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European Green Deal Strategies for Agriculture in Dynamic Urbanised Landscapes

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Abstract: Land use change and agricultural management have a considerable impact on land use patterns and greenhouse gas (GHG) emissions in dynamic urbanised landscapes. This study evaluated sustainable land allocation strategies in line with the European Green Deal. A constrained cellular automata land use model was employed to assess the impacts of Business-as-Usual (BAU), Land Sharing (LSH), and Land Sparing (LSP) scenarios, using open-access data from Flanders (Belgium). Under BAU, urban expansion reduced unregistered agricultural land by 495 km^2, leading to higher GHG emissions despite an 11% increase in green space. LSH increased green space by 36% and enhanced landscape diversity, while LSP improved habitat coherence by 24%. Livestock-related methane (3.09 Mt CO_2e) dominated GHG emissions, comprising more than 75% of the total, with cattle responsible for 73% of methane emissions. Nitrous oxide emissions reduced from 1.60 Mt CO_2e to 1.44 (BAU), 1.43 (LSP), and 1.42 (LSH) Mt CO_2e. Forest sequestration offset up to 34% of total emissions, removing −1.35 Mt CO_2e. Green Deal measures mitigated emissions in all scenarios, with LSH achieving the highest gains. The results highlight the need for spatial strategies that integrate sustainable agricultural practices and balance productivity, nature conservation, and climate action under the European Green Deal.

Keywords: European Green Deal; agriculture; land use model; land sharing; land sparing; greenhouse gas emissions

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1. Introduction

As urban populations continue to grow, pressure on food systems and natural resources increases, requiring sustainable strategies that address environmental and societal challenges [1,2]. The EU's Common Agricultural Policy (CAP) is central to transforming the food system into a sustainable model that ensures food security, reduces environmental impacts, and promotes resilience [3]. Through measures to protect soil, land, and biodiversity, the CAP provides a roadmap for a transition to competitive, environmentally friendly, and resilient food production under its "farm to fork" framework [4]. Complementing this strategy, the European Green Deal positions sustainable food systems as fundamental to achieving planetary health, societal well-being and economic viability, although more action is needed to address sustainability challenges [5].

The European CAP has progressively introduced environmental and nature measures such as cross-compliance, greening payments, and eco-schemes to incentivise sustainable farming practices and biodiversity conservation on agricultural land between 2005 and 2030 [3,4]. These reforms encourage farmers to adopt practices or measures that conserve natural resources, reduce greenhouse gas (GHG) emissions, and enhance ecosystem services, while balancing agricultural productivity with environmental sustainability. Farmers' participation in agri-environment-climate measures varies according to financial incentives, environmental motivations, and complexity of implementation, with more complex measures closely linked to environmental stewardship [6,7]. Many of the agri-environment-climate measures and farm practices, such as cover cropping, zero tillage, and crop rotation, impact land use/cover change and therefore also carbon sequestration and greenhouse gas emissions [8].

Recent advances in land use and land cover (LULC) modelling have improved local spatial planning by integrating high-resolution remote sensing, spatiotemporal processes, and artificial intelligence. Data-driven models, such as machine learning, agent-based simulations, and cellular automata, are increasingly being used to assess land transformation at the community and regional levels, enabling more accurate predictions of urbanisation, agricultural land changes, and habitat fragmentation [9,10]. High-resolution LULC models now support decision-making in dynamic rural–urban interfaces, where competing land demands for agriculture, forestry, and urban development require context-specific trade-offs. For example, dynamic modelling techniques have been applied to predict localised urban land use change, providing municipalities with detailed spatial scenarios for sustainable land allocation [11]. At the coarser kilometer-scale, land models are being refined to capture localised climate and land use impacts on ecosystem services, improving strategies for habitat conservation, flood mitigation, and biodiversity protection [12]. Scenario-based LULC modeling approaches, comparing business-as-usual trends with sharing-sparing strategies, have been refined to assess their impacts on ecosystem services at the local and regional scales [13,14]. Using LULC models allows policy-makers and planners to explore what-if scenarios and develop adaptive land management strategies that are consistent with policy goals and ensure resilience to environmental changes.

The AFOLU (Agriculture, Forestry, and Other Land Use) and LULUCF (Land Use, Land Use Change, and Forestry) sectors provide accounting frameworks for greenhouse gas (GHG) emissions and removals associated with land use and land management. The European LULUCF Regulation focuses on the greenhouse gas emissions of CO_2, CH_4 and N_2O in five key land use categories—wetlands, grasslands, croplands, forests, and urban areas—with targets expressed in CO_2 equivalents [15]. The AFOLU sector considers emissions from agricultural activities such as livestock, manure management, rice cultivation, and agricultural soils, in addition to land-use and forestry activities [16], offering opportunities for GHG mitigation and provision of ecosystem services. AFOLU currently accounts for about 20% of anthropogenic GHG emissions [16], with effective land management practices estimated to absorb more than a third of CO_2e total GHG emissions in the European Union [17].

Land management plays a dual role in the global carbon cycle. While greenhouse gases, such as carbon dioxide (CO_2), nitrous oxide (N_2O), and methane (CH_4), are emitted, carbon is also sequestered, although the magnitude varies with land cover type and management [18–21]. The CO_2e emission from land is released through the respiration of microorganisms as they decompose organic matter. Carbon sequestration, however, is the reverse process whereby carbon dioxide is removed from the atmosphere and stored on land. This can occur through a variety of natural processes, including plant photosynthesis, microbial activity, and the addition of organic matter to the land. These natural processes help mitigate climate change by reducing the amount of CO_2 in the atmosphere.

A critical interface between the AFOLU sector and land processes is their ability to influence the global carbon budget. AFOLU land use and management practices determine not only GHG emissions, but also the potential for carbon sequestration [17]. This dual capacity highlights the importance of understanding and optimising land processes to enhance carbon storage while minimising emissions. By integrating sustainable land management with targeted conservation strategies, it is possible to unlock the mitigation potential within the broader framework of climate policies such as the LULUCF Regulation [22].

This study aims to assess land allocation strategies for agriculture in dynamic urbanised landscapes, aligning a land use model with the objectives of the European Green Deal. A constrained cellular automata land use model was adapted using geomatics tools, incorporating environmental, socio-economic, and biophysical data, thereby considering climate neutrality, landscape diversity, and sustainable land management. Advanced spatial analysis was used to evaluate the potential for sustainable land use practices and tested in the dynamic urban-rural landscapes of Flanders in Belgium. The study highlights the importance of geomatics and publicly available open-access statistics and geodata in facilitating evidence-based sustainable land use planning and contributes to the definition of context specific strategies for agriculture to meet the objectives of the European Green Deal.

2. Materials and Methods

2.1. Study Area

The methodology was tested in Flanders, the northern region of Belgium, using publicly available open-access data. The region covers 13,521 km^2 and has a population of around 6.35 million, resulting in a high population density of 475 inhabitants per square kilometre, more than four times the European Union average. Only 7% of the territory is rural and 2.5% of the population lives in rural areas. The Flemish countryside is highly urbanised, with a fragmented landscape and strong links between rural and urban areas [23]. Geographically, functionally, and culturally, rural and urban areas are increasingly intertwined (Figure 1). Forests and nature cover only 1850 km^2.

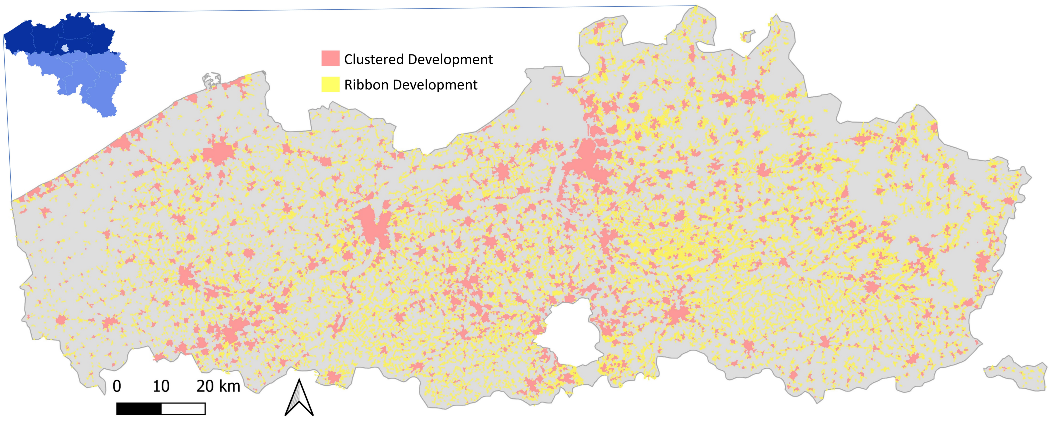

Figure 1. Location of Flanders in Belgium with clustered development in urban areas and ribbon development along roads. Data source: GDI Flanders (geopunt.be, accessed on 4 January 2025).

Agricultural land covers 6230 km^2, of which 70% is arable land (Figure 2). Meadows, pastures, and fodder crops account for 56% of the total area. Grassland is a dominant feature of the rural landscape, accounting for 36 to 50% of the utilised agricultural area regionally [24]. Of the registered agricultural land, 36% is owned and the rest is rented. Agriculture in Flanders is highly industrialised. Intensive sectors such as pig, poultry, and dairy farming, horticulture, and ornamental plant production occupy most of the land [25]. Flemish agriculture is intensive with high yields per hectare. In the public perception, this is associated with increased use of fertilisers and pesticides, negative impacts on soil and water quality and loss of biodiversity. In addition, agriculture, including fruit, vegetables, and potatoes, has increasingly suffered from the effects of adverse weather conditions [26,27].

In 2021, Flemish agriculture emitted 7.7 Mt CO_2e, representing 10% of total Flemish greenhouse gas emissions and a 12% reduction compared to 1990 [28]. Between 1990 and 2008, agricultural emissions fell from 8.8 to 6.6 Mt CO_2e, and then increased to 7.7 Mt CO_2e in 2021. This is an increase of 0.7 Mt compared to 2005 levels. The increases are attributed to increased CH_4 emissions from livestock and CO_2 emissions from greenhouse horticulture.

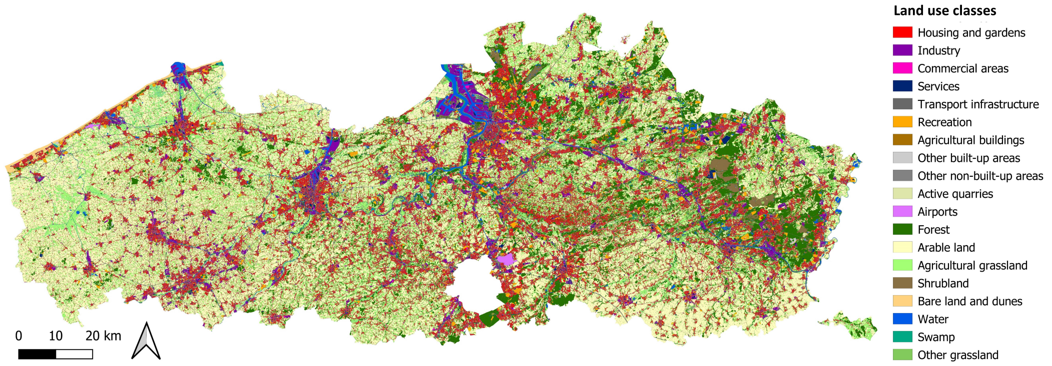

Figure 2. Land use in the Flanders region of Belgium. Data source: GDI Flanders (geopunt.be, accessed on 4 January 2025).

2.2. Land Use Model

Land use was modelled using a spatially explicit dynamic allocation model, incorporating current land use (Figure 2), socio-economic trends, and policy targets [29]. The model operated at three spatial scales: (1) regional for socio-economic data, (2) district for land use demand, and (3) grid for matching land use demand with cell availability, suitabilitym and accessibility [30]. A constrained cellular automata (CA) framework dynamically allocated land based on population density, economic activities, and land requirements for nature and agriculture [31], using a variable grid where the neighbourhood of each cell encompassed the entire modelled area. Transition rules were governed by distance decay functions to capture multi-scale interactions between regions, districts, and cells.

Inputs consisted of publicly available open-access data, obtained from the official Belgian statistics bureau (statbel.fgov.be, accessed on 4 January 2025), the federal plan bureau (plan.be, accessed on 4 January 2025), government data (data.gov.be, accessed on 4 January 2025) (Table 1) and regional Geographic Data Infrastructure (geopunt.be, accessed on 4 January 2025) to simulate land use for the period 2005–2030. Population data were converted to density, while employment figures were translated into sector-specific area requirements. Housing trends showed decreasing densities in built-up areas, urban expansion around smaller towns, and continued growth along roads in rural areas (Figure 1). Densification was reflected in slower suburban expansion, more multi-storey buildings, and smaller plot sizes, especially in densely populated regions.

Table 1. Summary of population and employment input data to the land use model.

Item	Unit	2000	2005	2010	2015	2020	2025	2030
Population	persons	5,940,251	6,043,167	6,230,775	6,426,863	6,586,737	6,705,741	6,784,507
Agriculture	employed	64,814	58,132	53,261	48,337	44,901	41,273	37,988
Industry	employed	566,179	525,239	518,285	506,129	486,243	457,564	428,095
Services	employed	1,585,637	1,713,996	1,875,941	2,002,481	2,093,599	2,139,499	2,166,911
Recreation	employed	134,979	130,806	138,660	146,442	153,138	161,257	171,108

Agriculture dominates rural areas, where farms larger than 2 ha or with at least 0.5 ha of greenhouses are required to register their parcels [25]. Unregistered agricultural land, which is land used for agriculture but not receiving income support, was assumed to be first allocated to other land users in the absence of policy data.

2.3. Land Use Scenarios

Scenario-based land use modelling is often used to compare land sharing and sparing strategies with business-as-usual projections for biodiversity conservation [13,14]. We developed three scenarios within the CA land use model, i.e., business as usual (BAU), land sharing (LSH), and land sparing (LSP) (Figure 3), to assess sustainable agricultural practices. The BAU scenario projected continued urban sprawl and ribbon development. LSH maintained biodiversity in rural landscapes, while LSP separated land uses, concentrating agriculture and nature in separate areas. In LSH, low-intensity agriculture incorporated small landscape elements such as trees and hedgerows, while LSP promoted large, contiguous areas of intensified agriculture and nature reserves.

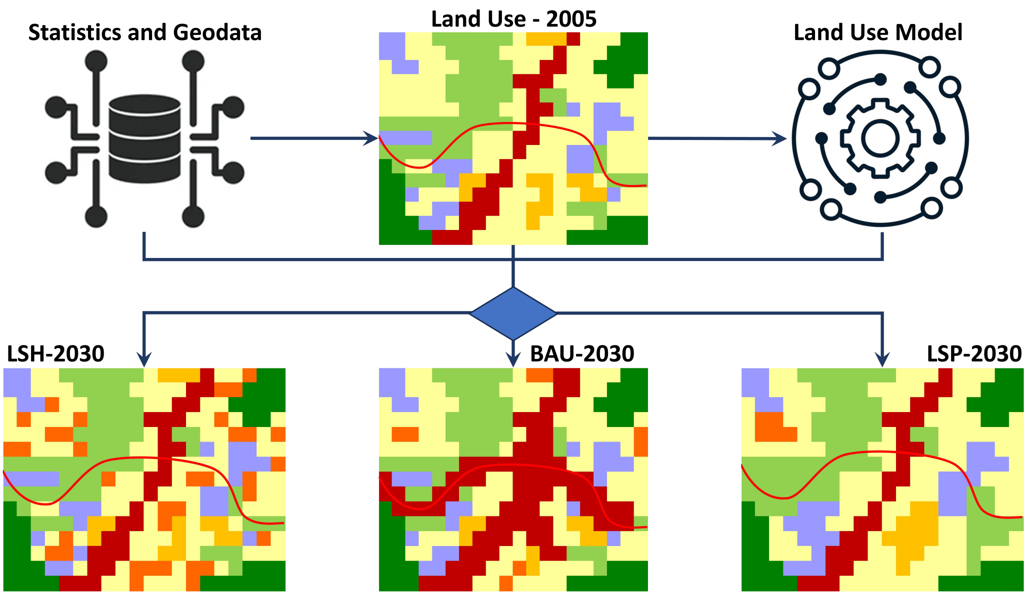

Figure 3. Schematic representation of land use scenario development, where BAU is business as usual, LSH is land sharing, and LSP is land sparing. The red line represents a road, with red pixels indicating housing.

Scenarios were developed in co-creation with land use policy stakeholders based on land suitability zoning, clustering, and planning objectives. Agricultural land use was projected to decrease from 6330 km^2 in 2005 to 6100 km^2 in 2030 (Table 2), with a ratio of 23.5% designated as permanent pasture to total agricultural land [24]. The suitability criteria placed two-thirds of the permanent pastures in valley areas and one-third in erosion-prone areas.

Flemish nature policy prioritises protected areas and devotes more than 80% of its annual budget to their establishment and management [29]. By 2030, conservation objectives will focus on designated target areas for each biotope (Table 2).

Table 2. Summary of input and target surface areas (in ha) to the land use model.

(a) Agriculture					
Class	**Subclass**	**REF2005**	**BAU2030**	**LSP2030**	**LSH2030**
Arable	Production	397,854	363,740	294,431	290,327
Arable	Green Deal *	12,782	16,178	118,175	122,679
Grassland	Production	213,721	205,589	156,827	137,930
Grassland	Green Deal *	16,722	25,630	47,900	69,098
(b) Nature					
Class	**Subclass**	**REF2005**	**BAU2030**	**LSP2030**	**LSH2030**
Forest	Production	119,936	126,036	123,671	129,872
Forest	Biodiversity °	14,794	20,968	16,439	16,022
Grassland	Biodiversity °	7952	16632	9295	9983
Heath	Biodiversity °	5983	7992	9581	8200
Swamp	Biodiversity °	4900	12,537	13,118	11,810
Marshes	Biodiversity °	1770	4145	4145	4145
Dunes	Biodiversity °	1186	2158	2253	1829

* Green Deal includes both agri-environment-climate measures and eco-schemes as operational instruments for achieving Green Deal objectives in the CAP. ° Biodiversity includes environmental instruments for achieving biodiversity targets.

2.4. Statistical Metrics and Pattern Analysis

Spatial patterns were quantified using descriptive statistics of land use change and cluster characteristics [32]. Cluster analysis assessed spatial coherence based on size, number and area. Each grid was analysed in relation to its neighbours to determine contiguous land use areas. Unique cluster IDs and sizes were assigned, with infrastructure elements considered as fragmenting clusters. Surface area (SA) was calculated using Equation (1):

$$SA = \frac{a_0 \sum_{\text{grid} \in C_A} \text{CS}(\text{CID}(\text{grid}))}{C_A}, \quad (1)$$

where a_0 is the grid size (150 × 150 m^2), C_A represents grids within a cluster in area A, CS is the cluster size, and CID is the cluster ID. Clusters were classified into four size ranges: 2.25–10 ha, 10–100 ha, 100–1000 ha, and >1000 ha. Green space and agriculture were fragmented by major transport infrastructure, excluding local roads, whereas the transport network was part of the urban fabric.

Land use change between 2005 and 2030 was analysed for agriculture, urban fabric, and green space under the different scenarios. Agriculture included both registered and unregistered land, with registered land subdivided into arable land, grassland, and areas under agri-environment-climate measures or eco-schemes [6]. The urban fabric included agricultural, residential, and commercial buildings, as well as infrastructure, industry, and ports. Green space included nature, forests, parks, and agricultural land with nature conservation measures. Cluster analysis was applied to these aggregated categories.

Agricultural land disturbance was assessed using the 2005 land use map, classifying agricultural areas as binary (1 for agriculture, 0 for non-agriculture). Comparing the 2005 and 2030 land use maps identified urban encroachment. An urban fringe indicator measured proximity of urban fabric to agricultural land within a 10-cell radius, assigning a disturbance factor from 0 (fully agricultural surroundings) to 1 (fully urban surroundings).

2.5. Land Related Emissions

Land-based greenhouse gas (GHG) emissions depend on land cover and transitions, which substantially influence emissions [16]. The year 2005, which marks the beginning of the European climate change adaptation policy through national adaptation strategies, serves as an important reference point for land related emissions [33]. GHG emissions were derived from national [28] and regional [34] inventories and then converted to area-specific emissions using land cover statistics [35]. Scenario-based land cover maps were integrated with these emissions, with fluxes in CO_2e calculated for each class (Table 3). Emissions from fertiliser application, croplands, grasslands, forests, and wetlands were estimated [34], converted to CO_2e, and compared with values from the literature values [18–21].

Table 3. Annual fluxes of emissions for different land cover classes in tonnes CO_2e per hectare [34]. Emissions from animals are in tonnes CO_2e per head [28].

Class	CO_2-Flux	CH_4-Flux	N_2O-Flux
Forest	−8.0133	−0.0650	0.0000
Grassland	0.3441	0.0378	1.3404
Arable	0.6892	0.0111	1.9989
Wetland	−0.0453	3.2750	0.0000
Urban Fabric	0.6450	0.0000	0.0320
Cattle		1.8043	0.1740
Pigs		0.1484	0.0090
Poultry		0.0006	0.0003
Other		0.4890	0.0776

Green deal measures, including agri-environment-climate measures and eco-schemes, reduce greenhouse gas emissions from agriculture [36,37]. Optimised nitrogen management reduces nitrous oxide emissions by 20–50% [38], while improved manure management reduces methane emissions by 30–70% [39]. Conservation tillage, cover crops, and agroforestry increase carbon sequestration (0.2–0.5 Mg $C.ha^{-1}{\cdot}year^{-1}$) and reduce CO_2 emissions from soil organic matter loss by 15–30% [17,37,40]. We have assumed conservative reductions for the implementation of green deal measures: 15% for CO_2, 30% for CH_4, and 20% for N_2O. In contrast, farming systems without these measures resulted in higher emissions due to excessive use of fertilisers, frequent tillage, and limited conservation or carbon farming practices.

Livestock N_2O and CH_4 emissions were estimated using agricultural statistics at the municipality level [41] and emission fluxes per head [28], subsequently converted to CO_2e. Total GHG emissions were aggregated by municipality and their spatial distribution was assessed in CO_2e for each scenario.

3. Results

3.1. Land Use Changes

3.1.1. Urban Fabric

Population density was converted into housing density using the land use map (Figure 4). Overall, the number of inhabitants per housing cell of 150 × 150 m^2 decreased from 55.6 to 52.0 inhabitants between 2005 and 2030. The number of inhabitants per housing cell was highest in the cities of Brussels (237), Antwerp (79), and Ostend (72) (see Figure 1) and lowest in provincial cities (almost 30). Only in Brussels did a densification of the number of inhabitants increase to 295.6 inhabitants. Bruges and Kortrijk experienced the greatest dilution of the number of inhabitants per residential cell, which amounted to an urban expansion. The rate of urban expansion was between 20 and 25 km^2 per year, while the annual expansion of industry was 2–4% depending on the location.

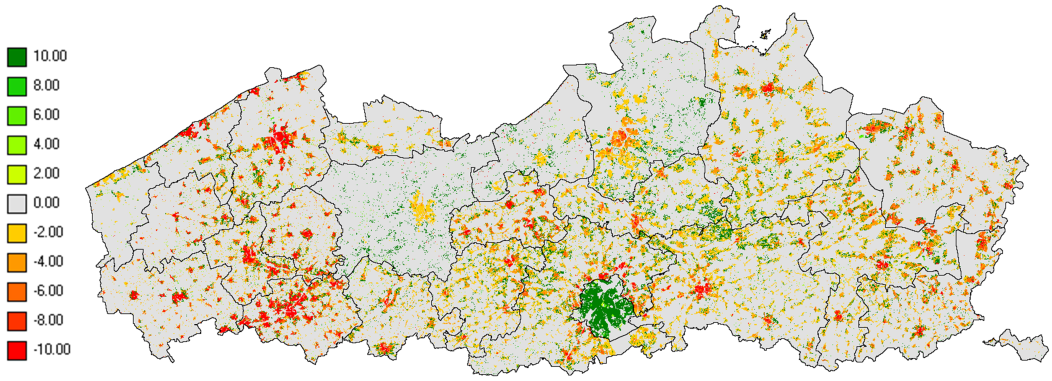

Figure 4. Trend in housing density between 2005 and 2030, in % increase or decrease.

3.1.2. Agriculture

Urbanisation took place mainly at the expense of agricultural land. Unregistered agricultural land decreased annually by 16.8 (LSP), 18.4 (BAU), and 19.8 (LSH) km^2/year between 2005 and 2030. Within the classes of registered agriculture, arable land and production grassland decreased in favour of agriculture with environmental and nature measures (Green Deal). Arable land and grasslands for production purposes decreased by 16.9 (BAU), 64.1 (LSP), and 73.3 (LSH) km^2/year between 2005 and 2030 (Figure 5). Agriculture with environmental and nature measures increased by 1.4 (BAU), 54.1 (LSP), and 64.1 (LSH) km^2/year. The area of agricultural grassland with environmental and nature measures remained stable for BAU and increased by a factor of 4.4 for LSP and 6.7 for LSH. Arable land with agri-environment-climate measures and eco-schemes increased by 1.4 (BAU), 42.2 (LSP), and 44.0 km^2/year between 2005 and 2030.

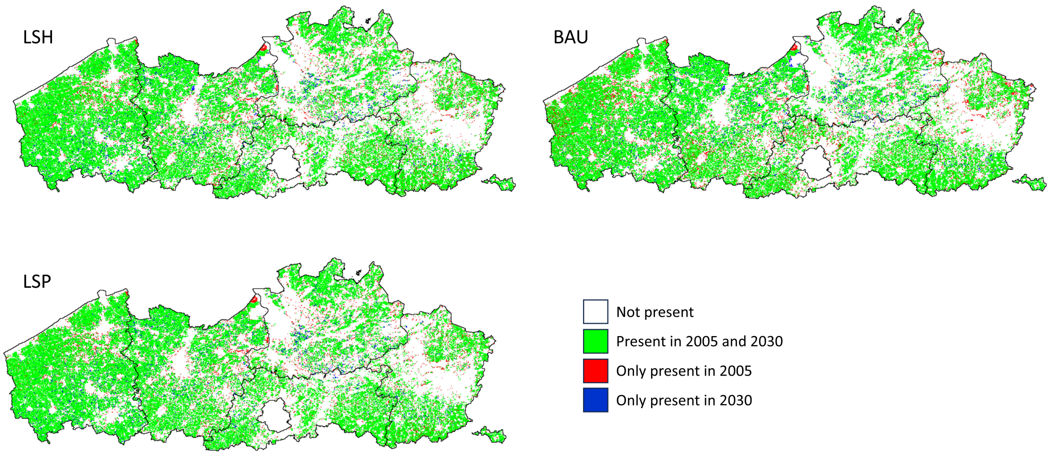

Figure 5. Difference in registered agriculture between 2005 and 2030 for Land Sharing (LSH), Business as Usual (BAU), and Land Sparing (LSP) scenarios.

3.1.3. Forest, Nature, and Green Space

Between 2005 and 2030, managed nature and forest increased by 340 km^2 or 13.6 km^2/year (BAU), 220 km^2 or 8.8 km^2/year (LSP), and 253 km^2 or 10.1 km^2/year (LSH). In BAU, more than a third of this increase was forest (4.9 km^2/year), more than a quarter grassland (3.5 km^2/year), and just under a quarter wetlands (3.1 km^2/year). A total increase of 23.7 km^2 was recorded for mudflats and salt marshes (0.9 km^2/year), 20.1 km^2 for heathland (0.8 km^2/year), and 9.7 km^2 for coastal dunes (0.4 km^2/year). In LSP, wetlands accounted for 37% of the increase (3.3 km^2/year), a quarter for forests (2.2 km^2/year), and heathland 16% (1.4 km^2/year). A total increase of 23.7 km^2 was recorded for mudflats and salt marshes (0.9 km^2/year), 13.4 km^2 grassland (0.5 km^2/year), and 10.7 km^2 coastal dunes (0.4 km^2/year). In LSH, 44% of this increase was attributed to forest (4.5 km^2/year), and more than a quarter to wetlands (2.8 km^2/year). A total increase of 23.7 km^2 accounted for mudflats and salt marshes (0.9 km^2/year), 20.3 km^2 for grassland (0.8 km^2/year), 22.2 km^2 for heathland (0.9 km^2/year), and 6.4 km^2 for coastal dunes (0.3 km^2/year). Areas without nature management decreased by 4.3 (BAU), 2.3 (LSP), and 1.2 (LSH) km^2/year.

Green space increased by 11% in BAU, 22% in LSP, and 36% in LSH (Figure 6). In the BAU scenario, the increase was mainly driven by an increase in forest and natural grasslands, which together represented 86.3% of the increase in green space. In the LSP scenario, the increase in green space was largely due to an increase in agricultural land with nature measures, which accounted for 65% of the increase. In the LSH scenario, agricultural land with nature measures was also the main driver of green space expansion, contributing 71% of the total increase in green space. In each of the scenarios, green space was created on unregistered agricultural land, which decreased the most between 2005 and 2030. The largest decreases were 459 km^2 (BAU), 421 km^2 (LSP), and 495 km^2 (LSH). All future scenarios incorporate previously unregistered and unmanaged wetlands into formal management frameworks. A total of 76 km^2 (BAU), 82 km^2 (LSP) and 69 km^2 (LSH), will transition to newly managed wetlands with improved ecological stewardship.

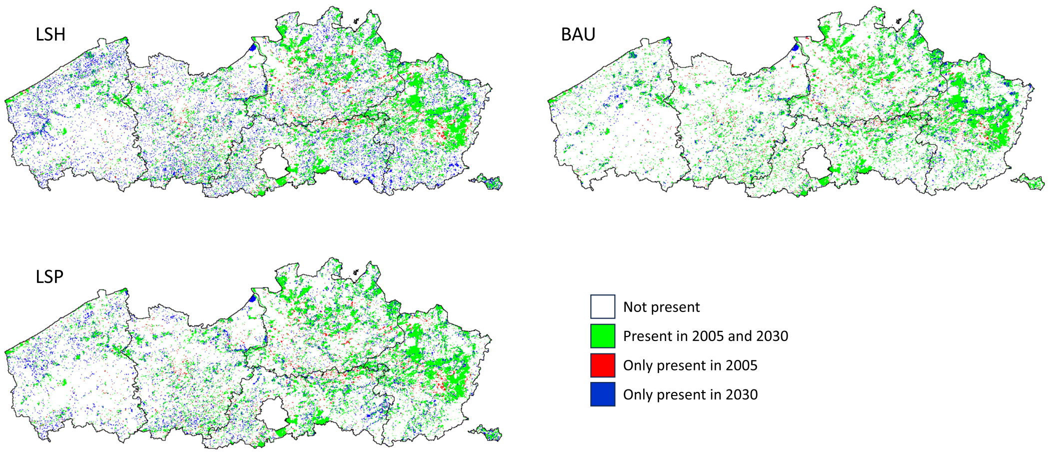

Figure 6. Difference in green space between 2005 and 2030 for Land Sharing (LSH), Business as Usual (BAU), and Land Sparing (LSP) scenarios.

3.2. Spatial Coherence

3.2.1. Urban Fabric

The average cluster size of the urban fabric evolved from 12 ha in 2005 to 14.4 ha (LSH), 14.7 ha (LSP), and 15.3 ha (BAU) in 2030 (Figure 7). The number of clusters decreased from 20,262 in 2005 to 19,506 (LSP), 19,539 (BAU), and 19,915 (LSH) in 2030, despite an increase in population. Overall, the cluster size of the urban fabric increased, which was most pronounced for clusters larger than 1 pixel size. These clusters increased from an average of 24.8 ha in 2005 (n = 8725) to 31.4 ha (LSH, n = 8308), 31.8 ha (LSP, n = 8255), and 33.3 ha (BAU, n = 8213). The largest clusters of urbanised fabric were located in and around the urbanised areas of major cities such as Brussels, Antwerp, and Gent. The total surface area located within the largest cluster increased from 1505 ha in 2005 to 3300 ha (LSP), 3357 ha (LSH), and 3902 ha (BAU) in 2030. The strongest growth in cluster areas occurred in and near secondary cities.

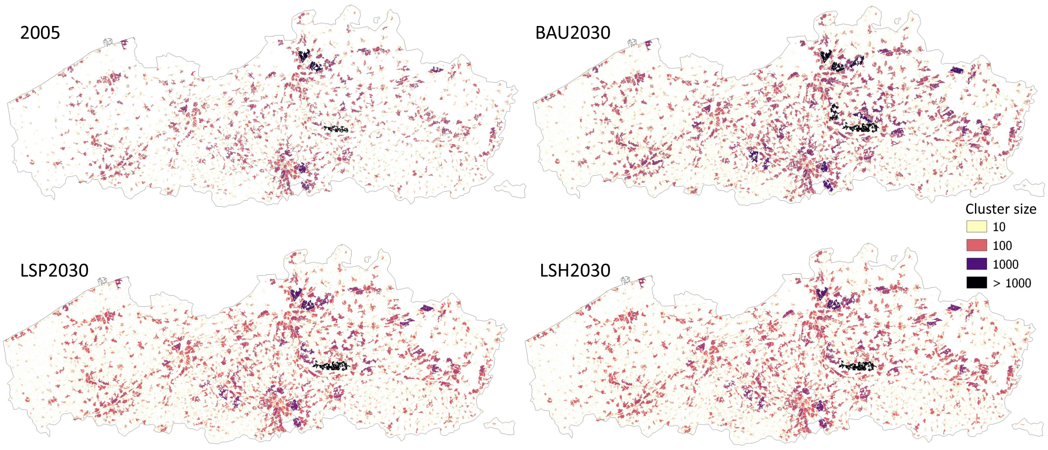

Figure 7. Difference in urban fabric cluster size between 2005 and 2030 for three scenarios, with cluster size classes 2.25–10 ha, 10–100 ha, 100–1000 ha, and >1000 ha.

3.2.2. Agriculture

External processes outside the agricultural sector are driving the expansion of the urban fabric into agricultural areas. This transition from agricultural to urban land use, also called urban sprawl, is most pronounced around urban areas and is most severe in the BAU scenario, followed by the LSH and LSP scenarios (Figure 8). The influence of the urban fringe on agriculture was strongest in the centre of the region and weakest in the west in all scenarios. Agriculture as the dominant land use category (disturbance < 0.25 in Figure 8) in 2005 covered 45.7% of the area, and it decreases in future scenarios, with values of 40.4% (BAU), 41.7% (LSH), and 42.9% (LSP). In contrast, there was a steady increase in predominantly urban land use (disturbance > 0.75 in Figure 8) from 13.7% in 2005 to 18.2% in BAU, 17.1% in LSH, and 16.3% in LSP, reflecting urban expansion over time. This shift underlines the pressure on agricultural land due to urbanisation trends. The greatest impact of urban sprawl was located near industrial cities, with the least impact near provincial cities in all scenarios.

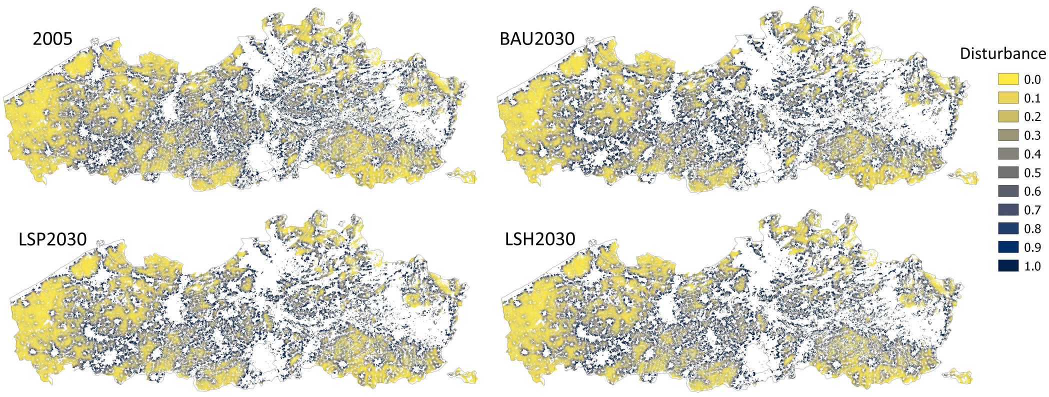

Figure 8. Urban fabric disturbance of agriculture between 2005 and 2030, with disturbance calculated within a neighbourhood of 100 × 100 grid cells.

3.2.3. Forest, Nature and Green Space

The presence of green space increased from 16% to 20% between 2005 and 2030. In 2005, there was a steep gradient from 1% of green space in the west to 31% in the east of the region. This gradient in the natural coherence of green space was maintained in the different scenarios, with high values corresponding to low levels of fragmentation. The coherence was highest for areas with nature management in all scenarios.

The largest green space clusters in 2005 and 2030 for all scenarios were located in the east to north-east and in the south-centre (Figure 9). The average size of the green space clusters developed from 13.5 ha in 2005 to 13.5 ha (LSH), 16.7 ha (BAU), and 16.8 ha (LSP) in 2030. Green space clusters larger than 1 pixel were on average 27.8 ha in 2005, and 26.6 ha (LSH), 33.5 ha (BAU), and 35.1 ha (LSP) in 2030. The number of clusters larger than 1 pixel was 6623 in 2005, decreased to 5994 (BAU) in 2030, and increased to 6941 (LSP) and 9576 (LSH) in 2030. The total surface area located within the largest cluster increased from 4061 ha in 2005 to 4273 ha (LSH), 4365 ha (BAU), and 4410 ha (LSP) in 2030. The total surface area located within green space clusters increased more significantly in the LSH scenario than in the LSP scenario, but the clusters were larger in the LSP and BAU scenarios.

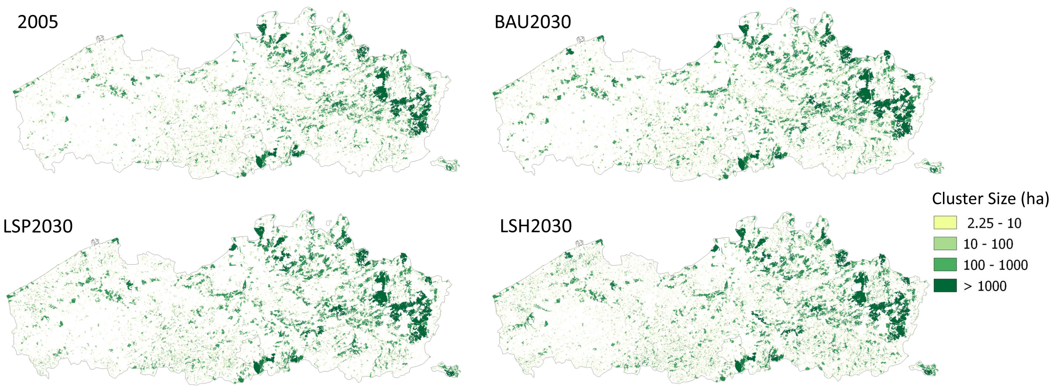

Figure 9. Size of green space clusters in 2005 and 2030 under BAU, LSP, and LSH scenarios, with cluster size classes 2.25–10 ha, 10–100 ha, 100–1000 ha, and >1000 ha.

3.3. Land Related Emissions

The spatial distribution of land use strongly influences net greenhouse gas (GHG) emissions, with forested areas acting as carbon sinks and agricultural land as net emitters (Figure 10). In 2005, net GHG emissions from agriculture, forestry and other land use (AFOLU) amounted to 323 g CO_2e per square metre, mainly from methane (76.5%) and nitrous oxide (36.1%). Agricultural land contributed 39.4% of emissions, while livestock, mainly cattle, accounted for 79.7% due to methane production. Carbon sequestration in forests offset 23.5% of agricultural emissions.

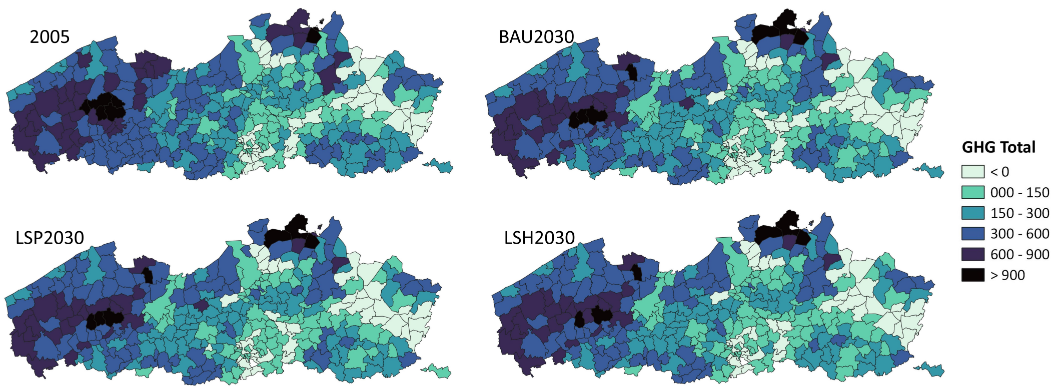

Figure 10. AFOLU based net greenhouse gas emissions in CO_2e per municipality (in g/m^2).

The land use allocation scenarios influenced emission reductions by 2030, with net AFOLU emissions decreasing by 10.1% (BAU), 10.5% (LSH), and 10.2% (LSP). Total GHG emissions in 2030 were projected to be around 4.0 Mt CO_2e, with agriculture being the dominant source, emitting 4.9 Mt CO_2e, mainly from methane (3.09 Mt CO_2e), of which 73% came from cattle. Forested areas acted as carbon sinks, sequestering −1.35 Mt CO_2e

(BAU), −1.33 Mt CO_2e (LSH), and −1.29 (LSP) Mt CO_2e, corresponding to −34% (BAU), −33% (LSH), and −32% (LSP) of the total emissions, respectively, thereby reducing the net balance.

The spatial distribution of agricultural activities and forest cover shaped the emission patterns at the municipal level (Figure 10). Livestock-related methane and nitrous oxide from soil amendments remain the dominant emission sources, particularly in the northern and western municipalities. Meanwhile, forests in central and eastern municipalities serve as carbon sinks, reinforcing the importance of forest conservation for mitigating land-based emissions.

4. Discussion

The results of this study highlight the profound impact of land use and agricultural management on land use patterns, spatial coherence, and greenhouse gas (GHG) emissions in dynamic urbanised landscapes. Spatially explicit land use modelling identifies key trade-offs between urban expansion, forest conservation, agricultural intensification, and Green Deal measures, including eco-schemes and agri-environment-climate measures. These insights can inform policy strategies to balance productivity goals with environmental sustainability in rapidly evolving rural-urban interfaces, similar to the recommendations of other studies [42,43].

In the business-as-usual (BAU) scenario, urban sprawl continues to encroach on agricultural land, reducing carbon-sequestering land cover such as forests and, to a lesser extent, grasslands. Despite a modest increase in managed green spaces and protected forests, this trajectory increases net greenhouse gas emissions. In contrast, the Land Sharing (LSH) and Land Sparing (LSP) scenarios illustrate alternative pathways for reconciling agricultural production activities with environmental objectives. The LSH scenario promotes a mosaic of low-intensity agriculture interwoven with natural features, increasing green space and landscape diversity. The LSP scenario, by spatially separating high-intensity agriculture from protected areas, improves habitat coherence and reduces fragmentation. Similar studies have shown that land-sparing strategies can expand natural and semi-natural habitats, thereby improving biodiversity outcomes and reducing nutrient pollution [13,14].

In line with global GHG mitigation strategies for agriculture [20], our study identifies that limiting emissions of, in order of effectiveness, CO_2 from deforestation, CH_4 from livestock farming, and N_2O from fertiliser use, is crucial for effective climate change mitigation. Across all scenarios, net GHG emissions—after accounting for carbon sinks—ranged from 4.0 to 4.4 Mt CO_2e, with forest sequestration offsetting 28% to 34% of total emissions. These results are consistent with broader global assessments of the AFOLU sector, where land use and management practices not only contribute to GHG emissions but also offer mitigation opportunities through sequestration [16]. Net GHG emissions in all scenarios show reductions due to increased adoption of Green Deal measures, including eco-schemes and agri-environment-climate measures, but the magnitude of the reductions varies. The LSH scenario shows the largest increase in green space and landscape diversity-oriented agriculture, demonstrating a potential pathway for enhancing agroecosystem services while mitigating emissions.

In the study area, soils under grasslands have the highest carbon and nitrogen stocks (Table 4) [44], highlighting the need for conservation measures to prevent emissions from soil degradation. Recent global shifts in grassland carbon dynamics indicate that managed pastures are now a near-neutral source of greenhouse gases, with warming effects of agricultural intensification counteracting the cooling effects of natural grasslands [18]. Soil emissions are a critical but often overlooked component of greenhouse gas budgets, contributing an estimated 15% of total radiative forcing [45]. Effective mitigation requires strategies that minimise soil carbon loss, improve nitrogen use efficiency, and reduce methane emissions [37,46]. Practices such as cover cropping and crop residue retention can increase soil organic carbon stocks and improve soil health, although their effectiveness varies with soil type and cropping system [47–49].

Table 4. Summary of land based carbon stocks in tonnes of organic C per hectare to 1 m depth [44].

Land Cover Class	Soil C-Stock	Soil N-Stock
Forest	107.4 ± 85.1	8.82 ± 6.34
Grassland	149.0 ± 97.0	13.67 ± 6.02
Arable	107.4 ± 49.6	10.61 ± 3.24
Wetland	100.0 ± 53.2	
Urban Fabric	146.1 ± 96.4	12.22 ± 9.65

By integrating spatial land use modelling with greenhouse gas accounting, this study provides insights into how land sharing and sparing strategies fit with European policy frameworks such as the Green Deal, the Common Agricultural Policy (CAP), and the LULUCF Regulation. CAP instruments, that include eco-schemes and agri-environment-climate measures as a contribution to the Green Deal, are essential to incentivise sustainable agricultural practices that reduce emissions while maintaining food production [3]. Our results suggest that land sharing approaches that integrate agriculture with semi-natural landscapes can maximise landscape diversity and minimise GHG emissions, supporting the farm-to-fork objectives of the CAP [4]. However, in regions facing intense urbanisation pressures, land sparing strategies may be more effective in protecting carbon-rich forests, grasslands, and wetlands. The capacity of the LULUCF sector to offset emissions highlights the need for stronger incentives to conserve high-sequestration land uses such as forests and permanent grasslands [22].

Advances in land use and land cover (LULC) modelling play an important role in informing adaptive land management strategies. The integration of high-resolution remote sensing, cellular automata models, and machine learning techniques has improved spatial decision making at local and regional scales [9,10]. Our study demonstrates how scenario-based land use modelling can assist policy-makers and planners in balancing competing land demands for agriculture, forestry, and urban development while optimising agri-environment-climate measures and minimising greenhouse gas emissions. Adopting measures that optimise nitrogen use efficiency, reduce methane emissions, and expand carbon-sequestering land cover offer the most promising mitigation strategies. The use of geomatics and open access spatial datasets further strengthens evidence-based policy making by enabling regionally tailored sustainability strategies that will be essential for achieving the European Green Deal objectives.

Future research should refine scenario modelling by incorporating finer temporal scales, dynamic climate variables, and socio-economic feedbacks. In addition, exploring synergies between carbon farming, water management, and biodiversity conservation could lead to integrated solutions for resilient and multifunctional landscapes [8,13,14]. As the European Green Deal progresses, land use planning needs to move towards a systems-based approach that optimises land functions at multiple scales. By aligning climate-smart agricultural practices with spatial planning, it is possible to achieve sustainable land management that balances food security, environmental resilience, and climate change mitigation.

5. Conclusions

The research contributes to exploring Green Deal strategies for agriculture in dynamic urbanised landscapes, using land use modelling and publicly available open-access data. The results provide valuable insights into the interactions between land use change, spatial coherence, and greenhouse gas emissions. Land use modelling of business-as-usual, land sharing, and land sparing scenarios demonstrate the need to balance agricultural productivity, urban development, nature conservation, and climate mitigation to achieve Green Deal goals.

The results show that land sharing offers the most significant gains in green space and landscape diversity, increasing green space by 36% while reducing net greenhouse gas emissions by 10.5%. In contrast, land sparing improves habitat coherence, demonstrating that targeted conservation can reduce fragmentation. However, both approaches benefit from the implementation of Green Deal measures in agriculture such as eco-schemes and agri-environment-climate measures.

Methane emissions from livestock and nitrous oxide from fertilisers remain dominant greenhouse gas sources, with methane from cattle accounting for 73% of total methane emissions. Forest conservation and expansion are critical, sequestering up to –1.35 Mt CO_2e and offsetting up to 34% of total emissions. These findings highlight the importance of integrating spatial planning with climate-smart agricultural strategies, focusing on optimising nitrogen use efficiency, improving manure management, and increasing carbon-sequestering land uses.

Policy frameworks need to be adaptable, prioritising land sharing strategies where agricultural and environmental objectives overlap, and land sparing approaches in areas of intense urban pressure. Further exploration of the synergies between carbon farming, water management, and biodiversity conservation will be key to designing resilient and multifunctional landscapes in line with the European Green Deal.

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