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Farming on the Edge: The 10-Fold Deficit in Lombardy's Agricultural Land

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Abstract

Lombardy is Italy's leading region in primary agricultural production, yet it faces a significant decline in agricultural soil, primarily due to urban expansion. This land consumption largely affects arable areas, as land is repurposed for low-density residential developments, roads, logistics, and commercial or industrial hubs. The reduction in agricultural land threatens regional food security and increases dependency on external markets. This study determines the long-term sustainability of this trend by estimating the actual quantity of agricultural land required to satisfy the food demand of the region's citizens. The research employed a two-part georeferenced analysis. First, a cross-tabulation matrix quantified the land consumption over two decades. Second, the Planning Forecasts Map was analyzed, coupled with new road projects, to estimate future potential land consumption embedded in Land Use Plans (PGT). Finally, food consumption was converted into the required hectares of agricultural land per capita and compared to the current stock of agricultural land to quantify the deficit by municipality. The dramatic spatial deficit confirms that the current trajectory of land consumption is unsustainable, leaving Lombardy's food security highly dependent on imports. While regional laws have reduced planned urbanization, the limitation of land take remains far from the goals. The results highlight the urgent need for effective compensatory measures and mitigation strategies that account for the true magnitude and spatial distribution of the agricultural land deficit, particularly in the most critical urban and peri-urban areas.

Keywords: land take; urbanization; agriculture; food security; compensation

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1. Introduction

According to the No Net Land Take by 2050 document, European cities should drastically reduce their rate of urbanization to reach a net zero balance between new urban areas and greenfields by 2050 [1,2]. This reduction is significant to achieving climate neutrality since the soil is the largest pool of carbon, and its biodiversity is crucial to limiting climate change [3]. As envisaged by the Soil Monitoring Law [4], soil is essential to deliver multiple ecosystem services [5,6], and the safety, liveability, and security of citizens on the planet strongly rely on the capacity to manage land use change wisely [7,8]. Unfortunately, even though policies of limitation, mitigation, and compensation of land take are taken by almost

all nations [9–11], the speed and the quantity of land that is taken by new industrial, commercial, and logistic hubs, when not infrastructures or low-density residential areas, is still unsustainable [12]. Soil is a limited, irreproducible resource [13–15], and once it is covered by an impermeable surface due to its conversion for urban uses, its ecological functions are lost [16,17]. Soil sealing directly affects the infiltration of water [18], the evapotranspiration [19], the carbon storage [20], and also the productive functions are lost in the transition to urban uses [21,22]. At the same time, land degradation is a process that has a variety of impacts; it spans from soil compaction to the most severe of soil sealing [23].

According to the most recent data on land take [24–26], the conversion of greenfields into urban features happens almost entirely on agricultural land and rural areas [26–28]. Particularly, land take occurs in the most fertile soils intensively used for primary productivity [12,27,28] while just a fraction of the total land take occurs in natural or seminatural land, thus exacerbating another connected problem: the reduction in agricultural surfaces threatens food security since the stock of productive soil is diminishing without being replicated [29]. If data on land take and the reduction in agricultural areas are nowadays well monitored [30–32] the debate around the effects of a massive reduction in rural land on primary productivity is overlooked [33,34], and nobody knows what the limit of this process is.

The problem should also be analyzed from the perspective of the Common Agricultural Policy, which discourages the massive use of fertilizers to maximize relative production [35,36] and does not consider vertical farming a feasible and sustainable solution to the problem [37].

All this being premised, the food security analysis [29] has recently broadened its focus to include dependency on imports [38], recognizing this reliance as a major source of vulnerability for the national supply. While agricultural intensification may offset land loss, the reliance on global markets means that the satisfaction of food demand becomes increasingly sensitive to market failures and price volatility, particularly those exacerbated by climate change [39], and the internal capacity to meet food demand has emerged as a critical policy concern [40,41].

Lombardy's high primary agricultural production does not translate into a regional food balance, as its output is largely exported [42], failing to directly meet internal food demand [43]. Consequently, the substantial production capacity offers limited assurance of regional food security. Lombardy also imports specific primary products because local self-production would likely incur higher costs, making imported goods more competitive and consequently reducing the profitability and income of regional farmers [42]. Furthermore, accurately assessing the land area required to meet internal needs is complicated by the changeable nature of the population's diet and the diverse agricultural production methods. This work aims to assess the sustainability of current and projected land consumption trends in Lombardy in the context of food security. Specifically, we estimate the quantity of agricultural land that should be conserved to meet the internal food demand of the region's citizens and determine whether agricultural land compensation is a feasible strategy to address this critical deficit [43,44].

For these purposes, a georeferenced analysis of different changes in land use and cover was conducted for the past and future [45,46] and compared with regional statistics on the food demand to check whether the existing and future stock of agricultural soil can satisfy the demand.

It is not the intention of this article to understand the real balance to achieve a true self-sufficiency, but rather to create a first assessment of the gap, if it exists, and how this knowledge can support compensation mechanisms [47,48].

The results will be used to discuss whether potential compensations for agricultural land can be set and what typologies can be taken into account according to the degree of deficit or surplus of agricultural land in each municipality.

This work is structured as follows: Section 2 describes the methodology we employed to answer the research questions. Section 3 presents the results of our investigations, while Section 4 discusses the results in light of potential compensation measures. Finally, Section 5 wraps up the research and presents some conclusive remarks.

2. Materials and Methods

2.1. An Introduction to Lombardy's Primary Production

Lombardy leads the primary production in Italy [49,50]. According to the most recent data from the 2020 Agricultural Census in Lombardy, there are 46,893 farms in the Region, managing approximately one million hectares (Figure 1) of utilized agricultural area [51], accounting for 4.1% of the total number of farms nationwide. A comparison with previous ISTAT (Agricultural Census Data 2011–2021) data highlights a restructuring process in the sector, marked by a 13% decrease in the number of farms and, at the same time, a 2% increase in utilized agricultural area [52].

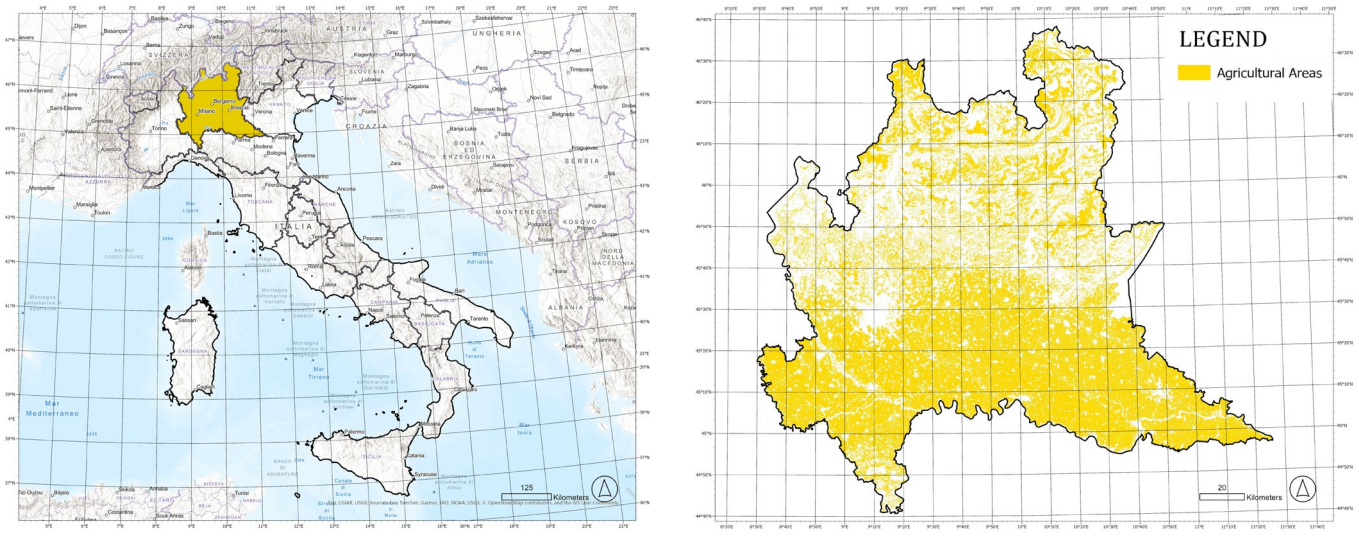

Figure 1. Agricultural areas in Lombardy in 2023. Source: author's elaboration based on the SIARL regional dataset.

Over the decade analyzed, the average size of farms increased from 18 hectares to around 22 hectares of utilized agricultural area, which is nearly doubling the national average of 11.1 hectares [49,53]. The region's traditional focus on livestock farming is evident, when compared to the rest of Italy, in the extensive use of agricultural land for arable crops and the allocation of areas such as permanent meadows and pastures in less favorable zones. In the year 2022, cereals, primarily intended for animal feed, were the most common arable crop, occupying 54% of the regional stock, compared to 43.6% at the national level [54].

Despite its historical vocation for productivity due to the fertility of the land [29,55,56], agricultural production in Lombardy is threatened by many factors, such as the competition for land use between agricultural and urban areas [27] and, due to this competition, agricultural land, particularly in Lombardy, has seen a dramatic reduction from the post-World War II period to the present day [57].

2.2. Land Use Change Analysis

The monitoring of land use changes [58,59] can be evaluated employing two distinct methodologies: the difference method or the flow method [60]. The construction of the so-called "cross-tabulation matrix" [61,62] allows for mapping and quantifying all individual transitions, thus evaluating the relationships between different land cover classes, the extent of variations, which covers have been most transformed, and detecting with higher precision what kind of process is responsible for the loss of agricultural land.

The flow matrix for this study was developed by intersecting the historical maps t0 = 1999 and t1 = 2021. The values from DUSAF (Land Use Land Cover data of Lombardy) 1.1 of 1999 were compared with those from DUSAF 7 of 2021. The subclasses examined belong to class 2, "Agricultural Areas," and their transitions to other land use classes were analyzed by measuring in hectares.

DUSAF is a detailed geographic database that was first published in 2000/2001 (the DUSAF 1999) and has now reached its 7th version. In this latest version, orthophotos (ground resolution of 1 pixel = 0.2 m) were used, based on color aerial photographs taken in 2021 [63]. The entire regional territory has been updated in terms of land use and cover, as well as hedges and tree rows, up to 2021. The detail level corresponds to an informational scale of 1:10,000, which means the minimum representable size threshold is 1600 m^2, which corresponds to a map surface at a scale of 1:10,000 of 16 mm^2.

2.3. Future Trends

A second diachronic analysis (2015–2021) has complemented the historical analysis of land use changes over the past twenty years (1999–2021). This additional analysis aimed not only to quantify the agricultural land that has already been consumed but also to estimate and measure the amount of agricultural land that could be consumed under the future implementation of urban projects that lie in the local Land Use Plans of Lombardy, coupled with the new infrastructures that will be built on top of agricultural land. This analysis was conducted at the municipal level using the mosaicked Planning Forecasts Map available at the geoportal of Lombardy Region [64], but results will be synthesized at the provincial scale (corresponds to NUTS 3). The plan was overlaid with two versions of the mosaicked local topographic dataset (2015 and 2021) and the DUSAF 7 (2021) to verify which urban transformation project occupies land that is still classified as agricultural (class 2) in the current state. The new timeframe (2015) was aimed at checking whether the regional Land Take Control Law (n.31/2014) was able to cut and reduce the amount of land designated to be urbanized by new settlements.

As for the quantification of the land taken by new roads, we first georeferenced all the single projects for new roads that the Lombardy Region shared in the geoportal [65]; subsequently, we processed the data to obtain a mosaicked digital version of all roads. Finally, we intersected the new roads with the agricultural areas extrapolated from category two—agricultural areas—of the DUSAF and obtained a final quantification and localization of the new roads.

2.4. The Quantification of Agricultural Land to Satisfy the Food Demand

The starting point for this research was a dietary survey carried out by the European Food Safety Authority (EFSA) in 2011 across 22 member states of the European Union [66]. This survey aimed to obtain data on average daily food consumption at the national level, with the results expressed in grams. Unfortunately, the EFSA research was not disaggregated at the regional level; therefore, we assumed the average food consumption in Italy as a fair proxy of Lombardy's food consumption.

For each country, the food consumption data are presented on the EFSA website according to the first level (which includes 20 categories) and the second level (which provides for about 160 categories) of the preliminary FoodEx system. These data are divided by age group, for the entire population, and for consumers only.

The following age groups were considered: Infants: 0–12 months; Toddlers: 1–3 years; Other children: 3–9 years; Adolescents: 10–17 years; Adults: 18–64 years; Elderly: 65–74 years; Very elderly: 75 years and older.

For each municipality in the Lombardy Region (1502), thanks to the 2021 census acquisition, we calculated the food consumption per age group, thereby obtaining the total food demand (in tons) per municipality.

The reference grid used to convert from one unit of measurement to another is shown in Table 1, and it contains all the conversion values needed to convert from quintals of product to hectares of agricultural land used.

Table 1. Conversion from agricultural products and land occupation. Source: [67].

Consumed Product	EFSA Associated Category	Ha of Land for a Ton of Product
Wine	Alcoholic beverages	0.01
Fats and oils	Animal and vegetable fats and oils and primary derivatives thereof	0.46
Coffee and dark chocolate	Coffee, cocoa, tea, and infusions	0.45
Eggs	Eggs and egg products	0.06
Fish (farmed)	Fish, seafood, amphibians, reptiles, and invertebrates	0.08
Fruit	Fruit and fruit products	0.01
Other fruits	Fruit and vegetable juices and nectars (including concentrates)	0.01
Wheat, rice, and maize	Grain and grain-based products	0.03
Cassava and potatoes	Legumes, nuts, oilseed, and spices	0.08
Meat and Lambs	Meat and meat products	1.81
Milk	Milk and dairy products	0.08
Groundnuts, peas, and tofu	Starchy roots or tubers and products thereof, sugar plants	0.01
Cane sugar	Sugar and similar confectionery and water-based sweet desserts	0.03
Vegetables	Vegetables and vegetable products	0.00

The right-hand column shows the number of hectares used to produce a single quintal of agricultural products. Regarding alcoholic beverages, the only available data was for wine production (an average was calculated between white and red wine). For legumes, an average was taken from the data available for two types of legumes. The same method was applied to fruit, vegetables, and tubers, while for the EFSA category "Meat and meat products," an average of the data (land used/product quantity) was calculated between beef and lamb.

For the supply data, we decided to employ the SIARL 2023 (Agricultural Information System of Lombardy Region) since this database provides information on the extent of agricultural land, measured in hectares, for each municipality in Lombardy. The database considers different categories. However, it also included water bodies and anthropized lands, which were not considered in our research. Additionally, the database lacked data on the hectares of agricultural land used for animal production (such as milk, cheese, meat, and eggs). Therefore, the SIARL dataset, which contains the number of hectares of agricultural land divided by category, was supplemented with ISTAT data on animal production, specifically milk, poultry eggs, and pastures.

The table represents the baseline diet, but a shift toward a diet higher in meat and dairy would directly increase the demand for land. For example, a scenario of a high-meat

diet would increase the calculated total food demand (in hectares) and consequently widen the gap [68].

Overall, the employed method is described in Figure 2.

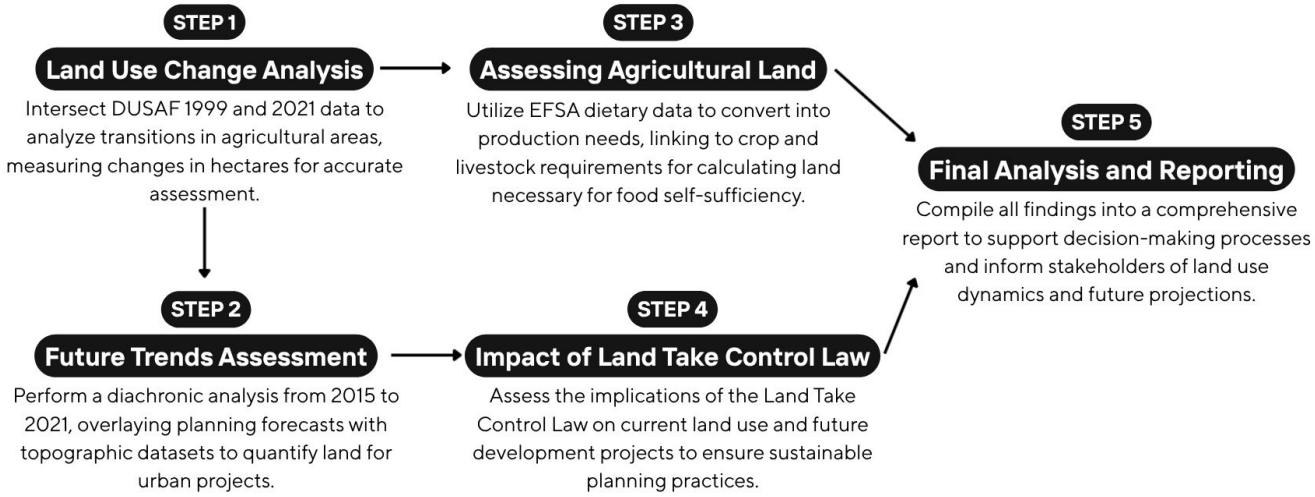

Figure 2. Five-step methodological flowchart.

3. Results

3.1. A Massive Reduction in Less than Twenty Years

The cross-tabulation matrix's most relevant outcomes are hereafter briefly presented: in the last two decades (1999–2021), over 100,000 hectares of agricultural land have been lost (Figure 3), representing a net 9.77% loss of the initial stock. Of this, 59,000 hectares were converted into new urbanized areas, representing an irreversible consumption of agricultural land that has been replaced by new urban areas for different functions while degrading soil conditions, biodiversity, and infiltration, among others. The remaining 46,000 hectares of agricultural land have been converted into natural or semi-natural areas, representing the so-called "afforestation" process that happens to those agricultural areas left abandoned that are slowly losing their primary productive function. A detailed presentation of the results is provided in the Supplementary Table S1.

This significant reduction in agricultural land has occurred unevenly across different regions of Lombardy, depending on the specific characteristics of the areas where agriculture was practiced. In the Alpine and pre-Alpine zones, the dominant trend has historically been the replacement of a significant portion of agricultural land with new forested areas and semi-natural environments (more than 30,000 ha of agricultural land has been replaced by forest in the Alpine environment). This phenomenon is the result of the abandonment of agricultural activities in marginal areas, which were naturally colonized by vegetation [33,69].

Conversely, in the hilly and plain areas, agricultural land is increasingly being consumed by new urban developments, which also significantly impacts forested areas and semi-natural environments.

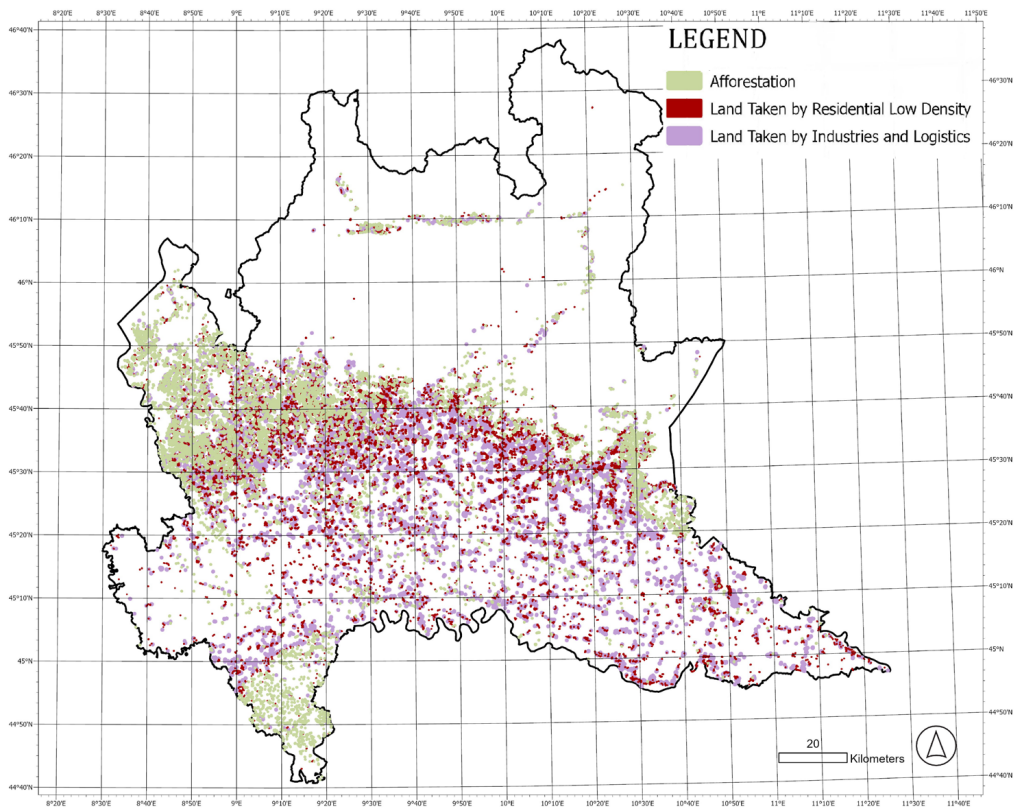

Figure 3. Distribution of agricultural land taken by other uses (forests, industries, logistics, and residential low-density settlements) between 1999 and 2021. Source: author's elaboration from DUSAF 1.1 vs. 7.0.

3.2. A Challenging Future for Agricultural Land

The following Table 2 shows the values in hectares of land affected by the plan's forecasts, split into provinces, illustrating the capacity of the Land Use Plans in each Province to reduce—cut- (downzone) the areas designated for potential new development on agricultural land between 2015 and 2021. Areas not subjected to this reduction were either realized (i.e., the transformation occurred, resulting in new land consumption) or reconfirmed in the updated Land Use Plans of 2021. In some instances, certain Provinces introduced new areas for potential transformation on agricultural land that were not developable within the 2025 planning horizon. Considering all provinces, on average, around 24% of areas designated for urban expansion on agricultural land have been cut across the Region, which is in line with the requirements of Regional Law No. 31 of 2014, "Provisions for the reduction in land consumption and the rehabilitation of degraded land" [70], which introduced a threshold for land take reduction.

This analysis, conducted at the provincial scale in Lombardy, shows that in total, the majority of the Transformation Areas (TA) planned in 2015 were also confirmed in 2021 (53%). However, the reduction made by municipalities is significant (5683 ha), accounting for a total of 24% in the entire Region. The implementation of the forecasts affected 16% of the total, and finally, 7% of the total agricultural land forecasts resulted from the inclusion of new TA that were not present in 2015.

Table 2. Land consumption forecasts from land use plans for each province. Comparison and rate of change in Transformation Areas between 2015 and 2021 (ha).

Typology of Action	Bergamo	Brescia	Como	Cremona	Lecco	Lodi
Cut (ha)	389.98	879.34	57.59	205.17	39.53	82.25
Cut %	11.77%	27.97%	7.47%	11.80%	10.92%	9.54%
Realized (ha)	622.21	679.26	106.04	216.73	43.28	190.16
Confirmed (ha)	1901.39	1358.30	447.90	1362.06	215.04	653.92
New (ha)	217.61	292.66	82.30	232.40	29.45	56.02
	Milano	Monza e Brianza	Mantova	Pavia	Sondrio	Varese
Cut (ha)	2800.58	333.04	173.94	417.41	161.83	142.80
Cut %	100.00%	31.48%	9.11%	13.51%	17.82%	25.41%
Realized (ha)	780.00	171.26	238.48	390.64	59.39	132.50
Confirmed (ha)	1380.67	472.22	1601.15	2311.12	194.73	462.90
New (ha)	149.57	73.41	110.54	189.17	98.58	123.50

In fact, the implementation of TA on agricultural land between 2015 and 2021 accounted for approximately 3600 hectares, while the reduction amounted to about 5700 hectares. The confirmation of pre-existing TA amounts to approximately 12,300 hectares, confirming a trend that, although decreasing, continues to exert strong pressure on the agricultural system of Lombardy. In total, over 14,000 hectares of agricultural land are still subject to potential urbanization in the municipal Land Use Plans, of which about 1600 hectares are new areas that were not present in 2015.

Additionally, results from the land taken by new roads show that 1570 hectares of agricultural land are expected to be taken by new road developments, and this trend aligns with the estimations of the Environmental Report of 2016, which in 2014 projected a new occupation of 1470 hectares of land for road infrastructures.

3.3. Assessing the Deficit

Figure 4 represents the balance between the land needed to satisfy food consumption and the quantity of available agricultural land for each municipality in Lombardy.

The greatest deficit corresponds to the main cities in Lombardy since the largest red area is Milan, followed by Monza and Lecco just above it, Varese to the northwest, and Bergamo and Brescia to the east. The areas further south are Pavia, Cremona, Mantua, and Lodi, while the only province with a positive value is Sondrio, likely influenced by the disproportion between population and available land for food production.

Also, the Valtellina is split in two by the Adda River: the lower Valtellina appears to be in slight surplus, followed by a red strip that seems to correspond to the river's course, leading to the upper Valtellina. The upper part of the valley, particularly the areas around the municipalities of Bormio and Livigno, shows a highly positive situation. In this area, according to the data, the quantity of hectares available significantly exceeds the population's actual needs. This phenomenon could be explained by the fact that the upper Valtellina region, especially Bormio and Livigno, is a major tourist attraction both in winter and summer, due in part to the presence of important ski resorts. The same applies to the Santa Caterina Valfurva area, and possibly also to the municipality of Tirano, which is a starting point for the famous Bernina Train Express. As for the other green areas (though a lighter green), in the southern part of the Region, they seem to correspond to the high-intensity agricultural production hubs of the Po Valley.

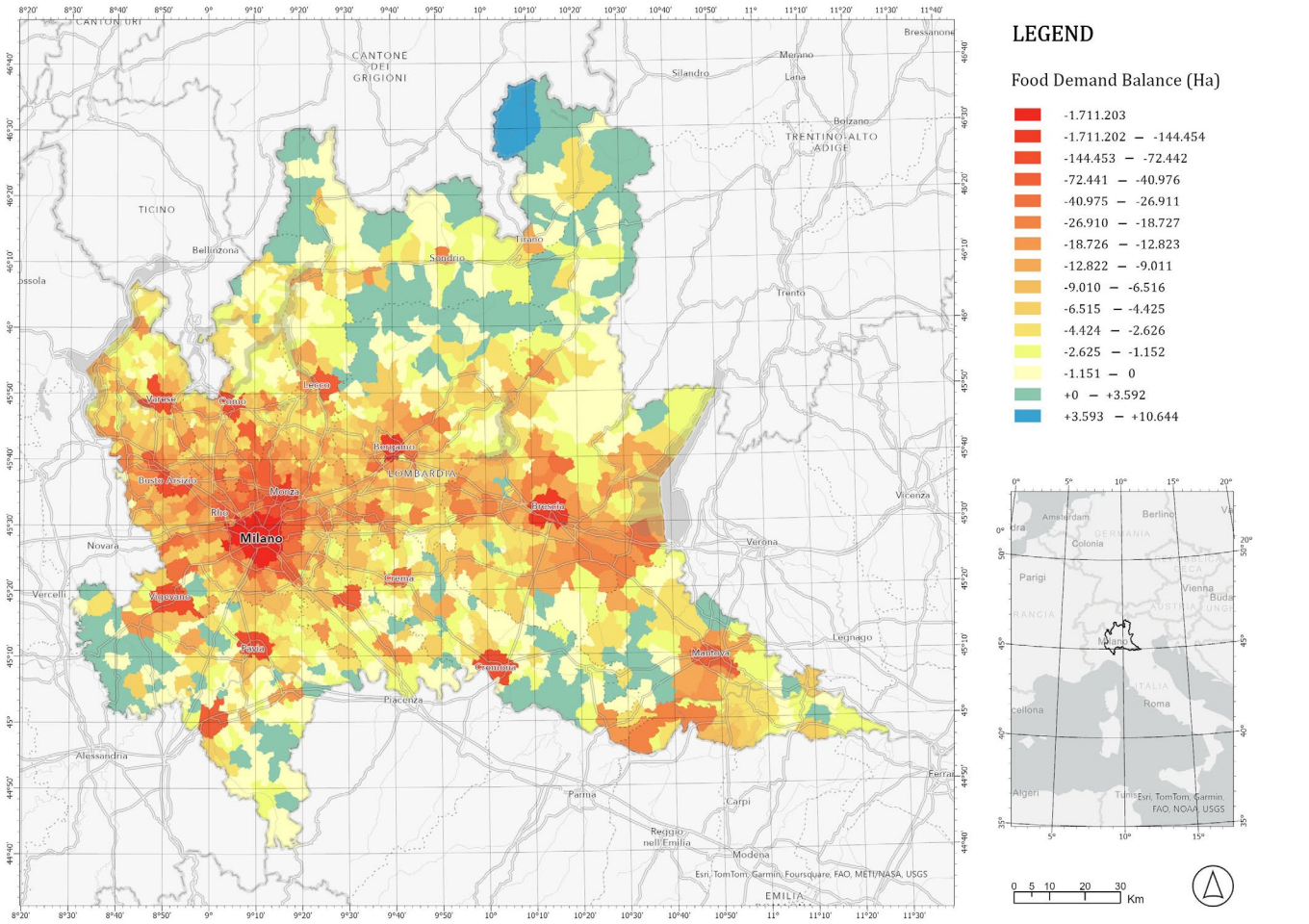

Figure 4. The gap (absolute) between the demand and the offer of agricultural land in 2023. Source: author's elaboration based on the last release of the SIARL 2023.

4. Discussion

4.1. Significant Findings

To meet the food demand per person, with the current population, an agricultural area equal to 5.12 times the entire extent of Lombardy would be needed. This is 9.55 times the current stock of agricultural land (1,277,636 hectares), compared to a requirement of 12,211,770 hectares. This means the available agricultural land is about ten times less than what it would be if the primary production in Lombardy were employed to meet the internal demand. The resulting deficit rate quantifies the structural shortfall, reflecting the remaining agricultural area's inability to sustainably meet the per capita food requirements of the regional population based on standard dietary consumption patterns. This metric does not forecast immediate scarcity but rather highlights the widening gap between the local land's intrinsic capacity to support its inhabitants and the rate of irreversible land consumption driven by urban expansion. As introduced, in case of high-meat demand, the final deficit ratio would be significantly higher, perhaps 12-fold or more, making the land scarcity conclusion much more severe and highlighting the unsustainable nature of a high-meat diet for a dense region like Lombardy. On the contrary, a Mediterranean low-meat scenario would significantly decrease the calculated total food demand (in hectares). The current 10-fold deficit would narrow considerably (e.g., to 5-fold or 6-fold). This would reveal that dietary change represents a powerful lever for mitigating the land deficit, offering a more optimistic perspective on regional self-sufficiency under specific consumption patterns.

The per capita deficit is confirmed in its relative spatial distribution to the municipalities (Figure 5). The lowest values are concentrated around the provincial capitals in the foothill area, reaching a deficit of −1.25 hectares per resident.

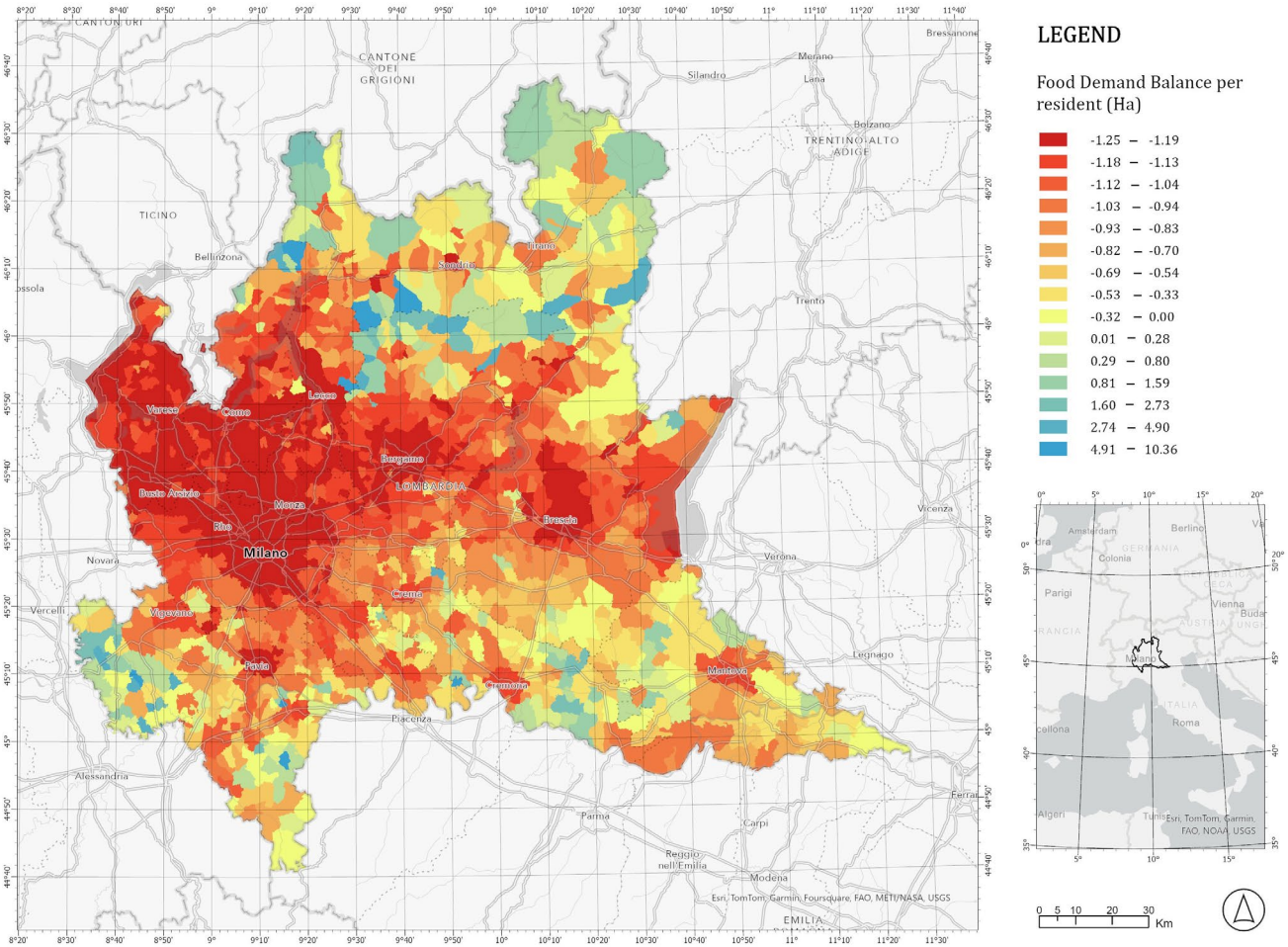

Figure 5. Per capita deficit (ha) in 2023. Source: author's elaboration based on EFSA and SIARL data.

The deficit is even more dramatic if we consider that more than 15 thousand hectares of agricultural land can potentially be affected by land taken by new urban areas or roads and other infrastructures (which is the sum of the remaining AT on agricultural areas and the new planned infrastructures).

While direct comparison is complicated by varying national data and consumption methodologies, Lombardy's 10-fold land deficit appears among the most severe in Europe. This rate significantly surpasses estimates reported at the global scale by Ritchie (2017) [71], underscoring the structural uniqueness and severity of the land scarcity challenge in this region.

To limit these impacts, with the approval of a specific law—Regional Law 31/2014, new regulations were introduced in territorial governance to limit land taken in agricultural areas and promote the regeneration of already urbanized areas [72]. But since Law 31/2014 does not restrict land take before it happens, compensatory measures are mandated. To offset the environmental degradation caused by urbanization, afforestation measures were often implemented for landowners. Unfortunately, these processes were mainly located on agricultural soil, creating a double loss: environmental degradation and a rapid shrinkage in agricultural land's productive capacity.

To move beyond mere description, we made an empirical evaluation of Law 31/2014 by comparing the average annual land take rate before the law, between 2012 and 2015 (593 ha/year) with the post-law rate, between 2015 and 2018 (500 ha/year) [73], we found

that the rate did not decrease as expected (18%) if compared to the more ambitious aims of reduction (20%). The effectiveness of the regional framework is highly dependent on the capacity to integrate different reduction policies, such as fiscal, morphological, and regulatory measures.

The severity of the Lombardy deficit must be interpreted against the backdrop of the broader European objective of achieving "No Net Land Take" (NNLT) by 2050. While this aspirational goal acknowledges that urban expansion primarily occurs at the expense of agricultural land (representing about 78% of new artificial areas across the EU), the Italian, and specifically the Lombardy, policy response shows critical divergence. Unlike countries such as Germany and the Netherlands, which have moved toward proactive spatial strategies focused on strict internal densification and binding targets to reduce daily land take, Lombardy's decentralized planning system has perpetuated a reliance on low-density sprawl and insufficient compensatory measures.

The study's finding reveals that local compensation mechanisms are inconsistent and inadequate, aligning with other comparative European research that blamed compensation for "downzoning" or restricting development rights as politically challenging to enforce. The potential of systems like Green Deposits or Eco-Accounts—which operate in other developed economies to monetize and trade the ecological value of land lost—also becomes critical. By proposing a mandatory multidimensional evaluation of land (considering productive, ecological, and flood regulatory functions), Lombardy's ecological strategy should evolve beyond mere compensation, which currently focuses mostly on planting native trees on external farmlands, aligning regional planning with the EU's wider climate and biodiversity goals.

4.2. Limits and Future Research Directions

Our reliance on regional datasets, specifically DUSAF and SIARL, introduces a primary limitation related to data inconsistency for non-matching construction procedures and thematic boundaries. Furthermore, the Minimum Detectable Area (MDA) of 1600 m^2 inherent in the DUSAF database potentially leads to the underestimation of diffuse land take [74,75], failing to fully capture the cumulative impact of minor infrastructure or the incremental conversion of small agricultural plots outside formal urban plans. The absence of a standardized dataset for linear infrastructure (roads) required manual quantification, which compromises the precision and replicability of the assessment and limits its utility for future automated updates. Also, the impact of the 2014 Land Take Control Law requires a more detailed, micro-level assessment to precisely gauge its actual effectiveness at the municipal level by tracking land take occurring outside officially selected planning areas and fully capture how policy mechanisms—or lack thereof—influence local land-use decisions.

A central conceptual constraint is the simplification of the food-land nexus: our method provides a static, theoretical assessment of the land needed for self-sufficiency, but it necessarily oversimplifies the dynamic reality of modern food systems. It does not account for critical variables such as regional import/export dynamics, year-on-year changes in agricultural productivity, technological advancements, or evolving dietary preferences. While the quantification of the severe 10-fold deficit effectively highlights the urgency of soil protection policy, the results must be interpreted cautiously, recognizing Lombardy's reality as both a net agricultural exporter and a region heavily reliant on global supply chains.

The regional analysis must be expanded to at least the national level or ideally integrated into a wider European food network model. This shift is essential to accurately assess the overall sustainability of land use changes by moving beyond administrative borders to reflect the complexity and mobility of real-world food systems.

While the analysis effectively highlights the urgency of soil protection policies within Lombardy, it overlooks the reality that food production and consumption are inextricably linked to national and global supply chains. As highlighted in the introduction, Lombardy is a net exporter of high-value agricultural products and, simultaneously, its food security heavily relies on global markets. Future work should transition from a static assessment to the integration of dynamic predictive models or scenario analyses. This would allow researchers to explore how the deficit rate might evolve under different future conditions, such as climate change impacts, varying rates of urban densification, or shifts in national agricultural policy.

To strengthen the robustness and applicability of these findings, a crucial direction for future research involves the implementation of a scenario-based sensitivity analysis of food consumption. This would entail modeling the agricultural land requirement under divergent dietary assumptions, specifically comparing the current EFSA-derived baseline with a high-meat consumption scenario and a Mediterranean or low-meat diet scenario. Quantifying the resulting deficit under these distinct consumption structures is essential for determining the conclusion's sensitivity to potential dietary shifts and for accurately assessing the leverage that public health and food policies could exert on Lombardy's land-use balance.

4.3. Policy Implication

Lombardy, despite being a region currently facing an urgent issue related to the loss of agricultural land, has already implemented in the recent past some deterrent mechanisms against the transformation of agricultural land. These mechanisms have been introduced through regulatory/morphological approaches such as the definition of Urban Growth Boundaries by including Strategic Agricultural Areas in land use plans [76–78], quantitative measures such as the introduction of the Regional Law mentioned above 31/2014 that defines the reduction in land that new settlements or infrastructures can take [79,80], and the introduction of fiscal instruments (Compensation Bank) that increase the amount of local fees that real estate operators have to pay to obtain building rights in case their intervention occupy an agricultural area [17,81,82]. Even though all these measures are aimed at safeguarding farmland and its productivity, the current trend of agricultural land take is highly negative. Indeed, all these initiatives appear to be unsystematic and poorly amalgamated into a comprehensive set of disincentives that can really affect the land-take trend.

The protective measure of designating Strategic Agricultural Areas in local plans [76,83] is frequently undermined by centrally approved, large-scale transformation projects [84]. These projects are often implemented through "negotiable agreements" between real estate developers, the Region, and the municipalities. This creates a fundamental governance conflict: the Regional administration simultaneously has one directorate (e.g., Infrastructure) acting as a major proponent of massive land take, while another (e.g., Agricultural and Forest Protection) is tasked with actively opposing it. In addition, the land take limitation law 31/2014 only partially reduced the urbanization speed because the municipal plans often oversize their building capacity, creating a disproportionate amount of landowner rent expectations. These rents can hardly be compensated if the municipality decides to withdraw the potential transformation, creating the impossibility to act with a serious reduction in the urbanization trend.

Finally, the fiscal measure introduced by the regional Compensation Bank appears to be intangible due to the poor increase (+5%) in the ordinary urbanization fees. Even though being a good principle, the increase of 5% does not affect the decision-making process when it comes down to the moment of deciding where to locate a new transformation. Therefore,

the lack of systemic coordination among the regulatory, planning, and fiscal tools, as well as the absence of additional requirements for the success of the individual initiatives put in place, has led to partial and inconsistent results.

The effectiveness of policies for protecting agricultural land can be greatly benefited from additional tools that create the preconditions for agricultural compensation to be implemented:

- the qualitative assessment of the soils involved in the land-use transformation process [34,85,86];
- the use of agencies with intermediary functions between the project developers and the municipalities that host the transformations [44,87];
- the availability of areas where compensations can be allocated, whether in urban areas to be unsealed or in public semi-natural areas to be ecologically equipped [88,89].

In all cases, it is evident that compensation for the consumption of agricultural land should not further happen upon productive land, resulting in a double loss in terms of potential productive capacity. Therefore, any evaluation of compensatory measures must certainly consider the average value of the productive capacity of the land affected by the transformation and, if necessary, counterbalance the loss by restoring productive capacity to lands that have undergone various forms of degradation [90,91].

The role of compensation agencies appears to be also crucial. Their role is not limited to identifying agricultural areas to be protected against potential settlement processes but also includes the prioritized selection of natural, wet, or urbanized areas where compensatory interventions can be hosted (sometimes also acting as facilitators between the developers and the administrations or landowners on whom the compensatory lands).

As for the replacement of the productivity loss, new techniques should be adequately studied to mitigate the impact that land take can have on food demand. On this matter, it seems that three main domains can be roughly identified:

- the potential productivity of Controlled Environmental Agriculture (CEA) [37], assuming that this typology mainly produces specific vegetables, and it can hardly replicate the typology and quantity of production that traditional farming can get;
- the installation of agrophotovoltaic on legumes, tomatoes, and other vegetables in semi-arid environments, as it seems demonstrated that this kind of installation can be compatible and even augment the production while providing more shade to the ground [92];
- the introduction of Assisted Evolution Techniques (TEA) to breed crops, fostering yields without using additional fertilizers (especially corn or rice), thus balancing the tradeoff between an increase in productivity and environmental sustainability [93].

In any case, these new potential techniques can experiment only through effective management of agricultural land compensation that is based on solid governance mechanisms based on (1) the availability of agricultural areas where compensatory actions can be located, (2) the activation of incremental taxation tools that on one side disincentive the location of new settlements on fertile land and, in case, it create the budget to introduce compensatory measures and, lastly, (3) a correct understanding of the multifunctional agricultural value of the land that can be used as a basis for estimating the kind and quantity of compensation. Beyond that, to determine the strength of the policy-practice linkage, future work must conduct a comparative analysis. Treating the adoption of specific compensation practices as an independent variable allows us to empirically measure its correlation with local land consumption rates, thereby providing evidence-based insights into the leverage of municipal planning choices over the overall regional deficit.

5. Conclusions

The study operates within the accepted framework that agricultural land take is inherently an irreversible and non-sustainable process unless countered by active compensation (a concept not yet fully scalable in this region). By demonstrating an escalating deficit in the land required for basic food provision, the research implicitly defines the critical level of land consumption as any other loss of high-value agricultural soil that further widens the gap between regional food demand and local productive capacity.

Any further agricultural land take will compromise the region's long-term food security or its resilience against external market and climate shocks. Since the study shows a 10-fold deficit, current consumption is unequivocally far from being considered sustainable. The research has shown that the continued conversion of agricultural land to urban uses is unsustainable both in terms of food production capacity and the broader ecosystem services that these lands provide. The georeferenced analysis, combined with national statistics on food demand, reveals a troubling trend: current land take patterns will increase the actual deficit of the agricultural capacity to satisfy the Region's food needs.

Beyond that, the investigation identifies a systemic failure in current policy: provincial and municipal compensatory mechanisms designed to offset land take are inconsistent, non-standardized, and demonstrably insufficient to mitigate the irreversible loss of productive soil. This gap is set to worsen the actual deficit in the capacity to satisfy regional food needs. To reverse this unsustainable trajectory, the paper advocates for an urgent and fundamental shift in planning methodology. We propose adopting a more integrated policy framework—inspired by successful international models such as green deposits and eco-accounts—that mandates a multidimensional valuation of land. This approach would require all future land-use decisions to account equally for a parcel's productive capacity, its ecological value, and its regulatory functions, ensuring that compensation measures genuinely replace lost natural capital rather than merely rubber-stamping its depletion.

However, the study also highlights the complexity of balancing land use with food security, particularly in a region like Lombardy, which is both a significant producer and consumer of agricultural products. The interconnectedness of local and global food markets, along with shifting dietary trends, adds layers of complexity to this issue. While our analysis provides a preliminary assessment of the agricultural land needed to achieve theoretical food self-sufficiency, it also points to the necessity of a more integrated approach to land use planning—one that accounts for these broader economic and environmental factors.

In conclusion, achieving a sustainable balance between land consumption and food security in Lombardy requires a concerted effort at multiple levels of governance. Policies must not only aim to reduce land take but also enhance the resilience of the remaining agricultural lands. This could involve stricter regulations on land conversion, incentives for sustainable agricultural practices, and the development of innovative compensatory mechanisms. Ultimately, the goal should be to maintain the Region's agricultural productivity while safeguarding the environmental and social benefits that these lands provide. Without such measures, the Region risks undermining its ability to achieve both climate neutrality and food security, jeopardizing the well-being of its citizens in the process.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/land14112112/s1, Table S1: Flow_Matrix_1999_2021.

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