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Modeling a localized metropolitan food system in the Midwest USA: Life cycle impacts of scenarios for Des Moines, Iowa

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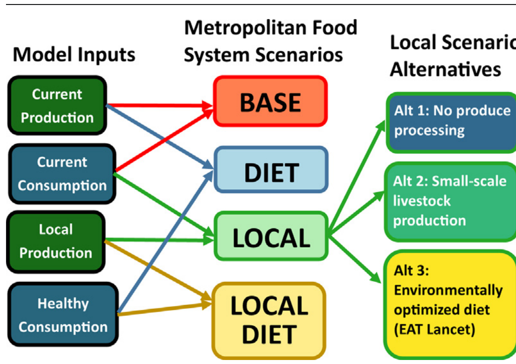
HIGHLIGHTS

- Assessment of metropolitan-scale food system scenarios could enhance local decisions.
- Localizing food production reduced impacts more than following USA dietary guidelines.
- Animal-based proteins were linked to the greatest share of environmental impacts.
- Diets could be optimized to reduce environmental impact and improve human health.

GRAPHICAL ABSTRACT



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ABSTRACT

Food systems are energy-intensive, causing ≈25 % of anthropogenic global warming potential (GWP) and contributing to challenges across the food-energy-water nexus. The state of Iowa, USA, is of particular interest as a rainfed agricultural region of the upper Midwest; despite its highly productive landscape, a large proportion of food consumed by Iowa residents is imported. This study focused on the Des Moines Metropolitan Statistical Area (DM-MSA), a six-county area in central Iowa with a 2020 population of ≈700,000. A life cycle assessment approach was used to quantify environmental impacts (GWP, fossil energy and water consumption, land use); scenarios modeled provision and consumption of 50 % of nutritional requirements for the current DM-MSA population by food group (e.g., grains, proteins, vegetables). The four DM-MSA food system scenarios were: 1) current conditions (baseline), 2) local production for 50 % of food, 3) consumption changed to follow USA dietary guidelines, and 4) combined changes to production and consumption. Localizing food production reduced all environmental impacts more than following USA dietary guidelines. Compared to the baseline, 50 % local production scenarios reduced GWP and energy consumption (18–24 %) and water use (35–41 %) annually. Decreases by food group were least for protein (−10 % GWP) and greatest for fruits and vegetables (−58–62 % GWP). Local scenario alternatives could further reduce some environmental impacts if paired with a nutritionally- and environmentally-optimized diet (EAT-Lancet) providing the greatest change (−30–38 % for GWP and energy use) compared to the local scenario. A 50 % local production scenario for the DM-MSA could decrease GWP by 102 million CO_{2eq} yr^{-1} and water use by 44 billion L yr^{-1}. However, this would require dietary changes based on seasonal food availability. Further development and co-simulation with other metropolitan-scale biophysical and social models will enhance understanding of food system drivers and support effective decision-making for urban food system improvements in the Midwest.

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1. Introduction

Food systems currently account for just over a quarter of global carbon emissions (Poore and Nemecek, 2018). By 2050, the global human population is projected to increase to 9 billion, and related food needs and agricultural production are expected to increase by up to 70 % (FAO, 2010). Much of the greenhouse gas emissions that create global warming potential (GWP) from food systems are directly related to fossil energy use: in the USA, about 15 % of total fossil energy demand is related to the food system (Mohareb et al., 2017). Life cycle assessment (LCA) studies have been conducted to assess the potential effect of increasing the amount of local foods available, particularly in urban areas, to reduce GWP and moderate energy inputs (Benis and Ferrão, 2017; Kulak et al., 2013; Rothwell et al., 2016). In an increasingly urban world (the global human population clustered in urban areas is at 50 % and rapidly rising), urban and peri-urban agriculture (UPA) has been proposed as an important path to reducing energy inputs and GWP from food systems (Kulak et al., 2013).In North America, 82 % of the human population lived in urban areas in 2018 (UN, 2019). Many areas in the USA rely heavily on food “imports” from outside state boundaries for the majority of their diet. In Iowa, for example, approximately 90 % of human food is shipped into the state from other locations, and in the Des Moines area approximately 95 % is imported. However, the optimal path toward reducing food system environmental impacts remains heavily debated (Krouse and Galluzzo, 2007).

1.1. LCA approaches to metropolitan-scale food system scenarios

Food system LCA studies commonly examine carbon emissions, fossil energy consumption, and water use across the supply chain. Modeling with LCA is useful to examine the externalities associated with complex system dynamics (Djekic et al., 2019). However, LCA does have limitations. Researchers can define different system boundaries depending on their objectives, which can lead to profoundly different results. For example, food system studies commonly use production inputs (cradle) as a starting point with differing end points of analysis (farm gate, retailer, grave). In this context, Pernollet et al. (2017) compared the effect of different system boundaries on GWP and found that changing food system boundaries from cradle-to-grave to cradle-to-farm gate reduced the GWP estimate by 70 %, and by 30 % for cradle-to-retailer. The International Organization for Standardization (ISO) has set standards for LCA studies (ISO 14040, ISO 14044; Pryshlakivsky and Searcy, 2013). In spite of the standards, it remains difficult to draw comparisons among various LCA studies based on differences in their spatial scales, methods, functional units, and system boundaries in addition to bona fide regional differences (Clune et al., 2017).

While national-scale food system LCA models are important, they are not as useful for large countries like the United States or China, for example, for which regional variations are considerable. Conducting LCAs for individual regions or cities could provide more precise information on the characteristics of local food systems. Increased specificity at local scales could also provide important insights into local challenges and opportunities to reduce GWP associated with food systems. Several such city-scale food system LCA studies from Spain, Portugal, the UK, and China have been conducted (Benis and Ferrão, 2017; Kulak et al., 2013; Pérez-Neira and Grollmus-Venegas, 2018; Yue et al., 2018). Although studies at the state (e.g., New York; Peters et al., 2009) and city scale (e.g., Chicago; Costello et al., 2021) have connected human populations to food production and local land requirements, we are not aware of metropolitan-scale food system LCA studies in the USA being used to develop scenarios for decision making. This is an important gap and conducting this type of study could inform food system policymaking in the Midwest region through a deeper understanding of food systems at this scale. Current conceptual frameworks designed to reduce environmental impacts for food systems in previous studies have led to different conclusions about the impacts of localizing food production (see Section 1.2 below) and of changing food consumption patterns (see Section 1.3 below). Our study presents a novel metropolitan-scale model that compares consequences of both localizing food production and changing patterns of human food consumption. We use our analyses to identify effective policy interventions to support potential environmental impact reductions for Midwest USA food systems.

1.2. Previous findings on environmental impacts of near-urban local food production in the Midwest

Although there is no consensus regarding the definition of local food it continues to receive political support and local markets have experienced continued growth (Low et al., 2015). This is true especially in response to the Covid-19 pandemic, which exposed low food system resilience and lack of social equity of conventional food systems in cities in the USA and across the supply chain (Klassen and Murphy, 2020; Wu, 2020). UPA may provide a promising alternative to current conventional food systems, which are often associated with increased environmental costs, greater incidence of foodborne illnesses, and reduced food quality, in addition to the larger scale energy-related drawbacks already mentioned (Reich et al., 2018). Opportunities for UPA have been studied for cities across the USA, including those in the Midwest such as Chicago, IL, Cleveland, OH, Detroit, MI, and Madison, WI (Saha and Eckelman, 2017). UPA could lead to many positive environmental and social outcomes by potentially reducing GWP, improving health and food security, and bolstering local economies (Enshayan, 2009; Gray et al., 2014; Guitart et al., 2012; Kirkpatrick and Davison, 2018; Kulak et al., 2013; Opitz et al., 2016; Telesetsky, 2014). However, Enthoven and Van den Broeck (2021) found that benefits of local food are often case specific, and although evidence supports that consumer access to healthy food increased with local prodcution, it did not support the common view that reducing transportation distance of foods reduces food system GWP.

UPA is not universally accepted as an effective means to reduce food GWP. For example, investigators for one LCA study found that local UPA did not result in the magnitude of GWP reductions that were anticipated for northern cities – they suggested that efforts should focus instead on reducing food waste (which may include up to one-third of all food produced) or on producing rooftop solar power rather than using roof spaces for gardens (Goldstein et al., 2016a). Researchers conducting an international study found that UPA has limited potential and recommended improving employment and income generation to enhance long-term food security (Badami and Ramankutty, 2015). Similarly, researchers examining city-scale food system models for two cities in the USA and two in India found that doubling urban agriculture produced few environmental benefits (Boyer and Ramaswami, 2020).Investigators of additional studies have found likewise (Clinton et al., 2018; Goldstein et al., 2017). However, successful examples of UPA have also been described for some cities, including Shanghai, China, where 60 % of vegetables and 90 % of eggs are produced within the city itself (Lovell, 2010)). Researchers conducting another study concluded that small-scale UPA could feed a significant number of people globally, although food production knowledge and employment opportunities associated with UPA are two possible barriers to increasing UPA (Nicholls et al., 2020).

1.3. Near-urban food consumption changes may lead to different environmental impacts in the Midwest

Investigators using LCA have shown that dietary choices can significantly affect food system GWP, with lower meat consumption generally corresponding to lower GWP (Curran, 2016; Gava et al., 2018; Goldstein et al., 2016b; Heller et al., 2018; Notarnicola et al., 2017; Rehkamp et al., 2017). Pernollet et al. (2017) found that GWP related to food consumption could be reduced by about 30 % without decreasing nutritional quality, cultural acceptability, or affordability of the diet. The exact impacts of dietary changes are difficult to assess – they varied more than six-fold in one review of LCA studies, largely due to variation in system boundaries used in individual studies (Pernollet et al., 2017). In their review of studies conducted between 2009 and 2014, Benis and Ferrão (2017) found potential reductions of 50 % for GWP as diets changed. In Lisbon, Portugal, meat, fish, and eggs were responsible for approximately 55 % of the global warming potential, making food selection a significant environmental impact mitigation strategy fora city-scale food system. Researchers in the USA who developed a biophysical model of human carrying capacity for ten different diets found the highest carrying capacity for lacto-vegetarian (i.e., including dairy) or ovolacto-vegetarian (i.e., including dairy and eggs) diets compared to vegan diets (Peters et al., 2016).

Current human consumption patterns place demands on environmental systems that exceed global capacity to adequately feed the human population over time (Wang, 2022). Countries with greater affluence, together with certain cultural preferences, are responsible for more GWP and water impacts per capita based primarily on higher animal product (especially red meat) consumption (D'Odorico et al., 2018; Kim et al., 2020). Typical food consumption patterns in the USA have relatively high environmental impacts, based on consumption of more meat and fewer fruits and vegetables compared to those in guidelines provided by the U.S. Department of Health & Human Services (HHS) and U.S. Department of Agriculture (USDA) (HHS-USDA, 2015). However, the HHS-USDA guidelines were developed to target nutritional health and wellbeing and do not explicitly address environmental impacts. In response to social and biophysical concerns, alternative diets have been proposed to enhance sustainability, many of which recommend plant-based alternatives for animal-based foods and attempt to balance environmental protection with human nutrition (Fanzo, 2019). For example, "EAT-Lancet" is a quantitative reference diet developed by a cross-disciplinary commission to develop scientific targets that balance human health with environmental sustainability based on six key parameters, including GWP, water use and land use (Willett et al., 2019). The EAT-Lancet diet includes more legumes, fruits and vegetables, and less meat and dairy than is currently consumed on average in the USA.

1.4. Objectives

Our overall objective of this study was to use an LCA approach to assess the Des Moines Metropolitan Statistical Area (DM-MSA), IA, USA food system. This area is considered representative of many metropolitan areas in the Midwest (e.g., Lansing, MI, Omaha, NE, Dayton, OH, Madison, WI), which have similar population sizes and are surrounded by rainfed agricultural landscapes (Thompson et al., 2021). We sought to assess current production and consumption patterns and examine potential scenarios in which local food production was increased to meet 50 % of residents' current nutritional intake and those for which food consumption was adjusted to reflect HHS-USDA dietary guidelines (Table 1).

The first study objective was to compare four food system scenarios using an LCA approach for 50 % of the dietary intake of the DM-MSA population including: BASE (current production of 45 % distant and 5 % local and current consumption), DIET (current production; consumption follows a diet constructed according to 2015–2020 dietary guidelines for Americans (per US-HHS and USDA, 2015), LOCAL (production is locally grown within the DM-MSA for current consumption), and LOCAL DIET (food production is local within the DM-MSA and consumption for residents follows HHS-USDA dietary guidelines). The second objective was to assess three potential alternatives (Alt) based on the LOCAL scenario within the DM-MSA (Fig. 1). For Alt 1 we did not incorporate fruit or vegetable processing locally as we did in the LOCAL scenario; this more closely resembles the status quo of little or no produce processing in Iowa. For Alt 2 we included small-scale and extensive (increased land use, free range or pasture based) animal production practices for all meat products (extensive dairy production was not included) since livestock production methods cause a large portion of food system environmental impacts and regenerative agriculture using rotational livestock grazing has been promoted extensively by state organizations such as the Practical Farmers of Iowa (Practical Farmers of Iowa, 2022). For Alt 3 we incorporated the EAT-Lancet diet for the DM-MSA population; this diet represents a much larger shift in consumption patterns than HHS-USDA dietary guidelines (Willett et al., 2019). The third objective was to determine LCA model sensitivity to three key variables: food consumption patterns, transport, and food waste.

2. Materials and methods

We used FoodCarbonScope™ (CleanMetrics, 2020) LCA modeling software to develop food system scenarios for current production and consumption in the DM-MSA compared to a scenario in which 50 % of the nutritional intake was produced locally, a scenario in which consumers followed 2015–2020 HHS-USDA dietary guidelines, and a scenario with both production and consumption alterations. FoodCarbonScope™ includes many USA datasets and complies to IPCC Guidelines for National GHG Inventories and current international standards for LCA analyses (e.g., ISO 14040) (Penman et al., 2006; Pryshlakivsky and Searcy, 2013). Environmental impacts (GWP, energy, water) were estimated across the food system cycle based on geographical location (e.g., California for produce) and production practices (e.g., livestock confinement systems versus pasture access), providing primary inputs for the BASE scenario. Adjustments to account for differences in the LOCAL scenario are described below (Section 2.1.2).

Global warming potential (GWP) included warming impacts from all greenhouse gas emissions normalized to carbon dioxide equivalents. Energy use included energy from both fuel and electricity throughout the food system under current USA conditions. Water use included only water withdrawn from freshwater sources, rainfall was not included in the model. Two functional units were selected for assessing food system impacts GWP (kg CO_{2eq}), energy (MJ) and water (L), all calculated on a (1) per kg food consumed per person for the DM-MS and (2) per land area (ha), both reported on an annual basis. The system boundaries included the entire life cycle of a system from raw resource extraction (cradle) to product disposal (grave) for 50 % of the nutritional intake for food consumed within our study area; we excluded environmental impacts for storage and cooking at the consumer level. Foods were selected by food group to reach 50 % of total consumption within the DM-MSA food system for all scenarios regardless of production location (distant or local) (Table 1). The food types were held constant in all four scenarios, though total amounts differed based on current consumption compared to modeled consumption where HHS-USDA dietary guidelines were followed in our study area. Individual foods were included in the current 50 % diet based on the following

Table 1
Four food system scenarios[a] were used to represent changes in production and consumption across the food system to understand how localizing production within the Des Moines Metropolitan Area (DM-MSA) and changing diets to healthy consumption patterns based on HHS-USDA dietary guidelines would affect environmental impacts.

DM-MSA Food System Scenarios	Current amount of local food production (about 5%)	Increased local food production within the DM-MSA
Current consumption	**BASE:** Current production and consumption patterns	**LOCAL:** 50% local production, current consumption patterns
Consumption based on HHS-USDA dietary guidelines	**DIET:** Current production, recommended consumption	**LOCAL DIET:** 50% local production, recommended consumption

[a] See Section 2.1. for an overview of scenarios.

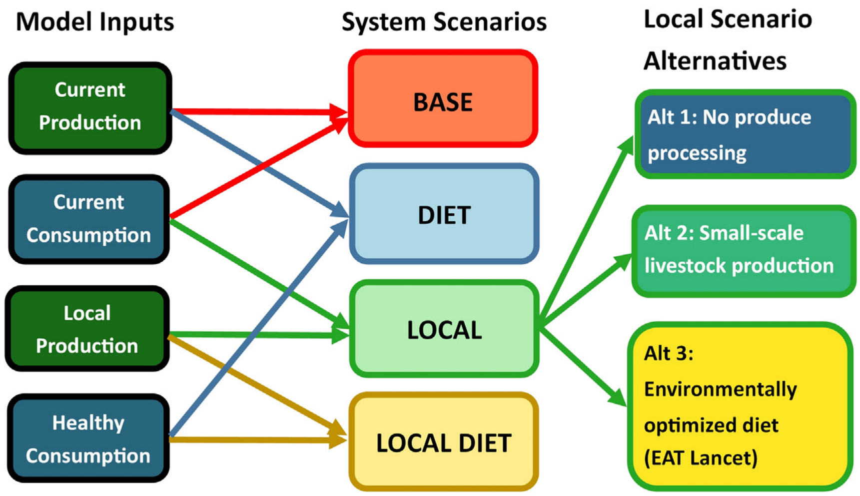

Fig. 1. Two conditions (production and consumption) are adjusted to create four Des Moines Metropolitan (DM-MSA) food system scenario analyses. The LOCAL scenario was further adjusted to describe three local alternatives designed to understand how these specific local food system changes impact GWP, energy, water use and land use to enhance decision-making at the metropolitan scale.

characteristics: 1) feasibility for on-farm production within the DM-MSA, and 2) relatively high consumption levels by food group. The four LCA scenarios were then examined to assess the importance of local production (LOCAL) and healthy consumption (DIET) for GWP, energy, water use and land use impacts. Thirty-nine food types were included within 13 food groups (Table 2).

2.1. Scenario overviews

The BASE and LOCAL scenarios used the same dietary assumptions by food type and quantity. For the DIET and LOCAL DIET scenarios, a diet that followed HHS-USDA recommended dietary guidelines was assembled using the same food types with modified quantities (HHS-USDA, 2015). To capture the most frequently consumed food types only those equal to or greater than 0.001 servings per person daily were included (USDA-ERS, 2016). The protein food category included animal proteins (chicken, beef, pork and eggs) as well as dried beans (which were included in two food categories, both as a protein and a vegetable). For the BASE scenario, dried beans were split equally between these two categories; for the DIET scenario, dried beans were distributed to meet nutritional guidelines for both categories with 50.4 % included as protein and 49.6 % as vegetable. Fish were excluded from this study due to low current local fish production in our study area. Fruit and vegetable processing was included for the LOCAL and LOCAL DIET scenarios to make seasonality less of a barrier to increasing local production to 50 %. Household cooking and cooled storage in the household were not included in the model because they were expected to be consistent across the four scenarios. The four scenarios were analyzed and compared to determine the importance of local production and dietary change at the metropolitan scale. Scenario assumptions were set based on available datasets at applicable scales. Assumptions by food system stage are summarized here (Table 3) and explained in detail in supplemental material (Appendix 1).

2.1.1. Current production and consumption (BASE)

The USDA dataset "food available per capita" was incorporated to approximate current food production, and the same dataset with loss adjustments was used to approximate current food consumption in the DM-MSA food system (USDA-ERS, 2016). These datasets are a proxy for food consumption at the national level and were compared to consumption data available through the Iowa State University Extension and Outreach Expanded Food and Nutrition Education Program (EFNEP) for low-income families in Polk County, IA (location of the City of Des Moines; EFNEP, 2020). Local and national data were very similar for consumption by food group, so national datasets were retained in the model. The BASE scenario assumed that locally produced food (within the DM-MSA) made up 5 % of the total consumption for our study area (Chase, 2020 - personal communication).

Table 2
Foods modeled by food group in current (BASE and LOCAL) and healthy (DIET and LOCAL DIET) diet scenarios. Food consumption was based on USDA 2016 Loss-Adjusted Food Availability. The diets were assembled to represent 50 % of the nutritional requirement for the DM-MSA by food group, with quantities given in servings per person (pp) per day. The percent of individual foods included in each food group was based on three criteria: 1) it could be grown outdoors in Iowa, 2) it had the highest consumption by food group, and 3) the same percent of each item by group was included to equal 50 % of total consumption.

Food groups	BASE / LOCAL (% by food group)	BASE / LOCAL (servings/pp./day)	DIET / LOCAL DIET (% by food group)	DIET / LOCAL DIET (servings/pp./day)
Protein	50.07	7.71	50.46	5.50
Protein legumes	50.00	0.32	50.40	0.21
Dairy	50.34	1.51	49.95	3.00
Fruit	49.89	0.88	50.05	2.00
Vegetable	50.16	1.85	50.13	2.50
Vegetable dark green		0.15	50.07	0.21
Vegetable red orange		0.20	50.10	0.79
Vegetable starchy		0.30	50.40	0.71
Vegetable legumes	50.00	0.05	49.61	0.21
Vegetable other		0.25	50.05	0.57
Grains	50.21	6.64	50.28	6.00
Oil	50.02	63.90	49.67	27.00
Sugar	50.33	22.40	50.00	12.50

Table 3
Modeling approaches and assumptions across the food system cycle for each scenario. The BASE scenario included current production and consumption in the DM-MSA, LOCAL incorporated local production and current consumption, DIET used current production and healthy consumption. LOCAL DIET was modeled by using production assumptions from the LOCAL scenario and consumption assumptions from the DIET scenario.

	BASE and DIET scenarios	LOCAL and LOCAL DIET scenarios
Local production	5 % of foods are produced and consumed within local markets (in the MSA); current production categorized by 2017 Ag Census	50 % produced within the MSA, production inputs based on Iowa practices identified by horticulture/agricultural specialists
Transport	Based on state cash receipts (USDA ERS), by one-way, semi-truck with exceptions based on current production quantity within the state (e.g., beef, swine, eggs)	Direct-to-consumer and wholesale included 160 km, round-trip by single-unit truck.
Packaging	Based on 11 package categories that represent mean emissions from an LCA literature review (Poore and Nemecek, 2018)	Food sold direct-to-consumer (67.5 %), did not include packaging, for wholesale/retail markets (32.5 %), packaging assumptions were the same as BASE assumptions
Wholesale/retail	Based on GWP and energy category means for wholesale/retail from an LCA literature review (Poore and Nemecek, 2018)	Food sold direct-to-consumer included no wholesale/retail emissions, food sold via wholesale/retail chains used BASE assumptions
Food waste	Based on waste by food group, according to USDA including both retail and consumer levels (Buzby et al., 2014)	Direct-to-consumer waste by food group included only consumer-level waste, wholesale/retail used assumptions created for the baseline (Buzby et al., 2014)

2.1.2. Local scenario (LOCAL)

A food system scenario with 50 % of the nutritional requirements for the DM-MSA population produced locally was constructed by selecting the same foods by food group used in the BASE scenario, according to their relative level of production in Iowa and consumption per capita (USDA-ERS, 2016). The Iowa-grown foods with higher daily consumption by food group were prioritized except for fruits. Given the high percentage of tropical fruits that were not suitable for production in our study area, the common fruits that can be grown outdoors in Iowa were included to reach 50 % of the recommended nutrition guidelines. The LOCAL scenario included the same proportion of fruits and vegetables that were preserved and processed as did the BASE scenario. Environmental impacts for food processing were based on an estimation tool for energy demand by food processing type for canning, freezing, and juice production (Sanjuán et al., 2014). Adjustments were made to match scale and production practices for vegetables and fruits typical for Iowa (Stone et al., 2021). For several animal products local production levels are high but used primarily for markets outside of Iowa (e.g., pork and eggs). For the local scenario we assumed that some of the animal products currently grown in Iowa were diverted to supply local markets. The feed necessary for these livestock was also considered to have been produced within the DM-MSA for the LOCAL scenario.

A recent survey indicated that 54 % of fruit and vegetable producers in Iowa sold direct-to-consumer, 19 % used only wholesale markets, and 27 % used both market types (Enderton et al., 2017). We assumed local market channels remained consistent and that the proportion of food sold to foodservice and institutional sectors also remained consistent for all scenarios. Producers using both market channels (27 % of producers) were split equally between the two, with direct-to-consumer markets making up 67.5 % and wholesale markets making up 32.5 % of the LOCAL scenario. Although only local fruit and vegetable producers were surveyed by Enderton et al. (2017), we assumed that all foods produced within the DM-MSA would be sold using the same market split. Different assumptions were then developed for food system stages (e.g., production, distribution, retail) based on the market type utilized (Appendix 1). Local crop and livestock yields were validated based on input from extension and horticulture specialists at Iowa State University and Farm Service Agency estimates (Appendix 1 & 2).

2.1.3. Healthy diet scenario (DIET)

For the DIET scenario, foods were scaled according to the 2015–2020 Dietary Recommendations for Americans (US-HHS and USDA, 2015). The amount of each food currently consumed by food group includes per capita amounts for the entire DM-MSA. Although the dietary recommendations do incorporate micronutrients, only macronutrients were assessed for model validation (Table 4).

2.1.4. Local healthy diet scenario (LOCAL DIET)

This scenario combined assumptions from the LOCAL scenario for production and the DIET scenario for consumption, as described above and in supplemental materials (Appendix 1).

2.2. Alternative assessments

Three additional alternatives were assessed to determine how changes to the LOCAL scenario would change environmental impacts. We included three alternatives. Alt 1 included no fruit and vegetable processing. Because there is currently very little fruit and vegetable processing infrastructure, Alt 1 represents a LOCAL scenario closer to the current situation for processing. In Alt 2, small-scale and more extensive (increased land use for grazing) livestock production systems were incorporated for local markets. Parameters for GWP, energy use and water use were built into FoodCarbonScope. Land use assumptions for extensive grazing in Alt 2 were based on conservative average daily gains for feed from grazing and supplemental feeds with medium plant yields for perennial (grassland) and cultivated crop production (Flachowsky et al., 2017). For Alt 3, consumption was based on the EAT-Lancet dietary guidelines optimized for both human and environmental health (Willett et al., 2019). The EAT-Lancet diet was selected because it is a flexible framework with strong empirical backing for scientific targets and could be adopted across food cultures and production systems to provide adequate nutrition for a future global population of 10 billion persons (Willett et al., 2019). This diet was also validated based on the macronutrient profile (Table 4). Assumptions and sources for each local alternative are provided in detail in supplemental materials (Appendix 2).

2.3. Sensitivity analyses

Sensitivity analyses were developed for three key independent variables: 1) food consumption patterns, 2) transportation, and 3) food waste. To determine sensitivity, each variable was increased and decreased by 20 % from the BASE scenario. Tornado plots were used to visualize sensitivity for GWP, energy and water use.

Table 4
Three diets were assembled for scenario and local alternative analyses. They were compared based only on macronutrient content (micronutrients were not assessed in this study). Each diet represents 50 % of nutritional requirements for current consumption (used in the BASE & LOCAL scenarios) following 2015–2020 Dietary Guidelines for Americans (used in DIET & LOCAL DIET scenarios), or consumption following the EAT-Lancet diet (used in Local Alternative 3 [Alt 3]).

Dietary nutrient summary	Units	BASE	DIET	Alt 3: EAT-Lancet
Total energy	kcal/day	1356.02	1251.80	1233.34
Protein	g/day	51.15	56.81	52.34
Fat	g/day	57.12	40.69	45.45
Carbohydrate	g/day	171.00	173.32	163.19

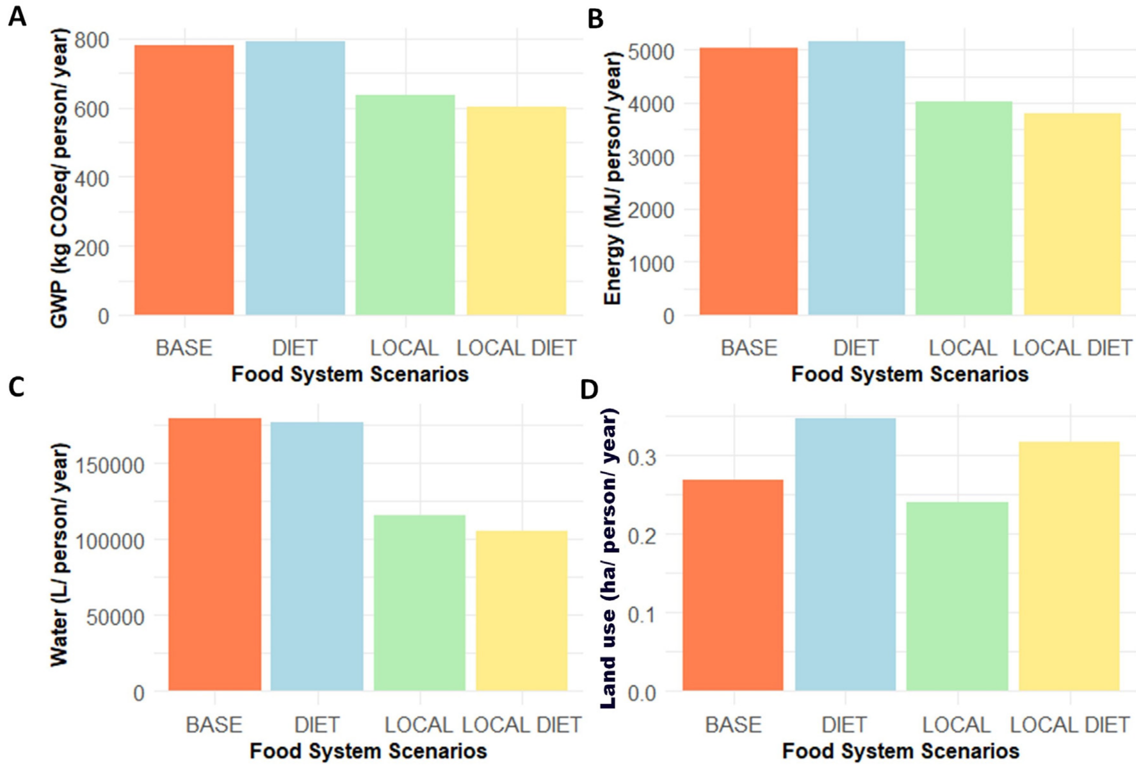

Fig. 2. Comparison of GWP (A), energy use (B), water use (C) and land use (D) for four food system scenarios: BASE (current production and consumption), DIET (current production, healthy consumption following HHS-USDA dietary guidelines), LOCAL (production localized within the Des Moines Metropolitan Statistical Area, current consumption), and LOCAL DIET (local production, healthy consumption) on a per person per year basis.

3. Results

3.1. Scenario comparisons

The BASE scenario produced slightly lower GWP (1.3 %) and energy (2.5 %) impacts per person and required slightly more water (1.4 %) compared to the DIET scenario (Fig. 2). The BASE scenario also used less land (29 %) relative to the DIET scenario. The LOCAL scenario had the least agricultural land use (LU), 10 % less than the BASE. The LOCAL DIET had lower impact than the LOCAL scenario across all categories except land use, which required 32 % more agricultural land than the LOCAL scenario. The LOCAL and LOCAL DIET scenarios both produced less GWP and lower energy impact, the LOCAL scenario produced 18–20 % less GWP, and LOCAL DIET produced 23–24 % less, compared to the BASE scenario. However, land use was a tradeoff, increasing by 19 % for LOCAL DIET compared to the BASE. Water use was significantly lower for the local scenarios decreasing by 35 and 41 % for the LOCAL and LOCAL DIET scenarios, respectively, compared to the BASE.

By food group, environmental impacts per person were largest for protein and dairy, which contributed an average of 76 % GWP, 63 % energy, 78 % water, and 60 % land use impacts across all four scenarios (Fig. 3). For the scenarios with modified consumption patterns (DIET / LOCAL DIET) the USDA the recommendation for decreased meat consumption reduced impacts for GWP and energy use by about 42 % compared to the BASE, and the recommendation for more dairy consumption increased impacts for GWP and energy use by 97 %. Although fruit and vegetable food group consumption and environmental impacts increased for the DIET scenario (128 and 52 %, respectively) compared to the BASE, this did not represent a large increase for the entire food system. Land use was greater in the local scenarios due to the area required for dairy, which made up 52 % of land use for the DIET and LOCAL DIET scenarios.

3.2. Local alternative assessments

The LOCAL scenario was compared to three alternatives (Fig. 4). Alternative 1 included no fruit and vegetable processing which resulted in reduced GWP and energy use (by about 0.12 %), but increased land use by 8 % compared to the LOCAL scenario. Changes in water use were not accounted for in this comparison (we did not find peer-reviewed data for quantities of water used for processing). Alternative 2 incorporated small-scale and extensive animal production. This shift increased land use (by 7 %) and GWP (by 2 %) but decreased energy (by 10 %) and water use (by 75 %) compared to the LOCAL scenario. Dairy production practices were not altered (this information was not available in FoodCarbonScope). Alternative 3 changed food consumption to meet EAT-Lancet dietary guidelines which reduced all environmental impacts - GWP (38 % decrease), energy (30 % decrease), water (50 % decrease), and land use (81 % decrease) compared to the LOCAL scenario.

By food group, protein and dairy produced the largest environmental impacts, making up 82 % of GWP, 70 % of energy use, 97 % of water use and 53 % of land use for Alt 1 (Fig. 5). Alt 3 reduced animal protein and increased dairy consumption. Protein and dairy made up a smaller percentage of the food system environmental impacts (about 10 % less for GWP, energy use and land use). In this case, reduction in impacts attributable to the protein food group were 65 % for GWP and 55 % for energy use and led to an overall reduction in impacts despite a 29 % increase in GWP and energy use for dairy consumption compared to the LOCAL scenario.

In Alt 1, only the vegetable and fruit food groups were impacted by the absence of processing, and the GWP changes were minor overall (−0.12 %) and by food group (vegetables (−3 %) and fruits (−1 %)) compared to the LOCAL scenario. Changes in water use were not included in Alt 1. Land use changed more for vegetables (+9 %) compared to fruits (+0.3 %) although these changes represented just a 0.44 % increase in land use overall. Changes for Alt 2 impacted only the protein food group, for which GWP and

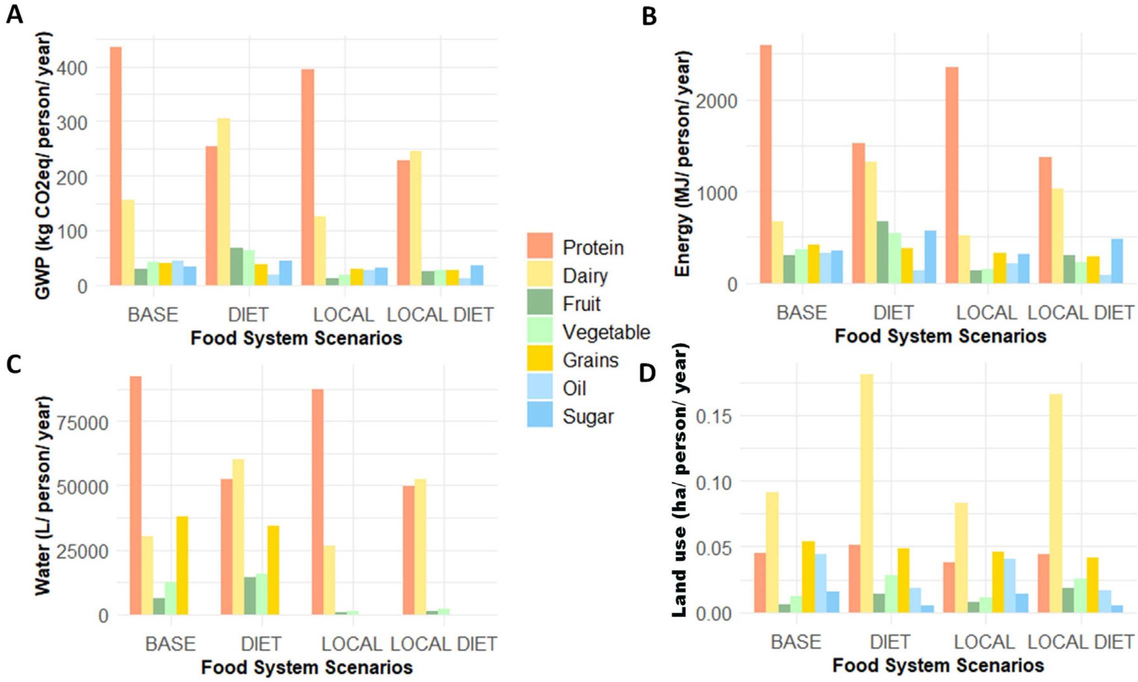

Fig. 3. Comparison of GWP (A), energy (B), water (C) and land use (D) for four food system scenarios: BASE (current production and consumption), DIET (current production, healthy consumption following HHS-USDA dietary guidelines), LOCAL (production localized within the Des Moines Metropolitan Statistical Area DM-MSA, current consumption), and LOCAL DIET (local production, healthy consumption) on a per person per year basis The assessment included 39 food types within seven food groups (protein, dairy, fruit, vegetables, grains, oil, sugar).

land use increased by 12 % and 47 % respectively; energy use and water use decreased by 17 % and 99.7 %, respectively, compared to the LOCAL scenario. In Alt 3, altered consumption patterns led to decreased GWP associated with protein, vegetables, oil, and sugar, and increased GWP for dairy, fruit, and grains compared to the LOCAL scenario. This pattern was the same for energy use except for the vegetable food group, which used more energy than the LOCAL scenario. Water use was higher for all food groups except protein (reduced by 77 %), resulting in a 50 % total water use reduction. Land use was reduced for all food groups and ranged from 34 % for vegetables to 96 % for sugar.

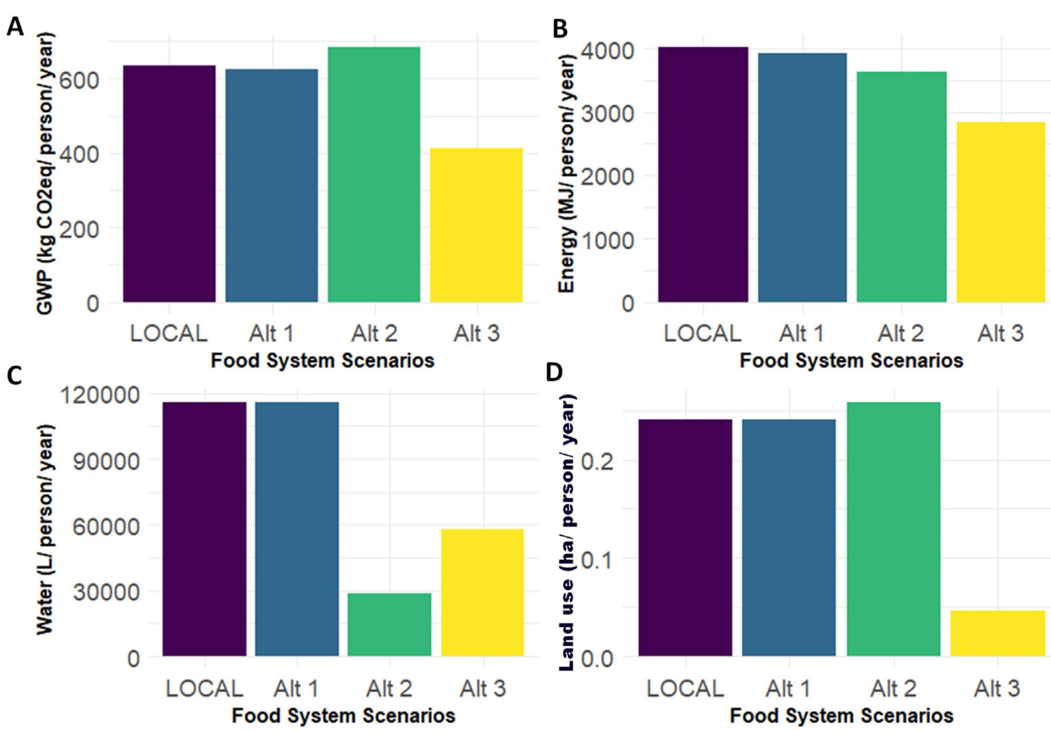

Fig. 4. Comparison of GWP (A), energy (B), water (C) and land use (D) for the LOCAL scenario (local production within the Des Moines Metropolitan Statistical Area DM-MSA, current consumption) to three alternatives (Alt). Alt 1 incorporated no fruit and vegetable processing locally; Alt 2 included small-scale and extensive animal production practices for all meat products; and Alt 3 incorporated the EAT-Lancet diet across the MSA on a per person per year basis.

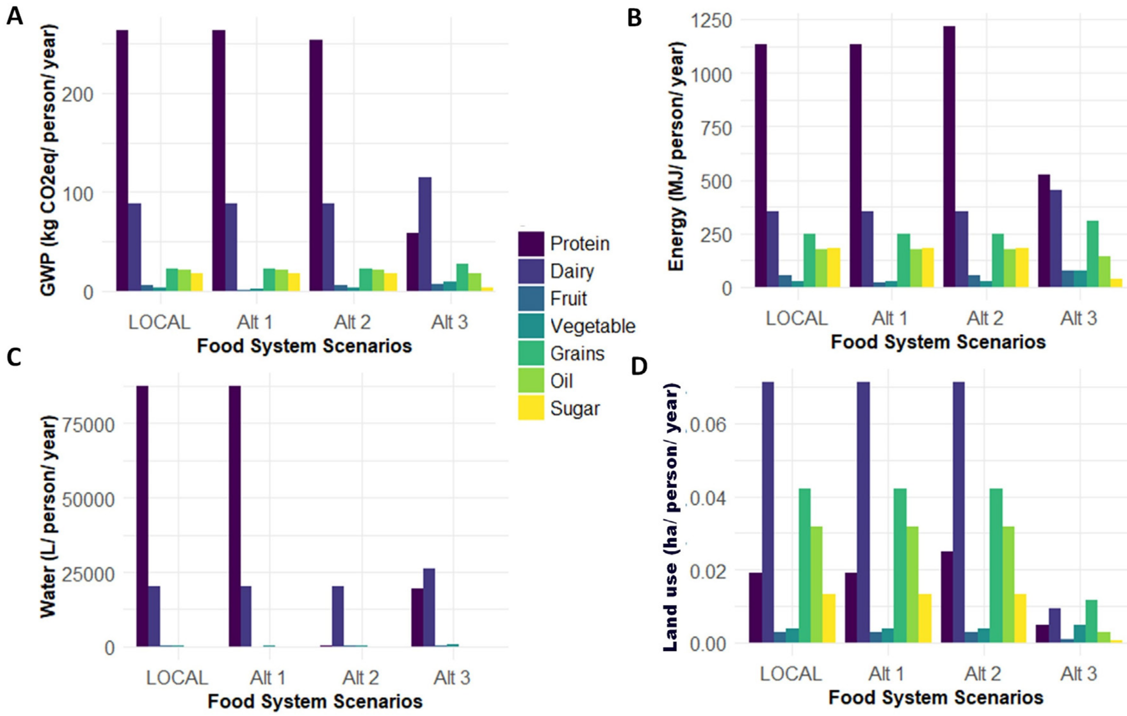

Fig. 5. Comparison of GWP (A), energy (B), water (C) and land use (D) for the LOCAL scenario (local production within the Des Moines Metropolitan Statistical Area DM-MSA, current consumption) and three alternative scenarios (Alt). Alt 1 incorporated no fruit and vegetable processing locally; Alt 2 included small-scale and extensive animal production practices for all meat products; Alt 3 incorporated the EAT-Lancet diet across the MSA on a per person each year basis.

3.3. Metropolitan-scale impacts

At the DM-MSA scale, the environmental impacts of changing consumption to match HHS-USDA dietary guidelines for Americans (DIET scenario) increased environmental impacts slightly compared to the baseline (1 to 3 %) except for land use which increased by 29 % (an increase of 56,000 ha) for the DIET scenario compared to the BASE. Reduction in environmental impacts associated with production of 50 % of food within the area (LOCAL) was larger compared to the BASE and generated 102 million kg less CO_{2eq} (18 %), used 703 million MJ less energy (20 %), and used 44 billion fewer L of water (35 %) for the DM-MSA each year. The LOCAL DIET scenarios resulted in an additional 5–6 % reduction in GWP and energy use, which amounts to 23 million kg CO_{2eq}, 159 million MJ, and 7 billion L (a 9 % reduction) in water use for the MSA each year compared to the LOCAL scenario. These additional reductions could come at a cost of increased land use in the MSA by 32 % (54,000 ha) each year compared to the LOCAL scenario. The LOCAL scenario would require use of 24 % of land zoned “agricultural” in the DM-MSA (8 % in perennial forages, 16 % in row crops), while the LOCAL DIET scenario would require 32 % of that land (14 % in perennial forages, 18 % in row crops).

Among alternatives within the LOCAL scenario, Alt 3 (the EAT-Lancet diet) had the largest reduction in environmental impacts. This diet reduced GWP production by 181 million kg CO_{2eq}, energy use by 837 million MJ, water use by 40 billion L, and land use by 137,000 ha. Alt 3 required just 5 % of the agricultural land in the DM-MSA. Results were mixed for Alt 2, which also reduced energy and water use compared to the local scenario but increased GWP by 10 million kg CO_{2eq} and land use by 12,700 ha, requiring a total of 183,000 ha or 26 % of agricultural land in the DM-MSA. Among the alternatives, Alt 1 produced least effect on parameters measured, with reductions in GWP (524,000 CO_{2eq}), and energy use (3 million MJ), but an increase in land use (13,000 ha) based on decreased marketable yields of produce for fresh markets compared to yields for processed fruits and vegetables.

3.4. Sensitivity analyses

Sensitivity analyses were conducted to determine how environmental impacts would be affected by a 20 % increase or a 20 % decrease in various model inputs (Fig. 6). The three variables tested were food consumption by food group, food waste, and food transport. The GWP and energy impacts were most sensitive to changes in protein and dairy for both consumption and food waste. This was expected based on the high environmental impacts of these food groups. By food group, water use sensitivity for protein and grain food groups were highest, followed by dairy and vegetables. For food waste, cheese was more sensitive than chicken or pork for both GWP and energy use, and soybean oil was more sensitive than chicken for GWP. The water use impacts of food waste were also greatest for changes in beef and cheese, wheat flour and vegetables. Land use sensitivity analyses were not conducted.

4. Discussion

4.1. Scenario comparisons

Results of our analyses indicate that local food production in our study area would greatly reduce environmental impacts. Our results differ from previous studies that defined local production based only on food miles rather than including other aspects of production and market practices that differ substantially from the national average, especially for fruits and vegetables (Goldstein et al., 2017; Weber and Matthews, 2008). Benis and Ferrão (2017) did not consider differences in local production methods or scale, as we did in our study for fruits and vegetables. We found average production-stage GWP reduction of 12 % for the LOCAL compared to BASE scenario, although we were not able determine local production differences for other food groups. In their city-scale LCA study of Lisbon, Portugal, Benis and Ferrão (2017) found that localizing food production within 30 km reduced GWP by 2.6 % for average consumption and 3.5 % for a diet that followed dietary recommendations (Benis and Ferrão, 2017).

Fig. 6. Sensitivity analyses for food group (A), food waste (B), and transport distance (C). Individual variables were adjusted by +/− 20 % to assess model sensitivity. For food waste and transport selected foods within each food group were assessed. Transport distance (C) did not impact water use, this is not shown.

Conversely, we found that local production is more impactful than following HHS-USDA dietary recommendations.

Food consumption following HHS-USDA dietary guidelines in our DIET scenario led to minimal energy use reductions, similar to a nationwide study of food system energy use conducted by Canning et al. (2017): Their result was a 3 % decrease and ours was a 2.5 % decrease. Eight studies focused on European dietary guidelines and healthy diet scenarios produced much greater reductions than those focused on HHS-USDA dietary guidelines for Americans, at 8 % to 32 % for GWP and 18 % to 38 % for land use, compared to current average national diets (Benis and Ferrão, 2017). As agricultural production methods that better address greenhouse gas emissions and changing climate conditions become more popular revision of dietary recommendations for Americans based on a broader set of health and environmental criteria will likely be required.

We investigated impacts associated with three diets constructed to meet 50 % of average nutritional needs based on current food availability per capita for the BASE, combined with dietary requirements for macronutrients (DIET, LOCALDIET, Alt 3). However, intake differences by age, sex and activity level were not separated in our analyses. In addition, certain micronutrients can be difficult to procure or provide locally. Costello et al. (2021) found that specific micronutrients (e.g., vitamin D, vitamin B_{12}, calcium) in their local production optimization model for Chicago could not be fully satisfied locally without much greater land use; these nuances were not included in our study.

The results of our study considered by food group highlight the effects of protein and dairy food groups for all environmental parameters, which are well established in the literature (Section 1.3). Altering consumption to follow HHS-USDA dietary guidelines required less meat and more fruit and vegetable consumption; however, a reduction in environmental impacts did not occur due to recommendations for increased milk and cheese consumption compared to current consumption in the USA (Canning et al., 2017). This added significantly to environmental impacts for the DIET and LOCAL DIET scenarios. Dairy represents 40 % of food system GWP, 26 % of energy used, 40 % of water used, and 52 % of land used. By contrast, fruits and vegetables represent just 13 % of land use for the DIET scenarios. Reducing the recommended amount of dairy consumption and replacing it with plant-based protein, such as milk substitutes, could decrease the environmental costs of this recommended diet.

Per capita GWP emissions in our model were 780 CO_{2eq} yr^{-1} for the BASE scenario, 791 CO_{2eq} yr^{-1} for the DIET scenario, 636 CO_{2eq} yr^{-1} for the LOCAL scenario, and 602 CO_{2eq} yr^{-1} for the LOCAL DIET scenario. Boehm et al. (2018) estimated that 50 % of current consumption (for system boundaries from cradle to consumer) would produce 1879 CO_{2eq} yr^{-1} based on an Economic Input-Output (I—O) LCA model, about 2.4 times the GWP impact of the 50 % diet we considered. Other studies using I—O LCA and the same system boundaries we used also had higher results compared to our findings, at 1022 CO_{2eq} yr^{-1} (Jones and Kammen, 2011), 1223 CO_{2eq} yr^{-1} (Canning et al., 2017), and 1533 CO_{2eq} yr^{-1} (Weber and Matthews, 2008). Although I—O LCA analyses can model entire economic sectors at large scales (e.g., the entire USA), and incorporate important interconnections between sectors, accounting for these interconnections might explain the larger estimated food system impacts compared to our results (Mattila et al., 2013; Yang et al., 2017). Process-based LCA methods on the other hand, can provide more targeted, scenario-specific results (Cucurachi et al., 2019). Based on compilations of LCA studies researchers have estimated that food system GWP would variously be less, at 475 CO_{2eq} yr^{-1} (Soret et al., 2014), slightly higher at 858 CO_{2eq} yr^{-1} (Heller et al., 2018), or similar to our study, at 657 CO_{2eq} yr^{-1} (Heller and Keoleian, 2015). Results most similar to our observations were for the study that also used the USDA food availability data set, combining this estimated consumption with emission factors based on a meta-analysis for various food types (Heller and Keoleian, 2015). Future research comparing different LCA methods and results in a food system context would be useful to identify strengths, weaknesses, and proper application of analytical approaches.

The GWP produced and fossil energy used for production are highly correlated in the context of food systems and changes for these parameters in our study were similar to each other, as expected (D'Odorico et al., 2018). Following HHS-USDA dietary guidelines increased per person GWP and energy impacts slightly compared to the baseline - one possible explanation for this could be the increase in dairy consumption. Heller et al. (2013) found that a shift to follow HHS-USDA dietary guidelines could increase dietary GWP by 6 % for a diet meeting 50 % of dietary requirements, while our analysis indicated only a 1.3 % GWP increase. Changes in GWP for both situations were primarily due to recommendations for more dairy consumption. Although the LOCAL DIET scenario followed HHS-USDA dietary guidelines, it produced less GWP and used less fossil energy per person, even compared to the LOCAL scenario. In this case, the reduction in GWP from lower meat (42 %), grain (10 %), and oil (58 %) consumption in the LOCAL DIET scenario offset increased dairy consumption and led to a 5 % to 6 % overall GWP reduction compared to the LOCAL scenario.

Reduced water use for the LOCAL and LOCAL DIET scenarios was also expected since the DM-MSA, like much of the Midwest, relies primarily on rain to supply water. Climate change is altering temperature and precipitation patterns, which will likely have different impacts on yields by crop type (Jabal et al., 2022). In our study area we anticipate a greater number of high-intensity rain events that are less frequent (Takle and Gutowski, 2020). This may impact planting dates and could increase the need for irrigation in the summer months, particularly for specialty crops (Johnson and Morton, 2015). Climate change is also expected to reduce precipitation amounts in California, where over 50 % percent of fruits and vegetables currently consumed in our study area are produced, adding to pressing water scarcity issues at that location (Johnson and Cody, 2015). These changing weather and precipitation patterns could make the localization of food systems increasingly desirable for the Midwest, USA.

An increase in land use for the DIET scenarios in our study was primarily due to areas needed to produce perennial forages necessary for increased dairy consumption to meet the HHS-USDA dietary guidelines. Dairy made up 52 % of food system land use for the DIET and LOCAL DIET scenarios. Of the land necessary for dairy production, 81 % was for growing forages (e.g., hay, alfalfa), which compared to row crops would be in perennial cover with lower nutrient inputs and could be grown on land that has high erosion potential. The environmental impacts of perennial forage production in terms of erosion and nutrient runoff would be mitigated compared to similar increases in row crop production (row crops increased by just 2 % in the DIET scenarios). It is important to note that livestock production practices for meat and dairy for these four scenarios were not altered from the current large-scale intensive livestock operations, and though a large proportion of these products are exported from the state we assumed some would be diverted to a local stream within the scenarios (USDA, 2019). To specifically explore the integration of extensive, small-scale livestock production (for meat products only) we developed local Alt 2 (Section 2.2).

In our study, information about production and retail practices were incorporated to build a novel LOCAL food scenario based on available literature and information from extension specialists at Iowa State University. This led to larger differences between the BASE and LOCAL scenarios because of the concentration of impacts in the production and manufacturing food system stages (28 % of GWP for fruits and nuts) and retail (27 % of GWP for fruits and nuts) compared to truck transportation (19 % of GWP for fruits and nuts, 13 % for fresh vegetables and melons) (Boehm et al., 2018). Consideration of the difference between local/regional and national/global food systems across the food system cycle together with more comprehensive sets of biophysical and social indicators (e.g., measures of resilience and social equity) would lead to more holistic food system assessments, accounting for important tradeoffs (Berardy et al., 2020). This could also minimize efficiency bias of LCA analyses, which can cause valuable food system characteristics such as social equity and resilience to be overlooked. Some of these food system characteristics were brought to light in the Midwest during the Covid-19 pandemic when supply chain issues led to large amounts of food waste (Bellamy et al., 2021; Berardy et al., 2020). A study of food waste in local Midwest food systems or local food systems with similar market channels would be of great value and could inform and refine our scenarios. Based on earlier research, political support through national waste management systems and initiatives were influential for waste minimization across Europe and could provide a useful model for post-pandemic food systems in the Midwest (Grinberga-Zalite and Zvirbule, 2022).

4.2. Local alternative assessments

Building novel alternatives to the local scenario based on biophysical and sociopolitical food system characteristics enabled an insightful and more nuanced evaluation of possible future scenarios. Alt 1, which excluded fruit and vegetable processing from our LOCAL scenario, presented additional challenges, particularly related to the seasonality of Iowa agriculture and the perishability of some fruits and vegetables. Alt 1 was selected because the infrastructure to process fruits and vegetables is extremely limited in our study area, even though processed produce makes up about 32 % of fruit and 26 % of vegetable consumption in current diets. Although including fruit and vegetable processing (Alt 1) minimally changed food system environmental impacts, produce processing reduces food waste and increases local produce consumption year-round. These impacts were not accounted for due to the lack of available data at appropriate scales. It is important to note that we did not incorporate year-round production (e.g., using greenhouses) in any of the models we considered.

Although this would reduce the need for processing and increase fresh produce availability, greenhouse production in our region is very energy- and GWP-intensive. For example, in previous LCA studies investigators found that GWP associated with growing 1 kg of tomato in a greenhouse in northern regions was large, between 1.27 and 1.97 CO_{2eq} compared to 0.27 CO_{2eq} in our LOCAL scenario (Goldstein et al., 2016a).

The greatest difference between Alt 1 and the LOCAL scenario was for land use. This 9 % increase in land use for vegetables was primarily due to lower yields for fresh fruits and vegetables compared to processed ones. Produce processed for wholesale markets can achieve much higher marketable yields based on USDA standards compared to fresh markets in which consumer preferences typically require unblemished produce. For tomatoes, average marketable yields for fresh consumption are about 34,000 kg ha^{-1} yr^{-1} compared to a yield of 86,000 kg ha^{-1} yr^{-1} for processed tomatoes. This represents an average increase of 150 %, which can account for the increase in land use for production based on lower expected fresh market tomato yields.

Alt 2 was important to elucidate how changes in livestock production practices could change food system environmental impacts. Extensive practices require more land for grazing and led to an increase in perennial cover for grazing. GWP increased for grass-fed ruminants (e.g., cattle) due to the time it takes to raise animals to market weight since a byproduct of their digestion is the greenhouse gas methane. Heller and Keoleian (2015) found that although beef accounted for 4 % of retail food supply by weight, it made up 36 % of GHG. Grass-fed or extensive beef production results for our Alt 2 were similar to other LCA studies, with grass-fed beef requiring more land (47 % increase), almost all of which was in perennial forage, compared to about 34 % of land use based on conventional feeding in the LOCAL scenario. This increase could be an important opportunity to increase biodiversity and stabilize erodible soils based on perennial land cover with diverse plant mixes compared with row crop production used to produce conventional feed (corn and soy in Iowa) (Tichenor et al., 2017). Although several studies have indicated that shifting toward grass-fed beef increased the carbon footprint of the system, this shift was also associated with lower eutrophication and acidification per unit of land, illustrating important tradeoffs (Pelletier et al., 2010; Tichenor et al., 2017). Our findings for Alt 2 are similar to those for other livestock studies with free-range poultry and eggs, resulting in a GWP increase of about 10 % in both cases (Nijdam et al., 2012). Assessing additional environmental impacts for livestock beyond GWP, energy use, water use and land use could be important to understanding other impacts of using more extensive and smaller-scale livestock management practices. Incorporating other normative improvements such as animal welfare and livestock supply chain resilience could provide a better understanding of impacts beyond decreased energy use and water use (Berardy et al., 2020; de Boer et al., 2011).

Alt 3 reduced environmental impacts more than the other scenarios we assessed. The large shift in consumption associated with the EAT-Lancet diet is not likely to be adopted in the DM-MSA if meat consumption remains near current levels (consumers in the USA eat three times as much meat as the global average; Chemnitz et al., 2021). However, consideration of this alternative diet could enhance decision makers' understanding of environmental impacts that could be avoided by developing a new set of dietary recommendations that balance human and environmental goals (and to better align with UN Sustainable Development Goals (UNDP, 2020)). To further optimize production and consumption, additional testing using combinations of local alternatives could be useful, such as combining adjustments in Alt 3 (consumption) with those in Alt 2 (livestock production) to possibly further reduce environmental impacts for the DM-MSA local food system.

4.3. Metropolitan scale impacts

With a population of approximately 700,000, the DM-MSA is similar to many other metropolitan areas. If food system changes were made to reduce environmental impacts across the Midwest, this could also increase food system biodiversity and resilience in the region, an important weakness of current food systems as highlighted by the Covid-19 pandemic (Prokopy et al., 2020). For perspective on how much agricultural land would be required to increase local production from 5 % to 50 % of dietary requirements on a metropolitan scale, the LOCAL scenario would require approximately 170,260 ha (25 % of land zoned "agricultural" in the MSA); 33 % of that area would be for perennial forage. By contrast, the LOCAL DIET scenario would require 232,590 ha (32 % of agricultural land in the MSA) to meet the same requirement, with 44 % of that quantity of agricultural land used for perennial forage. However, a shift to Alt 3 (EAT-Lancet diet) would reduce the land requirement to just 32,980 ha (or 5 % of agricultural land in the MSA). Importing livestock feeds from nearby counties could also decrease land use by about 51 % for the LOCAL scenario and 66 % for the LOCAL DIET scenario.

Although Alt 1 did not produce large environmental impact changes based on model output, the true impact of produce processing would include availability of additional markets for producers and year-round provisioning of local fruit and vegetables. Alt 2 produced variable results among environmental impacts assessed, and additional environmental impacts should be considered. The Alt 3 (EAT-Lancet) local alternative had the lowest environmental impacts for which DM-MSA scale reductions were 260 million kg CO_{2eq} yr^{-1} for GWP (−47 %), 1.5 billion MJ yr^{-1} for energy (−44 %), 85 billion L yr^{-1} for water (−68 %), and 156,148 ha yr^{-1} for land use (−83 %) compared to the BASE scenario. In our study area and in the Midwest in general city planners and practitioners interested in increasing environmental sustainability should consider the role of local food production and consumption patterns, while advocating for revising USA dietary recommendations to fulfill social and environmental sustainability objectives.

4.4. Sensitivity analyses

In our study, meat consumption had large environmental impacts. Consuming fewer animal products is important to both human and environmental health as described in many studies in the USA and worldwide (Chemnitz et al., 2021; Curran, 2016; Heller et al., 2018; Rehkamp et al., 2017). Food waste is a large source of inefficiency and causes environmental impacts across the food-energy-water nexus (Proctor et al., 2021). Our model was most strongly impacted by animal product food waste. Although estimates of food waste in the USA vary, recent studies have found that between 37 and 89 Mt. are wasted each year, and the stage at which food is wasted also changes the magnitude of associated environmental impacts (Muth et al., 2019; Read et al., 2020). In this study we used average food waste percentages by food group and stage for the USA, which did not account for waste that might be specific to local market channels (Buzby et al., 2014). Information regarding the amount of food waste in the Midwest or local food markets more generally would be important for reducing model uncertainty and of great value in future studies. Transport sensitivity was greatest for fruits and vegetables since these foods travel long distances (over 50 % come from California) to the Midwest; thus increasing the distance by 20 % in our sensitivity analysis produces the largest impact. Localizing fruit and vegetable production, in particular, could lead to environmental impact reductions, improve food system resilience. and create economic benefits for producers and consumers alike (Enshayan, 2009). In Iowa, where many livestock and commodity crops are produced, reducing transport distances for these products by 20 % had only a negligible effect on environmental impacts. Instead, livestock inputs at production and food waste stages should be carefully assessed to evaluate impacts.

5. Conclusions

Results of this study indicate that localizing food production would be more impactful than changing consumption to follow dietary recommendations for Americans provided by the federal government. Increasing local food production to meet 50 % of nutritional requirements for macronutrients based on food availability per capita in an important metropolitan area in the Midwest USA decreased global warming potential (GWP), energy and water use within the food system by 19, 20, and 35 %, respectively. It should be noted that in this study we used values for current consumption based on averages determined at the national scale and did not incorporate specific differences in consumption requirements for subgroups (by age, sex, or activity level) or for micronutrients. Future studies could address identity-based consumption patterns.

Local food production decreased land use by 10 % and would require approximately 25 % of land currently zoned for agricultural use to provide for 50 % of current food consumption. However, changing to a diet optimized for human and environmental health could provide 50 % of the dietary requirements for the metropolitan area using just 5 % of current agricultural land and decreasing GWP by 47 % compared to the baseline. In the context of climate change and increased environmental degradation, understanding the consequences of food system changes to support decision making at a metropolitan scale could be an important catalyst for appropriate planning near growing urban centers.

Food production and consumption are important drivers of environmental impacts, and urban and peri-urban agriculture could play an important role in improving food system sustainability. Local government policies and decisions can strongly influence local food systems. These systems are highly context-specific, and partnerships can lead to creation of food systems that produce positive environmental and social outcomes. For successful food system changes, place-based policies should be built based on regional and cultural context, ideally with participation from transdisciplinary teams using stakeholder engagement. It would also be valuable to work with local government and institutional partners to continue building food systems based on the integration of socio-political and biophysical realities to build resilient and sustainable food systems at the MSA scale and beyond.

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CRediT authorship contribution statement

Tiffanie F. Stone: Conceptualization, Methodology, Validation, Data curation, Formal analysis, Writing – original draft, Visualization, Investigation. **Janette R. Thompson:** Conceptualization, Methodology, Validation, Supervision, Funding acquisition, Writing – review & editing. **Kurt A. Rosentrater:** Conceptualization, Methodology, Validation, Supervision, Writing – review & editing. **Matt Liebman:** Conceptualization, Methodology, Validation, Funding acquisition, Writing – review & editing.

Data availability

The data used to build the scenarios are included in the supplemental materials, the specific results from the CleanMetrics model are proprietary and not included.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

Badami, M.G., Ramankutty, N., 2015. Urban agriculture and food security: a critique based on an assessment of urban land constraints. Glob. Food Secur. 4, 8–15. https://doi.org/10.1016/j.gfs.2014.10.003.

Bellamy, A.S., Furness, E., Nicol, P., Pitt, H., Taherzadeh, A., 2021. Shaping more resilient and just food systems: lessons from the COVID-19 pandemic. Ambio 50, 782–793. https://doi.org/10.1007/s13280-021-01532-y.

Benis, K., Ferrão, P., 2017. Potential mitigation of the environmental impacts of food systems through urban and peri-urban agriculture (UPA) – a life cycle assessment approach. J. Clean. Prod. 140, 784–795. https://doi.org/10.1016/j.jclepro.2016.05.176.

Berardy, A., Seager, T., Costello, C., Wharton, C., 2020. Considering the role of life cycle analysis in holistic food systems research policy and practice. J. Agric. Food Syst. Community Dev. 9, 1–19. https://doi.org/10.5304/jafscd.2020.094.009.

Boehm, R., Wilde, P.E., Ver Ploeg, M., Costello, C., Cash, S.B., 2018. A comprehensive life cycle assessment of greenhouse gas emissions from U.S. household food choices. Food Policy 79, 67–76. https://doi.org/10.1016/j.foodpol.2018.05.004.

Boyer, D., Ramaswami, A., 2020. Comparing urban food system characteristics and actions in US and Indian cities from a multi-environmental impact perspective: toward a streamlined approach. J. Ind. Ecol. 24, 841–854. https://doi.org/10.1111/jiec.12985.

Buzby, J.C., Wells, H.F., Hyman, J., 2014. The estimated amount, value, and calories of postharvest food losses at the retail and consumer levels in the United States, EIB-121.

Canning, P., Rehkamp, S., Waters, A., 2017. The Role of Fossil Fuels in the U.S. Food System And the American Diet. 224. United States Dep. Agric. - Econ. Res. Serv., pp. 2007–2008.

Chemnitz, C., Becheva, S., et al., 2021. Meat atlas. Heinrich Böll Stiftung, Berlin, Germany Friends of the Earth Europe, Brussels, 1st ed. Belgium Bund für Umwelt und Naturschutz, Berlin, Germany, Berlin, Germany New York, NY, USA.

CleanMetrics, 2020. FoodCarbonScope [WWW Document]. URL. https://www.cleanmetrics.com/foodcarbonscope.

Clinton, N., Stuhlmacher, M., Miles, A., Uludere Aragon, N., Wagner, M., Georgescu, M., Herwig, C., Gong, P., 2018. A global geospatial ecosystem services estimate of urban agriculture. Earth's Futur. 6, 40–60. https://doi.org/10.1002/2017EF000536.

Clune, S., Crossin, E., Verghese, K., 2017. Systematic review of greenhouse gas emissions for different fresh food categories. J. Clean. Prod. 140, 766–783. https://doi.org/10.1016/j.jclepro.2016.04.082.

Costello, C., Oveysi, Z., Dundar, B., McGarvey, R., 2021. Assessment of the effect of urban agriculture on achieving a localized food system centered on Chicago, Il using robust optimization. Environ. Sci. Technol. 55, 2684–2694. https://doi.org/10.1021/acs.est.0c04118.

Cucurachi, S., Scherer, L., Guinée, J., Tukker, A., 2019. Life cycle assessment of food systems. One Earth 1, 292–297. https://doi.org/10.1016/j.oneear.2019.10.014.

Curran, M.A., 2016. Life cycle assessment in the agri-food sector: case studies, methodological issues, and best practices. Int. J. Life Cycle Assess. 21, 785–787. https://doi.org/10.1007/s11367-015-0977-5.

D'Odorico, P., Davis, K.F., Rosa, L., Carr, J.A., Chiarelli, D., Dell'Angelo, J., Gephart, J., MacDonald, G.K., Seekell, D.A., Suweis, S., Rulli, M.C., 2018. The global food-energy-water nexus. Rev. Geophys. 56, 456–531. https://doi.org/10.1029/2017RG000591.

de Boer, I., Cederberg, C., Eady, S., Gollnow, S., Kristensen, T., Macleod, M., Meul, M., Nemecek, T., Phong, L., Thoma, G., van der Werf, H., Williams, A., Zonderland-Thomassen, M., 2011. Greenhouse gas mitigation in animal production: towards an integrated life cycle sustainability assessment. Curr. Opin. Environ. Sustain. 3, 423–431. https://doi.org/10.1016/j.cosust.2011.08.007.

Djekic, I., Pojić, M., Tonda, A., Putnik, P., Bursać Kovačević, D., Režek-Jambrak, A., Tomasevic, I., 2019. Scientific challenges in performing life-cycle assessment in the food supply chain. Foods 8, 301. https://doi.org/10.3390/foods8080301.

EFNEP, 2020. Digital resources: Polk county [WWW Document]. URLIowa State Univ. Ext. Outreach, Expand. Food Nutr. Educ. Progr (accessed 2.12.20). https://efnepdigitalresources.org/resources/.

Enderton, A., Bregendahl, C., Swenson, D., Adcock, L., Alexa, W., Topaloff, A., 2017. Iowa commercial horticulture food crop survey results 2015.

Enshayan, K., 2009. Community economic impact assessment for a multi-county local food system in northeast Iowa [WWW Document]. URLLeopold Cent. Complet. Grant Reports. https://lib.dr.iastate.edu/leopold_grantreports/330.

Enthoven, L., Van den Broeck, G., 2021. Local food systems: reviewing two decades of research. Agric. Syst. 193, 103226. https://doi.org/10.1016/j.agsy.2021.103226.

Fanzo, J., 2019. Healthy and sustainable diets and food systems: the key to achieving sustainable development goal 2. Food Ethics 4, 159–174. https://doi.org/10.1007/s41055-019-00052-6.

FAO, 2010. Climate-smart agriculture: Policies, practices and financing for food security, adaptation and mitigation [WWW Document]. URLHague Conf. Agric. Food Secur. Clim. Chang (accessed 1.6.21) https://www.fao.org/3/i1881e/i1881e00.htm.

Flachowsky, G., Meyer, U., Südekum, K.H., 2017. Land use for edible protein of animal origin—a review. Animals 7, 1–19. https://doi.org/10.3390/ani7030025.

Gava, O., Bartolini, F., Venturi, F., Brunori, G., Zinnai, A., Pardossi, A., 2018. A reflection of the use of the life cycle assessment tool for agri-food sustainability. Sustainability 11. https://doi.org/10.3390/su11010071.

Goldstein, B., Hauschild, M., Fernandez, J., Birkved, M., 2016a. Testing the environmental performance of urban agriculture as a food supply in northern climates. J. Clean. Prod. 135, 984–994. https://doi.org/10.1016/j.jclepro.2016.07.004.

Goldstein, B., Hauschild, M., Fernández, J., Birkved, M., 2016b. Urban versus conventional agriculture, taxonomy of resource profiles: a review. Agron. Sustain. Dev. https://doi.org/10.1007/s13593-015-0348-4.

Goldstein, B.P., Hauschild, M.Z., Fernández, J.E., Birkved, M., 2017. Contributions of local farming to urban sustainability in the Northeast United States. Environ. Sci. Technol. 51, 7340–7349. https://doi.org/10.1021/acs.est.7b01011.

Gray, L., Guzman, P., Glowa, K.M., Drevno, A.G., 2014. Can home gardens scale up into movements for social change? The role of home gardens in providing food security and community change in San Jose,California. Local Environ. 19, 187–203. https://doi.org/10.1080/13549839.2013.792048.

Grinberga-Zalite, G., Zvirbule, A., 2022. Analysis of waste minimization challenges to European food production enterprises. Emerg. Sci. J. 6, 530–543. https://doi.org/10.28991/ESJ-2022-06-03-08.

Guitart, D., Pickering, C., Byrne, J., 2012. Past results and future directions in urban community gardens research. Urban For. Urban Green. 11, 364–373. https://doi.org/10.1016/j.ufug.2012.06.007.

Heller, M.C., Keoleian, G.A., 2015. Greenhouse gas emission estimates of U.S. dietary choices and food loss. J. Ind. Ecol. 19, 391–401. https://doi.org/10.1111/jiec.12174.

Heller, M.C., Keoleian, G.A., Willett, W.C., 2013. Toward a life cycle-based, diet-level framework for food environmental impact and nutritional quality assessment: a critical review. Environ. Sci. Technol. 47, 12632–12647. https://doi.org/10.1021/es4025113.

Heller, M.C., Willits-Smith, A., Meyer, R., Keoleian, G.A., Rose, D., 2018. Greenhouse gas emissions and energy use associated with production of individual self-selected US diets. Environ. Res. Lett. 13. https://doi.org/10.1088/1748-9326/aab0ac.

HHS-USDA, 2015. 2015 – 2020 dietary guidelines for Americans. 2015 – 2020 Dietary Guidelines for Americans, 8th edition. https://doi.org/10.1097/NT.0b013e31826c50af. New York, NY, USA.

Jabal, Z.K., Khayyun, T.S., Alwan, I.A., 2022. Impact of climate change on crops productivity using MODIS-NDVI time series. Civ. Eng. J. 8, 1136–1156. https://doi.org/10.28991/CEJ-2022-08-06-04.

Johnson, A., Morton, L.W., 2015. Midwest climate and specialty crops: specialty crop leader views and priorities for midwest specialty crops. USDA Sociol. Tech. Rep. 1039 Department, pp. 1–21.

Johnson, R., Cody, B.A., 2015. California agricultural production and irrigated water use [WWW Document]. URLCongr. Res. Serv. https://crsreports.congress.gov/product/pdf/R/R44093.

Jones, C.M., Kammen, D.M., 2011. Quantifying carbon footprint reduction opportunities for U.S. households and communities. Environ. Sci. Technol. 45, 4088–4095. https://doi.org/10.1021/es102221h.

Kim, B.F., Santo, R.E., Scatterday, A.P., Fry, J.P., Synk, C.M., Cebron, S.R., Mekonnen, M.M., Hoekstra, A.Y., de Pee, S., Bloem, M.W., Neff, R.A., Nachman, K.E., 2020. Country-specific dietary shifts to mitigate climate and water crises. Glob. Environ. Chang. 62, 101926. https://doi.org/10.1016/j.gloenvcha.2019.05.010.

Kirkpatrick, J.B., Davison, A., 2018. Home-grown: gardens, practices and motivations in urban domestic vegetable production. Landsc. Urban Plan. 170, 24–33. https://doi.org/10.1016/j.landurbplan.2017.09.023.

Klassen, S., Murphy, S., 2020. Equity as both a means and an end: lessons for resilient food systems from COVID-19. World Dev. 136. https://doi.org/10.1016/j.worlddev.2020.105104.

Krouse, L., Galluzzo, T., 2007. Iowa's local food systems: a place to grow [WWW Document]. URLIowa Policy Proj. (accessed 6.3.20) https://www.iowapolicyproject.org/2007docs/070206-LocalFood.pdf.

Kulak, M., Graves, A., Chatterton, J., 2013. Reducing greenhouse gas emissions with urban agriculture: a life cycle assessment perspective. Landsc. Urban Plan. 111, 68–78. https://doi.org/10.1016/j.landurbplan.2012.11.007.

Lovell, S.T., 2010. Multifunctional urban agriculture for sustainable land use planning in the United States. Sustainability 2, 2499–2522. https://doi.org/10.3390/su2082499.

Low, S., Adalja, A., Beaulieu, E., Key, N., Martinez, S., Melton, A., Perez, A., Ralston, K., Stewart, H., Suttles, S., Vogel, S., Jablonski, B.B.R., 2015. Trends in U.S. Local And Regional Food Systems Report to Congress. 92. U.S. Dep. Agric. Econ. Res. Serv.

Mattila, T., Koskela, S., Seppälä, J., Mäenpää, I., 2013. Sensitivity analysis of environmentally extended input-output models as a tool for building scenarios of sustainable development. Ecol. Econ. 86, 148–155. https://doi.org/10.1016/j.ecolecon.2012.11.021.

Mohareb, E., Heller, M., Novak, P., Goldstein, B., Fonoll, X., Raskin, L., 2017. Considerations for reducing food system energy demand while scaling up urban agriculture. Environ. Res. Lett. 12, 125004. https://doi.org/10.1088/1748-9326/aa889b.

Muth, M.K., Birney, C., Cuéllar, A., Finn, S.M., Freeman, M., Galloway, J.N., Gee, I., Gephart, J., Jones, K., Low, L., Meyer, E., Read, Q., Smith, T., Weitz, K., Zoubek, S., 2019. A systems approach to assessing environmental and economic effects of food loss and waste interventions in the United States. Sci. Total Environ. 685, 1240–1254. https://doi.org/10.1016/j.scitotenv.2019.06.230.

Nicholls, E., Ely, A., Birkin, L., Basu, P., Goulson, D., 2020. The contribution of small-scale food production in urban areas to the sustainable development goals: a review and case study. Sustain. Sci. https://doi.org/10.1007/s11625-020-00792-z.

Nijdam, D., Rood, T., Westhoek, H., 2012. The price of protein: review of land use and carbon footprints from life cycle assessments of animal food products and their substitutes. Food Policy 37, 760–770. https://doi.org/10.1016/j.foodpol.2012.08.002.

Notarnicola, B., Sala, S., Anton, A., McLaren, S.J., Saouter, E., Sonesson, U., 2017. The role of life cycle assessment in supporting sustainable agri-food systems: a review of the challenges. J. Clean. Prod. 140. https://doi.org/10.1016/j.jclepro.2016.06.071.

Opitz, I., Berges, R., Piorr, A., Krikser, T., 2016. Contributing to food security in urban areas: differences between urban agriculture and peri-urban agriculture in the Global North. Agric. Hum. Values 33. https://doi.org/10.1007/s10460-015-9610-2.

Pelletier, N., Pirog, R., Rasmussen, R., 2010. Comparative life cycle environmental impacts of three beef production strategies in the upper midwestern United States. Agric. Syst. 103, 380–389. https://doi.org/10.1016/j.agsy.2010.03.009.

Penman, J., Gytarsky, M., Hiraishi, T., Irving, W., Krug, T., 2006. 2006 IPCC guidelines for national greenhouse gas inventories [WWW Document]. URLIPCC (accessed 2.11.21) http://www.ipcc-nggip.iges.or.jp/public/2006gl/index.html.

Pérez-Neira, D., Grollmus-Venegas, A., 2018. Life-cycle energy assessment and carbon footprint of peri-urban horticulture. A comparative case study of local food systems in Spain. Landsc. Urban Plan. 172, 60–68. https://doi.org/10.1016/j.landurbplan.2018.01.001.

Pernollet, F., Coelho, C.R.V., van der Werf, H.M.G., 2017. Methods to simplify diet and food life cycle inventories: accuracy versus data-collection resources. J. Clean. Prod. 140, 410–420. https://doi.org/10.1016/j.jclepro.2016.06.111.

Peters, C.J., Bills, N.L., Lembo, A.J., Wilkins, J.L., Fick, G.W., 2009. Mapping potential foodsheds in New York State: a spatial model for evaluating the capacity to localize food production. Renew. Agric. Food Syst. 24, 72–84. https://doi.org/10.1017/S1742170508002457.

Peters, C.J., Picardy, J., Darrouzet-Nardi, A.F., Wilkins, J.L., Griffin, T.S., Fick, G.W., 2016. Carrying capacity of U.S. agricultural land: ten diet scenarios. Elementa 4, 0–15. https://doi.org/10.12952/journal.elementa.000116.

Poore, J., Nemecek, T., 2018. Reducing food's environmental impacts through producers and consumers. Science(80-.) 360, 987–992. https://doi.org/10.1126/science.aaq0216.

Practical Farmers of Iowa, 2022. Livestock on the land [WWW Document]. https://practicalfarmers.org/programs/livestock/livestock-on-the-land/.

Proctor, K., Tabatabaie, S.M.H., Murthy, G.S., 2021. Gateway to the perspectives of the food-energy-water nexus. Sci. Total Environ. 764, 142852. https://doi.org/10.1016/j.scitotenv.2020.142852.

Prokopy, L.S., Gramig, B.M., Bower, A., Church, S.P., Ellison, B., Gassman, P.W., Genskow, K., Gucker, D., Hallett, S.G., Hill, J., Hunt, N., Johnson, K.A., Kaplan, I., Kelleher, J.P., Kok, H., Komp, M., Lammers, P., LaRose, S., Liebman, M., Margenot, A., Mulla, D., O'Donnell, M.J., Peimer, A.W., Reaves, E., Salazar, K., Schelly, C., Schilling, K., Secchi, S., Spaulding, A.D., Swenson, D., Thompson, A.W., Ulrich-Schad, J.D., 2020. The urgency of transforming the midwestern U.S. landscape into more than corn and soybean. Agric. Hum. Values 37, 537–539. https://doi.org/10.1007/s10460-020-10077-x.

Pryshlakivsky, J., Searcy, C., 2013. Fifteen years of ISO 14040: a review. J. Clean. Prod. https://doi.org/10.1016/j.jclepro.2013.05.038.

Read, Q.D., Brown, S., Cuéllar, A.D., Finn, S.M., Gephart, J.A., Marston, L.T., Meyer, E., Weitz, K.A., Muth, M.K., 2020. Assessing the environmental impacts of halving food loss and waste along the food supply chain. Sci. Total Environ. 712. https://doi.org/10.1016/j.scitotenv.2019.136255.

Rehkamp, S., Azzam, A., Gustafson, C.R., 2017. US dietary shifts and the associated CO2 emissions from farm energy use. Food Stud. 7, 11–22. https://doi.org/10.18848/2160-1933/cgp/v07i02/11-22.

Reich, B.J., Beck, J.T., Price, J., 2018. Food as ideology: measurement and validation of locavorism. J. Consum. Res. 45, 849–868. https://doi.org/10.1093/jcr/ucy027.

Rothwell, A., Ridoutt, B., Page, G., Bellotti, W., 2016. Environmental performance of local food: trade-offs and implications for climate resilience in a developed city. J. Clean. Prod. 114, 420–430. https://doi.org/10.1016/j.jclepro.2015.04.096.

Saha, M., Eckelman, M.J., 2017. Growing fresh fruits and vegetables in an urban landscape: a geospatial assessment of ground level and rooftop urban agriculture potential in Boston, USA. Landsc. Urban Plan. 165, 130–141. https://doi.org/10.1016/j.landurbplan.2017.04.015.

Sanjuán, N., Stoessel, F., Hellweg, S., 2014. Closing data gaps for LCA of food products: estimating the energy demand of food processing. Environ. Sci. Technol. 48, 1132–1140. https://doi.org/10.1021/es4033716.

Soret, S., Mejia, A., Batech, M., Jaceldo-Siegl, K., Harwatt, H., Sabaté, J., 2014. Climate change mitigation and health effects of varied dietary patterns in real-life settings throughout North America. Am. J. Clin. Nutr. 100, 490S–495S. https://doi.org/10.3945/ajcn.113.071589.

Stone, T.F., Thompson, J.R., Rosentrater, K.A., Nair, A., 2021. A life cycle assessment approach for vegetables in large-, mid-, and small-scale food systems in the Midwest US. Sustainability 13. https://doi.org/10.3390/su132011368.

Takle, E.S., Gutowski, W.J., 2020. Iowa's agriculture is losing its goldilocks climate. Phys. Today 73, 26–33. https://doi.org/10.1063/PT.3.4407.

Telesetsky, A., 2014. Community-based urban agriculture as affirmative environmental justice. Univ. Detroit Mercy Law Rev. 91, pp. 259–276.

Thompson, J., Ganapathysubramanian, B., Chen, W., Dorneich, M., Gassman, P., Krejci, C., Liebman, M., Nair, A., Passe, U., Schwab, N., Rosentrater, K., Stone, T., Wang, Y., Zhou, Y., 2021. Iowa urban FEWS: integrating social and biophysical models for exploration of urban food, energy, and water systems. Front. Big Data 4, 1–12. https://doi.org/10.3389/fdata.2021.662186.

Tichenor, N.E., van Zanten, H.H.E., de Boer, I.J.M., Peters, C.J., McCarthy, A.C., Griffin, T.S., 2017. Land use efficiency of beef systems in the Northeastern USA from a food supply perspective. Agric. Syst. 156, 34–42. https://doi.org/10.1016/j.agsy.2017.05.011.

UN, 2019. World urbanization prospects: the 2018 revision [WWW Document]. URLUnited Nations Dep. Econ. Soc. Aff. Popul. Div. (accessed 1.12.21) https://www.un.org/development/desa/pd/sites/www.un.org.development.desa.pd/files/files/documents/2020/Jan/un_2018_wup_report.pdf.

UNDP, 2020. The next frontier: human development and the Anthropocene. Human Development Report 2020 New York, NY, USA.

USDA, 2019. Cash receipts by commodity state ranking [WWW Document]. URLUnited States Dep. Agric. https://data.ers.usda.gov/reports.aspx?ID=17844#P306e5f77c69a4c35b7a3455c55ef73d6_2_251iT0R0x137.

USDA-ERS, 2016. Food availability (per capita) data system [WWW Document]. United States Dep. Agric. Econ. Res. Serv. New York, NY, USA https://www.ers.usda.gov/data-products/food-availability-per-capita-data-system/.

Wang, X., 2022. Managing land carrying capacity: key to achieving sustainable production systems for food security. Land 11, 484. https://doi.org/10.3390/land11040484.

Weber, C.L., Matthews, H.S., 2008. Food-miles and the relative climate impacts of food choices in the United States. Environ. Sci. Technol. 42, 3508–3513. https://doi.org/10.1021/es901016m.

Willett, W., Rockström, J., Loken, B., Springmann, M., Lang, T., Vermeulen, S., Garnett, T., Tilman, D., DeClerck, F., Wood, A., Jonell, M., Clark, M., Gordon, L.J., Fanzo, J., Hawkes, C., Zurayk, R., Rivera, J.A., De Vries, W., Majele Sibanda, L., Afshin, A., Chaudhary, A., Herrero, M., Agustina, R., Branca, F., Lartey, A., Fan, S., Crona, B., Fox, E., Bignet, V., Troell, M., Lindahl, T., Singh, S., Cornell, S.E., Srinath Reddy, K., Narain, S., Nishtar, S., Murray, C.J.L., 2019. Food in the Anthropocene: the EAT–Lancet Commission on healthy diets from sustainable food systems. Lancet 393, 447–492. https://doi.org/10.1016/S0140-6736(18)31788-4.

Wu, M., 2020. Food justice agenda for a resilient Boston [WWW Document]. URLOff. Bost. City Counc. http://m.manuals.plus/m/41aefb0a2416f2ccffbb5a13116baa85006c2884943d9de8b5ae5b0fdde4bc11.pdf.

Yang, Y., Ingwersen, W.W., Hawkins, T.R., Srocka, M., Meyer, D.E., 2017. USEEIO: a new and transparent United States environmentally-extended input-output model. J. Clean. Prod. 158, 308–318. https://doi.org/10.1016/j.jclepro.2017.04.150.

Yue, W., Cai, Y., Su, M., Yang, Z., Dang, Z., 2018. A hybrid copula and life cycle analysis approach for evaluating violation risks of GHG emission targets in food production under urbanization. J. Clean. Prod. 190, 655–665. https://doi.org/10.1016/j.jclepro.2018.04.061.