Abstract

Rapid urbanization has influenced the transformation of local and global food systems, altering the availability, access to, and distribution of healthy food. Micronutrient deficiency and hunger have been exacerbated worldwide. Balancing social, economic, and environmental needs and demands is complex, and often presents tradeoffs between nutritional security and sustainable practices. While various frameworks have been developed to support policy and decision makers in prioritizing tradeoffs that impact urbanization and food production, they are not easily operationalized due to complexities of implementation stemming from the availability of data, place-specific nuances, and methodological difficulties, among others. There is a need to develop analytical approaches to enable researchers, planners, and policymakers to better understand the impact of land use choices on sustainable local food production. The foodshed approach can be a powerful tool to improve the sustainability of regional and local food systems. This research proposes a simulation strategy to evaluate the impact of agricultural land use and crop choices on nutritional production in rapidly growing urban areas. The application of this framework for decision-making is exemplified in the Toluca Metropolitan Zone, Mexico by showing how tradeoffs between macronutrient and micronutrient daily requirements could be explored under a variety of land use scenarios. This analytical framework can be used to understand options for providing nutritional security to the local population.

1. Introduction

Micronutrient deficiency and hunger are a global concern that require prompt attention (Qaim 2020, FAO et al 2022). Micronutrient deficiency refers to the lack of vitamins and minerals that are necessary for essential body functions, growth, and development (WHO 2022). More than 2 billion people (about 30% of global population) lack one or more of these crucial micronutrients (WHO 2022). The most common global nutrition deficiencies include protein-energy malnutrition, iron, vitamin A and iodine (Jiang et al 2022). Prevalence of micronutrient deficiencies varies among regions and nations, often along economic and social dimensions (Safiri et al 2021, FAO 2022, Han et al 2022, Jiang et al 2022). Currently, Han et al (2022) report that the regions of Sub-Saharan Africa and South Asia have the highest incidence of micronutrient deficiencies. Additionally, all subregions of Africa and Latin America and the Caribbean, and most subregions of Asia showed increases in the prevalence of undernourishment in the past 3 years (FAO 2022). At a country level, Han et al (2022) report that Somalia has the highest rates of vitamin A and iodine deficiency, while Bhutan, Zambia and India have the highest rates of iron deficiency. Women and certain races and ethnicities are also at increased risk (Jiang et al 2022). Rates of iron deficiency, for instance, are greater in Hispanic and black women ages 25–54 years (Barton et al 2020). Iron deficiency is the most common cause of microcytic anemia and affects about one third of the world’s population.
mainly affecting children under 10 years old and women in reproductive age (Turawa et al 2021, Han et al 2022, Safiri et al 2021). Conversely, global vitamin A deficiency affects more males than females, and incidence decreases with age. The lack of this vitamin can affect growth and development in children, and can cause vision loss (Zhao et al 2022). Basic nutrient needs should be met to reduce the burden of diet-related disease. Further, the high cost a healthy diet serves as an additional deterrent to a populations’ ability to access nutritious food. For example, Latin America and the Caribbean is the region with the highest cost of a healthy diet (3.89 USD per person per day compared to 3.59 USD globally (FAO 2022)). In order to reduce disparities in access to nutrient-dense and appropriate foods, measures to improve accessibility and affordability of healthy foods are needed (Institute of Medicine 2012).

Nutritional insecurity translates into a high degree of vulnerability within the society, and it is strongly correlated with poverty (Craveiro et al 2016). Both food and agricultural systems play a major role in ensuring nutritional security and progressing toward sustainability, however, the current food system may require major transformations (Qaim 2020). A sustainable food system should ‘make optimal use of human resources, be culturally acceptable and accessible, environmentally sound, economically fair and viable, and provide the consumer with safe, healthy, and affordable food for present and future generations’ (Capone et al 2014). Various methods and concepts have been developed to examine sustainability in the food system (van Passel 2013, Nicholson et al 2021). Among these, the foodshed approach explores sustainable nutritional security by assessing the area of land and types of crops required to self-sustain a region. This approach is also known as local food production capacity and can be a powerful tool for policymaking and landscape planning (Horst and Gaolach 2015, Świąder et al 2018, Vicente-Vicente et al 2021). Despite the benefits of a globalized food system, such as the availability of a diverse range of foods all year round, a local approach is needed to foster connections between producers and consumers and enhance resilient food supply chains (O’Hara and Toussaint 2021, Schreiber et al 2021). A foodshed approach can help understand specific vulnerabilities in the society, use natural resources sustainably, mitigate climate impacts, enhance nutrient sufficiency and supporting local economy (Peters et al 2009, Schreiber et al 2021).

The ecosystem services concept is particularly relevant for regional and local sustainability and policy development (Zhou et al 2018). Yin et al (2021) suggest that ecosystem services underpin the achievement of various sustainable development goals (SDGs), including SDG2 ‘zero hunger’, which aims to achieve food security, improve nutrition, and promote sustainable agriculture. Food security includes the access, availability, utilization, and long-term stability of food (Nicholson et al 2021). Provisioning and regulating ecosystem services such as food production, erosion control, crop pollination, water provision, and biological control are crucial to meet the basic demands of urban populations (Power 2016). Cultural ecosystem services are also important since they motivate the multifunctionality of landscapes, being a powerful tool for policy and decision-making (Plieninger et al 2015). Community-based practices can often promote sustainable urban development (Marsden and Smith 2005).

While urbanization may have positive benefits for both urban and rural communities, such as concentrating economic growth and providing economic and social opportunities, it may also prompt adverse effects on the way people live, eat, and relate to nature (Richards et al 2020, de Bruin et al 2021). Szabo (2016) suggests that rapid urbanization can significantly increase the risk of food insecurity in a region, and the severity of it will depend on the region’s level of development. Urbanization concentrates nutritional demand and, along with a globalized food system, it may generate inequalities that hamper access to sufficient nutritious foods (Holdaway 2015, Szabo 2016, Barthel et al 2019). High demand and competition of land and commodities may lead to increases in food prices that perpetuate urban and rural vulnerabilities. Recent events, such as the COVID-19 pandemic, have exposed the fragile global supply chain and its relationship with income, health, and racial inequalities (Miszellhorn et al 2012, O’Hara and Toussaint 2021). O’hara and Stuiver (2022) illustrate that diversifying and localizing food and green infrastructure economies in metropolitan communities can have many social, cultural environmental, and economic benefits. Our research can help gain some insights into the possibilities of reducing nutritional deficits with locally grown foods.

As the world becomes increasingly urban, cities and metropolitan areas have become essential geographic units to gauge progress toward global sustainability. (Ahern et al 2014, McPhearson et al 2015). Metropolitan areas are continuously undergoing transformations and adapting to different drivers of change, and thus serve as units to study and analyze diverse spatial, social, economic, and ecological processes. Metropolitan transformations are shaped by complex heterogeneous interactions that are influenced by priorities and policies set forth by institutions and policymakers across distinct jurisdictions. Despite previous research in urban sustainability aimed at assessing the impact of urban landforms on social ecological systems (Gasparatos et al 2008, Cohen 2017, Sharifi 2021), there is continuing need to better understand how urban and agricultural components of such frameworks interact.
to impact different dimensions of human wellbeing. Specifically, the interaction between food systems and levels of urbanization moderated by available natural resources, climatic conditions, and policy impacts on the availability, access, and distribution of food in urban areas. The resulting landscape of food production and availability impacts human wellbeing through the availability of nutritious food. Our approach assesses how existing agricultural systems can be modified to achieve nutritional security for a local population while fostering sustainable practices.

This paper illustrates an analysis of a complex relationship between land use change, agricultural production, and nutritional security in a region of Latin America, and provides a flexible framework for decision makers to evaluate their region’s specific complex tradeoffs. The foodshed concept is operationalized through a coupled spatially explicit-computational model to evaluate the impact of land use change and agricultural production choices on nutritional security by (a) examining various combinations of crops with different yield and nutritional characteristics, and (b) determining if a nutrient-dense combination of crops can sustain a region. This model will enable policy and decision makers to improve urban sustainability in the context of nutritional security and will provide insights to initiate changes on local production patterns.

2. Data and methods

2.1. Study area

The Toluca Metropolitan Zone (TMZ) is situated in the State of Mexico in the center of the country. A total of 2353,924 people live in this region, making it the fifth largest metropolitan area in Mexico (SEDATU 2018). The expansion of this metropolis started in the 60s. The 16 municipalities that now constitute the TMZ cover a total surface of 2420 km² in the State of Mexico (figure 1). The TMZ has undergone major agricultural changes due to uncontrolled urbanization (Valencia Torres et al. 2017). The current agricultural system yields a low contribution to the national gross domestic product (GDP) and is characterized by the predominance of white corn monocultures and production of crops destined for livestock feed (Orozco-Hernández et al. 2017). The State of Mexico has the highest poverty rate among all states in Mexico (INEGI 2020). Additionally, about 66.3% households experience some level of food insecurity (Shamah-Levy et al. 2021).

2.2. Methods

Simulation strategies and scenario analysis can be useful tools for policy and decision makers. Benefits of scenario analysis include (a) exploring present, future, or alternative scenarios, (b) questioning old assumptions and producing new decisions, (c) promoting development of new strategies and ideas, and (d) anticipating threats and opportunities (Mietzner and Reger 2005). The simulation strategy used in this study is described in figure 2 and is comprised of three main components: (a) food production assessment using TMZ’s existing land use, (b) crop production simulation to assess current and alternative crop production systems, and (c) nutrition simulation, to assess current and alternative nutrition scenarios.

The first component, food production assessment, consists of an assessment of existing crop production in the TMZ using the crop production-percentile (CPP) model in the Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) software platform developed by the Natural Capital Project: https://naturalcapitalproject.stanford.edu/software/invest. The land cover data consisted of 16 classes including bare surface, urban settlement, different types of forest (e.g. oak, pine, fir, cultivated), secondary vegetation, grazing, peatland, prairie, and agriculture land. Agricultural land was classified as irrigated or rainfed but lacked spatial information on specific crop types at this scale. Therefore, economic data were used to estimate the types of crops grown, area of agricultural land used by each crop, and value of production. This information was obtained from ‘Sistema de Información Agroalimentaria y de Consulta’ (SIACON): www.gob.mx/siap/documentos/siacon-ng-161430. Pixels classified as agricultural land use were then reclassified into different classes of crops (n = 21) based on the production data from SIACON. This process of reclassification was done by randomly selecting a pixel classified as agriculture, and then randomly converting it to a crop type until the proportion of reclassified pixels matched the production proportions specified by SIACON. The outputs of InVEST CPP model were annual crop production and nutrients associated with each crop type, which were used for the next component in the simulation framework.

The second component, crop production simulation, consisted of an assessment of which crop mixtures are likely to improve crop production and nutrition. High-yield and nutrient-dense crops were identified for the region. Based on these crops, a synthetic land use scenario was created using the simulation framework. The CPP model was used to estimate new annual crop production based on the synthetic land use scenario generated in the previous step. The CPP model produces crop production in metric tons per year and resulting nutritional yield for each crop. Production value was calculated multiplying the mean rural price per crop in the TMZ by the annual crop production information from the CPP model. Nutritional data were analyzed to determine if daily macronutrient requirements (i.e. energy, protein, fat) were met for the TMZ population. Daily
recommended nutrition values were then divided by the dietary reference intake (DRI) for each macro and micronutrient (NIH 2019) to estimate the population size that could be supported by the TMZ. For example, the synthetic landscape indicates that 6336,836 g yr\(^{-1}\) of protein is produced from fava beans. The DRI for protein is approximately 51 g (table A in supplementary information). Therefore, the protein produced through the cultivation of fava beans would support 340,415 people. These results
are contextualized to the TMZ by reporting the percentage DRI of a specific nutrient that is available to each person in a given population for a specific crop production strategy. This was calculated by dividing the total DRI values for each crop by the total population in the TMZ (2202 886 people) and reported as a percentage. Continuing the previous example, each person will obtain 15% of their protein DRI from fava beans under the simulated scenario. Based on demographic data for the TMZ, DRI values were calculated based on women and men over 18 years old and excluding pregnant and lactating women (table A in supplementary information).

The third component, nutrition simulation, aimed to identify and model different crop mixes and the amount of agricultural land needed (outside TMZ) to sustain the entire population. Synthetic land use scenarios that extend beyond the existing TMZ boundaries between 10 and 40 km were generated using the methods described above where agricultural land was reclassified to a variety of high-yield and nutrient-dense crop mixes (figure 3). Crop production, macronutrients provided to the population, and production value were compared across existing land use and synthetic land use scenarios. Synthetic land use scenarios with varying percentages of crops and farmland were modeled and resulting DRI nutrient information was analyzed to determine percent of the TMZ’s population would be satisfied for each macronutrient and micronutrient.

3. Results

3.1. Assessment of crop yield and production value for existing crops in the TMZ
A variety of crops are cultivated in the TMZ for several purposes including direct human consumption (e.g. cereals, fruits, and vegetables), livestock feed, industrial, seeds for growing crops, and ornamental. In 2016, annual crop production was 1453 635 tons on 122 797 ha of agricultural land, which generated 2792 022 508 pesos (table 1). From this assortment of crops, white corn occupied almost 90% of the total agricultural land, accounted for 39% of the total crop production, and generated 74% of the production value. Other important crops in the TMZ included green oats and triticale, cultivated for feed, representing 7% of total farmland; baby’s breath, wallflower, and carnation that are grown for ornamental purposes accounting for 26% of the total production; and potato for direct human consumption representing 12% of the total production value.

3.2. Assessment of diverse crop mixtures to improve production and nutrition
InVEST’s CPP model was used to evaluate crop production and nutrition derived from the region’s land use and existing crops, but only included those destined for direct human consumption, including fruits, vegetables, cereals, and tubers. Although this mix may indicate crop diversity, it is important to
Table 1. Crop production and production value of existing crops in the TMZ.

| Crop Category          | Crop | Area (ha) | Production (tons) | Mean rural price (pesos ton$^{-1}$) | Production value (pesos) |
|------------------------|------|-----------|-------------------|-------------------------------------|-------------------------|
| Agave                  | Industrial | 6 | 46 | 4025 | 184 150 |
| Apple                  | Fruit | 256 | 184 | 7592 | 1395 767 |
| Avocado                | Fruit | 15 | 190 | 10 800 | 2052 108 |
| Baby’s breath flower   | Ornamental | 109 | 204 660 | 24 | 4958 912 |
| Barley                 | Cereal | 15 | 49 | 3210 | 156 488 |
| Bean                   | Vegetable | 7.2 | 9 | 8700 | 75 168 |
| Beets                  | Vegetable | 41.5 | 948 | 3524 | 3341 153 |
| Broccoli               | Vegetable | 39 | 741 | 4038 | 2992 128 |
| Cabbage                | Vegetable | 51 | 456 | 4390 | 2003 989 |
| Cactus                 | Vegetable | 17 | 894 | 5238 | 4681 951 |
| Canola                 | Industrial | 40.1 | 99 | 5027 | 496 476 |
| Carnation              | Ornamental | 15 | 114 525 | 118 | 13 513 950 |
| Carrot                 | Vegetable | 115 | 3020 | 2876 | 8687 221 |
| centered               | Vegetable | 37 | 285 | 4240 | 1208 096 |
| Christmas tree         | Ornamental | 70 | 15 255 | 322 | 4907 076 |
| Cilantro               | Vegetable | 46 | 271 | 3009 | 816 098 |
| Corn (grain)           | Cereal | 103 564 | 5110 367 | 3591 | 1834 913 259 |
| Corn in the cob        | Vegetable | 3880 | 57 869 | 4081 | 236 158 133 |
| Fava bean              | Vegetable | 1308 | 9367 | 6775 | 63 465 925 |
| Grass                  | Livestock | 577.35 | 14 894 | 544 | 8100 440 |
| Green alfalfa          | Livestock | 81.75 | 3024 | 505 | 1526 848 |
| Green corn             | Livestock | 10 | 450 | 606 | 272 502 |
| Green oats             | Livestock | 5289 | 122 119 | 657 | 80 254 480 |
| Lettuce                | Vegetable | 358 | 4127 | 5596 | 23 094 738 |
| Pea                    | Vegetable | 583 | 2316 | 6618 | 15 326 878 |
| Peach                  | Fruit | 1 | 2 | 7200 | 11 376 |
| Pear                   | Fruit | 8 | 21 | 5500 | 113 300 |
| Pecan nut              | Fruit | 38 | 186 | 29 500 | 5492 900 |
| Plum                   | Fruit | 17 | 118 | 4066 | 478 525 |
| Potato                 | Tuber | 20 967 | 60 647 | 5559 | 337 135 308 |
| Potato seed            | Seeds | 12 | 160 | 13 226 | 2118 230 |
| Raspberry              | Fruit | 9 | 30 | 28 400 | 1689 800 |
| Spinach                | Vegetable | 186 | 3534 | 4774 | 16 871 422 |
| Sword lilies (Gladiolus)| Ornamental | 76 | 71 440 | 303 | 21 614 172 |
| Tomato                 | Vegetable | 22 | 2879 | 11 284 | 32 487 189 |
| Triticale              | Livestock | 3471 | 11 230 | 3159 | 35 477 061 |
| Triticale seed         | Seeds | 280 | 527 | 11 520 | 6071 040 |
| Wallflower             | Ornamental | 113 | 177 539 | 24 | 4298 219 |
| Wheat                  | Cereal | 93 | 299 | 3220 | 963 452 |
| White chrysanthemum    | Ornamental | 44 | 57 640 | 182 | 10 490 480 |
| Zucchini               | Vegetable | 35 | 517 | 4107 | 2126 101 |
| **Total**              |       | **122 797** |       |       | **2792 022 508** |

The influence of capturing additional agricultural land within 10, 20, 30, and 40 km buffers was evaluated under the assumption that the TMZ’s population would only rely on a local plant-based diet (figure 3). Table 3 shows the crop production outputs of the CPP model for the region’s existing crop mix compared to the synthetic land use scenarios in different buffer sizes’ agricultural lands. Within the TMZ boundaries, the nutrient-dense crop combination identified above increased crop production by more than 1300% and raised production value by more than 280%. In terms of nutrition, daily recommended intake for energy increased by 280%, protein increased by more than 500%, and fat by more than 700%. Macronutrient...
Table 2. Nutrient-dense crops selected for TMZ, and agricultural land occupied by each crop within existing conditions and hypothetical scenario.

| Crop       | Crop area based on existing conditions (ha) | Crop area based on hypothetical scenario (ha) |
|------------|-------------------------------------------|---------------------------------------------|
| Apple      | 26                                        | 7474                                        |
| Barley     | 15                                        | 7474                                        |
| Bean       | 7                                         | 22 422                                      |
| Cabbage    | 51                                        | 22 422                                      |
| Corn       | 107 444                                   | 14 948                                      |
| Fava bean  | 1308                                      | 14 948                                      |
| Pea        | 583                                       | 7474                                        |
| Pecan nut  | 17                                        | 22 422                                      |
| Potato     | 2097                                      | 14 948                                      |
| Spinach    | 186                                       | 7474                                        |
| Tomato     | 22                                        | 7474                                        |

Table 3. Comparison of crop production and derived value among different crop mixes and farmland extensions.

| Land use                     | Crop production (tons) | % of energy DRI for population | % of protein DRI for population | % of fat DRI for population | Value of production (pesos) | Total agricultural hectares | Value per hectare |
|------------------------------|------------------------|-------------------------------|---------------------------------|-----------------------------|-----------------------------|---------------------------|-------------------|
| Existing crop mix            | 110 268                | 10                            | 16                              | 4                           | 2792 022 508                | 148 382                   | 18 816            |
| Nutrient-dense crop mix      | 1558 810               | 38                            | 109                             | 33                          | 10 651 740 480              | 148 382                   | 71 786            |
| Nutrient-dense crop mix 10 km buffer | 2502 208               | 58                            | 171                             | 43                          | 19 013 586 634              | 273 282                   | 69 575            |
| Nutrient-dense crop mix 20 km buffer | 4512 303               | 111                           | 315                             | 95                          | 30 415 271 245              | 415 414                   | 73 217            |
| Nutrient-dense crop mix 30 km buffer | 5920 872               | 145                           | 413                             | 124                         | 39 898 389 186              | 539 822                   | 73 910            |
| Nutrient-dense crop mix 40 km buffer | 7354 906               | 180                           | 511                             | 153                         | 49 659 948 568              | 671 625                   | 73 940            |

Dietary recommendations were completely met by the 30 km buffer. However, protein requirements were exceeded within the 10 km buffer, though energy and fat only met about half of the DRI. As the agricultural land expands out from the regional boundaries, the percentage increase of nutritional value is less dramatic than when switching crop mixture.

Micronutrition was also evaluated at the 10 km buffer scenario. Many nutrients exceeded the requirements for the population, including common limiting ones like iron, vitamin A, zinc, and selenium (Govindaraj et al. 2011, Okwuonu et al. 2021) but others did not (energy, fat, and vitamin E still highlighted in bold in table 4). In addition to crop production and nutrition data, the CPP model enables the exploration of agricultural production levels across the globe (Sharp et al. 2020). This information allows comparison of crop production with other similar climate regions by estimating if local production is 25%, 50%, 75% or 95% of the worldwide average yield. For example, table 4 suggests that crop production in the TMZ is sub-optimal since most of the production is comparable to the 25th percentile, therefore improvements in agricultural practices can further increase nutritional yields in the TMZ.

3.3. Tradeoffs between agricultural land, crop production, nutrition, and production value

Policy and decision makers can consider tradeoffs between agricultural land, crop production, nutrition, and production value prior to identifying sustainable pathways that can be taken to improve local nutrient production. Figure 4 shows scenarios of crop production under 2016 conditions (0 km buffer) and four expansion buffers (10, 20, 30, and 40 km) under three different agricultural production strategies (80% of production targeted for human consumption, 90% for humans, and 100% for humans). The 0 km buffer is split into two columns—crop production for existing and simulated crop mixes within
Table 4. Nutrient-dense crop mixture to improve nutrition based on crops cultivated in TMZ and surrounding areas (10 km buffer).

| Nutrients obtained from combination of crops | % population's recommended intake for nutrient under existing farming practices | % population's recommended intake for nutrient at 25th percentile of worldwide production yield | % population's recommended intake for nutrient at 50th percentile of worldwide production yield |
|---------------------------------------------|---------------------------------------------------------------------------------|---------------------------------------------------------------------------------|---------------------------------------------------------------------------------|
| Energy                                      | 70                                                                              | 94                                                                              | 120                                                                              |
| Protein                                     | 201                                                                             | 217                                                                             | 261                                                                              |
| Fat                                         | 61                                                                              | 56                                                                              | 77                                                                               |
| Calcium                                     | 115                                                                             | 102                                                                             | 115                                                                              |
| Iron                                        | 268                                                                             | 288                                                                             | 342                                                                              |
| Potassium                                   | 337                                                                             | 319                                                                             | 394                                                                              |
| Magnesium                                   | 355                                                                             | 309                                                                             | 372                                                                              |
| Manganese                                   | 510                                                                             | 519                                                                             | 635                                                                              |
| Copper                                       | 408                                                                             | 440                                                                             | 548                                                                              |
| Phosphorus                                  | 317                                                                             | 336                                                                             | 411                                                                              |
| Selenium                                    | 108                                                                             | 152                                                                             | 195                                                                              |
| Zinc                                        | 158                                                                             | 187                                                                             | 231                                                                              |
| Vitamin A                                   | 448                                                                             | 913                                                                             | 1001                                                                             |
| Vitamin C                                   | 1124                                                                            | 792                                                                             | 945                                                                              |
| Vitamin E                                   | 51                                                                              | 71                                                                              | 87                                                                               |
| Vitamin K                                   | 392                                                                             | 935                                                                             | 980                                                                              |
| Thiamine (B1)                               | 293                                                                             | 317                                                                             | 386                                                                              |
| Riboflavin (B2)                             | 164                                                                             | 192                                                                             | 226                                                                              |
| Niacin (B3)                                 | 161                                                                             | 183                                                                             | 238                                                                              |
| Pantothenic (B5)                            | 164                                                                             | 150                                                                             | 184                                                                              |
| Vitamin B6                                  | 340                                                                             | 334                                                                             | 437                                                                              |
| Folate (B9)                                 | 510                                                                             | 494                                                                             | 545                                                                              |

Figure 4. Crop production scenarios and agricultural land tradeoffs.
the TMZ boundary respectively. As discussed earlier, the simulated crop mix shows increased crop production. However, diversity in the crop mix may not be enough to support a population's dietary requirements, prompting increases in agricultural activity—either by land conversion within a metropolitan area or by expansion outside of agricultural activities outside the metropolitan area. Increases in agricultural activity withing the metropolitan area will almost certainly incur costs associated with changing existing land use. Further, the assumption that all agricultural land use is dedicated only for direct human consumption may not be realistic as most agricultural activity includes cultivation of crops for other purposes, particularly feed for animals. The red line in the graph indicates a scenario where 100% of the available agricultural land’s crop production is destined for human consumption; the gray line depicts 90%, and the yellow line depicts 80% of production for direct human consumption and 20% for livestock or other purposes.

The average price for agricultural land in TMZ is approximately 762 pesos m⁻² (IGECEM 2018), or 7627 500 pesos (≈$369 dollars) per hectare. In total, the estimated cost of agricultural land within TMZ would be over 1 trillion pesos ($54 839 732 902 dollars) and would rise to over 2 trillion pesos ($100 996 742 716 dollars), assuming the cost of land remains constant, when adding the 10 km buffer. However, it is important to note that the cost of land may increase as demand increases (i.e. demand for cropland expansion), this in turn may affect cost and demand for crops. The solid lines on the graph show that more agricultural land will be needed to accommodate any reduction in production for direct human consumption. The results can support policy and decision makers in evaluating tradeoffs between amount of agricultural land needed, crop production, and different levels of agriculture destined for direct human consumption.

4. Discussion

This research evaluates agricultural production using existing and hypothetical conditions to illustrate the possibilities of growing local healthy food in a developing metropolitan area and the impact on nutrition. The primary goal of this research was to identify the inputs and trade-offs that need to be considered in a decision-making process to move toward more sustainable food production systems that have the capacity to sustain a local population’s nutritional needs. Important factors considered in this process included available agricultural land, land use trade-offs, types of crops, farming practices, population demographics, geographic and climatic conditions, and production and nutritional value. Additionally, this simulation strategy provides pathways that a decision maker can take to understand future crop production and nutrition options. Pathways might include (a) conserving agricultural land and changing crop mix, (b) expanding agricultural land outside the region and conserving existing crop mix, (c) trading agricultural land that grows crops for livestock and other purposes with crops destined for direct human consumption, (d) exchanging agricultural land with pasture or other land uses, among others. It is important to note that there is no ideal pathway as each strategy represents a tradeoff and consequence that needs to be prioritized. However, a policymaker can use this information to consider tradeoffs and consequences and prioritize between them using a more balanced approach. These tradeoffs can also incorporate policy initiatives that prioritize sustainable land management and encourage farmers to transition to diverse cropping systems while evaluating associated costs/benefits of such transitions at the foodshed or metropolitan level. Examples of these policies include providing technical assistance to producers and connecting local farmers with local market outlets (Martínez 2016).

This research builds upon the foodshed concept that measures local food production capacity and has policymaking and landscape planning implications (Horst and GaoLach 2015, Świądor et al 2018, Vicente-Vicente et al 2021). This concept is relevant given the continuous demand for food, wood, fiber, and fuel that overburdens agricultural systems. As a response, more productive land is required, as well as more chemical inputs, higher-yielding crop varieties and other technologies to sustain the population (Nyström et al 2019, Qaim 2020, Bennett et al 2021). Farming practices have changed as policies incentivize crop monocultures, specialized productions, and mechanization (Altieri 2011). Despite these efforts, about 30% of the global population (2 billion people) are deficient in key vitamins and minerals (FAO 2019, Qaim 2020).

This research may also raise public-awareness about dietary choices since it suggests that urban populations could rely more on a plant-based diet to enhance local sustainable practices. This is highly relevant because only 55% of the calories provided by the world’s crops are destined for direct human consumption, 36% are used for livestock feed production, and the remaining 9% is used for industrial production, mainly pursued for the biofuel industry (Foley 2014). Cassidy et al (2013) suggest that growing food exclusively for human consumption could feed an additional 4 billion people worldwide. Nonetheless, growing crops for other purposes than direct human consumption can be beneficial. On one hand, animal food sources contribute to nutrition and provide calories and bioavailable micronutrients to the global population, including a reliable source of B12, which is essential for the development of the human body (da Silva and Bastos 2022). On the other hand, major industries like biofuels contribute to economic development,
including employment generation (Silalertruksa et al 2012). Prioritizing between environmental, social, and economic tradeoffs derived from crop production can be a challenging task for decision makers. Yet, the percentage of agricultural land that grows crops for direct human consumption should be reconsidered as the population increases.

Computational methods coupled with the InVEST CPP model enabled the evaluation of nutrition provided by crops grown in the area. This approach added value to the InVEST model, which can be applied to any part of the world, by providing useful information on how to improve crop production and nutrition at the landscape scale. The data generated can be useful for researchers and practitioners interested in improving nutritional security while conserving provisioning ecosystem services at the landscape scale.

The TMZ is a suitable example of a rapidly growing metropolitan area that has undergone major agro-cultural changes due to uncontrolled urbanization (Valencia Torres et al 2017). TMZ is considered one of the biggest urban agglomerations in Mexico with higher population growth rates and evident changes in the economic structure, currently led by modern industries instead of the agricultural sector (Sánchez and Hernández 2015, SEDATU 2018). This rapid expansion from agricultural to urban land and economic shift toward the tertiary sector is similar in other metropolitan areas in the world, particularly in developing economies (Thurlow et al 2019, Salem et al 2020). Adame Martínez et al (2020) reported that agricultural surface has decreased 36% meanwhile population has increased 308% and urban surface 236% from 1984 to 2017. The data collected for this research showed that 90% of agricultural land is dominated by white corn. This percentage also exemplifies the national production of corn, which is estimated to be 87%. In 2016, 52% of the national production of white corn was destined for human consumption, 19% destined for livestock, 18% for self-consumption, 6% was exported, 1% was purposed for seed (to regrow this crop), and the rest was wasted (4%) (SAGARPA 2017). Despite the dominant production of corn in Mexico, the results show that this crop alone provide very little calories and nutrition for the TMZ population (table 3), thus requiring imported food. Regional sustainability could be greatly improved in this metropolitan area by having plans and policies that prioritize local food production. Tables 3 and 4 show that growing a higher proportion of other fruits and vegetables (particularly legumes) within the TMZ boundary, would considerably increase production, derived nutrition (e.g., energy, protein, and fat) and production value. However, more agricultural land would still be needed to meet the daily recommended intake requirements by deemphasizing corn production and promoting a diversified crop mix. Further, production and nutrition results almost doubled when adding a 10 km buffer of available agricultural land outside TMZ. In fact, the intake for most nutrients exceeded the recommended daily nutritional values by significant amounts with increasing allocations of agricultural land. In some cases, the amount of available nutrition was well over 200% of the recommended values. Therefore, nutrient-dense crop combinations were modeled for the smallest buffer (i.e., 10 km extension), even though energy and fat did not quite meet the requirements. Additionally, other buffers (i.e., 20, 30, and 40 km) were not modeled since they were overlapping with the available agricultural land for the Mexico City Metropolitan Area, the largest urban agglomeration in Mexico (Son et al 2018). Given the additional amount of land needed to provide all nutrients to the population, it is important to acknowledge that trading some commodities is necessary from a cultural, social, and economic standpoint, and can also have potential benefits on sustainability (Daviron and Vagneron 2011, Grabs and Carodenuito 2021).

The InVEST CPP model also enabled the comparison of production and nutritional outputs with other world regions that have similar climate bins. The CPP model outputs showed that crop production and derived nutrition in TMZ is comparable to the 25th percentile, which represents sub-optimal production. Farming practices in the State of Mexico are conventional, where most farmers only rent tractors and use chemical herbicides to grow and harvest their crops (García Guadarrama 2021). Corn monocultures dominate the farming system in Mexico (SAGARPA 2017). Monocultures have shown to disrupt many supporting and regulating ecosystem services, such as biological control of pests. In return, farmers need to invest more in pest control (Altieri 2011, Bengtsson 2015). In the US, pests inflict various damages worth $23 – $34 billion dollars annually (Wyckhuys et al 2020).

Simulations showed that farming practices need to be improved and more agricultural land is needed to fully sustain the TMZ population. Limiting nutrients identified in the area were fat and vitamin E but most dietary requirements could be met with the existing local crops. Further, results suggest that both nutrition and production value would be higher when growing a diversity of crops with more balanced proportions (as opposed to current practices where white corn dominates). In terms of production value, an important assumption of our analysis is that the model does not consider market dynamics that influence a farmer’s decision about which crops to grow. To increase crop diversity, a necessary tradeoff would be decreasing the amount of corn and crops destined for livestock production. It is also important to highlight that corn is the most valuable
commodity in Mexico, economically and culturally, and it would be unrealistic to drastically reduce the production of corn in this area. Culture and traditions can complicate the prioritization of other crops that are more valuable from the nutrition perspective. A starting point can be switching corn monoculture to corn polycultures. Corn polycultures (corn, bean, and squash mix) were practiced by indigenous farmers in Mesoamerica. Sánchez Morales and Romero Arenas (2018) report that polycultures outperform monocultures by (a) increasing food diversity, (b) using available agricultural land strategically, (c) increasing biodiversity, and (d) decreasing use of chemical herbicides. However, agricultural trends have shifted in the TMZ, which is now characterized by a predominance of white corn monocultures and an increased production of crops destined for livestock feed (Orozco-Hernández et al 2017). Therefore, it is important to acknowledge that changing crop mixes and land allocation can be a very complex task that requires time. More realistically, a policymaker can use our approach to develop a long-term plan in which local production increases gradually. Synthetic scenarios could be generated to estimate tradeoffs between total production, nutrition, and production value when decreasing corn by 10%, 20%, 30%, 40%, etc. Peters et al (2009) suggest that although a transition to a more localized food system is difficult to initiate, it is possible to achieve by (a) reducing excess consumption of calories, and (b) increasing consumption of plant-based proteins rather than animal proteins. A transition to a more localized food system that focus on nutrient-dense crops would be particularly relevant in Latin American regions that face limited access and disproportionately high costs for healthy nutritious food.

4.1. Limitations and uncertainty
The proposed approach in this research uses computational approaches with spatially explicit models. This section summarizes known limitations from these perspectives. First, the InVEST CPP model requires a detailed crop type land use dataset, which might not always be available for some geographies and scales. This was the case with the TMZ. Simulation methods were used to generate this spatial information based on a raster of generalized land cover classes and a crop-type dataset that included crops names, hectares occupied by each crop, and economic value (table 1). The simulation system randomly converted pixels of agricultural land into specific crop types. However, this process might not accurately represent the exact distribution of crops. Second, the model is based on a Food and Agriculture Organization of the United Nations (FAO) dataset that includes 175 crops, but there may be missing data for sub varieties (e.g. Saladette versus Cherry tomatoes) or less common crops. Additionally, yield observed values are based on Monfreda et al (2008) calculations circa the year 2000. Yields can be underestimated when compared to current production numbers. This was the case for corn production. The CPP model can be selectively modified to update production numbers through manipulation of its input datasets. Third, the proposed model only evaluates nutrition derived from crops grown for direct human consumption. Nutrition from animal sources is not considered. Fourth, given the Climate Crisis, it is important to acknowledge that drastic temperatures, weather changes, and water shortages can greatly decrease agricultural production. The CPP model uses actual observed yield circa the year 2000, and therefore, crop production results might not account for these anomalies. Lastly, the analysis does not consider the effect of externalities, such as market effects and the influence of global commodity prices. Despite these limitations, researchers and practitioners can use this computational approach to create hypothetical scenarios and explore different combinations of crops to increase production, nutrition, and value in their area. Computational and spatially explicit approaches are emergent methodologies that help incorporate ecosystem services in land use planning, and support decision-making (Zhou et al 2018, Valencia Torres et al 2021). This model can be used by non-experts who are interested in achieving local nutritional security, conserving ecosystem services, and improving regional sustainability.

5. Conclusions
This paper presents a spatially explicit modeling approach to evaluate scenarios of local crop production and derived nutrition based on the foodshed approach. This can help policy and decision makers prioritize between environmental, social, and economic tradeoffs associated with agricultural production. We acknowledge that our simulations do not consider all tradeoffs. While thousands of different combinations can be simulated, our research simply provides a starting point to illustrate land use, agricultural production, and nutrition tradeoffs in support of local food production. Additionally, the proposed framework can be used to evaluate the impact of land use change over time as well as the incremental changes of policy decisions on the ability to support the nutritional capacity of the local region. Answers to many potential questions that decision makers might have regarding local crop production can be address using the simulation strategy. For instance, once a baseline simulation has been created, additional simulations for incremental time steps with determined changes of policy decisions on the ability to support the nutritional capacity of the local region.
might be achieved, while improving economic and environmental benefits in the area.

Data availability statement

The authors declare that the main data supporting the findings of this study are available within the article and its supplementary information file. Extra data are available from the corresponding author upon request.

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