urban expansion projection data (Chen et al. 2020) are calculated using panel data regression methods based on historical population, urbanization rate, and gross domestic product (GDP) data. Here, the urbanization rate is defined as the percentage of urban population to total population. The settlement extent data (i.e. all artificial cover and paved surfaces, not limited to urban) for the years 1975, 1990, 2000, and 2015 are from the Global Human Settlement Layer (GHSL), a dataset developed by the European Commission. The population and GDP data are from the World Bank and the United Nations. These data are fed into the built panel data regression model to project the built-up areas for each SSP scenario based on the predictions of future population, urbanization rate, and GDP from the SSP database. The projection outputs are then combined with other geographical information and inputted into the Future Land-Use Simulation (FLUS) model to

simulate the future spatial distribution of urban land. The final projection outputs, which have a spatial resolution of 1 km, are presented at 10-year intervals from 2020 to 2100, with 2015 being the reference year for baseline urban extent.

To overcome the uncertainty associated with climate change and illustrate the range of possible outcomes, Chen et al. (2020) adopt the SSP framework in producing the urban expansion projections. The five SSP scenarios, which are central to the Intergovernmental Panel on Climate Change (IPCC) reports, describe socioeconomic changes that affect demographic, economic, and climate change dynamics. The SSPs are part of a new scenario framework established by the climate change research community to facilitate integrated analysis of future climate impacts, vulnerabilities, adaptation, and mitigation (Riahi et al. 2017). The three main sets of scenario drivers are (1) population and education; (2) urbanization, defined as the urban share of the population (Jiang and O'Neill 2017); and (3) GDP per capita and interpersonal income inequality.[5] The scenarios are each associated with certain levels of assumed mitigation and adaptation challenges: the sustainability scenario (SSP1), for example, is marked by low mitigation and adaptation challenges, while the regional rivalry scenario (SSP3) depicts a future with high challenges to mitigation and adaptation. It is critical to note that the SSP scenarios underpinning Chen et al.'s (2020) urban expansion projections frame our results on potential impact on crop and livestock production.

2.2   Crop and livestock data

The data on crop production are drawn from MapSPAM (Spatial Production Allocation Model) (IFPRI 2019). MapSPAM provides global gridded data on the production of 42 crops, which are aggregated into eight groups in our analysis: cereals, fruits, oils, pulses, roots, sugar, vegetables, and non-food crops (see Table 1). We focus our analysis on food crops.[6]

Table 1. Crop group classification

Crop group	Corresponding crop in MapSPAM
Cereals	Wheat, rice, maize, barley, pearl millet, small millet, sorghum, other cereals
Fruits	Banana, plantain, tropical fruit, temperate fruit
Oils	Soybean, groundnut, coconut, oil palm, sunflower, rapeseed, sesame seed, other oil crops
Pulses	Bean, chickpea, cowpea, pigeon pea, lentil, other pulses
Roots	Potato, sweet potato, yams, cassava, other roots
Sugar	Sugar cane, sugar beet
Vegetables	Vegetables
Non-food	Cotton, other fibre crops, arabica coffee, robusta coffee, cocoa, tea, tobacco, rest of crops

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[5] The urbanization projections developed for the SSPs are on the country level and non-spatialized (Jiang and O'Neill 2017).

[6] Extending the analysis to non-food crops, such as those used for biofuels or fiber production, could be an interesting area of future research.

MapSPAM generates spatialized crop production data at 5 arc-minute resolution using a variety of inputs, including national and subnational agricultural data, satellite-based landcover datasets, irrigated areas, rural population, and other expert judgments on crop distribution. In the outputs, the crop production for each grid cell is the yield multiplied by harvested area. Note that the harvested area for a grid cell could be larger than the area of the grid cell if there are multiple harvests of a crop within the same year. The data are for the year 2010.

The livestock data come from the Gridded Livestock of the World database (GLW v3.1) (Gilbert et al. 2018). Similar to the crop data, this database also relies on inputs from a range of sources, including, most importantly, livestock census statistics from agricultural yearbooks or national governments. In addition, spatial data such as land use, topography, population, and vegetation are used to predict livestock distribution through random forest models where detailed data are missing. The resulting output from the dasymetric method[7] are used in our analysis to provide an estimate of global livestock at a spatial resolution of 0.0833 decimal degrees (approximately 10 km at the equator). The database encompasses eight types of livestock: buffaloes, cattle, chickens, ducks, goats, horses, pigs, and sheep.

2.3   Regions

We use the World Bank Official Boundaries for regional classification (World Bank 2022) for regional disaggregation of results. Countries are categorized into seven regions: Africa (AFR), East Asia & Pacific (EAP), Europe & Central Asia (ECA), Latin America & the Caribbean (LCR), Middle East & North Africa (MENA), South Asia (SOA), and Other (see Figure 1).[8] Disputed territories (e.g., Western Sahara) are not included in the regional classification. As a result, the regional breakdowns in this analysis do not necessarily add up to the global totals.

Figure 1. Regional classifications

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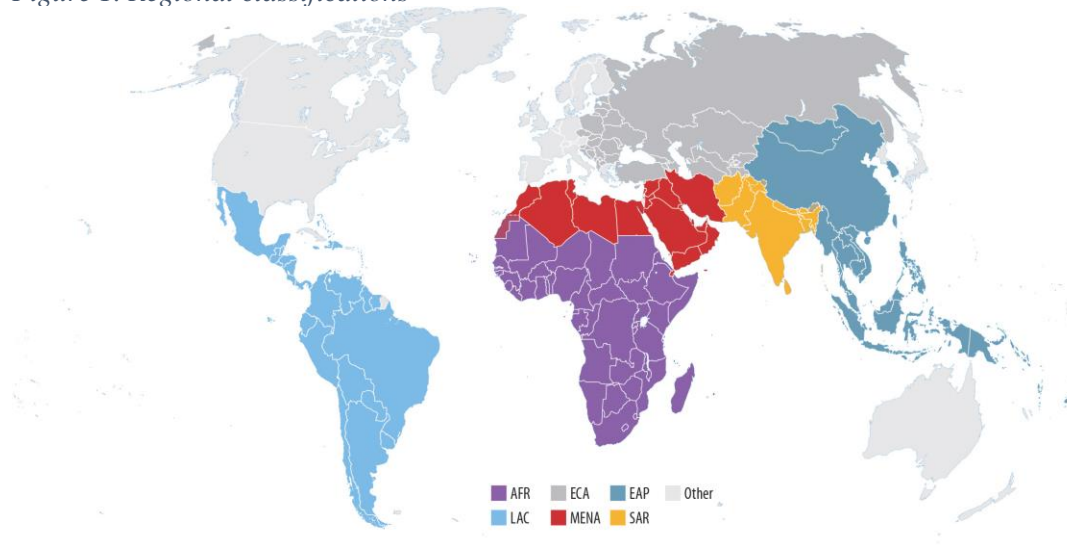
[7] Dasymetric mapping is a geospatial technique that uses information such as land cover types to distribute data more accurately over grid cells that have been assigned to selected boundaries.
[8] Other includes Canada, United States, Australia and New Zealand.

2.4 Methods and assumptions

Our analysis is based on several key assumptions. First, we assume that any urbanization that occurs on current land used for crop and livestock (i.e., as of 2010) will result in a significant impact on the agricultural production there. Specifically, such an overlap could culminate in either a loss of crop or livestock previously produced on the piece of land, or it could lead to a proximity of urban and agricultural functions, which may alter agricultural production cycles and scales.

Second, for the baseline condition, since the urban expansion data use 2015 as the starting year, any crop or livestock that overlap with the 2015 urban extent are *not* counted toward the initial agricultural production (see
Table 2). Consequently, only crop and livestock outside of the 2015 urban extent are aggregated for the baseline quantity of crop and livestock production. This would lead to eliminating about 2-6 percent of crop or livestock production in the data (see Table A1.6).[9]

Third, we assume no further expansion of land used for crop and livestock beyond its footprint in 2010. To clarify, the potential impact on crop and livestock production is calculated based on how much future urban expansion is projected to extend into current land used for crop and livestock production. This assumption is made despite acknowledging that a growing global population would entail increasing crop and livestock demands in the future. While such intricate dynamics would affect impacts on crop and livestock production, it is beyond the scope of this paper to devise robust models for future land uses.

Fourth, we assume that receding urban frontiers does *not* replenish land used for crop and livestock production. To elaborate, while the data from Chen et al. (2020) shows that across different SSP scenarios, urban extents could in fact decrease in some parts of the world, in part due to declining urban populations, we assume that these urban contractions will not result in land being reclaimed for agricultural use. Urban contractions may have implications for crop and livestock production. This assumption is based on historical trends, while shrinking cities often leads to vacant land and deteriorating infrastructure, rather than reconversion to land uses prior to urbanization (Florentin 2019). Therefore, once an area for crop and livestock production becomes urbanized, the production there is assumed to be part of the estimated production loss permanently. The urban expansion projection data, available in 10-year intervals, are used as proxies to estimate the cumulative urban extent around the world.

Based on the above assumptions, we adopt the following method for our analysis: First, raster calculations are performed to derive the areas of urban expansion for 2040 and 2100 for all five SSP scenarios. Since we assume that the potential impact on crop and livestock production due to urbanization is irreversible, we use cumulative urban extents for each time period. For example, to calculate the urban expansion for 2040, we overlay urban projections for all previous decades (2020, 2030, and 2040). Any area that has ever been marked as urban is considered part of the cumulative urban extent, regardless of whether the area subsequently deurbanizes or not.[10] Following this, we calculate the percentage of the urban extent that is *newly urban* compared to

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[9] Table A1 in the Annex displays the overlap percentages between food production and urban extent in grid cells.
[10] This assumption holds true for any of the years preceding the 10-year interval from 2010 to 2100. Only 3 years of dataset are extracted to analysis for this working paper; 2010, 2040 and 2100.

the 2015 urban boundaries to delineate projected urban expansion for the years 2040 and 2100. To determine the percentage of *newly urban* areas within a grid cell, we divide the newly urban areas in the SSP year by the total number of square kilometers in the grid cell.

To integrate our urban built-up data, which is represented as a percentage, with crop and livestock data we use a conversion factor. Both crop and livestock data use a grid cell size of 1/12 degrees, which is approximately 9-10 km at the equator (though this estimate may vary depending on latitude). On the other hand, the urban built-up projection data has a grid cell size of 0.010387 degrees, equivalent to 1 km at the equator. Since the grid cell size for the crop and livestock data is approximately 8.023 times larger than that of the urban built-up projection data, we adjust the values in the crop and livestock datasets by this factor (Figure 2).[11] In the process of matching the datasets, a few outliers have been identified and manually adjusted, so that no value exceeds 100 percent.

Figure 2. Grid-level matching of urban built-up projection and food production data
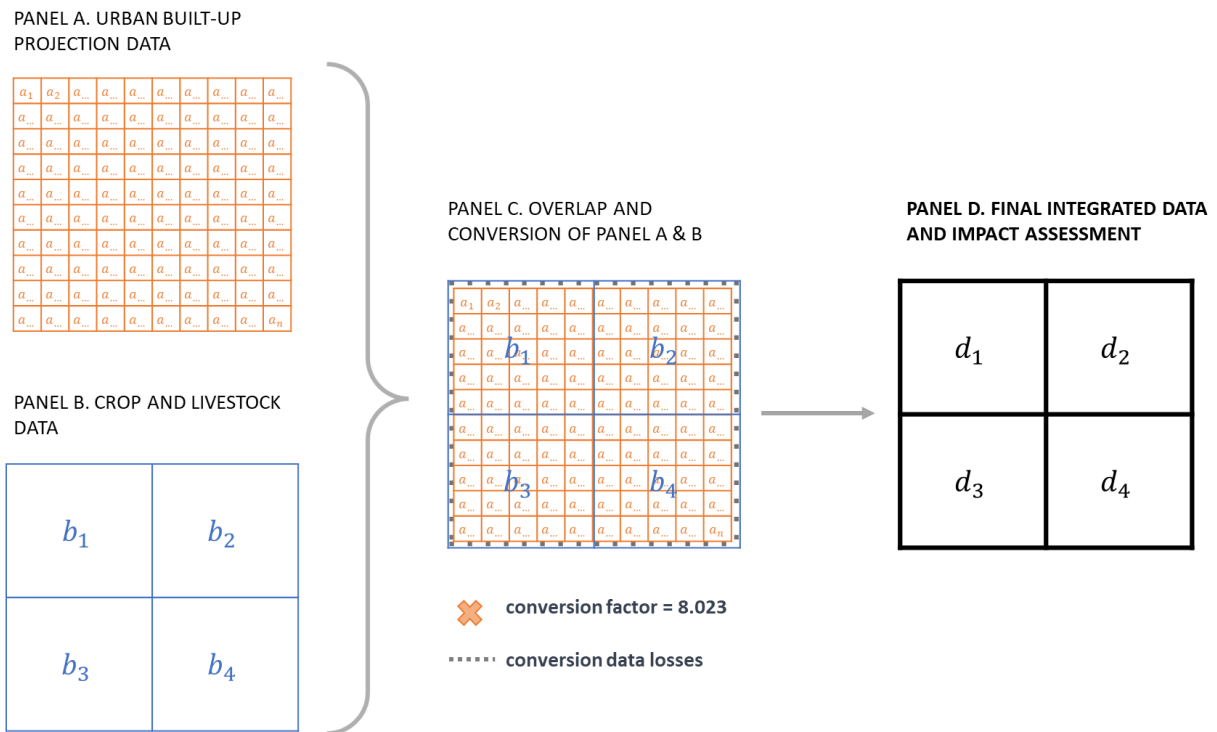
Note: Panel A displays 100 grid cells, each with a 0.010387-degree resolution (approx. 1 km at the equator). Note that this dataset only represents newly urbanized areas within each grid cell. Panel B presents 4 grid cells, each with a 0.0833-degree grid resolution (approx. 9-10 km at the equator). Panel C demonstrates the overlay of Panel A and Panel B. The urban built-up data is aggregated, and the values are summed to match the larger grid cell size of the crop and livestock data. The urban built-up data is converted using a conversion factor of 8.023, derived from the ratio of grid cell sizes, to align the grids. Although the conversion process aims for a precise match between the grids, minor data losses or inaccuracies may occur due to the nature of grid alignment (indicated by the dotted area). Panel D, the final panel, calculates the percentage of newly urbanized areas using our urban built-up projection data (by dividing the newly urban areas in the SSP year by the total number of square kilometers in the grid cell).

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[11] It is important to note that the "grid cell size" refers to the length of the edge of a grid cell and not the area of the grid cell.

Any cropland or livestock that coincides with the projected urban expansion area is considered part of the estimated overlap. These steps are replicated for each SSP scenario to arrive at estimated crop and livestock future overlap. However, it is important to note that this projection exercise assumes that the relevant food sectors will remain stagnant in terms of their technologies and productivity. While this allows us to estimate the overlap of urban expansion on crop and livestock production, it is important to recognize that actual overlap may differ if there are technological advances or changes in the economic or sociopolitical landscape affecting food production.

To determine current crop and livestock production, which are used as baseline values, we sum all crop and livestock production that that are *not* located in urban areas in 2015. Note that the most recent crop and livestock global data are from 2010, instead of 2015. Moreover, since the crop and livestock data come from two independent sources with two different methodologies, it is possible for a certain area to have both cropland and livestock. After generating the baseline values, we compare them with the absolute values of projected overlap to calculate the percentages for potential food losses. This method is then repeated for each of the seven regions to derive the regional results, and for select cities.

Due to the above limitations and model uncertainty of climate projections on land use, we caution against over-interpreting precise quantitative results, but rather one should focus on broad magnitudes and directions.

2.5 Summary statistics

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Table 2 we present grid-level summary statistics at baseline of urban extent (in 2015) and of crop and livestock production (in 2010) for the eight crop groups and the eight types of livestock, respectively. In Table 3 we present baseline total values for food crops and livestock globally and for each of the seven regions. For simplicity of the regional breakdowns, we aggregate the seven crop groups into four (fruits and vegetables, cereals and roots, sugars and oils, and pulses) and the eight livestock types into three (poultry, pigs, and ruminants).

Table 2. Baseline summary statistics

Variable	Obs	Mean	SD	Min	Max
Grid-Level Variables					
Urban Extent, 2015 (%)	2,033,283	0.004	0.035	0	1
Food crops, 2010, mt	832,827	9243.536	23981.23	0	1507168
Cereals	832,827	1237.446	4514.959	0	248531.1
Fruits	832,827	370.511	3325.975	0	424014.9
Oils	832,827	348.771	2564.369	0	180197.9
Pulses	832,827	33.505	216.89	0	25092.7
Roots	832,827	376.579	2397.17	0	355336.9
Sugar	832,827	966.807	12084	0	1507168
Vegetables	832,827	1104.765	5004.414	0	293567.5
Non-food crops, 2010, mt	832,827	66.487	472.811	0	34934

Livestock, 2010, mt	2,014,887	13021.28	73234.23	0	1060007
Buffaloes,	2,008,899	94.980	906.527	0	119607.5
Goats	2,014,567	475.125	2351.833	0	237936.2
Cattle	2,014,533	723.358	1943.561	0	328070.9
Sheep	2,014,215	558.121	1885.496	0	344862.1
Horses	2,013,909	30.783	153.932	0	105564.2
Pigs	2,014,572	484.444	2889.772	0	411115.7
Chickens	2,014,564	9994.698	67859.33	0	10500007
Ducks	2,012,134	663.042	7095.628	0	1311365

Note: Data for livestock cover not available. One grid cell has a spatial resolution of 1/12 degree - about 9 to 10 sq km. Urban extent is the percentage of urban area in a grid cell (ranging from 0 to 1). Crop production for each grid cell is defined as the yield multiplied by harvested area in metric tons. Food crops include cereals, fruits, oils, pulses, roots, sugar, vegetables food groups. Livestock production is the global population densities of eight types of livestock: cattle, buffaloes, horses, sheep, goats, pigs, chickens and ducks in each land pixel at a spatial resolution of 1/12 degree degrees (approximately 10 sq km at the equator). Missing values in the crop production dataset are specifically distinguished from crops that are not grown in a particular area. Crops not grown in an area are coded as zero, while crop data that is not available is coded as a missing value. This distinction is important as it helps to differentiate between areas where crops are not grown and areas where data is simply not available (Yu et al., 2020).

Table 3. Baseline values for crop production and livestock production

	Global	Africa	EAP	ECA	LCR	MENA	SOA	Other
Food crops, 2010, metric tons (mt)	7,510.9	575.0	2,263.5	636.7	1,435.5	226.6	1,049.9	1,323.7
Fruits and Vegetables	1,611.6	102.2	742.8	120.3	150.3	102.3	195.7	197.8
Cereals and roots	3,207.0	350.9	948.9	385.7	232.3	82	430.9	776.4
Sugars and oils	2,625.0	108.5	561.6	125.7	1,046.3	40.5	405.6	336.8
Pulses	67.3	13.4	10.1	5	6.6	1.8	17.6	12.7
Livestock, 2010, mt	24,884.6	1,997.1	9,503.5	1,638.0	3,599.1	2,020.2	1,983.5	4,143.5
Poultry	20,451.1	1,137.5	8,363.1	1,355.6	3,008.5	1,777.2	1,322.1	3,487.1
Pigs	939.3	31.0	538.9	64	82.4	0.1	12.6	210.4
Ruminants	3,494.1	828.6	601.6	218.4	508.2	243	648.8	445.6

Note: Since urban expansion data use 2015 as the starting year, any crop or livestock that overlap with the 2015 urban extent are not counted toward the initial agricultural production.

In Table 3, we present descriptive statistics on the percentage of grids that have overlap in urban extent, crop production, and livestock production. For example, 30 percent of grids that have cereal production also have fruit production, 90 percent of grids have both pig and chicken production, 35 percent of grids have both cereal production and pig production, 4 percent of grids have urban area and cereal production, and 5 percent of grids have urban area and pig production.

3. Results

We present spatial projections of the overlap of climate-induced urban expansion with crop and livestock production under each of the five SSP scenarios (or what we call, projected losses). In Section 3.1 we present projected losses in global crop production, in Section 3.2 we present projected losses in global livestock production. In Sections 3.3 and 3.4 we present regional disaggregation of projected losses for crop and livestock production, respectively. In Section 3.5, we depict urban expansion and crop and livestock production for six selected cities. Finally, in

Section 3.6, we estimate the grid-level correlation between projected urban expansion (in 2040 and 2100) and baseline crop and livestock production (in 2010).

Climate change projections and their impact on land use are inherently uncertain and subject to a range of assumptions and modeling choices. While we have used the SSPs as a framework for our urban expansion projections, it is important to note that these scenarios are not predictions, but rather represent a range of plausible futures. As noted by Chen et al. (2020), the use of SSPs in land-use projections comes with limitations and uncertainties, including the reliance on imperfect climate models and the inability to capture all relevant factors that may impact land use. Therefore, it is important to recognize the limitations and model uncertainty in our results and to exercise caution when interpreting precise quantitative estimates.

3.1 Projected urban overlap with global crop production

Figure 3: Projected impact of urban expansion on crop production by SSP scenarios, 2040, 2100 (in percent change relative to baseline)
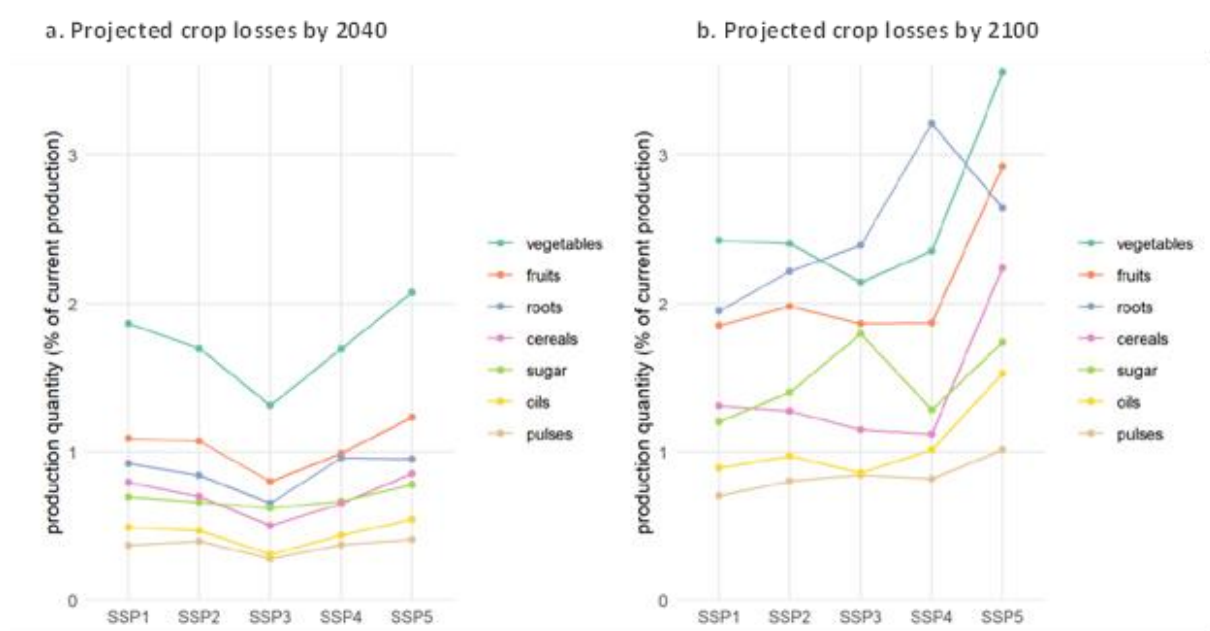
Note: SSP = Shared Socioeconomic Pathways.
Since urban expansion data use 2015 as the starting year, any crop or livestock that overlap with the 2015 urban extent are not counted toward the initial agricultural production.

The projected overlap of urban expansion in 2040 is largest for vegetables, followed by fruits, roots, and sugar and cereals (see Figure 3). The overlap is smallest for oils and for pulses. For vegetables (and for most other crops), the projected urban overlap is largest under SSP5 (fossil-fueled development), and also under SSP1 (sustainability). It is under these two scenarios that urban expansion is projected to be highest. For example, in 2040, the projected overlap of urban expansion and vegetable production is around 2 percent under SSP5. In contrast, the projected urban overlap for vegetables is smallest under SSP3 (regional rivalry). It is also under this scenario where urban expansion is projected to be smallest.

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Mechanically, by 2100, the cumulative projected overlap of urban expansion is larger than 2040 across all crops. We do note a few interesting results. First, urban expansion overlap is still largest for vegetables and fruits under SSP5 while cereals, sugar, oils, and pulses have smaller overlaps. Under SSP5, by 2100, projected overlap of urban expansion and vegetable production is around 4 percent. However, by 2100, the urban expansion overlap would be largest for roots under SSP3 (regional rivalry) and SSP4 (inequality). Second, the urban expansion overlap is still greatest under SSP5 for most crops, but not for roots (where it is greatest under SSP4) or for sugar (where it is greatest under SSP3). Third, the difference in the overlap of urban expansion with crops between SSP1 and SSP5 is much larger in 2100 than in 2040. This is because while urban area continues to grow under SSP5 through 2100, it grows quickly under SSP1 but peaks and declines prior to 2100. As such, the overlap of urban expansion with crop production in 2100 appears similar across scenarios (except SSP5). Similarly, for the first four SSPs, projected urban area converges by 2100. Finally, we note that the results do not indicate that the projected overlap is linear over time. The underlying trends in urban expansion across the different SSP scenarios are also non-linear.

3.2   Projected urban overlap with global livestock production

Figure 4: Projected impact of urban expansion on livestock production by SSP scenarios, 2040, 2100 (in percent change relative to baseline)

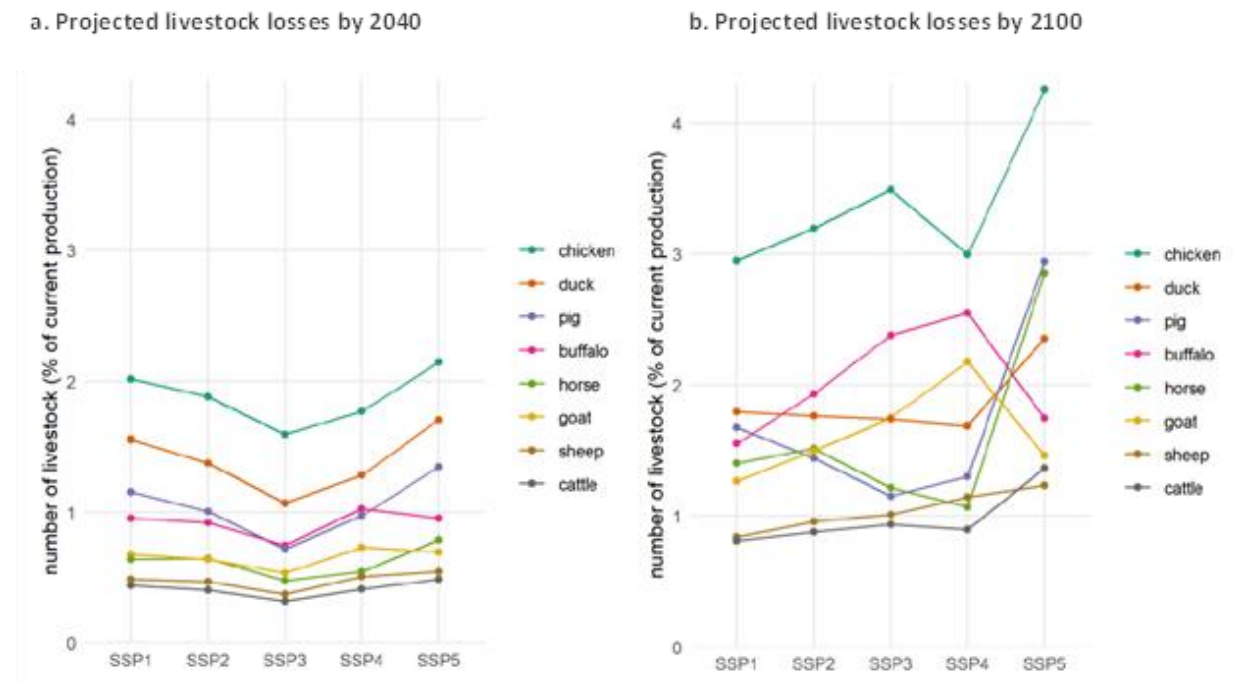Note: SSP = Shared Socioeconomic Pathway. Since urban expansion data use 2015 as the starting year, any crop or livestock that overlap with the 2015 urban extent are not counted toward the initial agricultural production.

Across different types of livestock, the projected overlap with urban expansion in 2040 is largest for chickens, followed by ducks, pigs, and buffalo (see Figure 4). The overlap is smallest for horse, goat, sheep, and cattle. For chickens (and most other livestock), the projected urban overlap is

largest under SSP5 (fossil-fueled development), and also under SSP1 (sustainability). For example, in 2040, the projected overlap of urban expansion and chickens is around 2 percent under SSP5. In contrast, the projected urban expansion overlap for chickens is smallest under SSP3 (regional rivalry).

As with crops, by 2100, the projected overlap of urban expansion with livestock is larger than in 2040. We highlight a few interesting results. First, urban expansion overlap is still largest for chickens by 2100, under all scenarios while sheep and cattle have smaller overlaps with urban expansion. Under SSP5, by 2100, projected overlap of urban expansion and chicken production is over 4 percent. However, by 2100, the overlap of urban expansion would be second highest for pigs and horses. Second, the overlap of urban expansion is still greatest under SSP5 for most livestock, but not for buffalo or goat (where it is greatest under SSP4). Third, the difference in overlap of urban expansion between SSP1 and SSP5 (for most livestock) is much larger in 2100 than in 2040.

### 3.3   Projected urban overlap with crop production, by region

We disaggregate projected urban overlap with crop production by region. In 2040, for most scenarios, the projected overlap with crop production will be largest in AFR, MENA, SOA, and EAP (see Figure 5). Africa, SOA, and EAP will experience the greatest urban expansion overlap particularly under SSP1 (sustainability), while AFR and SOA will experience the greatest urban expansion overlap under SSP4 (inequality). While MENA only has 3 percent of current global crop production, in 2040 it is expected to have the greatest urban overlap compared to all other regions under SSP2, SSP3, and SSP5. Compared to other regions, crop production in LCR and ECA are projected to have the smallest overlap with urban expansion.

By 2100, the regional results diverge quite significantly. AFR (currently with 8 percent of current global crop production) will have the largest urban overlap with its crop production across all scenarios, except SSP3. The overlap for AFR will be largest under SSP4, with 21 percent of crop production in AFR projected to overlap with urban expansion by 2100. The urban overlap with crop production in 2100 will be second largest in MENA (and first largest under SSP3), and third largest in SOA. The projected overlap continues to be smallest in LCR and ECA through 2100.

Note that EAP currently has about 30 percent of global crop production. The projected urban expansion overlap with crop production in EAP remains relatively low and stable from 2040 to 2100, thereby muting the overall projected overlap globally. Although, as noted above, the projected overlaps in AFR, MENA, and SOA are expected to be much larger.

A closer look at the projected overlap for AFR (see Figure 6) indicates that by 2100 and across all scenarios, the overlap of urban expansion will be largest for sugars and oils, then for fruits and vegetables, then for cereals and roots. The urban overlap with pulses is much smaller relative to other crops. A closer look at SOA indicates that by 2100 and across all scenarios, the overlap of urban expansion will be largest for cereals and roots, closely followed by fruits and vegetables, then by sugars and oils. This is contrary to AFR where sugar and oils would experience the largest overlap. But similar to AFR, the projected overlap of pulses with urban expansion is much smaller relative to other crops.

Figure 5: Projected impact of urban expansion on crop production by region under SSP scenarios, 2040, 2100 (in percent change relative to baseline)
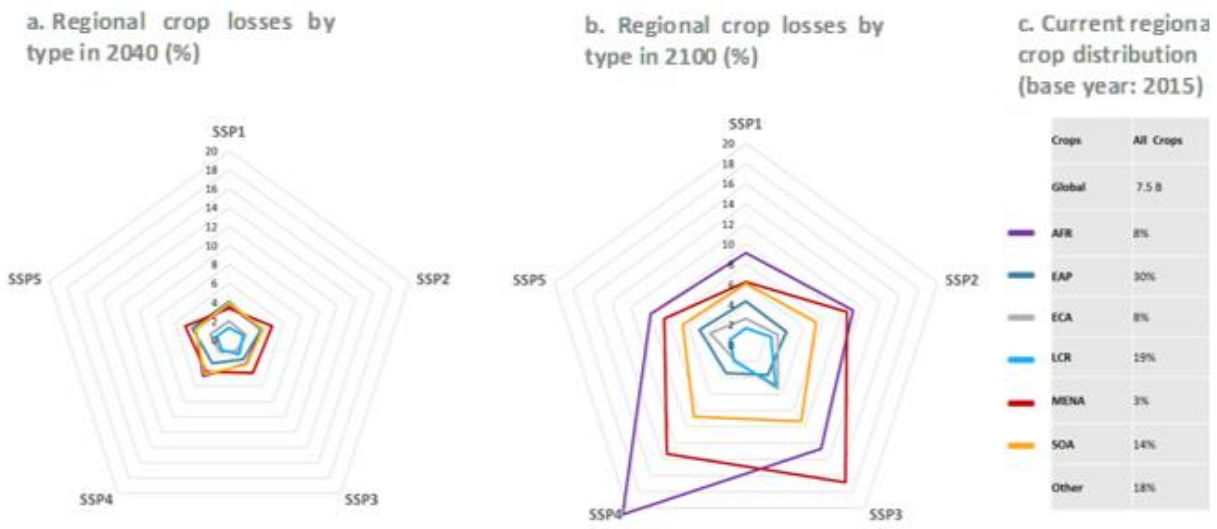
SSP = Shared Socioeconomic Pathway Since urban expansion data use 2015 as the starting year, any crop or livestock that overlap with the 2015 urban extent are not counted toward the initial agricultural production. Other region is excluded from the web charts in the figure and includes Canada, US, Australia, and New Zealand. Crop production is in millions metric tons and is defined as the yield multiplied by harvested area in metric tons.

Figure 6: Projected impact of urban expansion on crop production by region and crop type under SSP scenarios, 2040, 2100 (in percent change relative to baseline)

a. Regional crop losses by type in 2040 (%)

b. Regional crop losses by type in 2100 (%)

c. Current regional crop distribution (base year: 2015)

AFR

Crop Type	Global	Africa
Fruits and Vegetables	1.6 B	6%
Cereals and roots	3.2 B	11%
Sugars and oils	2.6 B	4%
Pulses	67.3 M	20%
All crops	7.5 B	8%

EAP

Crop Type	Global	EAP
Fruits and Vegetables	1.6 B	46%
Cereals and roots	3.2 B	30%
Sugars and oils	2.6 B	21%
Pulses	67.3 M	15%
All crops	7.5 B	30%

ECA

Crop Type	Global	ECA
Fruits and Vegetables	1.6 B	7%
Cereals and roots	3.2 B	12%
Sugars and oils	2.6 B	5%
Pulses	67.3 M	7%
All crops	7.5 B	8%

LCR

Crop Type	Global	LCR
Fruits and Vegetables	1.6 B	9%
Cereals and roots	3.2 B	7%
Sugars and oils	2.6 B	40%
Pulses	67.3 M	10%
All crops	7.5 B	19%

MENA

Crop Type	Global	MENA
Fruits and Vegetables	1.6 B	6%
Cereals and roots	3.2 B	3%
Sugars and oils	2.6 B	2%
Pulses	67.3 M	3%
All crops	7.5 B	3%

SOA

Crop type	Global	SOA
Fruits and Vegetables	1.6 B	12%
Cereals and roots	3.2 B	13%
Sugars and oils	2.6 B	15%
Pulses	67.3 M	26%
All crops	7.5 B	14%

Note: SSP = Shared Socioeconomic Pathway Since urban expansion data use 2015 as the starting year, any crop or livestock that overlap with the 2015 urban extent are not counted toward the initial agricultural production. Other region is excluded from the web charts in the figure. Other includes Canada, United State, Australia, and New Zealand

3.4 Projected urban overlap with livestock production, by region

We disaggregate projected urban overlap with livestock production by region. In 2040, for most scenarios, the projected overlap with livestock production will be largest in MENA, then AFR, then similarly for EAP and SOA (see Figure 7). While MENA only has 8 percent of current global livestock production, in 2040 it is expected to have the greatest urban overlap compared to all other regions under all scenarios. Compared to other regions, livestock production in LCR and ECA are projected to have the smallest overlap with urban expansion.

By 2100, the regional differences seem to hold. The largest urban overlap with livestock production will be in MENA, then AFR, then SOA (currently each with 8 percent of current global livestock production) across all scenarios. The overlap for MENA will be largest under SSP3, with over 43 percent of livestock production in MENA projected to overlap with urban expansion by 2100. The overlap for AFR will be largest under SSP4, with over 20 percent of livestock production in AFR projected to overlap with urban expansion by 2100. The projected overlap continues to be smallest in LCR and ECA through 2100.

Note that EAP currently has about 38 percent of global livestock production. The projected urban expansion overlap with livestock production in EAP remains relatively low and stable from 2040 to 2100, thereby muting the overall projected overlap globally. Although, as noted above, the projected overlaps in AFR, MENA, and SOA are expected to be much larger. A closer look at the projected overlap for AFR (see Figure 8) indicates that by 2100 and across all scenarios, the urban overlap will be largest for poultry (over 10 percent under SSP4), then for pigs (over 6 percent under SSP4), then for ruminants.
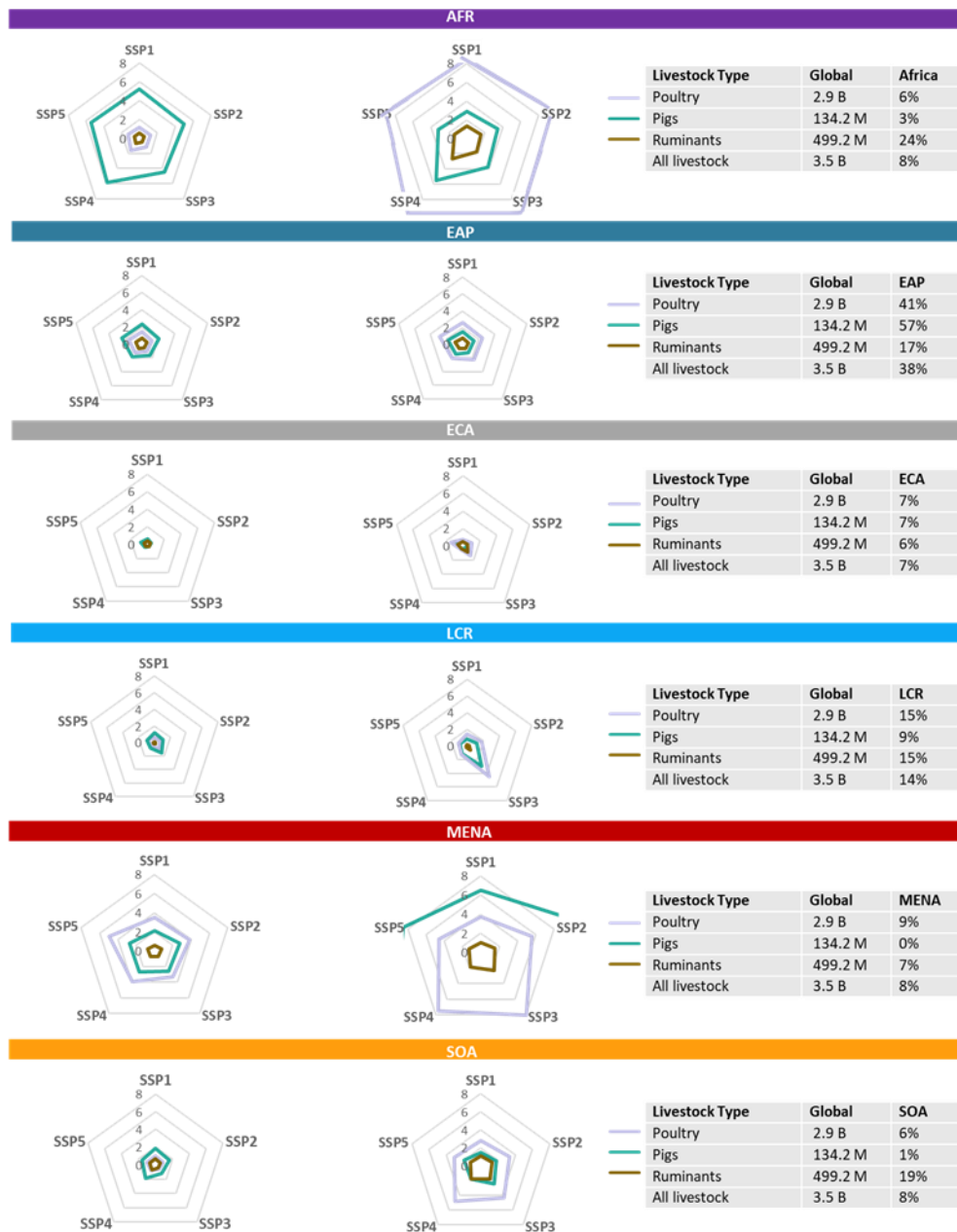
Figure 7: Projected impact of urban expansion on livestock production by region under SSP scenarios, 2040, 2100 (in percent change relative to baseline)

Note: SSP = Shared Socioeconomic Pathway Since urban expansion data use 2015 as the starting year, any crop or livestock that overlap with the 2015 urban extent are not counted toward the initial agricultural production. Other region is excluded from the web charts in the figure and includes Canada, US, Australia, and New Zealand. Livestock production is the global population densities of eight types of livestock: cattle, buffaloes, horses, sheep, goats, pigs, chickens and ducks

Figure 8: Projected impact of urban expansion on livestock production by region and type under SSP scenarios, 2040, 2100 (in percent change relative to baseline)

a. Regional Livestock losses by type in 2040 (%)

b. Regional livestock losses by type in 2100 (%)

c. Current regional livestock distribution (base year: 2015)

AFR

Livestock Type	Global	Africa
Poultry	2.9 B	6%
Pigs	134.2 M	3%
Ruminants	499.2 M	24%
All livestock	3.5 B	8%

EAP

Livestock Type	Global	EAP
Poultry	2.9 B	41%
Pigs	134.2 M	57%
Ruminants	499.2 M	17%
All livestock	3.5 B	38%

ECA

Livestock Type	Global	ECA
Poultry	2.9 B	7%
Pigs	134.2 M	7%
Ruminants	499.2 M	6%
All livestock	3.5 B	7%

LCR

Livestock Type	Global	LCR
Poultry	2.9 B	15%
Pigs	134.2 M	9%
Ruminants	499.2 M	15%
All livestock	3.5 B	14%

MENA

Livestock Type	Global	MENA
Poultry	2.9 B	9%
Pigs	134.2 M	0%
Ruminants	499.2 M	7%
All livestock	3.5 B	8%

SOA

Livestock Type	Global	SOA
Poultry	2.9 B	6%
Pigs	134.2 M	1%
Ruminants	499.2 M	19%
All livestock	3.5 B	8%

Note: SSP = Shared Socioeconomic Pathway Since urban expansion data use 2015 as the starting year, any crop or livestock that overlap with the 2015 urban extent are not counted toward the initial agricultural production. Other region is excluded from the web charts in the figure. Other includes Canada, United States, Australia, and New Zealand.

3.5 Projected urban overlap with crop and livestock production, for select cities

The growth of cities, including the extent and rate of growth, is largely determined by local urban planning policies and decisions. Protecting crop and livestock production can be guided by a better understanding of how and where cities are projected to grow and where current crop and livestock production is located. We select a set of six cities to demonstrate this point. We present some depictions for Lima in Peru, Nairobi in Kenya, Quezon in the Philippines, Abuja in Nigeria, Cirebon in Indonesia, and Ho Chi Minh in Vietnam. Each of these cities vary, for example, in population, area, and population density (see Figure 9). We demonstrate in each of these six cities, how the cities are projected to grow under SSP5, by 2040 and by 2100 (see Figure 10).

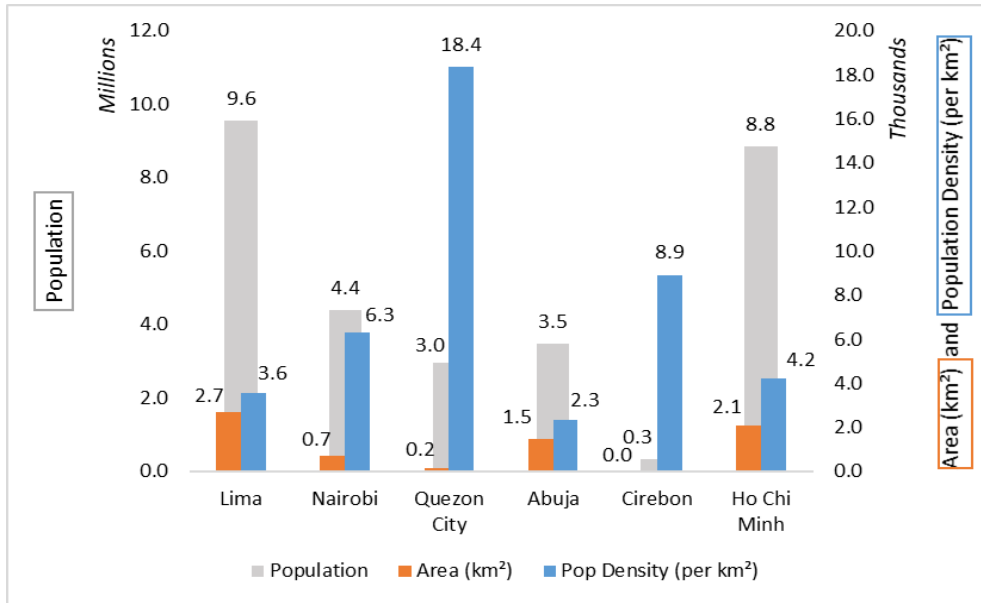*Figure 9: Characteristics of six select cities*

Figure 10A: Mapping of urban expansion on crop and livestock production by select cities under SSP3, 2040, 2100
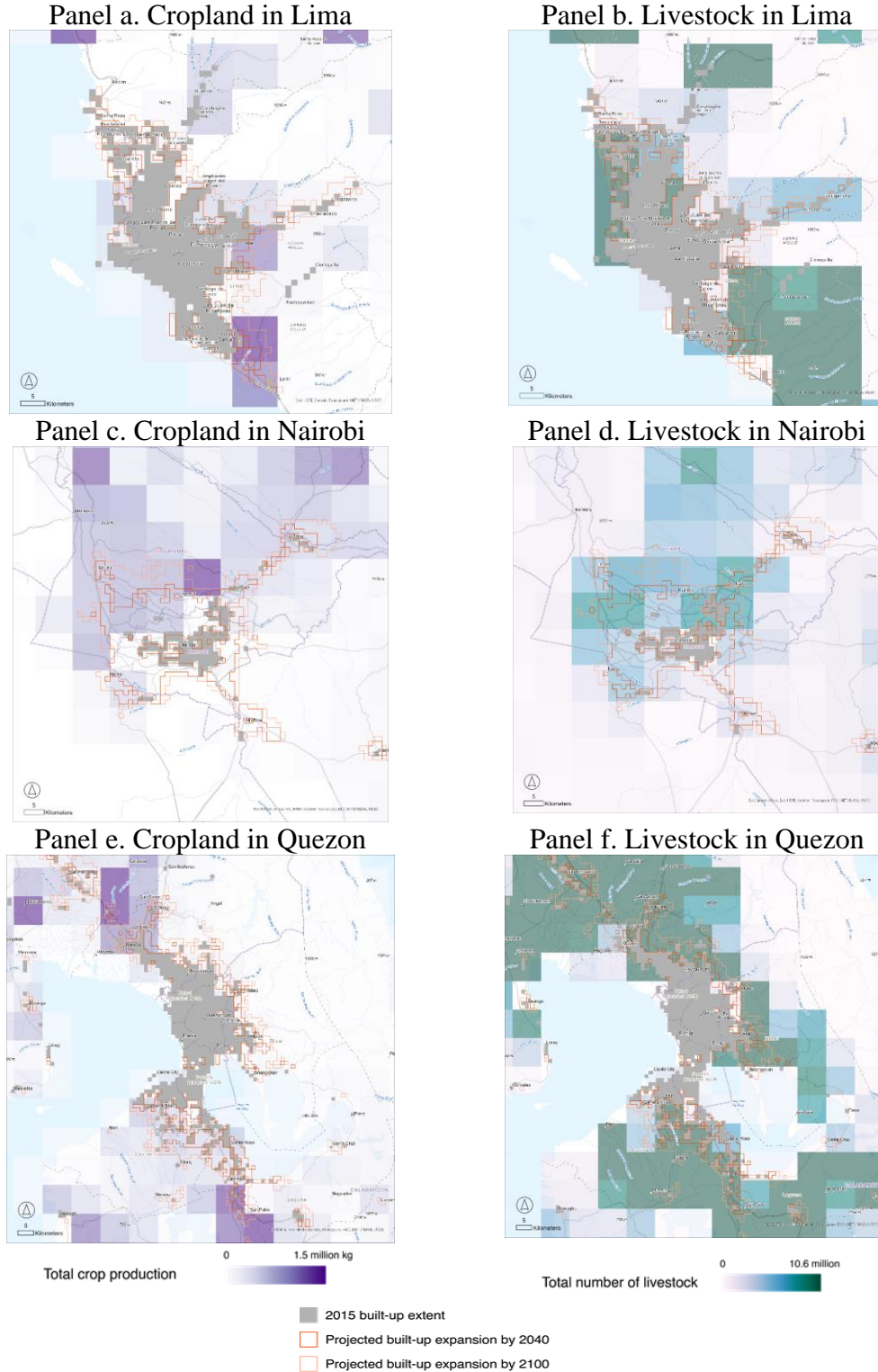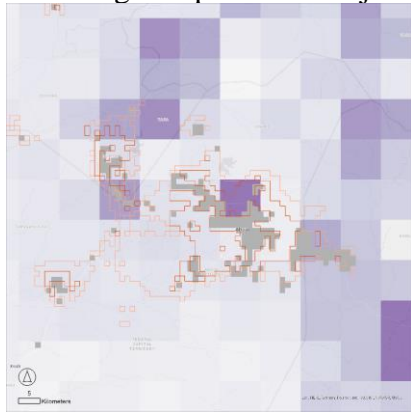
Overlap of urban expansion in 2040 and 2100 with…

Panel a. Cropland in Lima   Panel b. Livestock in Lima

Panel c. Cropland in Nairobi   Panel d. Livestock in Nairobi

Panel e. Cropland in Quezon   Panel f. Livestock in Quezon

Total crop production   0   1.5 million kg

Total number of livestock   0   10.6 million

2015 built-up extent

Projected built-up expansion by 2040

Projected built-up expansion by 2100

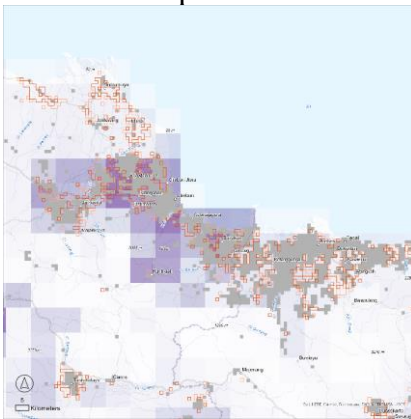*Overlap of urban expansion in 2040 and 2100 with…*
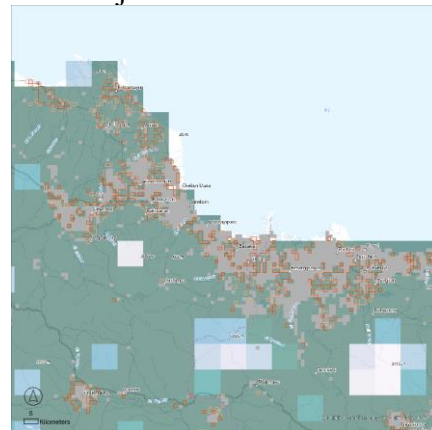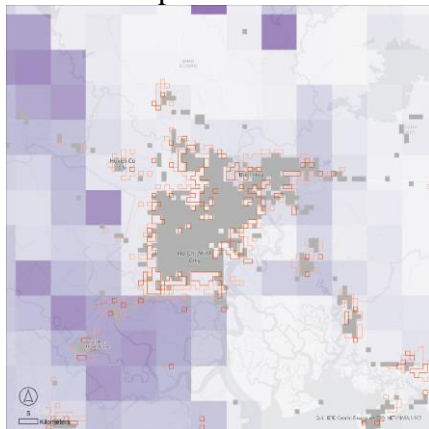
Panel g. Cropland in Abuja
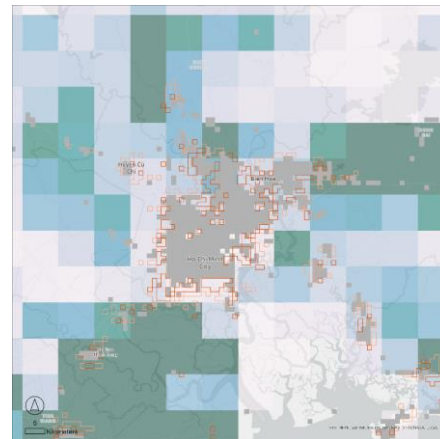
Panel h. Livestock in Abuja
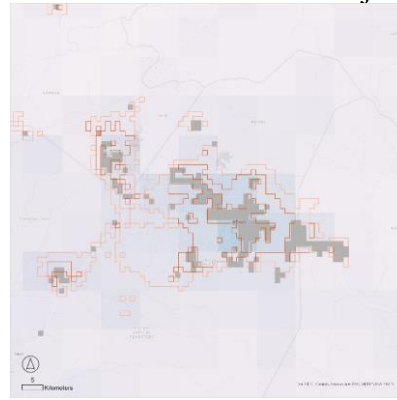
Panel i. Cropland in Cirebon

Panel j. Livestock in Cirebon

Panel k. Cropland in Ho Chi Minh

Panel l. Livestock in Ho Chi Minh

0   1.5 million kg

Total crop production

0   10.6 million

Total number of livestock

2015 built-up extent

Projected built-up expansion by 2040

Projected built-up expansion by 2100

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3.6 Correlation of crop and livestock production with urban expansion

For each SSP scenario, we estimate grid level regressions to estimate the correlation between crop and livestock production at baseline in 2015 with projected urban expansion (both in 2040 and 2100). These correlations indicate, for each of the SSP scenarios, to what extent grids that are more likely to become more urban in the future are those that have higher (or lower) crop and livestock production today. It sheds light on whether urban expansion will occur into higher production grids, but not on whether urban expansion occurs in more grids.

Table 4. Grid level regressions of crop production on urban expansion rates for five SSP scenarios

Outcome: Crop production (2010, mt)	(1) SSP 1	(2) SSP 2	(3) SSP 3	(4) SSP 4	(5) SSP 5
Panel A: Urban expansion to 2040					
Urban expansion rate in 2040	67,040.29***	67,547.62***	98,514.26***	70,278.82***	50,550.85***
	(998.5)	(1055.5)	(1357.25)	(1053.61)	(859.41)
Observations	832,827	832,827	832,827	832,827	832,827
R squared	0.0054	0.0049	0.0063	0.0053	0.0041
Mean crop production (2010, mt)	9,243.5	9,243.5	9,243.5	9,243.5	9,243.5
	(6) SSP 1	(7) SSP 2	(8) SSP 3	(9) SSP 4	(10) SSP 5
Panel B: Urban expansion to 2100					
Urban expansion rate in 2100	32,773.24***	33,660.66***	56,730.6***	37,474.94 ***	16,547.64***
	(582.03)	(567.5)	(648.1)	(564.4)	(368.67)
Observations	832,827	832,827	832,827	832,827	832,827
R squared	0.0038	0.0042	0.0091	0.0053	0.0024
Mean crop production (2010, mt)	9,243.5	9,243.5	9,243.5	9,243.5	9,243.5

Robust SE in parentheses. *** $p<0.01$, ** $p<0.05$, * $p<0.1$. Grid-level OLS estimation, where one grid has a spatial resolution of 1/12 degree - about 9 to 10 sq km. Urban expansion rate is the percentage of newly urban areas in a given grid cell for a given SSP scenario (ranging from 0 to 1). Crop production for each grid cell is defined as the yield multiplied by harvested area in metric tons. We include seven food group: cereals, fruits, vegetables, oils, pulses, roots, and sugar. We exclude non-food groups from the database (Cotton, other fibre crops, arabica coffee, robusta coffee, cocoa, tea, tobacco, rest of crops). Here, the urbanization rate is defined as the percentage of urban population to total population, and ranges from the value of 0 to 1. The urban expansion projection data (Chen et al. 2020) are calculated using panel data regression based on historical population, urbanization rate, and gross domestic product (GDP) data.

Table 4 presents results for crop production for both 2040 (Panel A) and 2100 (Panel B). First, we find that across all SSP scenarios and in both 2040 and 2100, grids that are expected to have higher urban expansion rates are grids which have higher levels of crop production today. This indicates that in the future, cities are likely to grow into areas with more crop production, regardless of SSP scenario. Second, in both 2040 and 2100, the positive correlation between projected urban expansion and current crop production is highest under SSP3 and lowest under SSP5. Third, the positive correlation between projected urban expansion and current crop production is large in both 2040 and 2100, but the magnitude dampens over time. This means that the cumulative

expansion into grids with higher crop production is less in 2100 than in 2040. This indicates that expansion occurs into areas with progressively less agricultural production over time. Cumulative crop losses will still be larger in 2100 than in 2040, but the average loss per grid cell will be less in 2100. This indicates that the higher producing areas will be impacted sooner (in 2040) than later (in 2100).

For example, under SSP3 grids that are projected to have a 10 percent higher urban expansion rate in 2040 are likely to have 106 percent higher crop production in 2010 (or double the crop production). While under SSP5, grids that are projected to have a 10 percent higher urban expansion rate in 2040 are likely to have 55 percent higher crop production in 2010. Under the similar SSP5 scenario, grids that are projected to have a 10 percent higher urban expansion rate in 2100 are likely to have only an 18 percent higher crop production in 2010. Thus, cities are predicted to grow into areas which produce higher levels of crops, more so early on (in 2040) and less so later (in 2100), and more so under SSP3 (a situation of regional rivalry with high challenges to mitigation and adaptation) than under SSP5 (a fossil-fueled development with high challenges to mitigation, but low challenges to adaptation).

The overlap of urban expansion with food production (i.e. projected food losses) presented earlier is a combination of two things: first, the *total number of grids* where projected future urban expansion is expected to coincide with, and second, the *average production density* of the grids that urban areas expand into under a given scenario. Here, we find that urban expansion under SSP5 will occur in less dense grids on average (relative to other SSP scenarios). But earlier we found that the overlap of urban expansion with food production (i.e. production losses) is greatest under SSP5. This indicates that the total number of grids that SSP5 is projected to overlaps with (which is greater than all other SSP scenarios) outweighs the lower production density of the average grid it impacts (relative to other SSP scenarios). Regardless, the urban expansion under SSP5 still coincides with more densely producing grids on average (relative to the areas without urban expansion under the same SSP5 scenario).

Table 5 presents results for livestock production for both 2040 (Panel A) and 2100 (Panel B). The three main qualitative results for crop production (Table 4) are similar to that for livestock density (Table 5). First, across all SSP scenarios and in both 2040 and 2100, grids that are expected to have higher urban expansion rates are grids which have higher levels of livestock density today. This indicates that in the future, cities are likely to grow into areas with more livestock. Second, the positive correlation between projected urban expansion and current livestock density is highest under SSP3 and lowest under SSP5. Third, the positive correlation between projected urban expansion and current livestock density is large in both 2040 and 2100, but the magnitude dampens over time. This means that the cumulative expansion into grids with higher livestock density is less in 2100 than in 2040. Note, however, that the projected urban expansion into areas with high livestock density is much higher than the projected expansion into areas with higher crop production.

For example, under SSP3 grids that are projected to have a 10 percent higher urban expansion rate in 2040 are likely to have 8.6 times higher livestock density in 2010. While under SSP5, grids that are projected to have a 10 percent higher urban expansion rate in 2040 are likely to have 4.6 times higher crop production in 2010. Under the similar SSP5 scenario, grids that are projected to have

a 10 percent higher urban expansion rate in 2100 are likely to have only a 1.6 times higher livestock density in 2010. As mentioned above, the magnitudes for the correlation between future urban expansion and current livestock production are much higher than those for the correlation between future expansion and current crop production.

Table 5. Grid level regressions of livestock production on urban expansion rates for five SSP scenarios

Outcome:	(1)	(2)	(3)	(4)	(5)
Livestock production (2010, mt)	SSP 1	SSP 2	SSP 3	SSP 4	SSP 5
Panel A: Urban expansion to 2040					
Urban expansion rate in 2040	604,006***	628,556***	887,535***	621,852***	481,385***
	(2952.30)	(3116.5)	(4006.3)	(3121.1)	(2544.2)
Observations	2,014,887	2,014,887	2,014,887	2,014,887	2,014,887
R squared	0.0204	0.0198	0.0238	0.0193	0.0175
Mean livestock (pop density)	13021.28	13021.28	13021.28	13021.28	13021.28
	(6)	(7)	(8)	(9)	(10)
	SSP 1	SSP 2	SSP 3	SSP 4	SSP 5
Panel B: Urban expansion to 2100					
Urban expansion rate in 2100	291,822***	302,128***	442,168***	293,287***	163,586***
	(1732.26)	(1684.69)	(1916.40)	(1678.8)	(1095.79)
Observations	2,014,887	2,014,887	2,014,887	2,014,887	2,014,887
R squared	0.0139	0.0157	0.0257	0.0149	0.0109
Mean livestock (pop density)	13021.28	13021.28	13021.28	13021.28	13021.28

Robust SE in parentheses. *** $p<0.01$, ** $p<0.05$, * $p<0.1$. Grid-level OLS estimation, where one grid has a spatial resolution of 1/12 degree - about 9 to 10 sq km. Urban expansion rate is the percentage expansion in urban area in a given SSP scenario (ranging from 0 to 1). Livestock production is the global population densities of eight types of livestock: cattle, buffaloes, horses, sheep, goats, pigs, chickens and ducks in each land pixel at a spatial resolution of 0.083333 decimal degrees (approximately 10 km at the equator). Here, the urbanization rate is defined as the percentage of urban population to total population, and ranges from the value of 0 to 1. The urban expansion projection data (Chen et al. 2020) are calculated using panel data regression based on historical population, urbanization rate, and gross domestic product (GDP) data.

4. Conclusions

This paper finds that, if poorly managed, urban expansion will be tied to a projected decline in key crops and animal-source foods that are important for diets and nutrition. There are important regional differences as well as differences across SSP scenarios and through time.

Under SSP1, by 2100, the largest projected decline among crops is for fruits, vegetables, and tubers/roots, and the smallest declines are for oils, sugar, and pulses (relative to current levels of production). Although food production initially declines faster under SSP1 than under SSP3 to 2040, it then slows so that the projected decrease in food production by 2100 somewhat aligns for both the SSP1 and SSP3 scenarios. Under SSP1, by 2100, there is also a projected decline in the number of livestock, important to the production of animal-source foods rich in protein. The largest declines are for poultry (chickens and ducks) and pigs, and the smaller declines are for ruminants (cattle, sheep, and goats). This aligns with the notion that the production of poultry and pigs is more peri-urban than that of ruminant production. By 2100, the largest urban overlap with food

production is under SSP5. We find that the overlaps are expected to be largest in Africa for both crops and for livestock, and particularly under SSP4.

Aggregating across crops and across livestock presents a slightly different picture. We estimate grid-level regressions to show that future urban expansion is most likely to occur under areas today that have higher levels of crop production and that have higher livestock density on aggregate. This projected correlation between future expansion and current crop and livestock density is largest under SSP3 and smallest under SSP5. This correlation is also large and positive in both 2040 and 2100, but is smaller in 2100 than 2040, suggesting that the correlation diminishes over time. This indicates that urban expansion occurs into increasingly marginal agricultural lands over time (but it occurs in still more densely producing areas than in areas that urbanization does not occur).

We discuss a few caveats and policy implications to our analysis and findings. First, these projections, do not account for the possibility of vertical and infill urban development, which can help cities to accommodate the growing demand for urban land without the need to expand as rapidly outward. To the extent that income per capita growth is projected to be faster under SSP1 than SSP3, vertical layering can, along with infill development, be expected to occur more quickly under the former than under the latter scenario. Policy and institutional reforms, which improve the functioning of urban land and property markets, thereby reducing vertical development costs, can likewise be expected to slow the horizontal expansion of cities, as can the relaxation of planning restrictions that constrain tall building development and foster car dependence.

The decline in food production projected to result from urban expansion reinforces the importance of policy measures and institutional reforms to promote more compact urban development. Because urban land expansion is projected to be faster and still higher by 2100 under a sustainable pathway than under a regional rivalry pathway, the projected decline in food production is slightly larger under the sustainable pathway. If anything, such a finding places even more importance on measures to reduce the costs of vertical development and reduce car dependence under a sustainable pathway than under a regional rivalry pathway.

Second, in addition to encouraging more compact development, the impacts of horizontal urban expansion on food production can be offset by enhancing agricultural productivity and reducing food loss and waste. Sustainably improving agricultural productivity requires accelerated innovation, as opposed to increasing the use of land, water, and other production inputs. Innovation through the invention, adaptation, and dissemination of locally adapted new technologies will be key (Fuglie et al. 2019). In addition, reducing food loss and waste (for example, via agro-logistics, cold chains, improved infrastructure, easier access to markets, enhanced consumer awareness, and improved urban waste and landfill policies) not only reduces the carbon footprint and environmental stresses of the food system, but also improves food security by making more food available in the supply chain and lowering prices (World Bank, 2020).

Measures to enhance agricultural productivity are also important because, in addition to land constraints, agriculture faces climate-related productivity losses and urbanization-related labor constraints. On the one hand, food systems have significant impacts on climate largely through agriculture and land use changes. On the other hand, climate change has also slowed the global

growth in agricultural productivity. Anthropogenic climate change has reduced global agricultural TFP by an estimated 21 percent since 1961, equivalent to losing the last seven years of productivity growth (Ortiz-Bobea et al. 2021). These negative impacts are largest in Africa and Latin America and the Caribbean.

Third, in addition to climate-related productivity losses, an important corollary to increased urbanization (and structural transformation more broadly) is that the shrinking share of labor employed in food production must become much more productive to meet the growing and changing food demand of a much larger nonagricultural population. There are other indications, however, that as people move from rural to urban areas, agricultural land constraints may be relaxed. Rural lands would be released for agriculture and farms would become less fragmented and potentially more efficient (Wang et al. 2021). Finally, the rising need for food could be addressed through international trade, combined with productivity gains in countries that have such comparative advantages. This must be balanced, however, by mitigating the risks of food production, which are concentrated in a narrower set of countries.

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Annex

Table A1.   Percent of grids with overlap of food production and urban extent

		Crop production (2010, mt)							Livestock production (2010, pop. density)							
		Cereals	*Fruits*	*Oils*	*Pulses*	*Roots*	*Sugar*	*Vegetables*	*Buffaloes*	*Goats*	*Cattle*	*Sheep*	*Horses*	*Pigs*	*Chickens*	*Ducks*
Crop production (2010, mt)	*Cereals*	100	30	34	34	32	34	30	35	38	35	35	35	35	36	36
	Fruits	30	100	35	35	30	35	30	35	29	32	35	33	35	32	30
	Oils	34	35	100	35	33	35	35	35	32	32	34	34	34	33	35
	Pulses	34	35	35	100	31	35	35	35	34	31	33	32	33	36	32
	Roots	32	35	35	31	100	35	31	33	32	30	33	35	29	38	34
	Sugar	34	33	35	35	36	100	30	34	36	29	32	35	32	33	32
	Vegetables	30	35	21	31	32	30	100	32	38	38	38	35	34	32	31
Livestock production (2010, pop. density)	*Buffaloes,*	35	35	35	35	33	34	32	100	98	98	96	41	98	98	98
	Goats	38	29	32	34	32	36	38	98	100	83	83	82	86	90	83
	Cattle	35	32	32	31	30	29	38	98	83	100	82	86	90	83	98
	Sheep	35	35	34	33	33	32	38	96	98	96	100	83	98	97	98
	Horses	35	33	34	32	35	35	35	41	82	86	83	100	96	89	96
	Pigs	35	35	34	33	29	32	34	98	86	90	98	98	100	89	98
	Chickens	36	32	33	36	38	33	32	98	90	83	97	97	90	100	97
	Ducks	36	30	35	32	34	32	31	98	83	98	98	98	92	96	100
Urban extent	*2015*	4	3	4	4	2	3	5	5	5	5	5	4	5	6	5

Note: *The percentages in the table represent the proportion of grid cells with an overlap of food production and urban extent. The values for crop production and livestock production represent the total production in 2010 in million metric tons (mt) and population density, respectively.*