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Navigating the nexus of food, energy, and ecology: Foodshed approaches for integrated land use policies

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Abstract

Increasing competition for land among food and feed production, renewable energy, settlement expansion, and ecological restoration creates a pressing policy challenge in many regions. Diets, farming practices, and food loss and waste jointly shape land demand and greenhouse gas emissions, while decisions on bioenergy versus wind and photovoltaic deployment affect both land availability and climate outcomes. Yet existing foodshed frameworks rarely integrate energy system alternatives and carbon sequestration potentials into a single scenario-based assessment. This study addresses that gap by extending the Metropolitan Foodshed and Self-sufficiency Scenario (MFSS) framework to quantify trade-offs across the food-energy-ecology nexus. The MFSS's primary contribution lies in embedding renewable energy land-use modeling, greenhouse gas accounting, and carbon sequestration estimation into a single comparative scenario framework, moving beyond self-sufficiency assessment toward integrated analysis.

We apply this extended MFSS framework to the governmental district of Lower Franconia (Bavaria, Germany). Building on region-specific yield data and consumption patterns, we quantify per-capita and aggregate land footprints, theoretical

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self-sufficiency rates, and surplus land available after meeting a 100% regional food supply threshold. Beyond prior MFSS applications, we allocate remaining land to renewable energy production (bioenergy crops, photovoltaic, wind) and carbon sequestration via conversion to potential natural vegetation, while estimating greenhouse gas emissions across diets and farming systems.

Across 24 scenarios combining four dietary patterns (baseline omnivorous, flexitarian, vegetarian, vegan), two production systems (conventional, organic), and food loss and waste assumptions, dietary shifts and waste reduction strongly reduce land footprints and expand surplus land for renewable energy and ecological restoration. Organic scenarios require more land due to lower yields but exhibit lower management-related emissions per hectare. Bioenergy crops cannot meet regional primary energy needs with available land, whereas wind and photovoltaic can satisfy regional energy demand while preserving substantial areas for carbon sequestration and biodiversity.

The framework offers governance-relevant opportunities for municipalities and food system actors seeking integrated, place-based land-use strategies that align food self-sufficiency, energy transitions, and climate performance.

Keywords
regional land use, scenario development, land footprints, energy production, emissions, communities, policymaking

Introduction

Global agriculture faces significant pressures that challenge global food security, including climate change, biodiversity loss, population growth, and competing land uses (Searchinger et al., 2018). Climate change alters growing seasons and reduces productivity (Clark et al., 2020), while biodiversity decline diminishes ecosystem services (Weiskopf et al., 2024). Population growth intensifies competition for limited agricultural land through urban expansion, energy production from renewables, and conservation, though pressures vary by country, depending on development level and land-use policies (Akmal & Mohammadi, 2025; Dong et al., 2021).

Dietary choices influence health and environmental sustainability (Springmann et al., 2018). Current food systems account for around one-third of global anthropogenic greenhouse gas (GHG) emissions (Crippa, Solazzo, et al., 2021), driven by lifestyle and diet (Ritchie et al., 2018). In Central Europe, the food system is responsible for 47% of GHG emissions (Crippa, Guizzardi, et al., 2021). Rising consumption of animal-based and processed foods increases land, water, and energy use (González-García et al., 2018; Halpern et al., 2022; Li et al., 2024; Meier et al., 2014; Ritchie et al., 2018; Röös et al., 2017; Treu et al., 2017; Vicente-Vicente, Doernberg, et al., 2021; Willett et al., 2019), with beef production requiring approximately 15 times more land than grains or vegetables (Poore & Nemecek, 2018; Treu et al., 2017). Despite the growing popularity of plant-based diets in high-income countries, global meat consumption continues to rise (FAO, 2025).

Food waste further influences environmental impacts (land, water, etc.), as roughly one-third of food produced globally is lost or wasted, leading to resource inefficiencies and emissions (Gustavsson et al., 2011). In Germany, 14-20% of food-related GHG emissions stem from food loss (Eberle & Fels, 2016). The United Nations Environment Programme (UNEP) estimates that 931 million tons of food are wasted annually (UNEP, 2021). Despite efforts to tackle food waste at the consumer level, effectiveness remains limited due to complex, context-specific factors, such as purchasing behavior. Waste reduction is therefore crucial for mitigating environmental burden (Beyer et al., 2022).

Land use contributes to climate change as both a carbon source and sink (Searchinger et al., 2022). Agricultural practices affect soil carbon stocks, with methods like agroforestry, conservation tillage, and organic farming offering potential for carbon sequestration and reduced emissions (Crippa, Solazzo, et al., 2021; Erhart et al., 2015; Halpern et al., 2022; Hülsbergen et al., 2022; Willett et al., 2019). Yet, alternative land-use options, such as reforestation and natural vegetation, can achieve even higher carbon sequestration rates and support biodiversity (Fehrenbach & Bürck, 2022).

Organic farming presents an alternative to conventional agriculture due to its systemic approach,

despite lower yields (in Bavaria and Lower Franconia, around 55% of conventional yields) and higher land use per unit of food produced (de Ponti et al., 2012; Joseph et al., 2019; Panday et al., 2024; Sanders et al., 2025; Vicente-Vicente & Piorr, 2021). While limited globally (1–2%), organic farming is prominent in Germany (11% of agricultural land) (Willer et al., 2024), highlighting ongoing debates on the extent to which organic and conventional methods can be integrated to simultaneously meet growing food demand, reduce environmental impacts, and promote sustainability objectives (Meemken & Qaim, 2018; Muller et al., 2017; Seufert & Ramankutty, 2017).

Energy production on agricultural land remains contentious due to trade-offs between bioenergy crops and food production. Miscanthus and similar bioenergy crops can mitigate such conflicts, especially on marginal lands (e.g., in Brandenburg, Germany) (Ben Fradj et al., 2016; Tavakoli-Hashjini et al., 2020). However, renewable energies such as wind and solar photovoltaic (PV) demonstrate higher energy output per land area compared to bioenergy crops (Böhm, 2024; Nitsch et al., 2012; Yin et al., 2024).

Thus, dietary choices, food waste, and organic farming practices influence the allocation of agricultural land for food and/or energy production. This creates trade-offs that affect the composition, availability, and distribution of food within regional food systems.

In Germany and across the European Union (EU), the Common Agricultural Policy (CAP) plays a key role in shaping the availability and distribution of food within regional food systems. Pillar I supports farm income and production capacity through direct payments, indirectly affecting food availability; Pillar II promotes rural development, agri-environmental schemes, organic farming, and regional value chains. The EU *Farm to Fork Strategy* complements the CAP by advancing sustainable food systems, shorter supply chains, and stronger producer-consumer links (European Union, n.d.).

Regional food systems are increasingly studied as socioecological systems that integrate production, processing, distribution, and consumption within a defined geographic area, emphasizing local economic linkages, social equity, and environmental sustainability over long-distance supply chains. They offer promising solutions for food security and rural development, as highlighted by disruptions from COVID-19, geopolitical conflicts, and climate events (Barrett, 2020; Kaufmann et al., 2022; Sylla et al., 2022; Tavakoli-Hashjini et al., 2020). Shortening supply chains and strengthening actor relationships can improve food security, adaptive capacity, and social cohesion at the community scale, fostering trust through direct producer-consumer connections and local value-adding activities, although benefits vary widely with context and supply chain characteristics (Enthoven & Van Den Broeck, 2021). Robust regional networks, supportive infrastructure, and multistakeholder governance are crucial for resilience and scaling up (Keegan et al., 2024). Beyond resource efficiency, regional food systems strengthen local capacity to shape food provisioning, retain regional value, and advance food sovereignty. Our research elucidates how dietary change, agricultural systems, waste reduction, and renewable energy adoption influence local action opportunities, including public procurement, community-supported agriculture (CSA), value chain coordination, and biodiversity-oriented land stewardship.

Several foodshed analyses have evaluated regional self-sufficiency capacity and demonstrated the importance of regionalized food production in reducing emissions and strengthening community resilience. In 2019, Zasada et al. developed the MFSS model to estimate the agricultural area required to feed four European cities. The term "foodshed" refers to the land needed to produce food for a specific population. An overview of European foodshed analyses is provided in Appendix Table A1.

Previous foodshed studies have primarily focused on self-sufficiency and agricultural practices, occasionally incorporating food waste or bioenergy as isolated additions. Critically, no prior MFSS-based application has simultaneously allocated surplus land across renewable energy alternatives and carbon sequestration scenarios or systematically compared their climate and land-use implications across a full factorial scenario matrix combining dietary patterns, farming systems, and food waste assumptions. This fragmented approach overlooks

how food production, energy generation, and environmental objectives interact and trade off under varying dietary and farming conditions.

Methodological Contribution

This study's contribution can be summarized as follows:

- It embeds dietary patterns, agricultural practices, food waste reduction, renewable energy alternatives, and carbon sequestration within a single, coherent scenario framework, an integration no prior MFSS-based study has achieved.
- It reveals cross-sectoral trade-offs across the food-energy-ecology nexus that incrementally extended foodshed analyses cannot capture.
- It demonstrates this framework for Lower Franconia, Bavaria, and is designed for broader regional transferability.

Study Objectives

We pursue two sets of objectives:

Analytical and modeling objectives

1. Quantify the individual and combined effects of dietary patterns, food waste reduction, and farming systems on regional land footprints and self-sufficiency rates.
2. Model whether renewable energy sources (bioenergy crops, PV, wind) can satisfy regional energy needs on surplus land without compromising agricultural productivity.
3. Estimate GHGs and carbon sequestration potential across farming systems and scenarios.

Policy and interpretive objective

- Identify governance-relevant land allocation pathways that reveal opportunities, rather than prescribe outcomes, for communities, municipalities, and regional food system actors seeking to balance food provision, renewable energy deployment, and ecological restoration.

Materials and Methods

This section outlines our methodology and data collection process, covering the study area, indicators, and databases used. This is followed by the MFSS model and our adjustments, the novel approach to calculate energy potential and soil organic carbon (SOC) on available areas for renewable energy (ARE) and carbon sequestration (ASE), and, finally, the scenario development. A schematic overview is provided in Appendix Figure A1.

Study Area

The study develops a comprehensive framework to evaluate regional land-use opportunities, demonstrated through a model region embedded in local policy agendas. The model region is the governmental district of Lower Franconia (Nomenclature of Territorial Units for Statistics or NUTS 2), Bavaria, selected for its institutional support; primary data availability; and diverse landscape spanning intensively cultivated arable land, marginal areas, and a substantial share of organic farming. For transferability, several structural characteristics align with conditions found across many European and temperate regions: mixed conventional-organic farming, trade-dependent supply balancing, intermediate food self-sufficiency, and an active multi-level policy environment. However, Lower Franconia's relatively high agricultural productivity, specific crop portfolio, and dense institutional setting are context-specific. Readers applying this framework elsewhere should treat both absolute land footprint values and the relative ordering of scenario outcomes as region-specific, since local yield conditions, dietary baselines, and land availability may alter which pathways perform best. However, the methodological approach, combining foodshed analysis, energy land-use modeling, and emissions accounting, is designed to be broadly adaptable. Details on the study area are provided in the Appendix.

Databases

This study used various variables, indicators, and databases to carry out its calculations (see Appendix Table A3).

Metropolitan Foodshed and Self-sufficiency Scenario Model (MFSS)

The study applies an extended version of the MFSS framework originally developed by Zasada et al. (2019). This framework integrates regional food

consumption patterns with agricultural production parameters to evaluate foodshed extent and theoretical self-sufficiency across food groups, production systems, and food loss and waste levels. The framework relies on utilizable agricultural area (UAA), encompassing arable land, permanent grassland, and permanent crops; home gardens are excluded here since no data were available. For animal products, land footprints are calculated using conversion factors based on European studies accounting for feed requirements and processing losses. Dual-use animals serving both dairy and meat production purposes are not separately considered, which may marginally affect land, carbon, and emissions footprints. Regional yield data from 2018 to 2024 were used to estimate conventional yields of plant-based products, with organic yields assumed at 55% of conventional yields, following established values reported in the literature (Bayerische Landesanstalt für Landwirtschaft, n.d.),. Consumption data were sourced from official German statistics (Bundesministerium für Ernährung und Landwirtschaft, n.d.) and complementary reports, forming a food basket of 79 products.

Food categories were aggregated into representative commodity groups to maintain computational tractability and ensure data consistency, focusing on system-level self-sufficiency patterns while acknowledging that high-variance crops may introduce uncertainty (Joseph et al., 2019; Zasada et al., 2019). Key product categories include cereals (wheat, rye, oats), vegetables, fruits, legumes, fats, sugar, and sausage (composed of 20% beef, 55% pork, and 23% poultry (Treu et al., 2017)). Fish and seafood consumption were derived from the FAO FishStatJ database (FAO, n.d.). The analysis excluded items not producible in the region, such as coffee, tea, citrus fruits, and cacao, focusing exclusively on crops and livestock theoretically producible in Lower Franconia. This approach is consistent with that of Joseph et al. (2019). Our assumptions are consistent with regional scale foodshed modeling conventions and primarily affect absolute land footprint values more strongly than the relative ordering of scenarios. This pattern is confirmed by the sensitivity analysis (see Results and Appendix), which shows that ±20% variation in yields and consumption values shifts absolute estimates but leaves the comparative relationships between dietary patterns, farming systems, and energy alternatives unchanged.

Applying the MFSS: Calculation of Land Footprints and Associated Analyses

The following analyses were conducted to calculate land footprints:

Calculation of the specific land footprint, i.e., area demand (*A*) for each dietary style, organically and conventionally produced; *qi*: quantity of a specific food product, *i*, which is consumed per capita and per year in Germany; and *yi*: yield of crop *i* in kg/m² in the research area:

$$A = qi * yi \qquad (1)$$

A formal probabilistic uncertainty analysis was not conducted, reflecting the study's focus on establishing comparative scenario estimates rather than predictive quantification. However, a scenario-based sensitivity analysis was performed to assess the influence of key parameter variation on model outputs (see Appendix). Several parameters exhibited significant variability—organic yield assumptions, food waste rates, and consumption data, derived from regional or national averages—leading to uncertainty about land footprint and self-sufficiency outcomes. The sensitivity analysis confirmed that ±20% variation in yields and consumption values shifts absolute land demand estimates but does not alter the relative ordering of scenarios. This indicates that the main comparative conclusions are robust to explain plausible parameter variations. Shifts in the organic yield ratio or a decrease in food loss and waste would both substantially increase surplus land estimates. The broad scenario design, spanning dietary patterns and farming systems, partially brackets this variability by capturing a wide range of plausible land-use outcomes.

Calculation of the potential land footprint by taking food loss and waste along the value chain into consideration (*Aw*: area considering loss and waste, *w*: percentage of waste and/or loss):

$$Aw = A * w \qquad (2)$$

Calculation of the overall regional area demand (*Agg*), multiplying the per capita demand with the population of the research area (*pop.*: population in Lower Franconia):

$$Agg = A * pop. \text{ or}$$
$$Agg = Aw * pop. \quad (3)$$

Similarly to the model of Zasada et al. (2019), food self-sufficiency is interpreted as the relationship between the aggregate area demand (*Agg*) and the available agricultural area (*UAA* in hectare [ha]), expressed as self-sufficiency rate (*SSR*). Accordingly, an SSR of 100% would be realized if the complete area demand for food production could be covered within a region. Below that value, additional influx, i.e., imports of food from outside the region, are required. If the rate is larger, exports would be possible.

$$SSR = \frac{UAA}{Agg} * 100 \quad (4)$$

Calculation of the Energy Potential and Area for Renewable Energy (ARE)

In this study, land use for food production is prioritized over land use for (bio)energy production. The next step aims to estimate the potential area available for renewable energy production or other uses under different scenarios. This is done by using available or surplus ARE. ARE includes areas for carbon sequestration or natural vegetation (ASE). This means that the area required to meet 100% self-sufficiency of the Lower Franconian population is excluded. As described, we have calculated the aggregated area demand (i.e., area required to feed the population, Agg) and the food SSR, expressed as a percentage. As a premise, the SSR achieve at least 100%; the ARE would be the remaining area for each scenario. The model does not differentiate between cropland, grassland, and marginal land within ARE. However, the quality of the land has a direct impact on its suitability for the cultivation of energy or food crops.

$$ARE = UAA - Agg \quad (5)$$

Where *ARE* is area available for planting bioenergy crops or other uses (in hectares [ha]), *UAA* is the total utilizable agricultural area (ha), and *Agg* is the area required to feed the population (ha), according to the specific scenario.

We estimated the potential electricity generation of different energy crops from the database of bioenergy in Germany (Fachagentur Nachwachsende Rohstoffe, n.d.) and regional data (Bayerische Landesanstalt für Landwirtschaft, n.d.). The average amounts of energy that can be produced, either for biogas or thermal use, are presented in Appendix Table A4.

Primary Energy Consumption

According to the calculations in the working paper of Agora Energiewende (2024), primary energy consumption in Germany will decrease from 13,129 petajoules (PJ) to 6,458 PJ from 2018-2045, a reduction of 50%. This is due to a large reduction in energy generation from fossil sources and an increase in energy derived from renewable sources such as wind turbines and solar. These values were broken down to the primary energy consumption per capita in Germany. Subsequently, based on the population of Lower Franconia, different energy consumption values were calculated for our research area (Appendix Table A5). National per-capita energy consumption was used as a proxy for the region to provide a consistent benchmark, acknowledging that local industrial energy needs may differ from the German average. From these values, area needs were calculated based on the needs of Lower Franconia (Appendix Table A6). As open-space PV and wind energy play a crucial role, area demands for these were also calculated.

Beyond bioenergy crops and renewable energy installations, surplus areas present significant potential for alternative or complementary utilization, most notably carbon sequestration, natural vegetation restoration (ASE), and the provision of associated ecosystem services.

Estimation of Soil Organic Carbon (SOC) Sequestration

Crop cultivation influences SOC accumulation, humus content, and soil fertility, while also enabling soils to function as CO_2 sinks. Considering the car-

bon (C) sequestration rate and the assumption that all the area designated for carbon sequestration (ASE) is converted to natural vegetation (after meeting 100% of ARE), it is possible to estimate the potential C and CO_2 equivalent (CO_2e) that could be sequestered in the soils of temperate continental zones (e.g., our research area). Similarly to Fehrenbach and Bürck (2022) for areas in Germany, the potential carbon storage capacity on surplus land or land left aside is determined based on the concept of today's potential natural vegetation, i.e., forests. The corresponding average annual carbon storage rate is 2.9 metric tons C/ha and year. However, soil carbon sequestration potential is highly site-specific and nonlinear, with accumulation capacity depending on existing carbon stocks and soil type characteristics, among other factors (Georgiou et al., 2025). This study does not differentiate soil type variability or land-use categories.

Comparison of Emissions Regarding Different Land Uses

Land emissions vary depending on the agricultural practices applied. Aside from soil composition and tillage methods, one crucial factor is whether agricultural land is managed conventionally or organically (Bennetzen et al., 2016). We used the values from Hülsbergen et al. (2022), where organically managed land had total GHG emissions of 1.22 t CO_2e/ha and conventionally managed land 2.99 t of CO_2e /ha. The data from Hülsbergen et al. (2022) come from a pilot network comprised of 40 organic and 40 conventional market crop and dairy farms in four regions in Germany. There was no regional data available on carbon content or the carbon source-sink relationship. Thus, the total CO_2 storage capacity of Lower Franconia was calculated using the UAA and the carbon storage rate for Germany. Single product emissions were calculated by using values from Chiriacò et al. (2022). As a result, CO_2 credits (storage capacity) and emissions (climate impact) were contrasted.

Scenario Development

This study applies the MFSS model to simulate 24 distinct land-use scenarios based on the following factors:

- Differences in agricultural practices (organic vs. conventional),
- Different dietary styles (see below), and
- Impacts of food loss and waste, from production to household level.

Production System

Organic agriculture typically requires more land per unit of food produced due to lower yields. In our study, organic yields were set at 55% of conventional yields (Bayerische Landesanstalt für Landwirtschaft, n.d.). This is consistent with yield gap estimates reported in the broader literature, which state that organic yields are approximately 20-45% lower than conventional yields, depending on crop type, soil quality, and management intensity (Röös et al., 2018). This suggests that our assumption represents a plausible central estimate for the region.

Dietary Styles

This study distinguishes between four different dietary styles: omnivorous diet (baseline), flexitarian diet, vegetarian diet, and vegan diet. The dietary compositions applied in this study are based on the EAT-Lancet Planetary Health Diet and Willett et al. (2019) and have been adapted following Eberle and Mumm (2024). Descriptions and compositions can be found in the Appendix and Appendix Table A7.

Food Loss and Waste

For the development of the scenarios on food loss and waste, five levels along the food value chain were distinguished according to Zasada et al. (2019) (see Appendix). The estimated waste percentages for each commodity group in each step of the food value chain for Europe are from Gustavsson et al. (2011) (Appendix Table A8).

Table 1 provides an overview of the developed scenarios. Conventional scenarios are shown on the left and organic scenarios are listed on the right.

To strengthen the policy and community relevance of the scenario comparison, we interpreted results through a governance lens. Specifically, three implementation domains were used to assess scenario outcomes: 1) community-level food practices and demand-side interventions, such as die-

tary change or food waste reduction; 2) municipal planning and public decision-making, including land-use zoning, renewable energy siting, public procurement, and biodiversity-oriented land management; and 3) regional food system coordination, including implications for farming strategies, processing, supply chain organization, and stakeholder collaboration. This interpretive step does not constitute a separate social-impact model, but it allows the quantitative scenario outputs to be translated systematically into potential pathways.

Results

In this section, we first describe land footprints and food self-sufficiency rates before reporting land use for energy production, followed by emissions and SOC sequestration.

Land Footprint and Food Self-Sufficiency

Table 2 (in conjunction with Appendix Table A9) shows the following calculations for each scenario: potential land footprint in square meters (m^2), aggregated for the research area (Agg in hectare), and SSR. The table also indicates how many people (P) per ha could be fed. Additionally, the area for ARE and its relative share are shown. Area for carbon sequestration or natural vegetation (ASE) is included in ARE. Note that UAA remains stable. Furthermore, the table illustrates land footprints across different dietary scenarios. For example, the first row shows the results of the conventional baseline scenario, Ic. Its land footprint is 1,229 m^2 and its (across the research area) aggregated area is 173,978 ha, which equals 49.7% of the UAA. The self-sufficiency rate is 201%. In total, 7.7 people (P) can be fed by one hectare on this diet. The calculated ARE is 176,094 ha, which equals 50.3% of the UAA.

Overall, conventional scenarios show lower land footprints than organic ones. The baseline organic scenario shows the highest land footprint at 1,877 m^2, with significant potential for reduction across alternative diets. In contrast, the baseline conventional diet has a land footprint of 1,229 m^2. The transition to reduced food loss and waste along the value chain, in both "without losses" and

Table 1. Scenario Framework

Conventional Scenarios							Organic Scenarios						
Scenario	Baseline	Flexi	Veget	Vegan	w/o hh	with hh	Scenario	Baseline	Flexi	Veget	Vegan	w/o hh	with hh
I_c	X						I_o	X					
II_c	X				X		II_o	X				X	
III_c	X					X	III_o	X					X
IV_c		X					IV_o		X				
V_c		X			X		V_o		X			X	
VI_c		X				X	VI_o		X				X
VII_c			X				VII_o			X			
$VIII_c$			X		X		$VIII_o$			X		X	
IX_c			X			X	IX_o			X			X
X_c				X			X_o				X		
XI_c				X	X		XI_o				X	X	
XII_c				X		X	XII_o				X		X

w/o hh = without household-level waste
with hh = with household-level waste
Different combinations of dietary styles plus considered waste (without household-level waste (w/o hh) or with household-level waste (with hh)) have different scenario codes. For example, the Ic scenario is the baseline conventional scenario. Scenario IIIc is the conventional baseline scenario, which considers food loss and waste at all levels, i.e., including household level.

"with losses" scenarios, consistently lowers land footprints across all dietary patterns. Flexitarian organic diets result in moderate reductions, with land footprints of 1,465 m^2 without losses and 1,262 m^2 with losses compared to the baseline. Vegetarian organic diets achieve more substantial reductions, with land footprints of 956 m^2 without losses and 809 m^2 with losses. Vegan conventional diets demonstrate the lowest land footprint, particularly when food losses are minimized, with values of 476 m^2 without losses and 422 m^2 with waste and losses.

All scenarios reach at least 100% SSR. The baseline organic scenario has the lowest SSR at 139%. SSR increases as dietary changes are introduced, reaching 158% without losses and 191% with losses for the organic scenario. In the conventional scenario, these rates climb to 201% for baseline, 228% without losses, and 284% with losses. Flexitarian diets further raise SSR, registering 264% for the conventional and 179% for the organic scenario. Vegetarian diets show a sharp increase in SSR compared to the status quo, reaching 508% for the conventional scenario with losses and 391% for the organic scenario with losses. Vegan diets demonstrate the highest overall values, with SSR reaching 620% for the conventional scenario with losses and 491% for the organic scenario with losses.

Breaking down the land footprints (without waste and food losses) to individual products and product groups, respectively, the large share of animal-based products becomes clear (see Appendix Table A10). By comparing the share of plant- and animal-based products in diets with the share of plant- and animal-based products in land footprints, it becomes clear that one third of animal-based food in diets contributes to more than 70% of the land footprints. In scenarios where organic yields are used, the land footprints of animal-based products are higher than in conventional scenarios. This is attributable solely to differences in yield.

When comparing area used for specific products or product groups with their respective consumed amount, Lower Franconia is characterized by high production rates of sugar beets, canola, winter wheat, and winter barley. Appendix Tables A11 and A12 illustrate the self-sufficiency values of select regionally produced food products.

Land Use for Renewable Energy

As shown in all scenarios, there is surplus area available after 100% self-sufficiency. The amount of surplus area ranges from 28.2% in the organic baseline scenario to 97.6 % in the organic vegan scenario where food waste (including household-level) is considered (Table 2).

When comparing the production potential of different energy crops such as silage maize, Miscanthus, Silphia, permanent grassland, and winter wheat to meet the primary energy need, none of these crops can deliver 100% in our research area. Moreover, as Lower Franconia has areas that are very suitable for agricultural use, the share of energy crops is very low; for example, maize had a share of around 10% of the UAA in 2020 (Bayerisches Landesamt für Statistik, 2024).

Regarding the three scenarios of Agora Energiewende (2024), the areas needed for open-space PV and wind energy to meet the primary energy consumption were calculated (ARE). As those renewables only use a portion of the land, they have a higher energy output per land area (Böhm, 2024; Yin et al., 2024). Thus, when using either open-space PV or wind energy in the remaining areas, there is still a substantial surplus of areas for other uses, such as carbon sequestration or natural vegetation (equal to ASE). This holds true for all three years (2018, 2025, 2045).

Emissions and Soil Organic Carbon (SOC) Sequestration

Environmental impacts vary between organic and conventional management, with organic agriculture generally producing lower emissions by avoiding mineral nitrogen fertilizers, combining crop and livestock production, and applying regional nutrient recycling, though results differ by GHG, climate, soil conditions, and crop type (Gerke, 2025). Appendix Table A15 presents the carbon sequestration potential of surplus areas alongside food-related emissions across scenarios. The total carbon storage capacity of available utilized agricultural area (UAA) in Lower Franconia is 3.73 million t CO_2e (own calculation), with natural vegetation

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Table 2. Land Footprints, Self-Sufficiency Rates, and ARE for Conventional and Organic Scenarios

	Conventional						Organic					
	Scenario	Footprint (A/Aw) in m²	Agg in ha (share of UAA in %)	SSR in %	P/ha	ARE in ha (share in %)	Scenario	Footprint (A/Aw) in m²	Agg in ha (share of UAA in %)	SSR in %	P/ha	ARE in ha (share in %)
Baseline	Ic											
Baseline w/o hh	IIc											
Baseline with hh	IIIc											
Flexi	IVc											
Flexi w/o hh	Vc											
Flexi with hh	VIc											
Veget	VIIc											
Veget w/o hh	VIIIc											
Veget with hh	IXc											
Vegan	Xc											
Vegan w/o hh	XIc											
Vegan with hh	XIIc											

Notes: w/o hh = without household-level waste, with hh = with household-level waste, m² = square meters, Agg = aggregated area in ha, SSR = self-sufficiency rate, P/ha = people fed per hectare (ha), ARE = area for renewable energy, total UAA: 350,072 ha (remains stable)
Land footprints (A/Aw): red: >1,000 m², orange: <1,000 m² and >750 m², yellow: <750 m² and >500 m², green: <500 m²
Agg: red: >200,000 ha, orange: <200,000 ha and >100,000 ha, yellow: <100,000 ha and >75,000 ha, green: <75,000 ha
SSR: red: <300%, orange: <400% and >300%, yellow: <500% and >400%, green: >500%
P/ha: red: <10.0, orange: >10.0 and >15.0, yellow: >15.0 and <20.0, green: >20.0
Surplus area: red: <150,000 ha, orange: >150,000 ha and <200,000 ha, yellow: >200,000 ha and <250,000 ha, green: >250,000 ha

sequestering 10.64 t CO_2e/ha (Fehrenbach & Bürck, 2022). Emissions are highest in the conventional baseline scenario (-0.52 million t CO_2e) and lowest in the vegan scenario with food waste reduction (-0.17 million t CO_2e), the latter also yielding the greatest carbon sequestration potential on areas for renewable energy and carbon sequestration (ARE/ASE) at 3.12 million t CO_2e. Organic scenarios show similarly low emissions (e.g., -0.09 million t CO_2e in XIIo), but their higher land footprints reduce available ARE/ASE, and thus carbon sequestration potential (2.97 million t CO_2e in XIIo). Our data indicate that emissions vary significantly across dietary styles, with plant-based diets producing the lowest emissions per capita due to the lower resource intensity of plant-based foods. Meat-intensive diets, conversely, require more land and generate higher emissions. In all scenarios, the carbon-saving potential of agriculturally used land is higher than respective food-related emissions. Moreover, we see the highest sequestration rates in ARE/ASE.

In the next step, we considered the areas, emissions, and sequestration effects that would be released if food waste and losses could be spared or minimized. Emissions in Appendix Table A14 are characterized by a minus sign to indicate a negative impact. Our results confirm that preventing food losses could not only save agricultural land but also spare emissions and enable more carbon sequestration. The organic scenarios (in grey) have the largest potential impact on releasing land. Again, the carbon-saving potential of land not used for agriculture is higher than food-related emissions. Calculated emissions for single products or product groups can be found in Appendix Table A15.

We calculated that the total carbon or CO_2e storage capacity of the UAA in Lower Franconia is 3.73 million metric tons. The highest carbon sequestration potential is achieved in scenarios with the smallest land footprint (a vegan diet, considering food waste and losses across all stages of the value chain), resulting in the greatest surplus area and sequestration purposes (ARE/ASE).

The lowest carbon storage rates were observed in scenarios where land use is high, such as in the baseline (meat-based) and organic farming scenarios. Thus, scenarios with relevant natural vegetation preservation or organic farming practices show higher carbon storage capacities, providing climate benefits. In contrast, land-intensive energy or conventional plant production contribute to higher CO_2 emissions.

Upon combining different land-use options and considering emissions of renewables such as wind or open PV on one hand and carbon storage capacities on the other hand, we calculated a decrease in emissions originating from different diets and an increase in storage potential. The results for wind energy are summarized in Tables A16 and Table A17 in the Appendix, alongside a projected decrease in primary energy consumption from 2025-2045, according to Agora Energiewende (2024). This reduction is derived from a substantial reduction in energy production from fossil sources and an increase from renewable sources. Table A18 and Table A19 in the Appendix show the results for the use of PV energy. In the baseline scenario and the baseline scenario where household-level food waste and loss are not considered, emissions exceeded storage capacity in 2025.

Sensitivity Analysis

Sensitivity analyses, which examine how changes in data or assumptions affect results, are essential for evaluating the robustness of conclusions (Thabane et al., 2013). A sensitivity analysis assessing ±20% variation in yields, consumption values, and waste rates, confirmed that while absolute land footprint values shift within this range, the comparative relationships between scenarios remain stable. Among all parameters tested, meat and dairy consumption emerged as the most influential, followed by organic yield assumptions and food waste rates. In contrast, variations in minor food categories and cereal yields produced comparatively modest effects on land demand. The relative ordering of dietary patterns, farming systems, and energy alternatives is robust to parameter variation across all tested conditions. Details can be found in the Appendix (in conjunction with Appendix Table A18 and Figures A3 and A4).

Discussion

In this section we interpret our results in the context of existing literature, give a narrative synthesis

of our main findings, and formulate implications for community development and local government. Additionally, limitations and recommendations for further research are described.

Interpretation of Results in the Context of Existing Literature

The MFSS model estimates land required to meet regional food demand based on dietary composition and agricultural yields (Zasada et al., 2019). Our study extends this framework to Lower Franconia, Germany, analyzing 24 scenarios combining dietary styles, agricultural practices, and food waste levels, while assessing alternative land uses including energy generation, emissions, and carbon storage to demonstrate how competing land-use demands can be reconciled regionally.

Our results indicate that dietary shifts, improved soil management, and reduced food loss can substantially mitigate environmental impacts, with regional land simultaneously supporting diverse diets, renewable energy, biodiversity conservation, and exports. Carbon sequestration potential exceeded food-related emissions across all scenarios, though as soil carbon saturates over time, production-side emission reductions become increasingly important.

Our findings align with German and EU climate and sustainability strategies. EAT-Lancet-based diets and reduced animal product consumption support lower agricultural GHG emissions and improved resource efficiency, while differentiated land use and diverse crop rotations—as explicitly prioritized in the German Sustainability Strategy—contribute to soil health and biodiversity (Bundesumweltministerium, n.d.). These outcomes also correspond directly to the European Farm to Fork Strategy's objectives of sustainable food production, responsible consumption, and food waste reduction (European Commission, n.d.).

At the EU level, the Nature Restoration Law 2050 (Regulation (EU) 2024/1991) mandates the restoration of 20% of land and sea areas by 2030 and all degraded ecosystems by 2050. Our results indicate that, even with 20% of agricultural land allocated to restoration, food self-sufficiency, energy production, and ecological objectives remain achievable.

Baseline land footprints in our scenarios are comparable to previous research (Eberle & Fels, 2016; Treu et al., 2017; Zasada et al., 2019). Hallström et al. (2015) reported land demands of 1,400-2,100 m^2 per capita, similar to our findings. As in Treu et al. (2017), organic scenarios required more land for animal-based products than conventional systems, whereas reductions in meat consumption substantially decreased land demand (Hallström et al., 2015; Wirsenius et al., 2020). Differences in land footprints across studies reflect variations in food basket composition and inclusion criteria; for instance, coffee and cacao were excluded here because their primary production occurs outside the study region. Organic farming reduces synthetic input use and runoff (Sanders et al., 2025; Seufert & Ramankutty, 2017) but requires more land due to lower yields. In our study, land footprint differences between conventional and organic systems ranged from 26% (vegan diets) to 48% (flexitarian), consistent with Treu et al. (2017).

Regional characteristics strongly shape outcomes. In Lower Franconia, limited grassland constrains meat and dairy production, while high-quality winter wheat and sugar beets support exports. Consequently, self-sufficiency of commodities differs from calculated land footprints. Some of the consumed products, such as citrus fruits and coffee, cannot be produced locally, making full self-sufficiency unattainable. Crop diversity and dietary habits are further influenced by heterogeneous soil, climate, cultural, and socio-economic factors (Vicente-Vicente, Sanz-Sanz, et al., 2021). Environmentally, plant-based diets reduce emissions and land demand. Health-wise, EAT-Lancet-aligned diets support disease prevention and nutritional adequacy. Yet, if regional production cannot supply sufficient protein diversity, tensions may arise between environmental and health goals. Culturally, food habits and traditions influence dietary adoption. If proposed diets diverge too far from established practices, transitions may be slow, limiting real-world impact compared to modeled scenarios. Comparisons with the Bavarian Food Consumption Survey (Rohm et al., 2025) indicate differences in consumption patterns due to sample size and reporting biases in the survey. Assessment metrics utilized also influence outcomes; land use ex-

pressed per kilogram, kcal, and nutrient intake yields all produce different results (Poore & Nemecek, 2018).

Our results confirm that food waste is a major driver of land demand. Losses of roots, fruits, cereals, pulses, and particularly cereals at the consumption stage substantially increase land footprints (Gustavsson et al., 2011). Reducing waste can lower per capita land use and support sustainability targets (Augustin et al., 2020; Schneider et al., 2022). Demographic trends, including declining rural populations and growing urban centers (Eurostat, n.d.), will further affect land-use dynamics. Despite sustainable intensification, global food self-sufficiency is projected to decline as demand outpaces production (Beltran-Peña et al., 2020).

Most food-related emissions originate from animal-based products. Differences between organic and conventional diets are less pronounced, as lower yields in organic systems offset reductions in emissions per hectare (Sanders et al., 2025). Nonetheless, organic farming can reduce environmental runoff by avoiding synthetic fertilizers and pesticides (Seufert & Ramankutty, 2017), though land-saving potential depends on closing the yield gap (Foley et al., 2005). Carbon storage potential was estimated using recent German data (Fehrenbach & Bürck, 2022), though sequestration is nonlinear and depends on soil type and existing carbon levels (Georgiou et al., 2025).

Narrative Synthesis of the Main Findings

Across all scenarios, three overarching patterns were identified. First, dietary shifts and food waste reduction are the strongest levers for lowering land demand within the regional food system. Second, organic production reduces some management-related environmental burdens but increases land demand because of lower yields, thereby intensifying trade-offs when land is scarce. Third, if food provision is secured first, wind and PV systems offer substantially higher energy output per unit of land than dedicated bioenergy crops, leaving greater scope for ecological restoration and carbon sequestration.

Taken together, the results show that the most promising pathways are not single-sector solutions but combinations of demand-side change, land-efficient renewable energy deployment, and context-sensitive agricultural strategies. Addressing these interactions requires an interdisciplinary perspective that integrates insights from agriculture, energy systems, and land-use governance. In this sense, the scenarios identify not one optimal blueprint, but a set of feasible regional pathways that differ in their implications for land competition, climate performance, and governance complexity.

Community Development and Local Governance Implications

The contribution of this study to regional food systems development lies less in predicting social outcomes than in clarifying which land-use pathways expand or constrain the options available to local actors. A key limitation is that the model does not incorporate socioeconomic, political, or institutional feasibility, factors that will shape which pathways are pursued in practice. Scenario results should therefore be read as evidence-based opportunity spaces. Within those boundaries, the findings have relevant implications for community development and municipal governance, as illustrated in Table 3.

Limitations

Our analysis is limited by the exclusion of trade flows, which may overlook dependencies on imported or exported food and associated environmental impacts. This limitation primarily affects absolute self-sufficiency estimates rather than the relative ranking of scenarios, as trade exclusion applies uniformly across all scenarios. Other limitations include the simplification of livestock systems, which may not capture variations in production intensity and could affect absolute land footprint values, particularly in omnivorous and flexitarian scenarios. However, the directional differences between dietary patterns remain intact. Moreover, the scenarios are static snapshots rather than dynamic projections and therefore do not capture transition pathways, such as the adoption of dietary changes, infrastructure development, or phased renewable energy deployment over time. This limitation affects the interpretation of all scenarios equally and does not alter relative comparisons.

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Table 3. Translation of Key Scenario Findings into Community and Governance Implications

Key scenario finding	What it means analytically	Community-level implications	Municipal and/or regional policy implications	Implications for regional food system stakeholders
Dietary shifts toward flexitarian, vegetarian, or vegan patterns reduce land demand relative to baseline scenarios.	Reduced dietary land footprints directly expand surplus land available for energy and restoration uses across all production systems.	Food literacy and school meal reform may support a shift away from the specific food groups—particularly beef and dairy—that the scenarios identify as driving the largest land footprint differences between omnivorous and plant-based dietary patterns.	Scenario-specific land savings suggest that food strategies and climate plans could reference these findings. Procurement policies may offer one avenue for operationalizing demand shifts already quantified in the model.	Findings indicate that product portfolios and processing capacity may need to reflect a gradual shift away from high-land-intensity animal products that the scenarios consistently identify as the dominant driver of regional land demand differences across all production systems.
Food waste reduction lowers required production area independently of dietary or farming system changes.	Land savings from waste reduction are additive to dietary shifts, suggesting combined measures yield the greatest surplus land across all 24 scenarios.	Awareness and redistribution initiatives may usefully prioritize the waste fractions—particularly at household and retail level—that the model identifies as carrying the highest land footprint per unit across dietary scenarios.	Model-derived land savings from waste reduction, which the scenarios show are additive to dietary shifts, suggest that municipal waste prevention plans could reference these findings to inform investment in redistribution and procurement standards.	Findings indicate that coordinating storage, logistics, and surplus redistribution may reduce the land demand embedded in wasted regional production, an effect the scenarios show holds independently of dietary pattern or farming system.
Organic scenarios require more land under the 55% yield assumption, offsetting some ecological gains.	Ecological benefits of organic systems come with quantifiable land competition trade-offs that vary by dietary scenario, most pronounced in omnivorous patterns and reduced in plant-based diets (vegetarian or vegan).	Scenario evidence suggests that community dialogue on organic transitions may benefit from engaging with the specific modelled land trade-offs, which the scenarios show are most manageable when combined with dietary shifts toward lower land-intensity patterns.	Modelled land constraints suggest that organic expansion targets could be considered alongside demand-side measures. The scenarios indicate that flexitarian or vegetarian diets substantially reduce the net land penalty associated with organic production.	Findings suggest that crop choice, contracting, and processing capacity could be considered in relation to land availability scenarios, particularly given that organic land requirements vary considerably depending on the dietary context in which they are assessed.

Wind and PV satisfy regional energy demand on a fraction of the land required by bioenergy crops.	The model indicates bioenergy cannot meet regional energy needs within available surplus land. Wind and PV can, while preserving land for food and restoration.	Model results may inform participatory planning for wind and PV siting by indicating which surplus land areas, greatest under plant-based and low-waste scenarios, appear least needed for food or carbon uses.	Findings suggest that land-efficient renewables may warrant prioritization across all scenarios; agrivoltaic options on lower-quality soils may merit further examination, particularly where surplus land is limited under conventional omnivorous conditions.	Scenario evidence suggests that farm-level diversification into wind and PV leasing or cooperatives may be viable across all dietary and farming system combinations, as energy goals do not require trade-offs in land available for food production in any scenario tested.
Surplus land supports carbon sequestration and ecological restoration with quantifiable climate co-benefits.	Land set-aside for natural vegetation carries modelled carbon sequestration potentials that the scenarios show are greatest under plant-based diets (vegetarian, vegan) and low food waste conditions.	Where surplus land is identified, particularly under vegetarian and vegan scenarios, scenario evidence may support community deliberation on prioritizing ecological restoration and multifunctional landscape uses alongside food and energy goals.	Findings suggest that restoration could be considered as a quantified climate measure within regional land strategies. The scenarios indicate that its feasibility increases substantially under plant-based dietary patterns and waste reduction measures.	Modelled sequestration values, which vary across dietary and farming system scenarios, may support farms and regional organizations in developing stewardship and ecosystem-service arrangements grounded in scenario-specific regional evidence.
Exclusion of trade flows means self-sufficiency rates reflect theoretical production capacity, not realized supply autonomy.	Model results represent an upper bound on self-sufficiency. Actual regional food provision depends on trade infrastructure and market linkages not captured in any of the 24 scenarios.	Findings suggest that community messaging may benefit from distinguishing between the theoretical production potential identified in the scenarios and actual food security, avoiding overstatement of self-sufficiency, particularly under high-surplus plant-based scenarios.	Results indicate that foodshed findings may be most informative when combined with food flow and infrastructure analyses before informing supply chain or resilience policy, as high modelled self-sufficiency rates do not necessarily translate into realized regional autonomy.	Findings suggest that processing, wholesale, and market dependencies could usefully be mapped alongside model outputs when designing regional sourcing or resilience strategies, as these structural factors shape whether modelled surplus land translates into actual food system change.

This study does not provide a formal probabilistic uncertainty analysis for yields, SOC sequestration, or energy production, as its primary aim is a comparative, scenario-based assessment of land-use trade-offs rather than predictive quantification. While these parameters are uncertain and spatially heterogeneous, the sensitivity analysis confirmed that ±20% variation in key parameters shifts absolute land demand estimates but leaves the relative ordering of dietary patterns, farming systems, and energy alternatives unchanged. A further limitation of this study is that the model provides comparative scenario insights but does not account for sociopolitical, economic, or cultural constraints, meaning the results indicate potential trade-offs and opportunities rather than prescriptive policy guidance. Furthermore, the framework remains a capacity-based foodshed analysis and does not model actual trade flows or market exchange. The reported self-sufficiency rates should therefore be interpreted as theoretical production capacity under the specified assumptions, not as realized regional autonomy. This distinction is particularly important in regions with strong import or export linkages, where production and consumption are not tightly aligned. In such contexts, land released under alternative dietary or waste scenarios may not translate directly into local food system transformation, because producer decisions, processing infrastructure, contracts, and broader market conditions will shape how these opportunities are used.

More generally, the results should be interpreted comparatively rather than as precise forecasts. Several assumptions, notably organic yield gaps, emission factors, conversion efficiencies, and the allocation of surplus land to renewable energy or ecological restoration, affect the absolute values but do not alter the directional conclusions of the scenario analysis. However, the main purpose of the scenario analysis is to compare directional differences between pathways under a common set of assumptions.

The strongest conclusions of the study therefore concern the relative ordering of options, such as the consistently high land efficiency of wind and PV systems compared to dedicated bioenergy crops, and the substantial land-saving effects of dietary change and food waste reduction, findings that remain robust across the range of parameter variation tested.

Recommendations

Our results highlight the need for integrated regional governance linking agriculture, climate, and energy strategies (Jónsdóttir & Gísladóttir, 2023). Three findings are particularly policy-relevant. First, dietary guidelines should align with climate objectives (Ritchie et al., 2018), emphasizing reduced meat consumption and promotion of legumes, given their influence on regional land demand (Balázs et al., 2021; van Selm et al., 2022). Second, wind and PV systems offer higher land-use efficiency than bioenergy crops, enabling energy transitions without displacing food production (Böhm, 2024; Nitsch et al., 2012). Third, integrated land and resource planning, combining waste reduction, circular land-use practices, and nature-based solutions can simultaneously strengthen ecological sustainability (Searchinger et al., 2022; Seddon, 2022).

Regional food systems can enhance resilience but must balance local sovereignty with global food security (Beyer et al., 2022; Kaufmann et al., 2022). Ikerd (2025) proposes food-based communities committed to food sovereignty as a model for local empowerment. By applying our framework to a model region, we demonstrate how local policies and conditions could shape feasible pathways for these dimensions, with the framework's value lying in making complex land-use trade-offs understandable to the communities, institutions, and food system actors who may need to negotiate them. For communities, the model illustrates how dietary transitions, particularly toward plant-based or flexitarian diets, may reduce land demand and environmental pressures while maintaining cultural acceptability. Importantly, these transitions are not purely technical choices but involve food culture, social norms, and equity considerations that communities themselves must navigate. Scenario results may guide public awareness campaigns, institutional food policies, and CSA. For municipalities, the framework may support integrated land-use and energy planning. Comparing scenarios for food production and renewable energy may help munici-

palities consider land allocations that minimize competition, protect high-value soils, and align with climate and biodiversity goals. Results could inform zoning policies, dual land-use strategies such as agrivoltaics, and public procurement decisions, enhancing policy coherence across departments. Yet their translation into policy requires engagement with local planners, farmers, and residents whose priorities and constraints shape what is institutionally and politically feasible. For food system stakeholders, including producers, processors, retailers, and civil society organizations, the framework demonstrates how production strategies may interact with regional demand and ecological constraints. Organic and conventional farming scenarios may identify where sustainable practices are viable without increasing land pressure. Such insights on crop-livestock balance and regional self-sufficiency may support value-chain coordination, investment planning, and resilience strategies, particularly for smaller producers and cooperatives whose decisions collectively shape regional land use but who rarely have access to integrated scenario evidence of this kind.

While the framework is grounded in modeling, its application in practice is inherently a social and political process. The pathways pursued, and by whom, are dependent on community agencies, local priorities, and the inclusiveness of governance processes. Translating scenario evidence into food system change requires participatory processes that engage diverse stakeholders, including smallholder farmers as well as community food initiatives, whose perspectives may not be reflected in aggregate land-use metrics. Equity considerations are equally important, as dietary transitions and land reallocation may have uneven distributional consequences across income groups, land tenure arrangements, and farming scales. Future applications would therefore benefit from integrating scenario development into participatory planning processes that are directly responsive to the needs and priorities of the communities under study.

Looking ahead, future reforms of the European CAP may further shape regional food availability through more targeted production incentives. In the context of sustainability transitions and the growing demand for plant-based foods, policy instruments could potentially be used to encourage the production of plant-based protein crops, such as soybeans or other legumes. Expanding domestic production of such crops could contribute to diversifying regional food systems, strengthening local value chains, and reducing reliance on imported protein sources.

Our framework may function as a multi-level governance tool, translating complex interactions into accessible, scenario-based evidence for policymakers and food system stakeholders. By revealing unintended consequences of single-sector decisions, the framework may support more coherent consideration of land-use strategies across communities, municipalities, and regional food systems. Overall, this approach offers a structured evidence base that may help bridge scientific analysis and deliberation around diets, production, and energy planning, identifying potential pathways and offering opportunity spaces for actors seeking to align food, energy, and ecological objectives.

Future research should expand this approach to other regions, refine land-type differentiation, incorporate realistic organic farming scenarios, and evaluate diverse dietary patterns. Additional dimensions, including water, nutrient cycles (N, P), and biodiversity footprints must be assessed to fully align with policy frameworks. Addressing these aspects may support comprehensive strategies for ecologically sustainable regional food systems. 

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Appendix. Supplementary Figures and Data

Overview of European Foodshed Analyses

Zasada et al. (2019) developed the Metropolitan Foodshed and Self-sufficiency Scenario (MFSS) model to estimate the agricultural area (as a radius) required to feed the populations of four European cities: London (GB), Berlin (DE), Milan (IT), and Rotterdam (NL). The original model focuses on domestic and imported products but does not consider food flow networks between spatial entities, categorizing it as a capacity study (Schreiber et al., 2021). Excluding these flows can bias regional self-sufficiency assessments, particularly in areas with high import or export activity, by disconnecting local production from actual consumption patterns. In import-dependent regions, self-sufficiency may be underestimated, while in export-oriented regions, it may be overestimated, potentially misinforming policy decisions. Table A1 gives an overview of further local-scale studies.

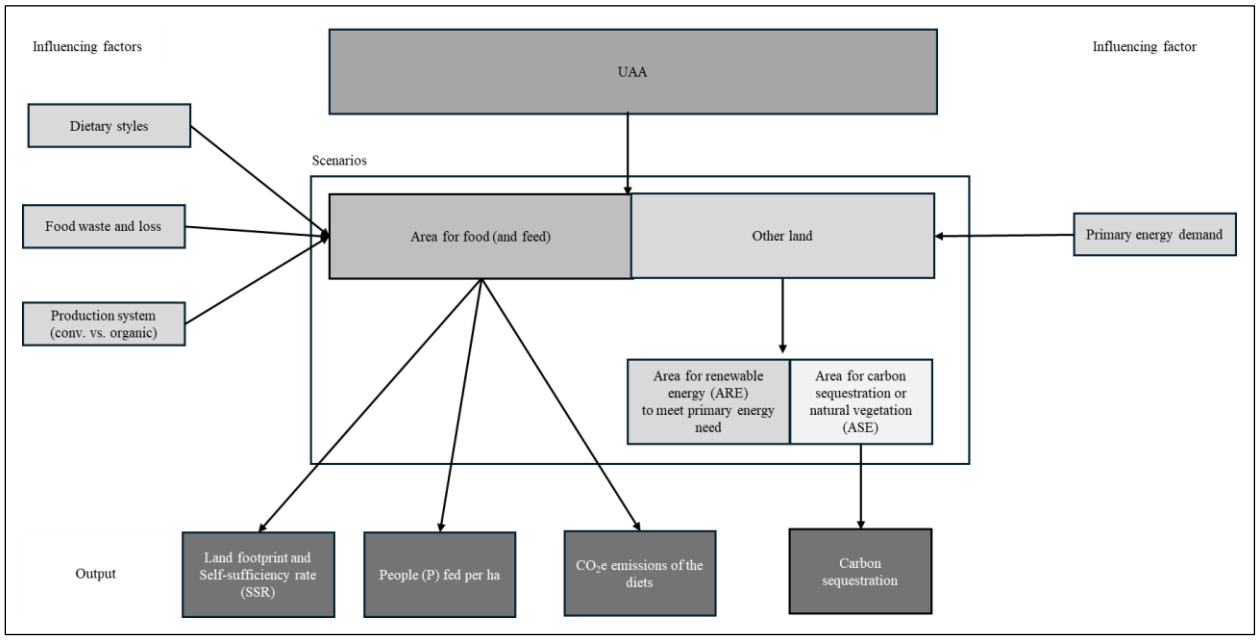
Table A1. Thematic Grouping of Relevant Local-Scale Literature

Theme	Author(s), year	Focus or objective	Geographic scope	Method or model
Foodshed Analyses	Joseph (2019)	Calculated local food self-sufficiency potential under different diets and production system combinations	Hamburg (DE)	Foodshed analysis
	Sylla (2022)	Analyzed capacity of local food systems to supply vegetable-based diets	Nine European cities: Wrocław (PL), Ostend (BE), Berlin (DE), Avignon (FR), Copenhagen (DK), Bari (IT), Brașov (RO), Athens (EL), Barcelona (ES)	MFSS model
	Vicente-Vicente, Doernberg, et al. (2021)	Assessed self-sufficiency considering organic production, diet, food waste, and population growth	Vienna (AT), Bristol (UK)	MFSS model
	Vicente-Vicente, Sanz-Sanz, et al. (2021)	Combining MFSS with data on cropping patterns, soil and topography to develop a "foodshed archipelago"	Avignon (FR)	MFSS model
	Vicente-Vicente & Piorr (2023)	Conducted foodshed analysis to support local food strategy	Munich and Bavaria (DE)	MFSS model
Bioenergy & Food Systems	Tavakoli-Hashjini et al. (2020)	Evaluated potential bioenergy production from Miscanthus while ensuring food self-sufficiency and ecosystem services	Brandenburg (DE)	MFSS model and backcasting
Flow Analyses	Moschitz & Frick (2021)	Investigated city food flows	Leutkirch (DE), Waldkirch (DE)	Flow analysis

Source: Own compilation. This list does not claim to be exhaustive.

Schematic View of the Research Approach

Figure A1. Schematic View of the Research Approach

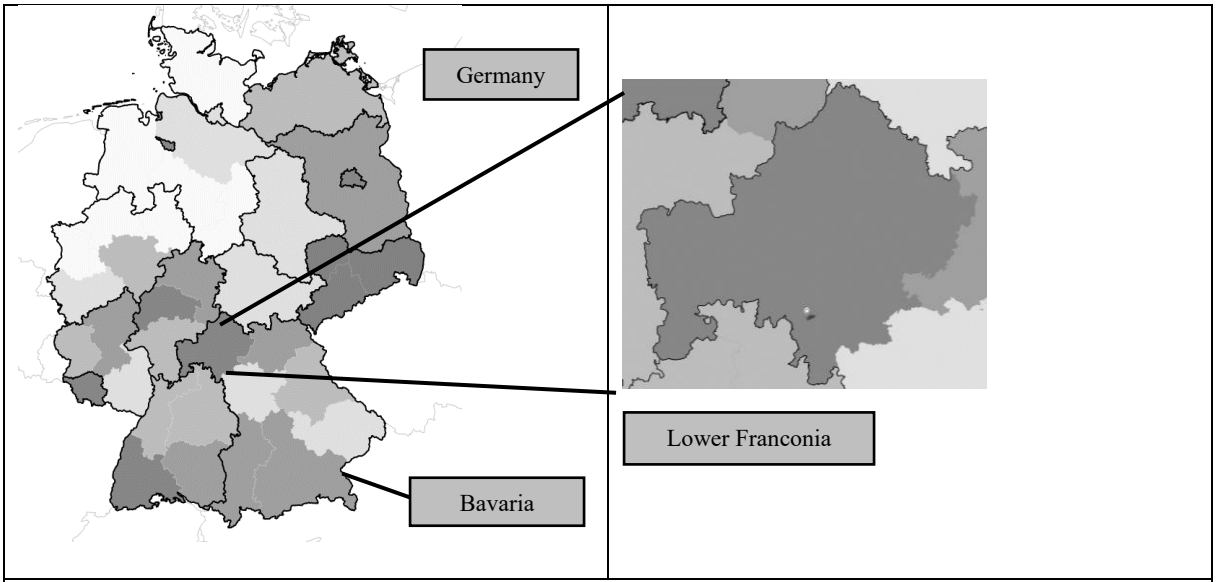


Source: Own compilation. UAA: utilized agricultural area, SSR: self-sufficiency rate, ARE: area for renewable energies, ASE: area for carbon sequestration or natural vegetation

District of Lower Franconia

The district of Lower Franconia is located in northeastern Bavaria (Figure A2), has a population of 1.34 million people, and covers an area of 3293.8 square miles (8,531 km²) (Bayerisches Landesamt für Statistik, 2024).

Figure A2. Map of Germany, Bavaria, and the Research Area, Lower Franconia



Note: The different shades have no significance for this study. Source: Statistische Ämter des Bundes und der Länder (n.d.)

Lower Franconia ranks fifth place in terms of area among the Bavarian districts. The altitude varies between 335.6 and 1,978.4 feet (102 and 603 meters) above sea level. Agricultural land accounts for 41% of Lower Franconia's area, of which 78.5% is arable land, 19.4% permanent grassland, and 2% permanent cropland (mainly viticulture). For a comparison of Lower Franconia to Bavaria and Germany, see Table A2. Lower Franconia has no peatland, its permanent grassland is managed extensively, and the region has a low livestock density (Bayerisches Staatsministerium für Ernährung, Landwirtschaft, Forsten und Tourismus, 2025).

Table A2. Comparisons between Lower Franconia, Bavaria, and Germany

Indicator	Lower Franconia	Bavaria	Germany
Average size of agricultural businesses in hectares (ha)	44.0	36.6	63.2
Share of arable land	78.5%	66%	70.3%
Share of grassland	19.4%	33%	28.5%
Share of permanent cropland	2.0%	0.4%	1.2%
Share of organic agriculture	13.9%	11.6%	11.4%
Average yield of conventional winter wheat (organic = 55%) in tons per ha	6.21 (3.42)	7.17 (3.97)	7.08 (3.89)
Livestock units/ha utilized agricultural area	0.33	0.84	0.72

Sources: Bayerisches Landesamt für Statistik, 2024; Bayerische Landesanstalt für Landwirtschaft, n.d. ; Bayerisches Staatsministerium für Ernährung, Landwirtschaft, Forsten und Tourismus, 2025; Bundesministerium für Landwirtschaft, Ernährung und Heimat, n.d.

In Lower Franconia, the annual precipitation is 29.4 inches (747 millimeters (mm)). The average German precipitation is 31.1 inches (789 mm) (Deutscher Wetterdienst, n.d.). Thus, most crops are rain-fed. However, due to climate change, farmers face longer growing seasons, increasing drought, more frequent heavy rainfall events, and changes in nutrient availability (e.g., Verma et al., 2025).

Soils in the research area contain sandstone, loess, and limestone. Thus, parts of Lower Franconia are very suitable for agricultural use. The most prominent crops in Lower Franconia are winter wheat, canola, soybeans, and sugar beets, which are often produced in food-quality and are crucial export goods. Consequently, the share of energy crops is relatively low (Bayerisches Landesamt für Statistik, 2024). High export orientation does not affect assumptions of local self-sufficiency in the MFSS model. The proportion of organic agriculture ranges from 5% in favorable areas to 25% in less favorable areas (Bayerische Landesanstalt für Landwirtschaft, n.d.; Bundesministerium für Landwirtschaft, Ernährung und Heimat, n.d.).

Relevant Indicators and Literature Sources

Most parameters were compiled using a single reference year, which served as the main basis for the data set. When values for that exact year were not available in the literature or statistical sources, we used data from years that were closest to the reference year and considered representative for the same production context. No formal temporal standardization of the data sets was performed.

Table A3. Relevant Indicators and Literature Sources

Indicator or value	Spatial scale	Reference year	Source(s)
Structural and resource use indicators			
Data on agricultural structure	Lower Franconia, Bavaria, and Germany	2024 2025	Bayerisches Landesamt für Statistik, 2024 Bayerische Landesanstalt für Landwirtschaft, n.d. Bundesministerium für Ernährung und Landwirtschaft, n.d. Bayerisches Staatsministerium für Ernährung, Landwirtschaft, Forsten und Tourismus, 2025
Share of land use for energy crops	Bavaria	2024	Bayerisches Landesamt für Statistik, 2024 Fachagentur Nachwachsende Rohstoffe, n.d.
Land-use footprints per kg of food product of select food items	World	2018	Poore & Nemecek, 2018
Production and yield indicators			
UAA	Lower Franconia, Bavaria, Germany	2025	Bundesministerium für Ernährung und Landwirtschaft, n.d. Bayerisches Staatsministerium für Ernährung, Landwirtschaft, Forsten und Tourismus, 2025
Yield data	Lower Franconia and Bavaria	2024	Bayerisches Landesamt für Statistik, 2024 Bayerische Landesanstalt für Landwirtschaft, n.d.
Emission, carbon, and greenhouse gas (GHG) indicators			
Annual carbon storage rate (2.9 t C/ha*a)	Germany	2022	Fehrenbach & Bürck, 2022
Emissions of conventional and organic fields	Germany	2022	Hülsbergen et al., 2022
GHG emissions of major food products	Germany	2018 2025	Poore & Nemecek, 2018 Umweltbundesamt, n.d.
Emissions for single products or product groups	Europe	2022	Chiriacò et al., 2022

Emissions from PV and wind energy generation	Germany, Europe	2020	Kaltschmitt et al., 2020
Energy production and efficiency indicators			
Average and range of energy that can be produced from energy crops	Germany	2024	Fachagentur Nachwachsende Rohstoffe, n.d. Kaltschmitt & Stampfer, 2024
Primary energy consumption	Germany	2024	Agora Energiewende, 2024
Consumption and food intake indicators			
Consumption data	Germany	2024	Eberle & Mumm, 2024 Joseph et al., 2019 Vicente-Vicente & Piorr, 2023
Fish consumption data	Germany	2024	FAO FishStatJ database FAO, n.d.
National food balance and food intake	Germany	2024	FAO, 2025
Food loss and waste indicators			
Food loss at different stages of the value chain	Europe	2011	Gustavsson et al., 2011
Demographics			
Population	Lower Franconia	2023	Bayerisches Landesamt für Statistik, 2023

Average and Range of Energy that can be Produced from Energy Crops

Table A4. Average and Range of Energy that can be Produced from Energy Crops

Crop	Energy production (for biogas or thermal use) in MWh/ha	Yield in t DM/ha (unless indicated otherwise)
Maize WPS (32% DM)	47	25
Miscanthus WPS (80% DM)	85	18 (10-30)
Silphium WPS (25% DM)	35.1	10-20
Perennial ryegrass WPS (20% DM)	37.9	10-19
Permanent grassland	7.4-14.0	6-14 t DM/a (intensive) 2.3-15.5 t DM/a (extensive)
Green rye WPS (35% DM)	12.6	20 t FM/ha
Winter rye WPS (86% DM)	17	8-12
Triticale WPS (86% DM)	18.6	8-12
Winter wheat WPS (86% DM)	25	8-12

WPS = whole-plant silage, MWh = megawatt-hour, ha = hectare, DM = dry matter, FM = fresh matter, a = year. Source: Kaltschmitt & Stampfer, 2024

Primary Energy Consumption

Table A5. Primary Energy Consumption in Germany and Lower Franconia

Year	Primary energy consumption in Germany in PJ	Primary energy consumption in Lower Franconia in GWh
2018	13,129	57,653
2025	9,897	43,460
2045	6,458	28,359

PJ = petajoule; 1 PJ equals 278 GWh (gigawatt-hour)
Source: Agora Energiewende, 2024

Table A6. Energy Production and Area Needed to Meet Primary Energy Consumption Needs (2018, 2025, and 2045)

	Energy production in MWh/ha	Area needed to meet primary energy consumption needs in 2018 in ha	Area needed to meet primary energy consumption needs in 2025 in ha (reduction in %)	Area needed to meet primary energy consumption needs in 2045 in ha (reduction in %)
Open-space PV	1,000	57,653	43,460 (-25%)	28,359 (-50%)
Wind energy	20,000	2,883	2,173 (-25%)	1,418 (-50%)

MWh/ha = megawatt-hour per hectare
Source: Agora Energiewende, 2024; Kaltschmitt & Stampfer, 2024

Dietary Compositions

An **omnivorous diet** (baseline) includes both animal- and plant-based foods—meat, fish, dairy, eggs, grains, legumes, fruits, and vegetables. Diets high in processed meats and saturated fats are linked to increased risks of cardiovascular disease, obesity, and certain cancers (Godfray et al., 2018; Pan et al., 2012).

A **flexitarian diet** is mainly plant-based with occasional animal products, often chosen for health, ethical, or environmental reasons. It is associated with lower risks of chronic diseases, including heart disease, type 2 diabetes, and some cancers (Derbyshire, 2017).

A **vegetarian diet** excludes meat, poultry, and fish, relying on plant proteins and often including dairy and eggs. It is linked to reduced body weight, blood pressure, and inflammation (Key et al., 2006). In 2024, 7% of Germans and 36% of Indians identified as vegetarians (Statista, 2025a).

A **vegan diet** excludes all animal-derived products and is entirely plant-based. It is associated with reduced disease risks (Craig, 2009; Key et al., 2006). In 2024, 4% of Germans and 10% of Indians followed a vegan diet (Statista, 2025b).

The dietary compositions applied in this study are based on the EAT-Lancet Planetary Health Diet and Willett et al. (2019) and have been adapted following Eberle and Mumm (2024) (Table A5). "Baseline" refers to the average balanced German nutrition with products that can be produced locally.

Table A7. Summary of the Different Dietary Patterns (in descending order for the baseline column)

Product or product group	Baseline kg/(capita*a)	Flexitarian kg/(capita*a)	Vegetarian kg/(capita*a)	Vegan kg/(capita*a)
Cereals	92.60	87.90	84.68	84.68
Vegetables	77.66	117.06	126.47	219.00
Fruits	77.18	79.46	85.85	109.50
Milk	44.74	36.38	39.30	0.00
Sugar	26.69	10.95	10.95	10.95
Potatoes	26.44	19.50	21.07	33.91
Yogurt	25.96	28.74	31.05	0.00
Sausage	21.85	6.08	0.00	0.00
Cheese	21.04	2.91	3.15	0.00
Fats and oils	15.68	16.83	18.30	18.30
Eggs	9.94	4.59	4.75	0.00
Pork	8.62	5.11	0.00	0.00
Poultry	6.33	8.10	0.00	0.00
Beef	5.78	5.11	2.58	0.00
Butter	5.16	0.36	0.39	0.00
Fish	4.98	7.62	0.00	0.00
Legumes	2.97	57.58	72.40	81.09
Nuts	2.73	8.69	9.13	9.13
Sum	489.35	507.49	512.13	569.13

Source: Data calculated from Eberle & Mumm, 2024.

Food Loss and Waste

The following five levels of food loss and waste along the food value chain were distinguished according to Zasada et al. (2019):

- Reduced production output due to mechanical damage and rejects during harvest or disease and death of animals in agricultural production;
- Rejects and damage during postharvest treatment, postharvest handling, storage, and transportation;
- Inefficiencies in processing and packaging (e.g., due to technical failure and over- or underproduction); and
- Losses and waste in the wholesale, retail, and distribution systems (depreciation or spoilage and within the food service industry).
- Waste by the end consumer at home or eating out.

Table A8. Estimated or Assumed Waste Percentages for Each Commodity Group in Each Step of the Food Value Chain for Europe, Including Russia

	Agricultural production	Postharvest handling and storage	Processing and packaging	Distribution: Supermarket Retail	Consumption
Cereals	2%	4%	10%	2%	25%
Fish and seafood	9.4%	0.5%	6%	9%	11%
Fruits and vegetables	20%	5%	2%	10%	19%
Meat	3.1%	0.7%	5%	4%	11%
Milk	3.5%	0.5%	1.2%	0.5%	7%
Oilseeds and pulses	10%	1%	5%	1%	4%
Roots and tubers	20%	9%	15%	7%	17%

Source: Gustavsson et al., 2011

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Table A9. Land Footprint and Food Self-Sufficiency

	Conventional						Organic					
	Scenario	Footprint (A/Aw) in m²	Agg in ha (share of UAA in %)	SSR in %	P/ha	ARE in ha (share in %)	Scenario	Footprint (A/Aw) in m²	Agg in ha (share of UAA in %)	SSR in %	P/ha	ARE in ha (share in %)
Baseline	Ic	1,229	173,978 (49.7)	201	7.7	176,094 (50.3)	Io	1,877	251,316 (71.8)	139	5.3	98,756 (28.2)
Baseline w/o hh	IIc	1,147	153,552 (43.9)	228	8.7	196,520 (56.1)	IIo	1,652	221,173 (63.2)	158	6.1	128,899 (36.8)
Baseline with hh	IIIc	922	123,369 (35.2)	284	10.8	226,703 (64.8)	IIIo	1,368	183,053 (52.3)	191	7.3	167,019 (47.7)
Flexi	IVc	993	132,846 (37.9)	264	10.1	217,226 (62.1)	IVo	1,465	196,103 (56.0)	179	6.8	153,969 (44.0)
Flexi w/o hh	Vc	852	114,013 (32.6)	307	11.7	236,059 (67.4)	Vo	1,262	168,945 (48.3)	207	7.9	181,127 (51.7)
Flexi with hh	VIc	729	97,536 (27.9)	359	13.7	252,536 (72.1)	VIo	1,085	145,227 (41.5)	241	9.2	204,845 (58.5)
Veget	VIIc	732	98,005 (28.0)	357	13.7	252,067 (72.0)	VIIo	965	127,975 (36.6)	274	10.5	222,097 (63.4)
Veget w/o hh	VIIIc	619	82,893 (23.7)	422	16.1	267,179 (76.3)	VIIIo	809	108,268 (30.9)	323	12.4	241,804 (69.1)
Veget with hh	IXc	515	68,973 (19.7)	508	19.4	281,099 (80.3)	IXo	670	89,615 (25.6)	391	14.9	260,457 (74.4)
Vegan	Xc	618	82,660 (23.6)	424	16.2	267,412 (76.4)	Xo	781	104,475 (29.8)	335	12.8	245,597 (70.2)
Vegan w/o hh	XIc	476	63,751 (18.2)	549	21.0	286,321 (81.8)	XIo	603	80,669 (23.0)	434	16.6	269,403 (77.0)
Vegan with hh	XIIc	422	56,462 (16.1)	620	23.7	293,610 (83.9)	XIIo	533	71,280 (20.4)	491	18.8	278,792 (97.6)

w/o hh = without household-level waste, with hh = with household-level waste, m² = square meters, Agg = aggregated area in ha, SSR = self-sufficiency rate, P/ha = people fed per ha, ARE = area for renewable energy, total UAA: 350,072 ha (remains stable)
Land footprints (A/Aw): red: >1,000 m², orange: <1,000 m² and >750 m², yellow: <750 m² and >500 m², green: <500 m²
Agg: red: > 200,000 ha, orange: < 200,000 ha and > 100,000 ha, yellow: < 100,000 ha and >75,000 ha, green: < 75,000 ha
SSR: red: <300%, orange: <400% and >300%, yellow: <500% and >400%, green: >500%
P/ha: red: <10.0, orange: >10.0 and >15.0, yellow: >15.0 and <20.0, green: >20.0
Surplus area: red: <150,000 ha, orange: >150,000 ha and <200,000 ha, yellow: >200,000 ha and <250,000 ha, green: >250,000 ha

Share of Products or Product Groups on Selected Land Footprints

Animal-based products include meat and dairy products, which contribute at least one-third to the land footprints. Due to lower feed conversion efficiency, beef products contribute to a high land footprint: 37% in the conventional baseline scenario and 45% in the organic baseline scenario. The results highlight the role of beef and dairy in driving high land footprints (Table A10).

Table A10. Share of Products or Product Groups on Selected Land Footprints in %

Scenario		Meat and sausage	Dairy	Cereals	Fats	Fruits	Potatoes	Vegetables	Eggs	Fish	Legumes	Nuts	Sugar
Baseline conv.	**Ic**	37	30	12	7	5	1	2	3	<1	0	1	2
Baseline org.	**Io**	45	23	11	6	4	1	2	5	<1	0	1	2
Flexi conv.	**IVc**	32	15	15	10	6	1	4	2	<1	12	3	1
Flexi org.	**IVo**	39	14	14	8	5	1	3	3	<1	9	3	1
Veget conv.	**VIIc**	22	22	20	15	9	1	5	3	N/A	20	4	1
Veget org.	**VIIo**	23	23	21	14	9	1	6	5	N/A	17	5	1
Vegan conv.	**Xc**	N/A	N/A	23	17	14	2	11	N/A	N/A	26	5	2
Vegan org.	**Xo**	N/A	N/A.	25	17	14	2	12	N/A	N/A	23	6	2

Conv. = conventional, org. = organic, N/A = not applicable

Self-Sufficiency Values of Select Food Products or Product Groups

Tables A11 and A12 illustrate the self-sufficiency values of select (i.e., regionally produced) food products or product groups in conventional and organic scenarios, respectively.

Table A11. Food Product or Product Group Self-Sufficiency Values in % across Dietary Scenarios (Conventional)

Scenario		Cereals	Fats and oils	Potatoes	Vegeta-bles	Legumes	Fruits	Beef	Pork	Eggs
Baseline	**Ic**	1,159	590	118	100	510	14	80	171	24
Flexi	**IVc**	1,221	550	160	66	26	13	91	288	51
Veget	**VIIc**	1,268	506	148	61	21	12	0	0	50
Vegan	**Xc**	1,268	506	92	35	19	10	0	0	0

Table A12. Food Product or Product Group Self-Sufficiency Values in % across Dietary Scenarios (Organic)

Scenario		Cereals	Fats and oils	Potatoes	Vegeta-bles	Legumes	Fruits	Beef	Pork	Eggs
Baseline	Io	67	16	28	22	187	2	N/A	N/A	N/A
Flexi	IVo	71	15	38	15	10	2	N/A	N/A	N/A
Veget	VIIo	73	14	35	14	8	2	N/A	N/A	N/A
Vegan	Xo	73	14	22	8	7	2	N/A	N/A	N/A

N/A = no data available

The tables break down self-sufficiency values by food category across four dietary scenarios: baseline, flexitarian (Flexi), vegetarian (Veget), and vegan. Food categories include cereals, oilseeds/fats, potatoes, vegetables, legumes, fruits, beef, pork, and eggs. Dairy is excluded, as its production is very limited in Lower Franconia. The results show that cereals dominate the self-sufficiency values in all scenarios, with 1,159% in the baseline, 1,221% in the flexitarian, and 1,268% in the vegetarian and vegan diets. Values from oilseeds and fats remain consistent across all scenarios. Beef has an influence on the self-sufficiency values in the baseline and flexitarian diets, with values of 510% and 506%, respectively, but its value is eliminated in vegetarian and vegan scenarios. Pork and eggs contribute modestly to the baseline and flexitarian diets, while their self-sufficiency values are negligible or absent in vegetarian and vegan diets. Legumes, vegetables, fruits, and potatoes have lower self-sufficiency values than cereals and meats, though their contributions increase slightly in vegetarian and vegan diets.

Emissions and Soil Organic Carbon (SOC) Sequestration

Table A13. Emissions vs. Storage Capacities

	Conventional					Organic			
	Scenario	**Carbon sequestration** potential in million t CO_2e of **diets**	**Emissions** of the **diets** in million t CO_2e	Carbon sequestration potential in million t CO_2e of **ARE/ASE areas**		Scenario	**Carbon sequestration** potential in million t CO_2e of **diets**	**Emissions** of the **diets** in million t CO_2e	Carbon sequestration potential in million t CO_2e of **ARE/ASE areas**
Baseline	Ic	1.85	-0.52	1.87		Io	2.67	-0.31	1.05
Baseline w/o hh	IIc	1.63	-0.46	2.9		IIo	23.5	-0.27	1.37
Baseline with hh	IIIc	1.31	-0.37	2.41		IIIo	1.95	-0.22	1.78
Flexi	IVc	1.41	-0.40	2.31		IVo	2.09	-0.24	1.64
Flexi w/o hh	Vc	1.21	-0.34	2.51		Vo	1.80	-0.21	1.93
Flexi with hh	VIc	1.04	-0.29	2.69		VIo	1.55	-0.18	2.18
Veget	VIIc	1.04	-0.29	2.68		VIIo	1.36	-0.16	2.36
Veget w/o hh	VIIIc	0.88	-0.25	2.84		VIIIo	1.15	-0.13	2.57
Veget with hh	IXc	0.73	-0.21	2.99		IXo	0.95	-0.11	2.77
Vegan	Xc	0.88	-0.25	2.85		Xo	1.11	-0.13	2.61
Vegan w/o hh	XIc	0.68	-0.19	3.05		XIo	0.86	-0.10	2.87
Vegan with hh	XIIc	0.60	-0.17	3.12		XIIo	0.76	-0.09	2.97

t = metric tons. Sequestration potential of the available area: 3.73 million metric tons.

Table A14. Emissions vs. Carbon Storage Potential on Additional "Free" Agricultural Land Due to Food Loss and Waste

	Scenario	Additional freed-up area in ha	Total emissions in million t CO_2e	Total carbon sequestration potential in million t CO_2e	Δ (sequestration - emissions)
Baseline	Org./Conv.	77,338	-0.23*	0.82	0.59
	Conv. to losses w/o hh	20,425	-0.06	0.22	0.16
	Conv. to losses with hh	50,608	-0.15	0.54	0.39
	Org. to losses w/o hh	30,143	-0.04	0.32	0.28
	Org. to losses with hh	68,263	-0.08	0.73	0.64
Flexi	Org./Conv.	63,257	-0.19*	0.67	0.48
	Conv. to losses w/o hh	18,833	-0.06	0.20	0.14
	Conv. to losses with hh	35,310	-0.11	0.38	0.27
	Org. to losses w/o hh	27,158	-0.03	0.29	0.26
	Org. to losses with hh	50,876	-0.06	0.54	0.48
Veget	Org./Conv.	29,970	-0.09*	0.32	0.23
	Conv. to losses w/o hh	15,112	-0.05	0.16	0.12
	Conv. to losses with hh	29,032	-0.09	0.31	0.22
	Org. to losses w/o hh	19,707	-0.02	0.21	0.19
	Org. to losses with hh	38,360	-0.05	0.41	0.36
Vegan	Org./Conv.	21,815	-0.07*	0.23	0.17
	Conv. to losses w/o hh	18,909	-0.06	0.20	0.14
	Conv. to losses with hh	26,198	-0.08	0.28	0.20
	Org. to losses w/o hh	23,806	-0.03	0.25	0.22
	Org. to losses with hh	33,196	-0.04	0.35	0.31

*: calculated using 2.99 tons CO_2e per ha, w/o hh = without household-level waste, with hh = with household-level waste

Emissions for single products or product groups were calculated as described. When compared at an aggregated level, all dietary patterns show comparable emissions when calculating either with organic or conventional yields (Table A15). Broken down to single food products or product groups, we can confirm that emissions for meat production are among the highest. High values for cereals derive from the large amount of cereals consumed (e.g., bread and pasta). Note that cereals for feed were not considered here.

Table A15. Emissions of Products or Product Groups in CO_2e kg/(cap*a) – Conventional and Organic Scenarios

Conventional										
Scenario		Cereals	Vegeta-bles	Fruits	Milk	Legumes	Nuts	Beef	Pork	Poultry
Baseline	Ic	109	17	9	40	1	3	75	20	7
Flexi	IVc	104	26	10	33	13	8	66	12	9
Veget	VIIc	100	28	10	35	17	9	0	0	0
Vegan	Xc	100	48	13	0	19	9	0	0	0
Organic										
Baseline	Io	144	14	7	36	1	3	64	34	6
Flexi	IVo	136	21	7	30	12	8	57	20	7
Veget	VIIo	131	23	8	32	14	9	0	0	0
Vegan	Xo	131	39	10	0	16	9	0	0	0

Emissions vs. Storage Capacities - Wind Energy and PV Energy, 2025 and 2045

Table A16. Emissions vs. Storage Capacity - Wind Energy 2025

		Conventional					Organic		
Scenario		Emissions of wind turbines in million t CO_2e	Emissions of diets in million t CO_2e	Carbon sequestra-tion potential in million t CO_2e for the respective scenario		Emissions of wind turbines in million t CO_2e	Emissions of diets in million t CO_2e	Carbon sequestra-tion potential in million t CO_2e for the respective scenario
Baseline	**Ic**	-0.017	-0.52	1.85	**Io**	-0.017	-0.31	1.03
Baseline w/o hh	**IIc**		-0.46	2.07	**IIo**		-0.27	1.35
Baseline with hh	**IIIc**		-0.37	2.39	**IIIo**		-0.22	1.75
Flexi	**IVc**	-0.017	-0.40	2.29	**IVo**	-0.017	-0.24	1.62
Flexi w/o hh	**Vc**		-0.34	2.49	**Vo**		-0.21	1.90
Flexi with hh	**VIc**		-0.29	2.66	**VIo**		-0.18	2.16
Veget	**VIIc**	-0.017	-0.29	2.66	**VIIo**	-0.017	-0.16	2.34
Veget w/o hh	**VIIIc**		-0.25	2.82	**VIIIo**		-0.13	2.55
Veget with hh	**IXc**		-0.21	2.97	**IXo**		-0.11	2.75
Vegan	**Xc**	-0.017	-0.25	2.82	**Xo**	-0.017	-0.13	2.59
Vegan w/o hh	**XIc**		-0.19	3.02	**XIo**		-0.10	2.84
Vegan with hh	**XIIc**		-0.17	3.10	**XIIo**		-0.09	2.94

Calculated area needed for wind energy: 2,173 ha.

Table A17. Emissions vs. Storage Capacity - Wind Energy 2045

		Conventional				Organic		
Scenario		Emissions of wind turbines in million t CO_2e	Emissions of diets in million t CO_2e	Carbon sequestration potential in million t CO_2e for the respective scenario		Emissions of wind turbines in million t CO_2e	Emissions of diets in million t CO_2e	Carbon sequestration potential in million t CO_2e for the respective scenario
Baseline	**Ic**	-0.011	-0.52	1.86	**Io**	-0.011	-0.31	1.04
Baseline w/o hh	**IIc**		-0.46	2.08	**IIo**		-0.27	1.36
Baseline with hh	**IIIc**		-0.37	2.40	**IIIo**		-0.22	1.76
Flexi	**IVc**	-0.011	-0.40	2.30	**IVo**	-0.011	-0.24	1.62
Flexi w/o hh	**Vc**		-0.34	2.50	**Vo**		-0.21	1.91
Flexi with hh	**VIc**		-0.29	2.67	**VIo**		-0.18	2.17
Veget	**VIIc**	-0.011	-0.29	2.67	**VIIo**	-0.011	-0.16	2.35
Veget w/o hh	**VIIIc**		-0.25	2.83	**VIIIo**		-0.13	2.56
Veget with hh	**IXc**		-0.21	2.98	**IXo**		-0.11	2.76
Vegan	**Xc**	-0.011	-0.25	2.83	**Xo**	-0.011	-0.13	2.60
Vegan w/o hh	**XIc**		-0.19	3.03	**XIo**		-0.10	2.85
Vegan with hh	**XIIc**		-0.17	3.11	**XIIo**		-0.09	2.95

Calculated area needed for wind energy: 1,418 ha.

Table A18. Emissions vs. Storage Capacity - PV Energy 2025

		Conventional				Organic		
Scenario		Emissions of PV in million t CO_2e	Emissions of diets in million t CO_2e	Carbon sequestration potential in million t CO_2e for the respective scenario		Emissions of PV in million t CO_2e	Emissions of diets in million t CO_2e	Carbon sequestration potential in million t CO_2e for the respective scenario
Baseline	**Ic**	-1.26	-0.52	1.41	**Io**	-1.26	-0.31	0.59
Baseline w/o hh	**IIc**		-0.46	1.63	**IIo**		-0.27	0.91
Baseline with hh	**IIIc**		-0.37	1.95	**IIIo**		-0.22	1.32
Flexi	**IVc**	-1.26	-0.40	1.85	**IVo**	-1.26	-0.24	1.18
Flexi w/o hh	**Vc**		-0.34	2.05	**Vo**		-0.21	1.47
Flexi with hh	**VIc**		-0.29	2.23	**VIo**		-0.18	1.72
Veget	**VIIc**	-1.26	-0.29	2.22	**VIIo**	-1.26	-0.16	1.90
Veget w/o hh	**VIIIc**		-0.25	2.38	**VIIIo**		-0.13	2.11
Veget with hh	**IXc**		-0.21	2.53	**IXo**		-0.11	2.31
Vegan	**Xc**	-1.26	-0.25	2.38	**Xo**	-1.26	-0.13	2.15
Vegan w/o hh	**XIc**		-0.19	2.58	**XIo**		-0.10	2.40
Vegan with hh	**XIIc**		-0.17	2.66	**XIIo**		-0.09	2.50

Calculated area needed for open PV: 43,460 ha.

Table A19. Emissions vs. Storage Capacities - PV Energy 2045

		Conventional				Organic		
Scenario		Emissions of PV in million t CO_2e	Emissions in million t CO_2e	Carbon sequestration potential in million t CO_2e for the respective scenario		Emissions of PV in million t CO_2e	Emissions in million t CO_2e	Carbon sequestration potential in million t CO_2e for the respective scenario
Baseline	Ic	-0.82	-0.52	1.57	Io	-0.82	-0.31	0.75
Baseline w/o hh	IIc		-0.46	1.79	IIo		-0.27	1.07
Baseline with hh	IIIc		-0.37	2.11	IIIo		-0.22	1.48
Flexi	IVc	-0.82	-0.40	2.01	IVo	-0.82	-0.24	1.34
Flexi w/o hh	Vc		-0.34	2.21	Vo		-0.21	1.63
Flexi with hh	VIc		-0.29	2.39	VIo		-0.18	1.88
Veget	VIIc	-0.82	-0.29	2.38	VIIo	-0.82	-0.16	2.06
Veget w/o hh	VIIIc		-0.25	2.54	VIIIo		-0.13	2.27
Veget with hh	IXc		-0.21	2.69	IXo		-0.11	2.47
Vegan	Xc	-0.82	-0.25	2.54	Xo	-0.82	-0.13	2.31
Vegan w/o hh	XIc		-0.19	2.75	XIo		-0.10	2.57
Vegan with hh	XIIc		-0.17	2.82	XIIo		-0.09	2.67

Calculated area needed for open PV: 28,359 ha.

Sensitivity Analysis

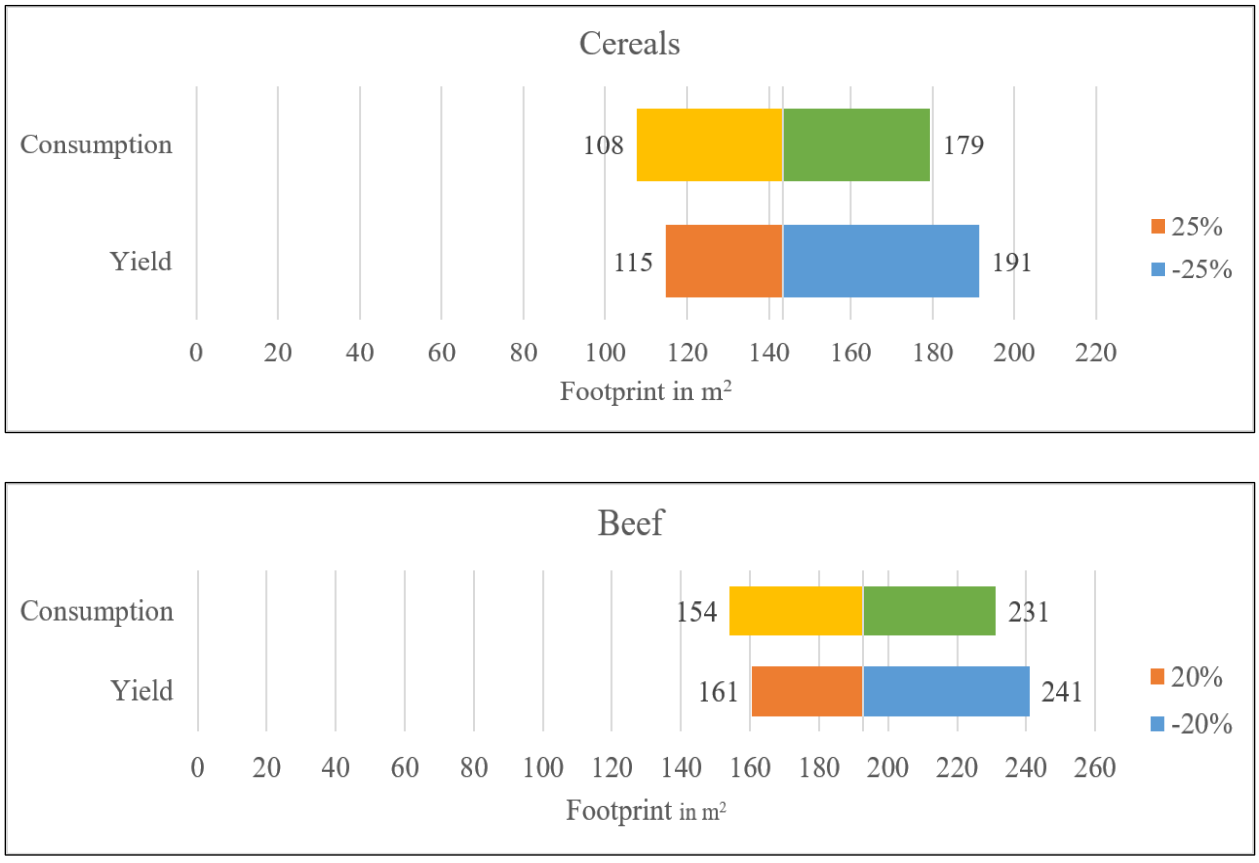
This study conducted two sensitivity analyses. The first was a breakdown of agricultural land use for each food product or product group. Some products and product groups were assigned to arable land (e.g., cereals, vegetables), some to permanent cropland (e.g., nuts), and some to permanent grassland plus arable land (e.g., meat, sausage, and dairy). The latter product groups were assigned 60% to grassland and 40% to arable land. The results reveal that there is no difference in the share of different land-use types within agriculture when conventional or organic production is considered (Table A20). This is because yield gaps are similar for most products.

Table A20. Share of Assigned Land in %

		Conventional			Organic		
	Scenarios	Arable land	Permanent grassland	Permanent cropland	Arable land	Permanent grassland	Permanent cropland
Lower Franconia	-	79.0	19.0	2.0	79.0	19.0	2.0
Baseline	Ic, Io	59.0	36.0	5.0	62.0	33.0	5.0
Flexi	IVc, IVo	68.0	23.0	9.0	69.0	22.0	8.0
Veget	VIIc, VIIo	73.0	13.0	14.0	73.0	14.0	13.0
Vegan	Xc, Xo	81.0	0.0	19.0	81.0	0.0	19.0

Second, the effects of ±20% changes in yield and consumption of food products and product groups on land footprint were analyzed to identify the most influential factors. Results confirmed that both the amount of food consumed and crop-specific yields are significant contributors to land footprint estimates. Under this range of variation, absolute values of land demand and related indicators, including self-sufficiency rates and surplus land availability, shift meaningfully. This underscores the importance of regional production conditions and sustainable dietary patterns as primary drivers of land-use outcomes. However, the overall comparative relationships between scenarios remain stable across this parameter range (not shown). The relative ordering of dietary patterns, farming systems, and energy alternatives is not altered by ±20% variation in yields, consumption, or waste rates, indicating that the main conclusions of the study are robust to plausible uncertainty in these parameters. Among individual product groups, meat and dairy consumption exert by far the greatest influence on land footprints, consistent with the scenario results reported in the main text (Fig. A3 and A4). Other product groups contribute more modestly to overall land demand variation. This pattern holds across both conventional and organic production systems, reinforcing the finding that dietary composition, particularly the share of animal products, is the dominant determinant of regional land footprints.

Figure A3. Results of the Sensitivity Analysis for ±20% Variation in Yields and Consumption for Single Products



The figure below shows ±20% variation in yields for all product categories in the baseline scenario.

Figure A4. ±20% Variation in Yields for All Products and Product Categories

