SPATIAL ANALYSIS OF THE (CIRCULAR) BIOECONOMY

Regional Spatial Analysis of Land Use and Farming Systems in Ireland

Abstract

This report analyses rural Ireland's agricultural landscape to guide regional bioeconomy strategy aligned with sustainability and circular economy principles. Using Census of Agriculture 2020 and CORINE Land Cover 2018 geodata, it examines land use, farm size, livestock distribution, and natural capital. It also assesses air quality, geology, soils, and biodiversity across regions, forming a natural capital profile that informs environmental suitability and constraints for bioeconomy planning. The analysis reveals significant regional disparities: the Southern region features intensive agricultural systems with larger farms and high livestock densities, offering opportunities for large-scale livestock and grass-based biorefinery development, integrating renewable energy projects and advanced waste management practices. In contrast, the Northern and Western region is characterized by smaller, fragmented farms interwoven with extensive natural ecosystems, such as wetlands, peatlands, and heterogeneous agricultural areas, which are well-suited for biodiversity-driven initiatives and community-based bioeconomy models. The Eastern and Midlands region, with its emphasis on arable and cereal production, shows potential for crop-based bioeconomy innovations, including biofuel production and high-value bioproducts derived from cereal residues. The report further evaluates how circular sustainability and the cascade principle are embedded in Irish agriculture and land-use policy at both national and EU levels, and illustrates their practical application in areas such as nutrient cycling, forestry, and waste valorisation. It proposes an integrated regional approach to bioeconomy development, aligning ecological potential with policy frameworks and sustainability goals. Addressing income challenges and environmental impacts, the report recommends precision farming, circular resource use, and regionally tailored strategies to foster sustainable rural development and a robust national bioeconomy.

Jon Paul Faulkner

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Introduction

This report provides a spatial analysis of rural Ireland to inform the development of regional bioeconomy strategy. It primarily utilises Ireland's Census of Agriculture 2020 (Central Statistics Office Ireland, 2020) and the CORINE Land Cover Geodatabase 2018 (Environmental Protection Agency Ireland, 2018) in order to accomplish this task. The report explores the spatial distribution of farmed land, variations in farm size, and the types of land use prevalent across regions. These insights provide a crucial foundation for understanding regional disparities and opportunities, offering a pathway to develop bioeconomy strategies that align with Ireland's commitments to sustainability and circular economy principles.

The report is structured to systematically address the diverse facets of Ireland's agricultural landscape. It begins with an analysis of farmed land and farm size, highlighting regional variations in the extent and intensity of agricultural activity. These findings are contextualised with insights into grassland use, which accounts for a substantial portion of the country's landmass, to evaluate its implications for livestock systems and biomass production. Crop systems and areas of commonage are then explored to uncover opportunities for diversifying land use, enhancing biodiversity, and integrating sustainable practices. The analysis extends to livestock distribution, offering a detailed breakdown of animal density and farm structures across counties. This section identifies both the challenges and potential for adopting bioeconomy innovations, such as circular resource use and bio-based product development.

Complementing the Census data, a spatial analysis using the CORINE Land Cover Geodatabase 2018 provides an overarching perspective on Ireland's land typology. This includes land categories such as wetlands, forestry, and heterogeneous agricultural areas, with emphasis on their ecological value and bioeconomy potential. Air quality, geological conditions, soil types, and biodiversity are also evaluated to build a natural capital profile that informs regional planning and sustainability considerations.

The report incorporates findings from the 2023 National Farm Survey to contextualise the socio-economic conditions facing Irish farmers, including income pressure, rising input costs, and the shift toward sustainability. It then assesses how circular sustainability and the cascade principle are embedded in national and EU-level policy frameworks, including the Bioeconomy Action Plan, Food Vision 2030, the Climate Action Plan, and CAP 2023–2027. These strategies promote a transition from linear agricultural models to systems that prioritise efficient resource use, nutrient cycling, and high-value utilisation of biomass.

Finally, the report presents region-specific bioeconomy profiles for the Northern and Western, Southern, and Eastern and Midlands regions. These profiles integrate environmental, agricultural, and socio-economic data to identify the most promising and sustainable bioeconomy pathways for each region. Through this structured approach, the report moves from spatial and environmental data analysis to policy and practice, providing actionable recommendations for co-designed, regionally grounded bioeconomy strategies. The findings align with national and international policy objectives, offering a framework for inclusive rural development and Ireland's leadership in sustainable land use and circular bioeconomy innovation.

Spatial Analysis using Census of Agriculture Ireland 2020

Farmed Land, Farm Number and Farm Size

According to Census of Agriculture Ireland 2020, approximately 64% (4,504,858 ha) of Ireland's landmass is farmed. From a regional perspective, the highest proportion of farmland occurs in the Southern region (69%) and the lowest occurs in the Northern and Western region (57%). At the county level, some of the highest proportion of farmed land occurs in counties such as Meath (84%), Monaghan (80%) and Kilkenny (79%), while some of the lowest proportions occurs in urbanised counties such as Dublin (34%), but also in more rural areas such as Mayo (50%), Wicklow (51%) and Donegal (53%) (see Table 1 and Figures 1 and 3).

As of 2020, there were a total of 132,972 farms in Ireland. The Northern and Western (NW) region exhibited the highest number at 2.22 farms per Km2 (2.22), while the Eastern and Midlands (EM) region exhibited the lowest number at 1.67 per Km2. Some of the largest farm numbers were recorded in counties Monaghan (3.45 per Km2), Cavan (2.64) and Roscommon (2.39), while some of the lowest numbers were recorded in Wicklow (1.21 farms per Km2), Kerry (1.31) and Waterford (1.39) (see Table 1).

In terms of farm size, Ireland exhibits an average farm size of 36 ha, with the EM region presenting the largest farm sizes (41 ha) and the NW region presenting the smallest average farm sizes (27 ha). Some of the largest farms are located in counties such as Dublin (50 ha), Waterford (48 ha), and Kilkenny (47 ha), with the smallest farm sizes located in counties such as Monaghan (24 ha), Mayo (25 ha) and Leitrim (26 ha) (see Table 1 and Figures 2 and 4).

Figure 1: Area of Land Farmed in Ireland 2020 (Hectares)

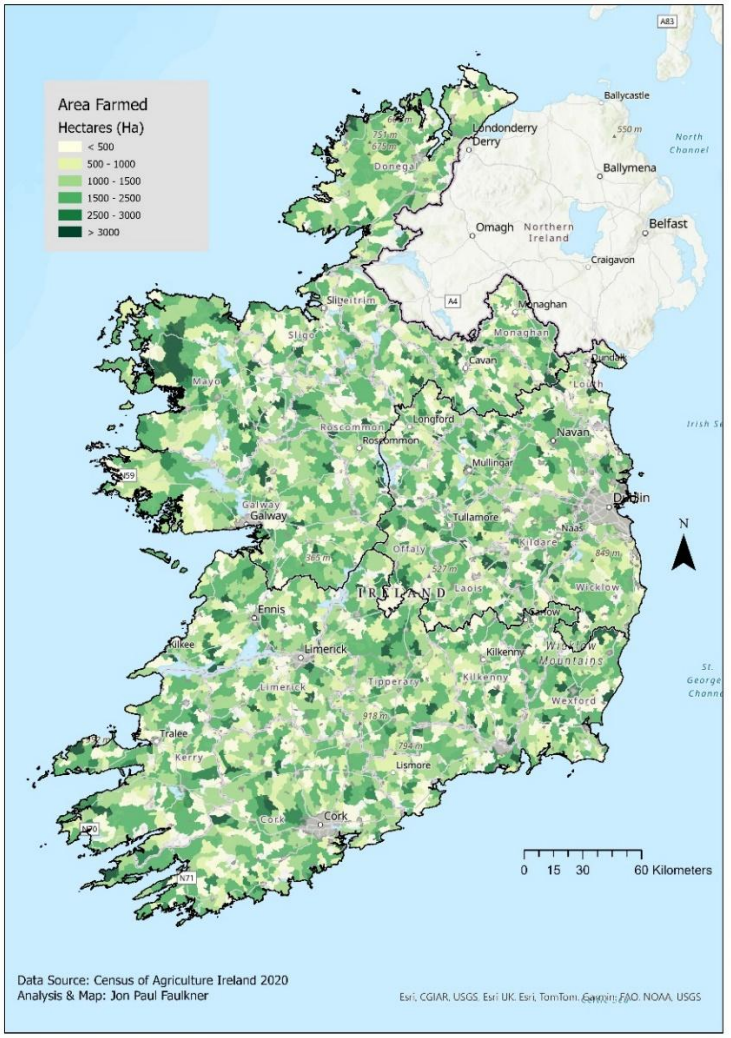


Table 1: Area, Number and Size of Farms in Ireland 2020

	Area Farmed (Total Ha)	Area Farmed (as % of Area)	Farms N (per Km2)	Average Farm Size (Ha)
REGION				
NW	1,479,224	57.33	57,252 (2.22)	26.76
Southern	2,072,663	69.01	51,511 (1.72)	40.41
EM	953,971	65.93	24,211 (1.67)	40.69
COUNTY				
Donegal	256,463	52.74	9,346 (1.92)	27.84
Sligo	113,202	61.61	4,177 (2.27)	28.12
Leitrim	87,777	55.25	3,445 (2.17)	25.61
Cavan	134,042	69.38	5,109 (2.64)	26.5
Monaghan	103,955	80.29	4,473 (3.45)	23.86
Galway	336,124	54.64	12,701 (2.06)	27.71
Mayo	279,126	49.94	11,913 (2.13)	24.8
Roscommon	168,535	66.14	6,088 (2.39)	27.86
Clare	201,830	58.50	6,297 (1.83)	33.46
Tipperary	312,215	72.52	7,395 (1.72)	43.19
Limerick	203,621	73.88	5,625 (2.04)	37.05
Waterford	121,713	65.49	2,585 (1.39)	48.33
Kilkenny	163,156	78.74	3,569 (1.72)	47.12
Carlow	70,028	78.10	1,718 (1.92)	42.27
Wexford	181,198	76.42	4,329 (1.83)	42.48
Cork	529,337	70.54	13,696 (1.83)	39.83
Kerry	288,565	60.03	6,297 (1.31)	36.65
Dublin	31,684	34.21	656 (0.71)	49.45
Wicklow	103,065	50.87	2,452 (1.21)	42.92
Kildare	113,447	66.93	2,533 (149)	46.46
Meath	197,332	84.22	4,505 (1.92)	44.33
Louth	61,457	74.30	1,628 (1.97)	40.61
Longford	71,039	65.08	2,513 (2.3)	29.13
Westmeath	130,625	71.03	3,428 (1.86)	38.63
Offaly	123,780	61.86	3,297 (1.65)	37.8
Laois	121,542	70.67	3,199 (1.86)	39.07

Figure 2: Average Farm Size in Ireland 2020 (Hectares)

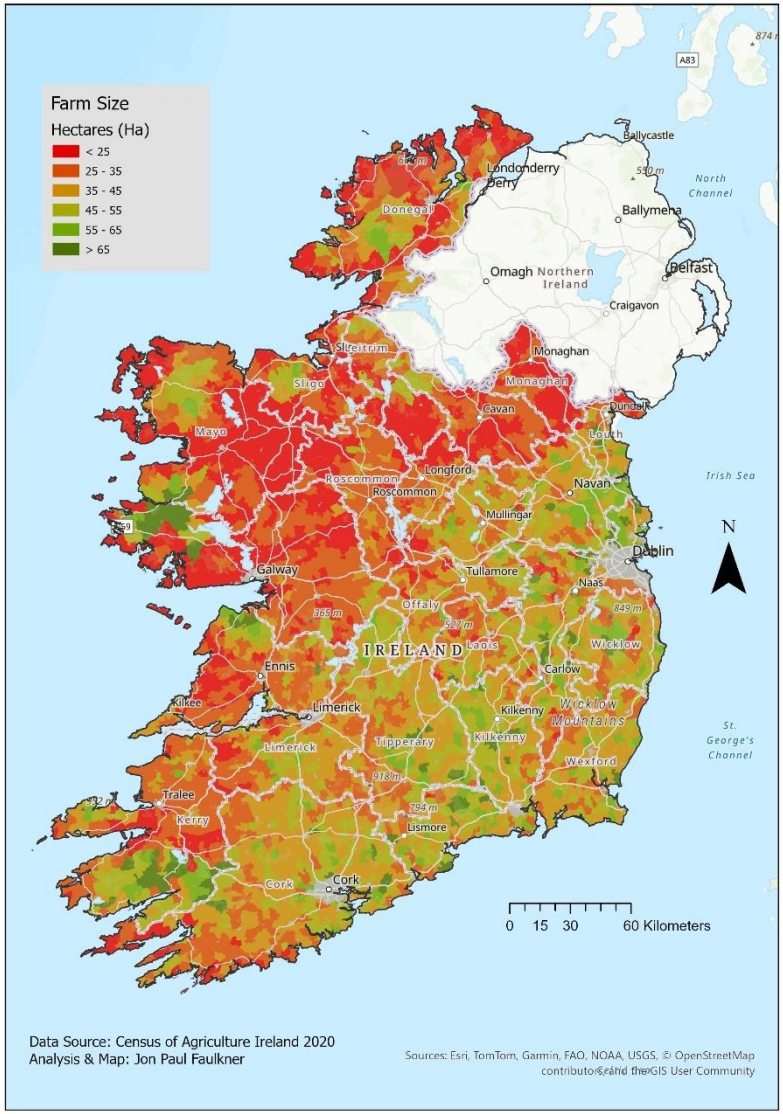


Figure 3: Percentage of Land Area Farmed by County 2020

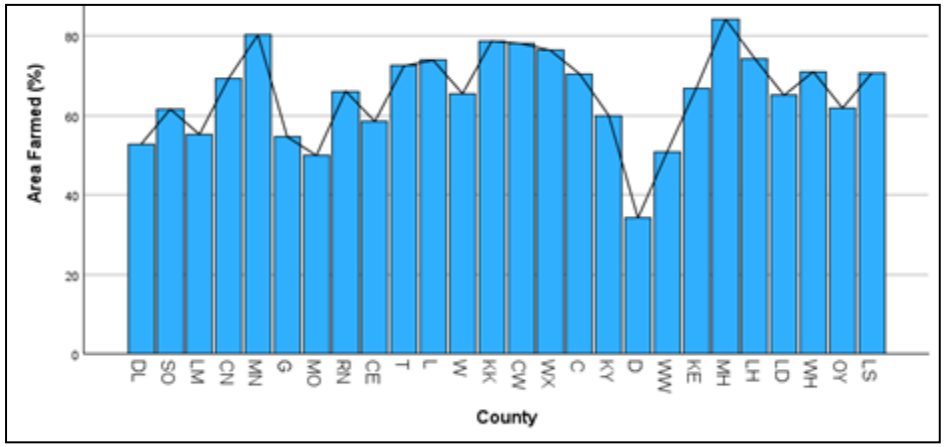
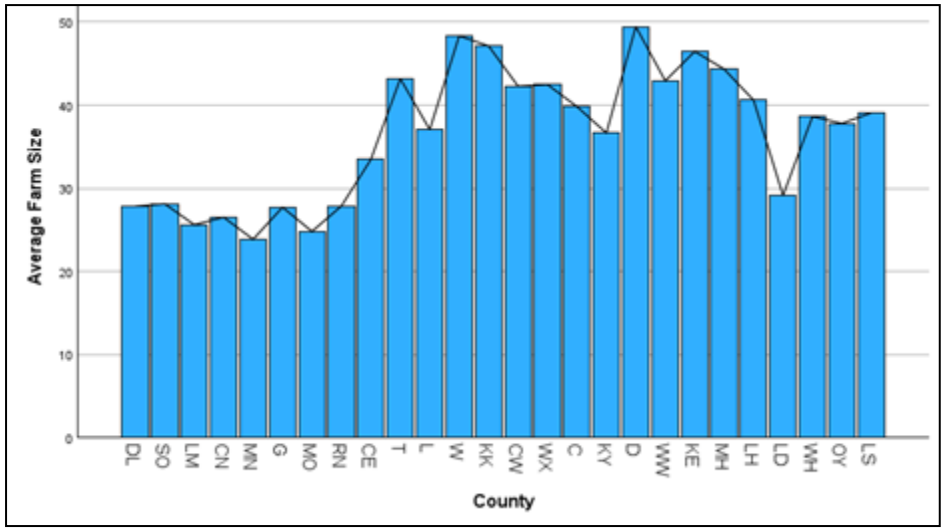


Figure 4: Average Farm Size by County 2020 (Ha)



Discussion

Introduction

The results from the spatial analysis provide significant insights into land use and farm size distribution across Ireland, laying a foundation for advancing bioeconomy development. These findings highlight the spatial variability in farming practices and land use, offering critical considerations for regionally tailored bioeconomy strategies that align with Ireland's natural capital and sustainability goals.

Regional Variability in Farmland Use

Approximately 64% of Ireland's landmass is dedicated to farming, underscoring the vital role of agriculture in shaping the country's economy and environment. However, the proportion of farmed land varies significantly between regions. The Southern region has the highest percentage of farmland (69%), whereas the Northern and Western (NW) region has the lowest (57%). This variability reflects regional differences in land availability, topography, and agricultural intensity.

Counties such as Meath (84%), Monaghan (80%), and Kilkenny (79%) exhibit high proportions of farmland, indicating their agricultural prominence. These counties present significant opportunities for implementing bioeconomy initiatives focused on maximising land productivity while ensuring environmental sustainability. Conversely, counties with lower proportions of farmland, such as Dublin (34%), Mayo (50%), and Donegal (53%), may require alternative approaches that integrate urban, peri-urban, and rural development strategies. For instance, urbanised counties like Dublin could emphasise vertical farming, urban agriculture, or bio-based industries relying on advanced technologies and small-scale production systems.

Farm Density and Structural Characteristics

Ireland supports 132,972 farms, with farm density varying between regions and counties. The NW region has the highest farm density (2.22 farms per km²), while the Eastern and Midlands (EM) region exhibits the lowest (1.67 farms per km²).

Counties like Monaghan (3.45 farms per km²) and Cavan (2.64 farms per km²) show particularly high farm densities, reflecting smaller-scale farming systems and fragmented landholdings. These characteristics suggest a strong potential for bioeconomy strategies emphasising high-value, niche markets that cater to small and medium-sized farm structures. For example, these counties could focus on producing organic products, specialty crops, or other high-value bio-based goods, supported by certification schemes and value-added markets (Philip and Winickoff, 2019).

Farm Size Distribution and Bioeconomy Potential

The average farm size in Ireland is 36 hectares, but significant regional and county-level disparities exist. The EM region has the largest average farm size (41 ha), while the NW region has the smallest (27 ha). Counties like Dublin (50 ha), Waterford (48 ha), and Kilkenny (47 ha) boast the largest farm sizes, reflecting economies of scale that can facilitate large-scale bioeconomy initiatives, such as bioenergy production or large-scale biorefineries. Smaller farms, located in counties such as Monaghan (24 ha), Mayo (25 ha), and Leitrim (26 ha), offer a contrasting opportunity. These farms are better suited to adopt diversified, low-input, and sustainable farming practices, such as agroecology or mixed farming systems. Such approaches can enhance biodiversity, build ecological resilience, and contribute to circular economy principles. For instance, small farms could prioritise cascading systems that utilise agricultural residues for composting, biochar production, or small-scale energy generation (Singh et al., 2024).

Understanding characteristics related to farm size is essential to the strategic implementation of bioeconomy development at the regional scale. Hence, authorities and policymakers need to be cognisant of farm size typology in their respective governance area.

Small to Medium Farms

Small to medium sized farms are more capable of implementing diverse cropping systems, thus increasing biodiversity and enhancing ecosystem services. Smaller systems also have more capacity to efficiently adopt new practices and new technologies, which may be beneficial for niche bioeconomy markets focused on high-value, specialised biomass production. However, smaller systems face challenges such as higher production costs per unit, and limited access to capital and advanced technologies, which can hinder their ability to scale bioeconomy initiatives (Meyer, 2017). It may be advantageous to encourage such systems to produce high-value, niche bio-based products such as specialty crops, organic goods, and artisan goods and services (Shevchenko et al., 2022). The promotion of sustainable farming practices like agroecology and organic farming is particularly applicable to small to medium sized farms, supported by certification programs that add market value and build consumer trust (Jouzi et al., 2017). Capacity building through training and extension services on sustainable practices, new technologies, and business management is important (Paris et al., 2023). Authorities should provide microloans, grants, and subsidies tailored to the specific needs of small primary production, and invest in research focused on low-input, high-diversity farming systems and resilient crop variety.

Medium to Large Farms

Medium to large farming systems benefit from economies of scale, with the capacity to produce bio-based products at lower costs per unit, making them competitive in larger markets (Lange, 2022). Such systems have greater access to capital and technology, allowing for significant investments in research and development. However, such systems often rely on monoculture, which degrades the environment and reduces biodiversity (Crews et al., 2018). For such systems the promotion of industrial symbiosis is key, where waste streams are utilised as inputs for other processes (Bijon et al., 2022). Authorities should encourage the adoption of circular economy principles to minimise waste and optimise resource use. Such systems have a greater capacity to invest in large-scale biorefinery projects and can implement sustainable intensification practices such as conservation tillage and precision fertilisation (von Cossel et al., 2019). Large-scale agroforestry and carbon sequestration projects can further enhance sustainability in such systems (Calvin et al., 2021). Promoting corporate social responsibility initiatives that emphasise sustainability, ethical labour practices, and community engagement is also important, along with supporting certification programs that meet consumer demand for sustainably produced bioproducts (Andronicanu,

2019). Facilitating access to global markets through trade agreements, export support, and compliance with international standards is crucial for driving development in such operations. Finally, developing regulatory frameworks that mandate or incentivise sustainable practices and responsible resource use, along with policies supporting large-scale investments in bioeconomy infrastructure and innovation, is also necessary (Singh et al., 2021).

Implications for Circular and Sustainable Bioeconomy Development

The variations in farmland use, density, and size have direct implications for circular economy principles and sustainability. Larger farms in the EM region and counties like Kilkenny and Waterford can serve as key players in implementing large-scale circular systems. These systems may include precision farming technologies, efficient resource recovery processes, and partnerships with biorefineries to convert agricultural residues into bio-based materials or energy. In contrast, the smaller, denser farms in the NW region and counties such as Monaghan and Mayo are better positioned to implement localised, community-based bioeconomy initiatives. These may include cooperative ventures for shared equipment, resources, and infrastructure. For example, smallholders could collectively invest in small biogas plants or composting facilities to manage waste sustainably while generating additional income streams.

Challenges and Recommendations

Despite the opportunities presented, challenges must be addressed to fully realise the potential of Ireland's bioeconomy. Small-scale farms, which dominate certain regions, often face limited access to capital, advanced technologies, and markets. These barriers can hinder their ability to adopt innovative bioeconomy practices. Tailored financial support mechanisms, such as microloans, grants, and subsidies, are crucial for enabling small farms to invest in bioeconomy initiatives. Similarly, capacity building through training programs and extension services is essential for equipping farmers with the knowledge and skills needed to adopt sustainable practices (Paris et al., 2023). Larger farms face distinct challenges, including managing environmental impacts such as nutrient runoff, greenhouse gas emissions, and soil degradation (Gogoi et al., 2020). Policies promoting best practices, such as riparian buffer zones, nutrient management plans, and renewable energy integration, are essential to mitigate these impacts and align large-scale operations with sustainability goals (Fritsche et al., 2020).

Conclusion

The analysis of farmland utilisation and farm size in Ireland highlights the need for regionally customised approaches to bioeconomy development. Regions with larger farms should focus on large-scale, technologically advanced bioeconomy initiatives, while regions with smaller farms should emphasise diversified, niche markets and community-based models. By addressing the unique challenges faced by farms of varying sizes and densities, Ireland can harness its agricultural potential to drive sustainable economic growth, enhance ecosystem services, and build resilience in rural communities. These findings provide a robust foundation for co-designing strategies that balance economic productivity with environmental stewardship, aligning with Ireland's commitments to the circular economy and bioeconomy development.

Grassland

As per Census of Agriculture Ireland 2020, 59% (4,151,475 ha) of Ireland's landmass is accounted by grassland. Grassland accounts for pasture (2,326,289 ha, 33%), hay (139,266 ha, 2%) grass silage (1,234,369 ha, 18%), and rough grazing (451,538 ha, 6%). In a regional context the largest amount of pasture is found in the Southern region (35% of landmass, 1,055,168 ha) while the lowest is found in NW region (30.7%, 479,764 ha) (see Figure 5 and Table 2). At the county level, some of the largest extents of pasture areas as a percentage of total hectare (ha) were found in counties such as Monaghan (44.4%, 57,512 ha), Limerick (42.2%, 116,415 ha) and Tipperary (41.3%, 177,604 ha), while some of the lowest areas were found in rural counties such as Donegal (24.2%, 117,438 ha), Wicklow (26.4%, 53,511 ha), and Mayo (26.55, 147,923 ha) (see Table 2 and Figure 6). Approximately 59% (4,151,475 ha) of Ireland's landmass is accounted by grassland. Grassland accounts for pasture (2,326,289 ha, 33%), hay (139,266 ha, 2%) grass silage (1,234,369 ha, 18%), and rough grazing (451,538 ha, 6%). In a regional context the largest amount

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In terms of hay, the Eastern and Midlands region exhibited the largest extent (2.6%, 63,874 ha), while the Northern and Western region exhibited the smallest extent (1.4%, 37,099 ha). Some of the largest amounts of hay were found in Kildare (3.6%, 6,065 ha), Carlow (3.4%, 3,022 ha) and Limerick (3.2%, 8,858 ha), while some of the lowest amounts were found in rural areas such as Mayo (0.9%, 4,862 ha), Donegal (0.9%, 4,386 ha), and Kerry (1.4%, 6,885 ha) (see Table 2 and Figure 7). In respect to grass silage, the Southern region exhibited the largest amount (19.9%, 597,392 ha), while the NW region exhibited the lowest (15.4%, 396,782 ha). Monaghan had the largest extent of grass silage (29.7%, 38,411 ha), followed by Kilkenny (25.4%, 52,614 ha) and Limerick (24.9%, 68,732 ha), with Donegal (9.5%, 46,252 ha), Wicklow (11.2%, 22,750 ha) and Kildare (11.5%, 19,558 ha) showing the lowest extents (see Table 2 and Figure 8). In terms of land used for rough grazing, the NW region exhibited the largest extent (9.1%, 235,506 ha), while the Eastern and Midlands region exhibited the smallest extent (2.5%, 36,539 ha). Donegal exhibited the largest extent of rough grazing land (16.8%, 81,462 ha), followed by Kerry (16.4%, 78,613 ha), and Mayo (9.0%, 50,560 ha). Wexford exhibited the lowest extent (1.3%, 3,086 ha), followed Figure 8 by Kilkenny (1.5%, 3,032 ha) and Kildare (1.5%, 2,575 ha) (see Table 2 and Figure 9).

Figure 5: Area of Grassland in Ireland 2020 (Ha)

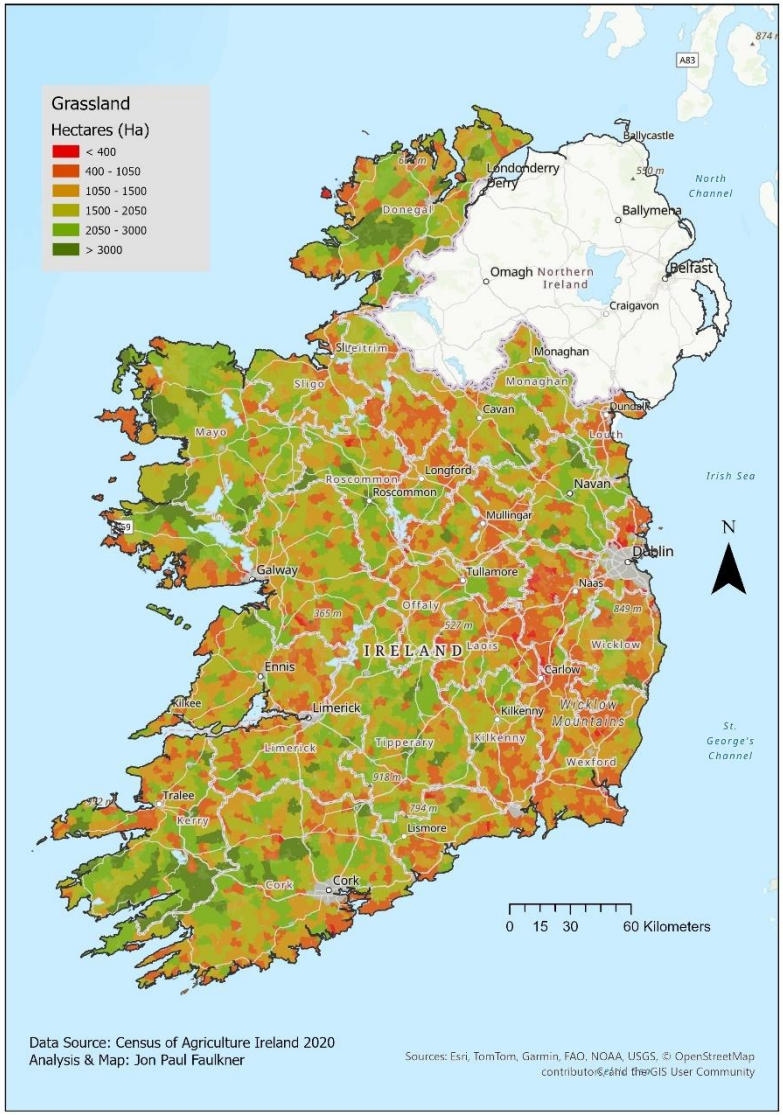


Table 2: Grassland in Ireland 2020

	Pasture (Total Ha, %)		Hay (Total Ha, %)		Grass Silage (Total Ha, %)		Grazing (Total Ha, %)	
REGION								
NW	791,357	30.7	37,099	1.4	396,782	15.4	235,506	0.17
S	1,055,168	35.1	63,874	2.1	597,392	19.9	179,493	0.08
EM	479,764	33.2	38,293	2.6	240,195	16.6	36,539	0.09
COUNTY								
DL	117,438	24.2	4,386	0.9	46,252	9.5	81,462	16.8
SO	68,051	37.0	2,879	1.6	27,977	15.2	13,858	7.5
LM	49,109	30.9	2,804	1.8	21,885	13.8	13,610	8.6
CN	75,073	38.9	2,784	1.4	46,536	24.1	9,023	4.7
MN	57,512	44.4	2,598	2.0	38,411	29.7	4,653	3.6
G	178,325	29.0	10,393	1.7	91,042	14.8	50,366	8.2
MO	147,923	26.5	4,862	0.9	74,386	13.3	50,560	9.0
RN	97,926	38.4	6,393	2.5	50,293	19.7	11,974	4.7
CE	104,032	30.2	7,025	2.0	61,751	17.9	28,103	8.1
T	177,604	41.3	9,589	2.2	91,317	21.2	9,186	2.1
LM	116,415	42.2	8,858	3.2	68,732	24.9	8,199	3.0
W	67,425	36.3	2,771	1.5	36,329	19.5	6,445	3.5
KK	84,921	41.0	5,003	2.4	52,614	25.4	3,032	1.5
CW	30,542	34.1	3,022	3.4	15,670	17.5	1,952	2.2
WX	73,313	30.9	7,600	3.2	42,534	17.9	3,086	1.3
C	268,403	35.8	13,121	1.7	160,595	21.4	40,877	5.4
KY	132,513	27.6	6,885	1.4	67,850	14.1	78,613	16.4
D	11,002	11.9	1,234	1.3	3,201	3.5	1,728	1.9
WW	53,511	26.4	3,937	1.9	22,750	11.2	9,066	4.5
KE	51,715	30.5	6,065	3.6	19,558	11.5	2,575	1.5
MH	96,485	41.2	7,434	3.2	49,139	21.0	4,408	1.9
LH	23,885	28.9	2,262	2.7	13,120	15.9	2,045	2.5
LD	41,625	38.1	2,369	2.2	22,365	20.5	3,627	3.3
WH	75,817	41.2	4,671	2.5	37,475	20.4	5,781	3.1
OY	66,014	33.0	5,363	2.7	36,912	18.4	4,107	2.1
LS	59,710	34.7	4,958	2.9	35,675	20.7	3,202	1.9

Figure 6: Pasture as a percentage of Total Land Farmed 2020

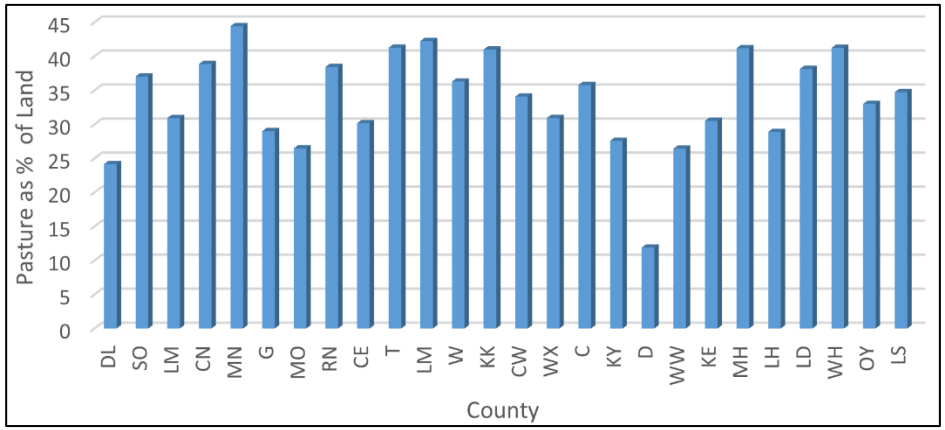


Figure 7: Hay as a percentage of Total Land Farmed 2020

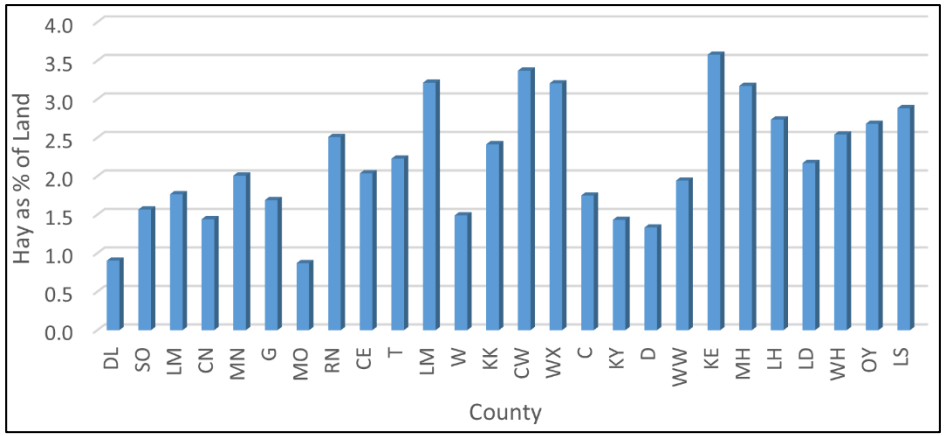


Figure 8: Grass Silage as a percentage of Total Land Farmed 2020

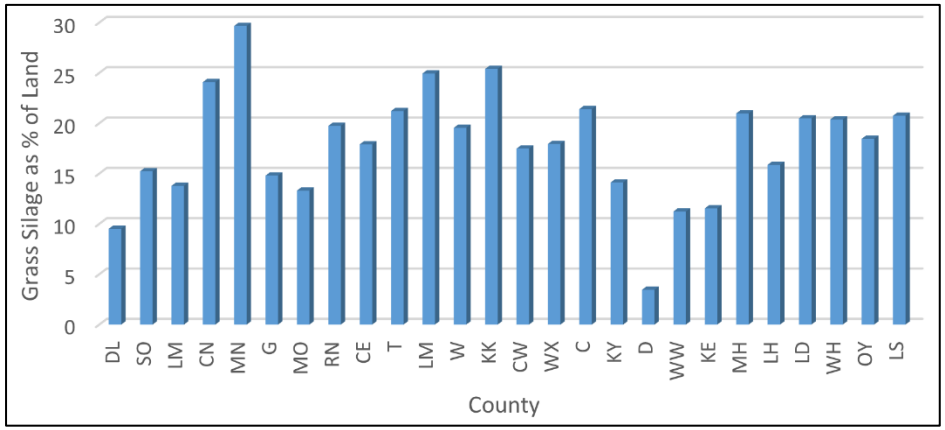
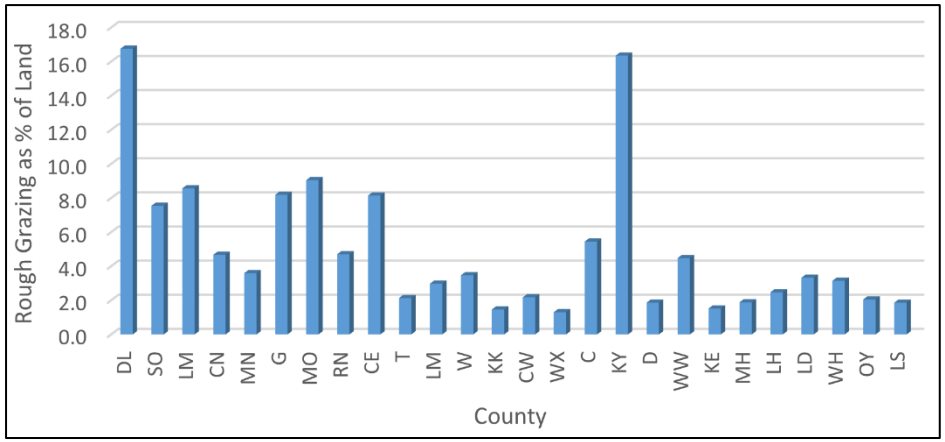


Figure 9: Rough Grazing as a percentage of Total Land Farmed 2020



Total Crops and Commonage

Figure 10: Area of Total Crops, Fruit and Horticulture in Ireland 2020 (Hectares)

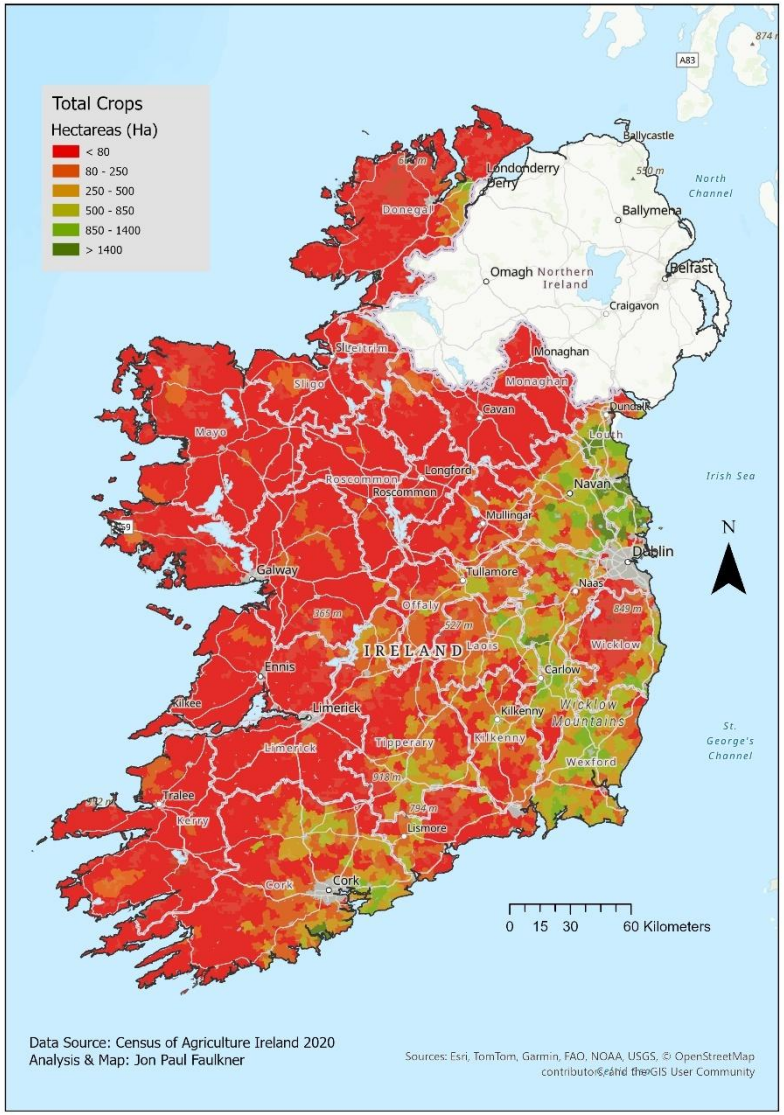


Table 3: Total Crops and Commonage in Ireland 2020

	Total Crops (Total Ha, %)		Cereals (Total Ha, %)		Commonage (Total Ha, %)	
REGION						
NW	19,213	0.7	8,549	0.3	270,479	10.5
Southern	177,267	5.9	135,296	4.5	115,803	3.9
EM	161,320	11.1	121,641	8.4	35,007	2.4
COUNTY						
Donegal	6,931	1.4	4,372	0.9	72,659	14.9
Sligo	560	0.3	95	0.1	12,673	6.9
Leitrim	369	0.2	0	0.0	13373	8.4
Cavan	663	0.3	0	0.0	4,287	2.2
Monaghan	873	0.7	295	0.2	0	0.0
Galway	6,276	1.0	2,912	0.5	62,761	10.2
Mayo	1,587	0.3	306	0.1	103,446	18.5
Roscommon	1,954	0.8	569	0.2	1,280	0.5
Clare	918	0.3	164	0.0	3,983	1.2
Tipperary	24,660	5.7	19,632	4.6	12,242	2.8
Limerick	1,528	0.6	844	0.3	2,181	0.8
Waterford	9,262	5.0	6,463	3.5	9,215	5.0
Kilkenny	17,773	8.6	13,223	6.4	491	0.2
Carlow	19,023	21.2	14,889	16.6	2,331	2.6
Wexford	54,668	23.1	42,660	18.0	2,527	1.1
Cork	46,671	6.2	35,423	4.7	21,099	2.8
Kerry	2,764	0.6	1,998	0.4	61,734	12.8
Dublin	15,876	17.1	11,021	11.9	2,290	2.5
Wicklow	13,962	6.9	10,727	5.3	26,860	13.3
Kildare	33,536	19.8	27,667	16.3	1,281	0.8
Meath	39,900	17.0	28,255	12.1	59	0.0
Louth	20,161	24.4	15,766	19.1	2,664	3.2
Longford	1,100	1.0	294	0.3	200	0.2
Westmeath	7,174	3.9	4,539	2.5	4	0.0
Offaly	11,456	5.7	8,692	4.3	209	0.1
Laois	18,155	10.6	14,680	8.5	1,440	0.8

According to Census of Agriculture 2020, approximately 5.1% (357,800 ha) of Ireland's landmass is accounted for by crops (including cereals), fruit and horticulture. The largest amount of cropland is found in the EM region (11.1% of landmass, 161,320 ha), while the lowest is found in the NW region (0.7%, 19,213 ha) (see Figure 10 and Table 3). At county level, some of the largest extents of cropland is found in Louth (24.4%, 20,161 ha), Wexford (23.1%, 54,668 ha) and Carlow (21.2%, 19,023 ha), while some of the lowest extents are found in Leitrim (0.2%, 369 ha), Sligo (0.3%, 560 ha) and Cavan (0.3%, 663 ha (see Table 3 and Figure 11). In respect to land reserved as commonage, some of the largest extents were found in Mayo (18.5%, 103,446), Donegal (14.9%, 72,659 ha) and Wicklow (13.3%, 26,860 ha), with little or no commonage land found in Monaghan (0%, 0 ha), Westmeath (< 0.1%, 4 ha) and Meath (< 0.1%, 59 ha) (see Table 3 and Figure 12).

Figure 11: Crops as a percentage of Total Land Farmed 2020

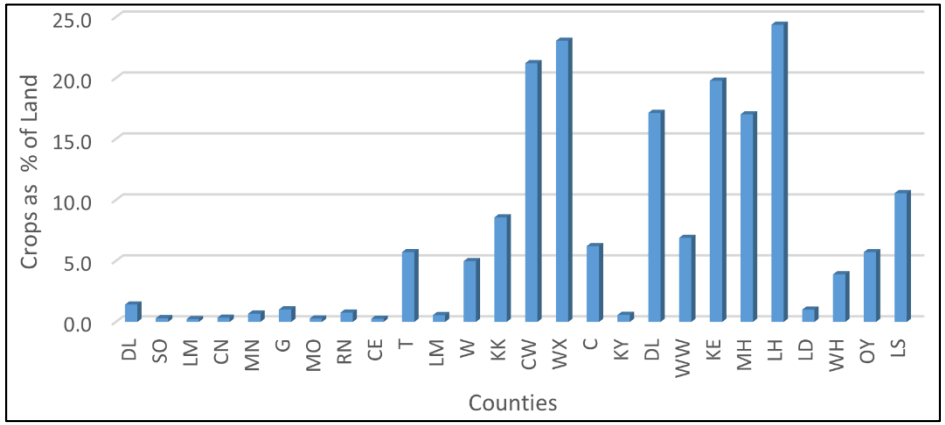
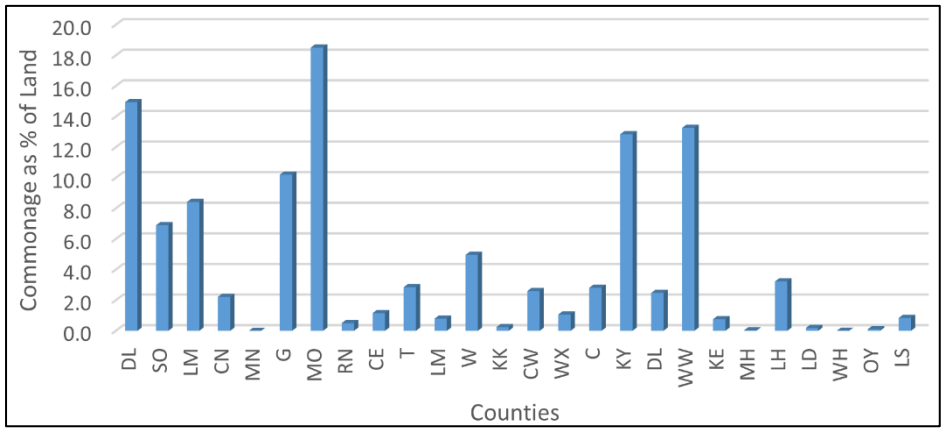


Figure 12: Commonage as a percentage of Total Land Farmed 2020



Discussion

Introduction

The results highlight the extensive role of grassland and crop systems in shaping Ireland's agricultural landscape, revealing potential contributions for bioeconomy development. Grassland, which accounts for 59% of Ireland's landmass, and cropland, which comprises 5.1%, are central to sustaining agricultural productivity and ecological health. Results point to the importance for regionally tailored bioeconomy strategies that maximise resource efficiency, enhance sustainability, and promote rural development. For biomass production, different land use types offer varying degrees of suitability based on their productivity and the type of biomass they produce. Pasture provides biomass primarily through grass, which can be used for biogas production when managed sustainably (Ding et al., 2024). However, its biomass yield per unit area might be lower compared to arable crops (Antar et al., 2021). Land use for hay production produces a considerable amount of biomass in the form of dried grasses, which can be used for animal feed or bioenergy production, though its seasonal nature might affect the consistency of supply (Stoof et al., 2015).

Grassland Utilisation and Regional Variability

Grassland systems dominate Ireland's agricultural landscape, with 33% of the landmass dedicated to pasture, 18% to grass silage, 2% to hay, and 6% to rough grazing. This distribution reflects Ireland's suitability for livestock grazing and forage production, which form the backbone of its agricultural economy. However, the variation in grassland composition across regions and counties presents opportunities for diverse bioeconomy applications. The Southern region, which has the highest proportion of pasture (35% of its landmass), is well-positioned for large-scale livestock production. Counties like Tipperary (41.3%), Limerick (42.2%), and Monaghan (44.4%) have particularly high percentages of pasture, making them ideal hubs for initiatives such as biogas production from manure, organic fertiliser manufacturing, and grazing-based dairy systems. These counties should integrate circular economy principles by repurposing agricultural by-products into renewable energy or bio-based materials. Conversely, regions with lower pasture proportions, such as the NW (30.7%) and counties like Donegal (24.2%) and Mayo (26.5%), may benefit from alternative strategies. These could include promoting agroforestry systems that combine grazing with tree planting, thereby enhancing carbon sequestration and biodiversity while maintaining livestock productivity. Additionally, these regions can focus on enhancing the productivity of rough grazing lands, which are significant in Donegal (16.8%) and Kerry (16.4%), through targeted soil and grazing management practices.

Grass Silage and Hay: Enhancing Resource Efficiency

Grass silage is highly productive in terms of biomass, providing a reliable and consistent source of fermented forage that can be used for biogas production (Dussadee et al., 2016). It is an efficient use of land for high-yield biomass generation. Grass silage, accounting for 18% of Ireland's landmass, is an essential component of livestock feed, particularly in areas like the Southern region, where 19.9% of land is dedicated to silage. Counties such as Monaghan (29.7%), Kilkenny (25.4%), and Limerick (24.9%) lead in silage production. These areas have the potential to adopt innovative technologies such as precision silage harvesting and anaerobic digestion to improve feed efficiency and reduce waste. In contrast, hay production, which accounts for only 2% of the landmass, is concentrated in counties like Kildare (3.6%), Carlow (3.4%), and Limerick (3.2%). Promoting high-quality hay production in these counties could support niche bioeconomy markets, such as organic livestock systems or export-oriented hay industries, adding value to traditional practices.

Crop Systems and Regional Disparities

In general, land utilised for crops, fruit and horticulture tends to provide a diverse range of biomass sources, including crop residues, which can be used for bioenergy and bio-based products. However, the primary focus on high-value food production might limit their overall biomass yield. More specifically, cereals are particularly well-suited for biomass production due to their high yield of crop residues which can be used for bioenergy and other applications. This makes cereals a strong contender for efficient biomass production. Although cropland represents only 5.1% of Ireland's landmass, its distribution highlights significant regional disparities. The EM region, which accounts for 11.1% of its landmass in cropland, leads in cereal production, contributing to food security and feedstock for bio-based industries. Counties like Louth (24.4%), Wexford (23.1%), and Carlow (21.2%) have the highest cropland proportions, making them ideal for integrating crop-based bioeconomy initiatives. These could include advanced crop rotation systems, soil health improvement practices, and the use of cereals for bioethanol or other bio-based products (Pant et al., 2019). In contrast, the Northwest region has the lowest cropland proportion (0.7%). Counties like Leitrim (0.2%), Sligo (0.3%), and Cavan (0.3%) may benefit from alternative land-use strategies. These could include the cultivation of high-value, low-input specialty crops such as herbs, medicinal plants, or fibre crops, which align with the goals of a diversified bioeconomy (Singh et al., 2023).

Commonage and Rough Grazing: Opportunities for Biodiversity and Carbon Sequestration

Commonage is typically less productive in terms of biomass due to its extensive use and focus on grazing rather than crop production. The biomass from such land is usually limited to natural vegetation and grazing residues. Nevertheless, such land has potential to enhance biodiversity. Land designated as commonage plays a crucial role in supporting biodiversity and traditional farming practices. Counties like Mayo (18.5%), Donegal (14.9%), and Wicklow (13.3%) have significant commonage areas, offering opportunities for conservation-based bioeconomy initiatives. These lands could be used to promote agroecological tourism, carbon farming, or the production of specialty products like wildflower honey, which enhance biodiversity while generating economic value (Cammerino et al., 2024). Rough grazing land typically yields the least biomass due to the low-intensity management and the natural vegetation type, making it less suitable for high-volume biomass production (Johnston et al., 2015). On the other hand, such land tends to be rich in biodiversity due to its low-intensity management. Rough grazing, which accounts for 6% of the landmass, is particularly prominent in the NW region and counties like Donegal and Kerry. These areas can support extensive grazing systems that promote biodiversity and provide ecosystem services, such as water regulation and carbon storage (Teague and Kreuter, 2020). Developing payment schemes for ecosystem services in these areas should incentivise sustainable land management practices.

Challenges and Policy Implications

The regional disparities in land use and productivity present challenges that must be addressed to unlock the full potential of Ireland's bioeconomy. For high-pasture regions, challenges include nutrient runoff and greenhouse gas emissions from intensive livestock farming (Horan et al. 2019). These issues necessitate policies that promote precision agriculture, efficient nutrient management, and the adoption of low-emission technologies. In regions with low cropland proportions or extensive commonage, challenges include limited access to technology and markets for niche bio-based products (Brüntrup et al., 2016). Tailored financial support, such as microloans, grants, and subsidies, can help farmers in these areas invest in innovative practices. Capacity building through training programs on sustainable land management and bioeconomy practices is equally essential.

Conclusion

For biomass production in Ireland, cereals and grass silage stand out as the most effective land use types, offering high yields and reliable biomass sources. Other land use types have their specific advantages but generally provide lower biomass yields compared to these. Ireland's grassland and crop systems provide a strong foundation for developing a regionally tailored bioeconomy that aligns with circular economy principles. High-pasture regions offer opportunities for integrating livestock systems with renewable energy and resource recovery initiatives. Low-pasture and commonage-rich regions can focus on biodiversity-friendly practices and niche bio-based products. By addressing regional disparities and leveraging each region's strengths, Ireland can create a resilient, sustainable, and inclusive bioeconomy that contributes to economic development and environmental conservation. The results underscore the need for coordinated policies, stakeholder collaboration, and targeted investments to achieve these goals.

Livestock

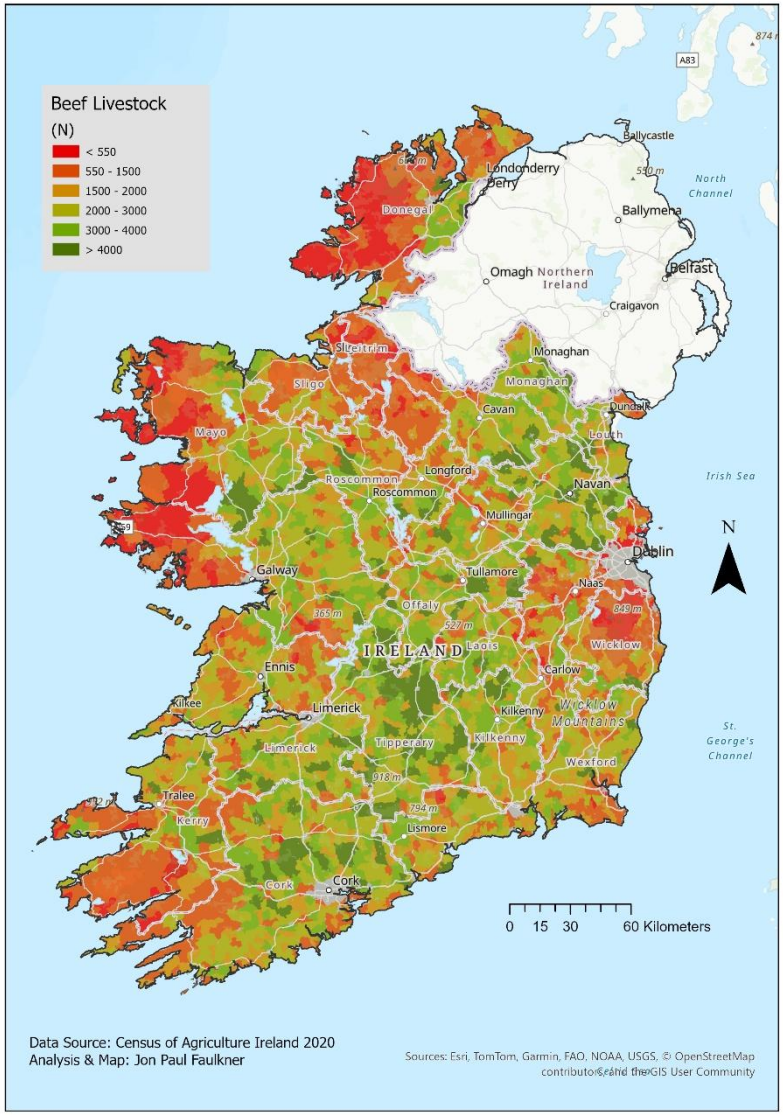
According to the Census of Agriculture Ireland 2020, there are a total of 6,209,618 livestock units (LSU)[1] in Ireland. These predominantly consist of beef livestock (n = 5,746,862), diary (n = 1,567,681), sheep (n = 4,763,582), pigs (n = 1,554,440) and poultry (n = 15,114,812). There are 86,490 farms with beef livestock in Ireland with an average stock of 66 animals per farm, 17,495 farms with dairy livestock and an average stock of 90 per farm, 35,505 farms with sheep (μ = 134 per farm), 1,196 farms with pig livestock (μ = 1,300 per farm) and 35,505 farms with poultry (μ = 426 per farm).

At the regional level, the Southern region exhibits the highest LSUs per farm (54 per farm), while the Northern and Western (NW) region exhibits the lowest LSUs per farm (20 per farm) (see Table 4). At the county level, some of the highest LSUs per farm were found in Waterford (86 per farm), Kilkenny (76 per farm) and Tipperary (68 per farm), while some of the lowest were found in Leitrim (12 per farm), Donegal (13 per farm) and Mayo (14 per farm) (see Table 4 and Figure 14). In respect to beef farms, there are a total of 86,490 farms in Ireland. The Southern region exhibited the highest number of cattle per beef farm (81 per farm), followed by the EM (70 per farm) and NW (30 per farm) regions. Waterford (136 per farm), Kilkenny (131 per farm) and Tipperary (107 per farm) exhibited the highest number of livestock per beef farm, while

[1] A livestock unit (LSU) is a standard measurement unit that allows the aggregation of numbers of livestock across different categories. Each livestock category is assigned a coefficient on the basis of the nutritional or feed requirement of each type of animal. The reference unit used for the calculation of livestock units (=1 LSU) is the grazing equivalent of one adult dairy cow as per Eurostat definition.

Leitrim (16 per farm), Mayo (23 per farm), and Sligo (24 per farm) exhibited some of the lowest (see Table 4, Figure 15).

Figure 13: Beef Livestock in Ireland 2020



In terms of dairy farms, there are a total of 17,495 farms in Ireland. The Southern region exhibited the highest number of cows per dairy farm (95 per farm), followed by the EM (90 per farm) and NW (67 per farm) region. Again, Waterford (113 per farm) exhibited the highest number of cows per dairy farm, followed by Meath (112 per farm) and Louth (110 per farm), with Clare (60 per farm), Monaghan (58 per farm), and Leitrim (50 per farm) exhibiting some of the lowest (see Table 4 and Figure 16).

Figure 14: Livestock Unit per Farm by County 2020

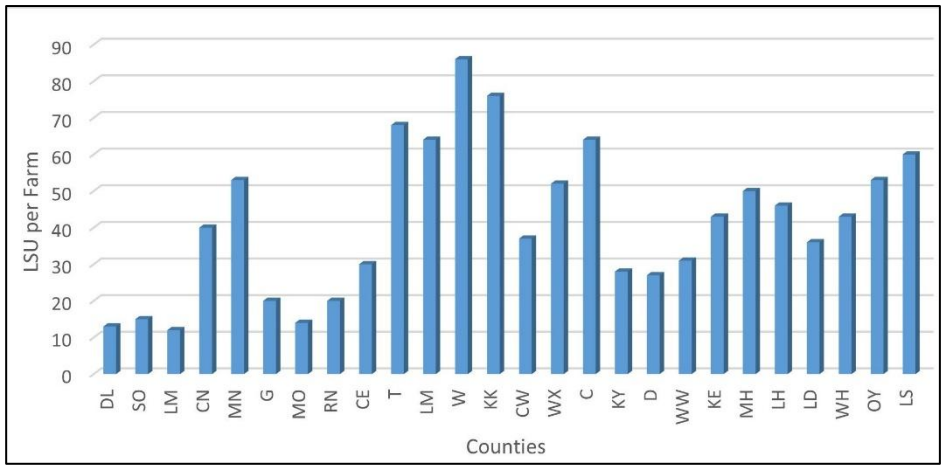


Table 4: Livestock in Ireland 2020

	Livestock Unit (Total, per Farm)		Beef Livestock (Farms, per Farm)		Dairy Livestock (Farms, per Farm)	
REGION						
NW	1706958	20	40,391	30	2,630	67
Southern	3,234,123	54	30,309	81	12,244	95
EM	136,8882	45	15,790	70	2,621	90
COUNTY						
Donegal	214,364	13	4,647	27	227	98
Sligo	97,792	15	3,078	24	137	60
Leitrim	58,742	12	2,556	16	37	50
Cavan	259,683	40	3,794	39	632	62
Monaghan	265,824	53	3,267	45	663	58
Galway	370,926	20	9,889	31	504	78
Mayo	260,314	14	8,127	23	309	62
Roscommon	174,976	20	5,033	31	121	74
Clare	211,347	30	5,183	37	583	60
Tipperary	547,402	68	4,348	107	1,832	98
Limerick	358,554	64	3,534	83	1,507	83
Waterford	238,689	86	1,194	136	793	113
Kilkenny	292,397	76	1,855	131	947	107
Carlow	95,849	37	957	77	182	99
Wexford	257,941	52	1,922	98	836	100
Cork	919,131	64	6,631	97	4,094	95
Kerry	312,813	28	4,685	43	1,470	70
Dublin	19,719	27	285	63	32	93
Wicklow	129,637	31	1,222	68	253	105
Kildare	128,766	43	1,454	72	190	108
Meath	277,924	50	2,758	80	598	112
Louth	83,150	46	892	72	173	110
Longford	112,042	36	2,082	40	159	74
Westmeath	195,080	43	2,600	62	320	99
Offaly	212,705	53	2,408	78	392	91
Laois	211,304	60	2,089	87	504	100

Figure 15: Beef Livestock per Beef Farm by County 2020

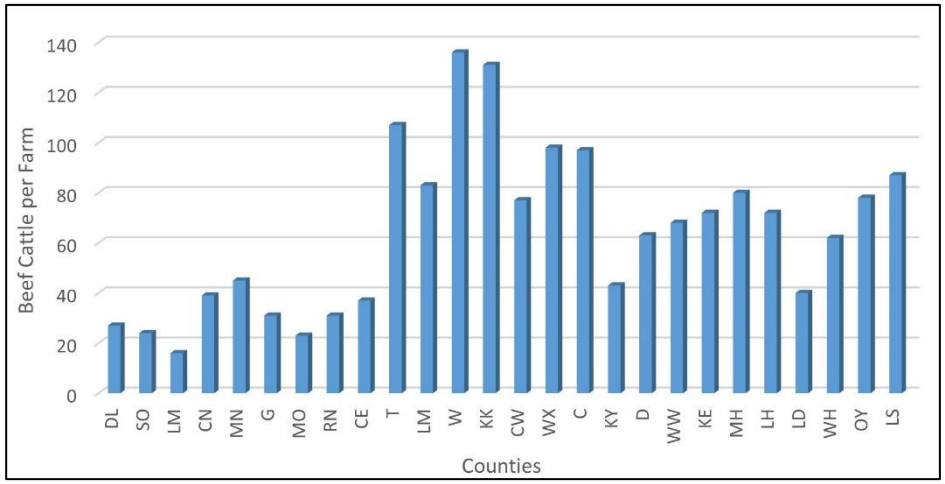


Figure 16: Dairy Livestock per Dairy Farm by County 2020

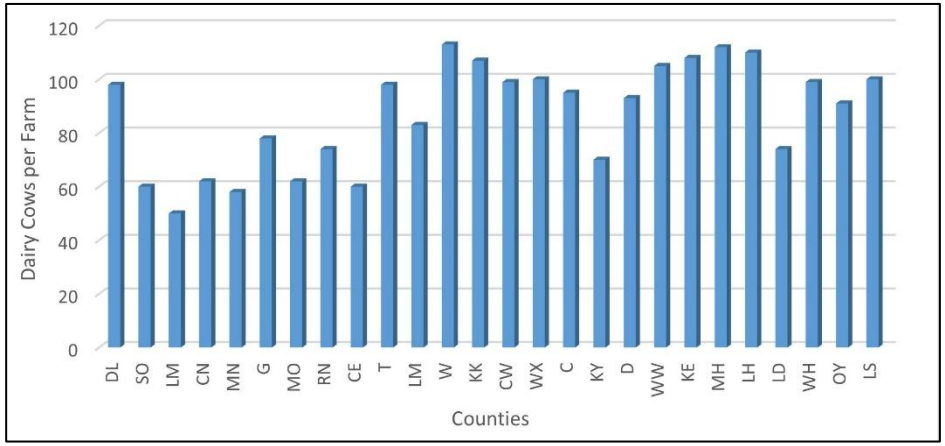
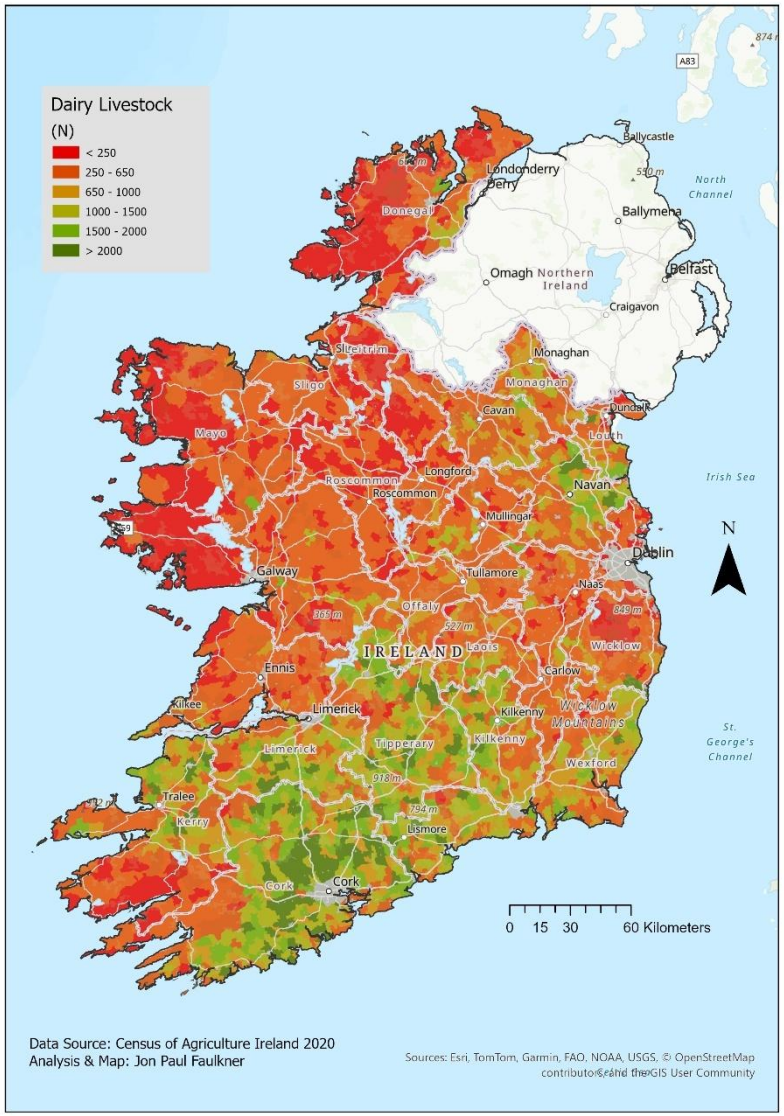


Figure 17: Diary Livestock in Ireland 2020



Ireland had 35,505 sheep farms according to Census of Agriculture Ireland 2020. The Southern region exhibited the highest number of sheep per farm (95 per farm), followed by the EM (90 per farm) and NW (67 per farm) region. Wicklow (243 per farm) had the highest number of sheep per farm, followed by Waterford (241 per farm) and Kildare (237 per farm), while Clare (69 per farm) had the lowest number of sheep per farm, followed by Cavan (118 per farm) and Clare (125 per farm) (see Table 5 and Figure 18). Ireland had 1,196 pig farms according to Census of Agriculture Ireland 2020. The NW region exhibited the highest number of pigs per farm (1,460 per farm), followed by the Southern (1,277 per farm) and EM regions (1,220 per farm). Waterford had the highest number of pigs per farm (3,168 per farm), followed by Cavan (3,073 per farm) and Longford (3,031 per farm). The counties Louth, Dublin, Mayo, Galway, Leitrim, and Sligo were reported to have no pig farms according to Census of Agriculture Ireland 2020 (See Table 5 and Figure 19). There are a total of 4,448 poultry farms in Ireland according to Census of Agriculture Ireland 2020. The NW region (7,436 per farm) exhibited the highest number of poultry farms, followed by the Southern (1,524 per farm) and EM (758 per farm) region. Monaghan (28,602 per farm) exhibited the highest number of poultry per farm, followed by Cavan (7,736 per farm) and Louth (5,467 per farm). Counties Kerry, Cork, Roscommon and Galway were reported to have no poultry farms (see Table 5 and Figure 20).

Table 5: Livestock in Ireland 2020

	Sheep Livestock (Farms, per Farm)		Pig Livestock (Farms, per Farm)		Poultry Livestock (Farms, per Farm)	
REGION						
NW	21041	67	268	1460	1586	7436
Southern	6058	95	551	1277	1504	1524
EM	8406	90	377	1220	1358	758
Donegal	6017	125	88	593	273	126
Sligo	1616	128	0	0	201	84
Leitrim	1105	140	0	0	89	37
Cavan	963	118	97	3073	184	7736
Monaghan	536	137	40	699	355	28602
Galway	4081	148	0	0	0	0
Mayo	4906	129	0	0	484	334
Roscommon	1817	152	43	301	0	0
Clare	605	69	40	216	250	19
Tipperary	868	184	83	1309	297	106
Limerick	247	138	44	828	306	5069
Waterford	383	241	33	3168	137	4824
Kilkenny	507	193	48	1115	191	154
Carlow	709	216	31	765	104	41
Wexford	1048	188	79	1042	219	46
Cork	1691	141	193	1480	0	0
Kerry	2497	192	73	480	0	0
Dublin	202	174	0	0	75	50
Wicklow	1330	243	44	363	173	214
Kildare	674	237	34	844	196	240
Meath	1093	226	61	939	224	1667
Louth	363	211	0	0	59	5467
Longford	436	133	28	3031	82	332
Westmeath	795	185	44	1426	171	418
Offaly	573	181	37	2970	160	344
Laois	443	148	56	1170	218	422

Figure 18: Sheep per Sheep Farm by County 2020

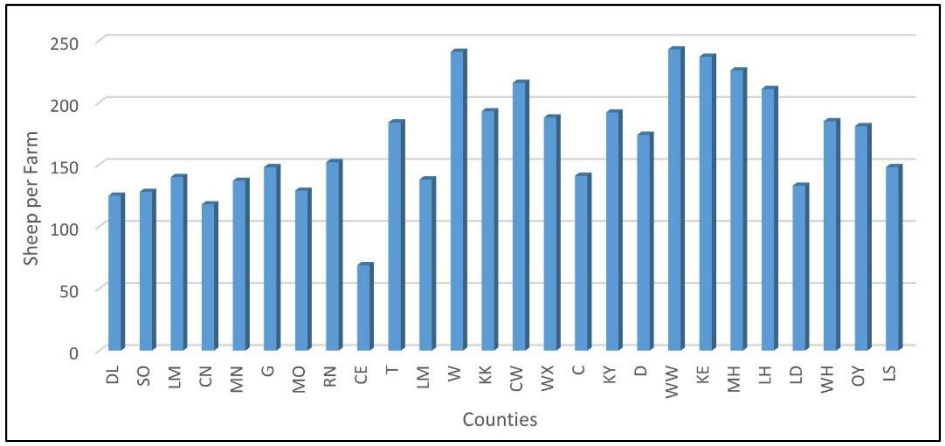


Figure 19: Pigs per Pig Farm by County 2020

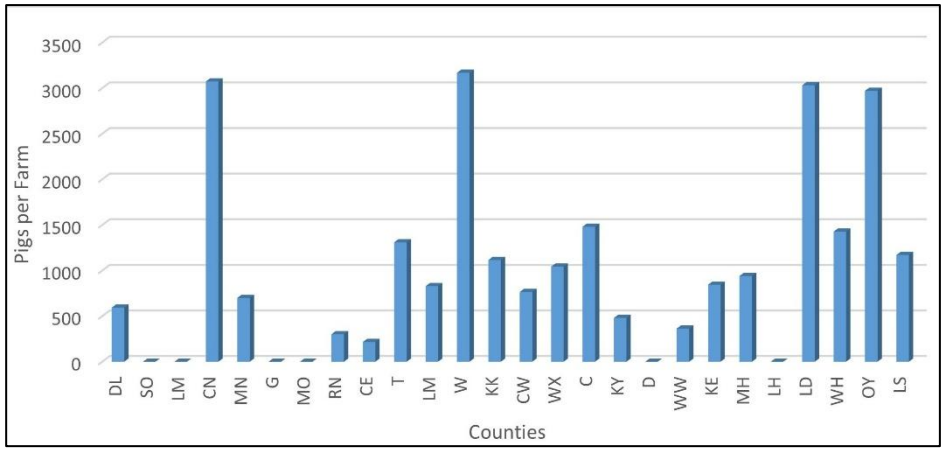
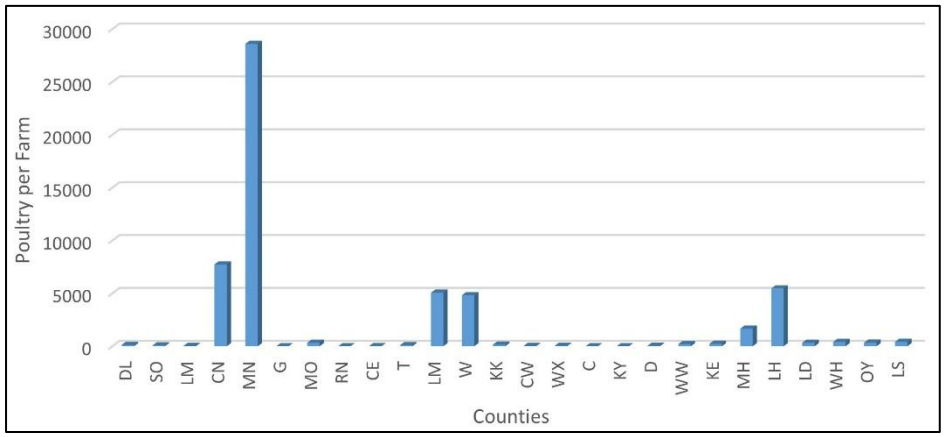


Figure 20: Poultry per Poultry Farm by County 2020



Discussion

Introduction

The spatial analysis revealed significant regional and sectoral variations in livestock density and distribution across Ireland, important in the development of regional strategies. These variations underscore the need for tailored approaches to maximise the potential of natural capital while ensuring sustainable agricultural practices and resource efficiency.

Regional Variability in Livestock Density and Implications

The Southern region exhibited the highest livestock density, with a particular emphasis on beef and dairy farming. Counties such as Waterford, Kilkenny, and Tipperary stand out for their high livestock units (LSU) per farm, with Waterford averaging 86 LSUs per farm. This level of concentration suggests that these counties could serve as focal points for bioeconomy development initiatives aimed at animal husbandry. For instance, these regions could prioritise the implementation of circular economy practices, such as advanced manure management systems, which convert livestock waste into renewable energy through anaerobic digestion (Awasthi et al., 2022). Such technologies would not only address waste management challenges but also provide alternative energy sources, contributing to local energy self-sufficiency.

In contrast, regions like the Northern and Western (NW) region have the lowest livestock densities, with an average of 20 LSUs per farm. Counties such as Leitrim, Donegal, and Mayo, with their smaller-scale farms and lower livestock numbers, face different challenges and opportunities. In these areas, bioeconomy strategies may need to focus on sustainable intensification (Stark et al., 2022). Efforts could include integrating agroforestry practices, which combine tree planting with grazing, or promoting the use of biodiverse grasslands to improve ecological resilience and enhance ecosystem services (Lewandowski et al., 2024). These approaches would ensure that the natural capital in these less intensive regions is leveraged sustainably while fostering agricultural productivity.

Opportunities for Circular Economy Integration

The data reveal considerable potential for integrating the principles of the circular economy, particularly the cascade principle, which emphasises maximizing resource efficiency through reuse and recycling. Livestock-rich regions such as the Southern region offer an opportunity to develop resource recovery systems tailored to specific agricultural activities (Duque-Acevedo et al., 2020). For example, manure and slurry generated by high-density beef and dairy farms can be processed into bio-based fertilisers or biogas (Stacey et al., 2021). This would simultaneously address the dual challenges of nutrient waste and greenhouse gas emissions, creating a more sustainable agricultural cycle.

Similarly, the concentration of dairy farms in counties like Waterford and Meath highlights opportunities for valorising by-products from milk

production. Whey, a by-product of dairy processing, can be repurposed for high-value uses such as nutritional supplements or as feedstock for bio-based plastic production (Soumati et al., 2023). In sheep farming regions like Wicklow, with an average of 243 sheep per farm, wool by-products could be harnessed for textile industries or as insulation materials, aligning with both bioeconomy and sustainability goals (Dalbanjan et al., 2024). For poultry-rich areas like Monaghan, the high concentration of poultry per farm (28,602 on average) suggests opportunities to explore the use of feathers and other by-products in biomaterials or industrial applications (Tarafdar et al., 2021).

Environmental Sustainability Challenges and Strategies

The high concentration of livestock in specific regions presents environmental sustainability challenges, particularly regarding water quality, soil health, and air pollution. Nutrient runoff from farms with high livestock densities, such as those in Waterford and Kilkenny, can lead to eutrophication of nearby water bodies, while ammonia emissions from livestock farming contribute to air quality degradation (de Vries et al., 2023). To mitigate these impacts, bioeconomy strategies should integrate robust environmental safeguards. These could include precision farming techniques that optimise nutrient application, thereby reducing runoff, or the establishment of riparian buffer zones to protect waterways (Juncal et al., 2023). In low-density regions like Leitrim, there is an opportunity to maintain and enhance biodiversity through the preservation of extensive grasslands, which provide critical habitats for native species (Petermann and Buzhdygan, 2021).

Alignment with Policy Frameworks

The spatial analysis highlights the importance of aligning regional bioeconomy strategies with broader policy initiatives such as the European Green Deal, the "Farm to Fork" strategy, and the United Nations Sustainable Development Goals (SDGs). For high-density regions, policies should incentivise the adoption of renewable energy technologies, such as biogas plants, by providing subsidies or tax benefits. In low-density regions, policies should focus on supporting smallholder farmers through financial assistance and capacity-building programs to adopt sustainable agricultural practices. For instance, counties with smaller farms, such as Leitrim and Donegal, may require targeted support to implement resource-efficient technologies and diversify their agricultural practices.

Cross-Sectoral Synergies and Economic Potential

The development of the bioeconomy in Ireland presents significant opportunities for fostering cross-sectoral synergies. Livestock farming can be integrated with renewable energy sectors, utilising agricultural residues such as manure and crop by-products for energy production. Additionally, partnerships between agriculture and industrial sectors could create new value chains. For example, poultry and pig farms could collaborate with composting industries to produce organic fertilisers, while dairy farms could provide feedstock for emerging bio-material industries. These synergies not only enhance resource efficiency but also contribute to rural economic development by creating new employment opportunities and markets.

Conclusion

The livestock distribution data underscore the need for regionally specific approaches to bioeconomy development in Ireland. High-density regions, particularly in the Southern area, have the potential to act as innovation hubs for circular economy practices, leveraging their concentrated livestock resources to develop advanced waste management and bioenergy solutions. In contrast, low-density regions like the NW region offer opportunities for sustainable intensification and the preservation of natural capital. By

addressing environmental sustainability challenges, aligning with policy frameworks, and fostering cross-sectoral synergies, Ireland can unlock the full potential of its agricultural sector within the bioeconomy framework. The insights derived from this analysis serve as a critical foundation for designing strategies that balance economic growth with environmental stewardship, ensuring a sustainable future for rural communities.

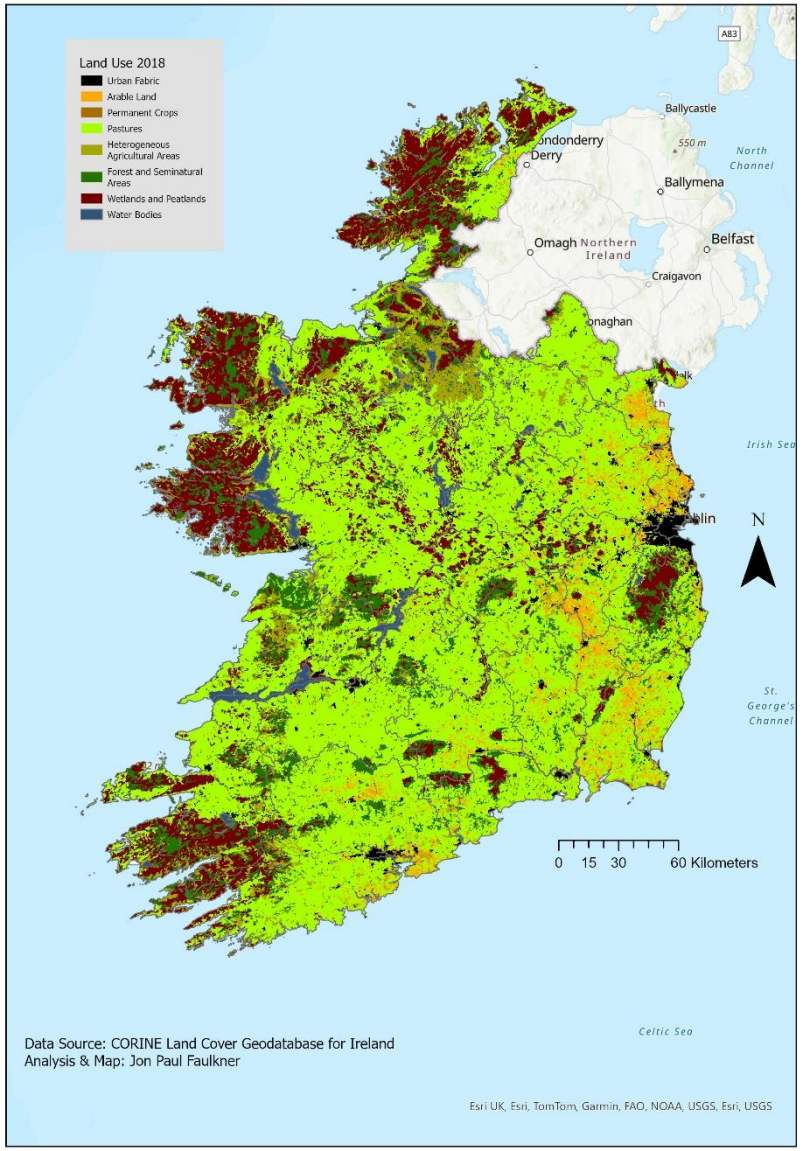
Spatial Analysis using the CORINE Land Cover Geodatabase 2018

Ireland's Land Cover

Figure 21 shows an amended[2] CORINE land cover typology of Ireland for the latest year of iteration, 2018. As indicative from the Census of Agriculture analysis, pastures dominate Ireland's landscape, accounting for 55% (3,892,082 Ha) of total land cover. The typology is particularly prevalent in central and eastern parts of the country, where lowlands that provide favourable conditions for livestock grazing. Pastureland is also evident along coastal regions, though less extensively in the west, where the terrain becomes more rugged. Wetlands and peatlands account for 16% (1,133,736 Ha) of Ireland's land mass, and are prominent in central and western areas, such as County Offaly, Galway, and Mayo. These areas represent the countries natural bogland where poorly drained soils predominant and where agricultural use is limited. Forests and semi-natural areas represent 12% (812,611 Ha) of Irelands total land mass and are mainly concentrated in the west and northwest of Ireland. Counties like Wicklow, Kerry, Mayo, and Donegal represent the majority of this land cover, reflecting rugged terrain and less favourable conditions for agriculture. Smaller patches of forested land are scattered across the country, often reflecting reforestation efforts or managed woodland. Heterogeneous agricultural land, which represents complex cultivation patterns, agriculture with significant natural vegetation, and agroforestry areas (see Appendix Table 1) represents 8% (544,360 Ha) of Ireland's landmass and is scattered across the country representing less dominant variegated agricultural practice. Arable land represents 5% (320,142 Ha) of Ireland's land mass, and is more prominent in the east and southeast, including regions around Dublin, Kilkenny, and Wexford, characterised by fertile soils and flatter terrain, making them ideal for crop cultivation. Finally, urban fabric (2%, 168,026 Ha), water bodies (2%, 154,902 Ha), and permanent crops, which include vineyards, fruit trees, and

[2] See Appendix Table 1.

Figure 21: CORINE Land Cover Typology for Ireland 2018



olive groves (0%, 295 Ha) represent the remainder of Ireland's land cover according to CORINE 2018. Since the main agricultural typologies relating to pasture and arable land have been previously investigated in the Census of Agriculture analysis, the present focus in concerned with the regional distribution of Ireland's wetlands and peatlands, forest and seminatural areas, and heterogeneous agricultural areas (the permanent crop typology is more relevant to the continental European context).

The distribution of wetlands and peatlands, forestry and semi-natural areas and heterogenous agriculture is illustrated in Figures 22-24 and described in Table 6. The spatial analysis of wetlands and peatlands (Figure 22 and Table 6) is highly concentrated in the NW region, which accounts for the highest percentage of wetlands at 27% (705,833 hectares). Counties such as Donegal, Mayo, and Galway dominate this land type, occupying between 33% and 43% of their total area. In contrast, the EM region has comparatively smaller wetland areas, making up only 10% and 8% land cover, respectively. Counties such as Kilkenny, Wexford, and Monaghan have minimal wetland coverage, contributing less than 5% land mass. Forestry and semi-natural areas exhibit a more even distribution compared to wetlands but are still most prominent in the Southern region which has 364,055 hectares (12%) (See Figure 23 and Table 6). Counties such as Wicklow, Kerry, and Clare feature a relatively high percentage of forestry, with Wicklow standing out with 21% forest cover. In contrast, counties like Louth, Monaghan, and Meath have limited forestry coverage, comprising less than 5% of their land area. The spatial analysis indicates that forestry areas are typically concentrated in upland and less densely populated regions.

Heterogeneous agricultural areas are less dominant in overall land use compared to wetlands and forestry. These areas are concentrated primarily in regions with more intensive farming activities, with the Northwest contributing 11% (296,678 hectares) and the Southern region accounting for 6% (187,624 hectares). Counties such as Leitrim display the highest percentage of heterogeneous agriculture at 62%, emphasising mixed land-use practices.

Figure 22: Wetlands and Peatlands in Ireland 2018

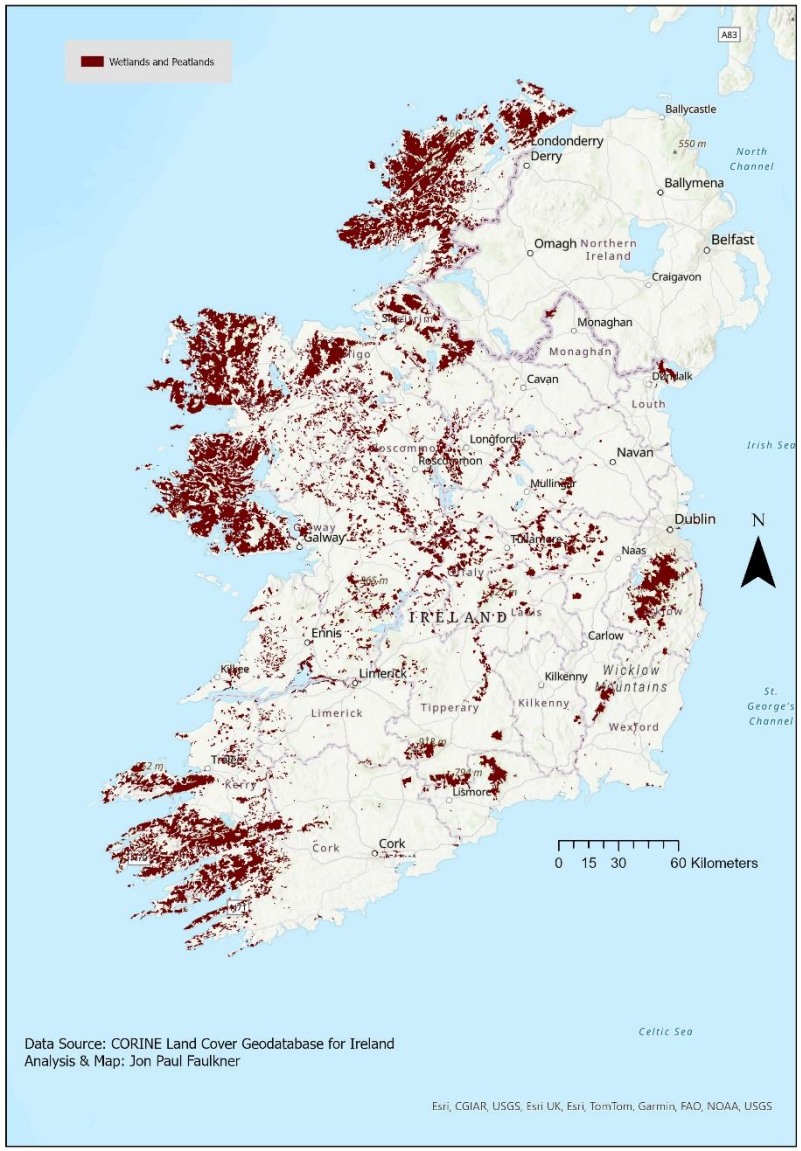
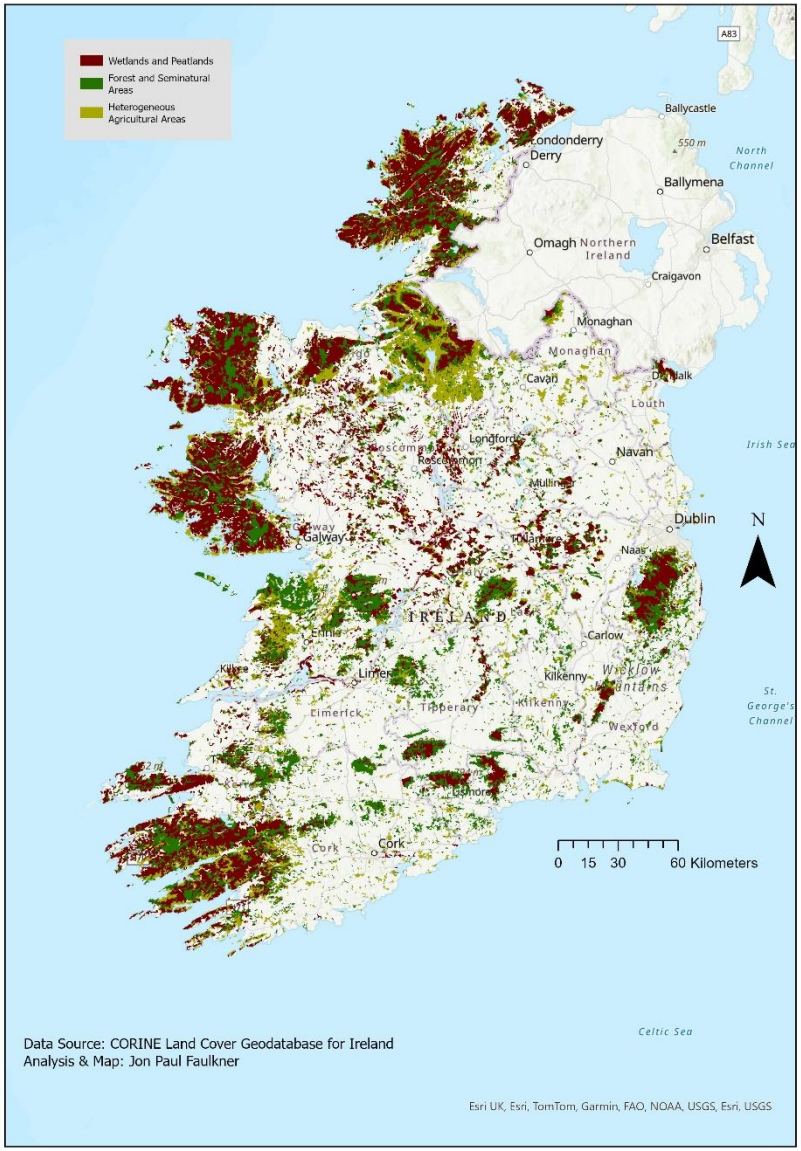


Figure 23: Forestry and Seminatural Areas in Ireland 2018

Table 6: Wetlands, Forestry and Heterogeneous Agriculture in Ireland 2018

	Wetlands (Total Ha, %)		Forestry (Total Ha, %)		Heterogeneous Ag. (Total Ha, %)	
REGION						
NW	705833	27	318953	12	296678	11
Southern	305278	10	364055	12	187624	6
EM	122625	8	129603	9	60058	4
COUNTY						
Donegal	211024	43	74205	15	47604	10
Sligo	13497	7	18618	10	8221	4
Leitrim	42092	26	31514	20	98132	62
Cavan	2594	1	13839	7	17135	9
Monaghan	1552	1	4260	3	10025	8
Galway	203635	33	92654	15	51520	8
Mayo	202620	36	63670	11	53273	10
Roscommon	28819	11	20193	8	10768	4
Clare	27012	8	60676	18	38328	11
Tipperary	25449	6	45587	11	8733	2
Limerick	14751	5	37835	14	17965	7
Waterford	11597	6	26583	14	7237	4
Kilkenny	1180	1	16349	8	7212	3
Carlow	5796	6	7459	8	6021	7
Wexford	2282	1	13064	6	6936	3
Cork	81206	11	83041	11	61556	8
Kerry	136005	28	73461	15	33636	7
Dublin	13800	15	4216	5	6099	7
Wicklow	27688	14	43071	21	11305	6
Kildare	13138	8	11029	7	5786	3
Meath	4319	2	5204	2	5595	2
Louth	4142	5	2550	3	4281	5
Longford	12930	12	8500	8	2611	2
Westmeath	6861	4	11105	6	5528	3
Offaly	29811	15	19412	10	8378	4
Laois	9936	6	24516	14	10475	6

Figure 24: Wetlands, Forestry and Heterogeneous Agriculture 2018



Discussion

Introduction

The analysis of the CORINE Land Cover Geodatabase 2018 provides a comprehensive overview of Ireland's land cover, focusing on the spatial distribution of wetlands and peatlands, forestry and seminatural areas, and heterogeneous agricultural areas. The analysis provides a detailed regional breakdown of land use patterns, highlighting disparities and opportunities across different areas. The investigation facilitates a regional approach to bioeconomy development that is grounded in spatially explicit data in order to optimise on the country's differentiated natural capital and land use profile.

Pastureland and its Implications for the Bioeconomy

As evident in the Census of Agriculture analysis, the dominance of pastureland, accounting for 55% of Ireland's total land cover, reflects the traditional emphasis on livestock grazing as the backbone of Irish agriculture. These areas are concentrated in the central and eastern lowlands, where fertile soils and favourable climatic conditions have historically supported cattle and sheep farming. While pastureland is crucial to Ireland's agricultural economy, its ecological impacts—such as methane emissions from ruminants and soil degradation from overgrazing represent significant challenges for bioeconomy integration.

To incorporate pasturelands into the bioeconomy, innovative approaches are required to enhance their sustainability. For example, regenerative grazing techniques can improve soil carbon sequestration while maintaining livestock productivity (de Otálora et al., 2021). Additionally, the integration of pasture-based systems with biogas production, using manure as a feedstock for anaerobic digestion, offers a pathway to create renewable energy while reducing agricultural waste (McCabe et al., 2020). These practices would align with the cascade principle of the circular economy by utilising livestock by-products to generate energy and fertiliser, thus closing resource loops.

Wetlands and Peatlands: Natural Capital for Carbon Storage and Ecosystem Services

Ireland's wetlands and peatlands, which account for 16% of the total land area, represent one of the country's most valuable natural assets in terms of carbon sequestration and biodiversity. These areas are predominantly located in the NW region, including counties such as Donegal, Mayo, and Galway, which have between 33% and 43% of their landmass covered by wetlands. The ecological significance of these areas is underscored by their role in storing vast amounts of carbon, maintaining water quality, and providing habitats for unique flora and fauna.

For bioeconomy development the restoration and protection of these ecosystems should be funded and prioritised to maximise their carbon storage potential and biodiversity contributions. Programs such as rewetting drained peatlands or implementing paludiculture (wetland farming) can offer sustainable ways to generate economic value while maintaining ecological integrity. For instance, paludiculture could potentially focus on cultivating wetland-compatible biomass crops, such as reeds or sphagnum moss, which can be used in bio-based industries like construction materials or horticulture (Ziegler et al., 2021). The NW region's significant wetland coverage makes it an ideal region for implementing large-scale restoration and sustainable utilisation initiatives that align with a (circular) bioeconomy economic strategy.

Forestry and Semi-Natural Areas: Opportunities for Bio-Based Industries

Forests and semi-natural areas make up 12% of Ireland's land area and are concentrated in regions with rugged terrain and lower suitability for intensive agriculture, such as Wicklow, Kerry, and Donegal. These areas provide a range of ecosystem services, including carbon sequestration, biodiversity support, and the production of timber and biomass. However, Ireland's overall forest cover remains relatively low by European standards, indicating significant potential for afforestation and reforestation initiatives.

Forestry's role in the bioeconomy lies not only in timber production but also in the development of bio-based industries such as bioenergy, biochar production, and the extraction of high-value biochemicals. For example, using forest residues for biomass energy production can contribute to Ireland's renewable energy targets while creating local employment opportunities in rural areas (Singlitico et al., 2018). Efforts to expand forest cover should prioritise native species and biodiversity-friendly practices to avoid monoculture plantations, which can have negative ecological impacts (Montagnini and del Fierro, 2024). In areas like the Southern and NW regions, where forestry is more prominent, investment in processing facilities for wood-based products and renewable energy infrastructure can enhance the contribution of forestry to bioeconomy development.

Heterogeneous Agriculture: Supporting Diversity and Resilience

Heterogeneous agricultural areas, which represent 8% of Ireland's landmass, play a critical role in integrating agriculture with natural ecosystems. These areas, characterised by complex cultivation patterns, natural vegetation, and agroforestry (see Appendix Table 1) are particularly prominent in counties such as Leitrim, where they account for 62% of the land area. The high prevalence of heterogeneous agriculture in regions like Leitrim highlights opportunities for agroforestry and diversified farming systems, which combine agricultural production with ecosystem services.

Agroforestry systems, which integrate trees with crops or livestock, can enhance soil health, increase biodiversity, and provide additional income streams for farmers (Fahad et al., 2022). These systems align well with circular economy principles, as they make efficient use of land and resources while reducing reliance on chemical inputs. In regions with significant heterogeneous agriculture, such as the Northwest, policies and subsidies should encourage farmers to adopt agroecological practices that support circular and sustainable practice. Conversely, in areas like Tipperary and Dublin, where heterogeneous agriculture is less common, targeted interventions are needed to diversify land use and promote sustainable farming.

Regional Disparities and Tailored Strategies for Bioeconomy Development

The spatial analysis reveals significant regional disparities in land-use patterns, which have important implications for bioeconomy development. The NW region, with its extensive wetlands, forestry, and heterogeneous agriculture, offers significant potential for low-intensity, biodiversity-friendly bioeconomy initiatives. This could include wetland restoration projects, agroforestry systems, and sustainable forestry practices. In contrast, the Southern region, with higher concentrations of forestry, may be better suited for bio-based industries that rely on timber and biomass production. The Eastern and Midlands region, dominated by pasture and arable land, presents both challenges and opportunities. While its reliance on intensive agriculture poses sustainability concerns, its fertile soils and established agricultural infrastructure make it an ideal region for transitioning to circular farming systems that integrate renewable energy and biobased innovations.

Alignment with Broader Sustainability Goals

In respect to the objectives of the European Green Deal, the Farm to Fork Strategy, and the United Nations Sustainable Development Goals (SDGs), protecting wetlands and peatlands supports SDG 13 (Climate Action) and SDG 15 (Life on Land) by enhancing carbon storage and biodiversity; expanding forestry and adopting biodiversity-friendly practices contribute to SDG 12 (Responsible Consumption and Production) and SDG 15; while diversifying agriculture and promoting heterogeneous systems align with SDG 2 (Zero Hunger) by fostering sustainable food systems that are resilient to climate change.

Conclusion

The integration of Ireland's land-use patterns into a bioeconomy framework requires region-specific strategies that reflect local ecological and socio-economic conditions. Wetlands and peatlands should be prioritised for conservation and carbon sequestration, while forestry areas should focus on biodiversity-friendly practices and bio-based industries. Pastureland, as the dominant land type, must adopt innovative approaches to reduce its environmental impact and integrate into (circular) bioeconomy systems. Heterogeneous agricultural areas represent an opportunity to enhance agricultural resilience and ecosystem services through agroecology and diversification. By leveraging its natural capital and aligning with circular economy principles, Ireland can develop a regional strategy for bioeconomy development that balances economic growth with environmental stewardship, thus aligning with international sustainability targets.

Insights from Ireland's National Farm Survey 2023

Introduction

The 2023 National Farm Survey (NFS) of Ireland presents a detailed picture of the challenges facing the agricultural sector, with significant economic, environmental, and social implications. The findings reveal a substantial decline in farm incomes across all systems, driven by a combination of lower output prices, reduced production volumes, and sustained high input costs. Average family farm income fell by 57% to €19,925, the lowest level in over a decade (Teagasc, 2024). Dairy farms experienced the steepest decline, with average income dropping by 69% to €49,432, primarily due to a sharp decrease in milk prices and high operational costs (Teagasc, 2024). Tillage farms were similarly affected, as cereal prices fell by 30–35%, compounded by reduced yields (Teagasc, 2024). Dry stock farms, including cattle and sheep operations, also suffered income reductions under the weight of persistently high production costs and lower market returns.

Beef Farming

Cattle rearing farms, primarily focused on suckler cow operations, experienced a significant decline in financial performance in 2023. The average Family Farm Income (FFI) for these farms fell by 15%, reaching €7,425, the lowest recorded level for this sector (Teagasc, 2024). This decrease reflects the persistent income volatility faced by farmers in the suckler beef sector. Cattle finishing farms, which focus on purchasing and fattening cattle for slaughter, also faced financial pressures. The average gross margin per hectare for these enterprises was €663, representing an 11% decline compared to the previous year. Production costs rose by 5.7% to €1,525 per hectare, driven largely by a 24% increase in concentrate feed costs (Teagasc, 2024). Despite a 4% increase in gross output value, the average net margin per hectare remained narrow at €41, emphasising the tight profit margins in this area of beef farming (Teagasc, 2024).

In terms of technical performance, cattle finishing farms showed some improvements in efficiency. The stocking rate rose by 7% to 1.44 livestock units per hectare, indicating a trend toward more intensive production. Concentrate feed usage per livestock unit increased by 12%, reflecting higher feed inputs required to sustain output levels (Teagasc, 2024). Labour efficiency also improved, with livestock units per labour unit increasing by 10% to 57, suggesting better utilization of resources (Teagasc, 2024). Economic viability remains a significant concern for beef farming. The proportion of economically viable cattle farms decreased, underscoring the sector's vulnerability to fluctuations in market prices and rising input costs. These findings emphasise the need for targeted interventions to improve both the sustainability and profitability of beef farming in Ireland.

As indicated from the spatial analysis, such findings are most important for the NW region where beef farming is most prevalent, particularly in counties Galway, Mayo and Roscommon, but also the Southern region, particularly in counties Cork, Clare and Kerry (see Table 4).

Dairy Farming

In 2023, Irish dairy farmers experienced a substantial decline in income. The average Family Farm Income (FFI) dropped by 69%, falling from €157,591 in 2022 to €49,432 (Teagasc, 2024). This decrease is primarily attributed to a sharp reduction in milk prices, which fell by 31% to 42.79 cents per litre (Teagasc, 2024). Despite stable production costs, the significant drop in milk prices led to a 45% reduction in gross margins, decreasing from 41.21 cents per litre in 2022 to 22.60 cents per litre in 2023 (Teagasc, 2024).

The technical efficiency of dairy farms also declined in 2023. Milk production per cow decreased by 5%, from 5,740 litres in 2022 to 5,474 litres (Teagasc, 2024). Similarly, milk solids per cow reduced from 446 kg to 423 kg, and the average somatic cell count increased by 6%, indicating a deterioration in milk

quality. These declines are partly due to challenging grazing conditions and a shorter grazing season, which was reduced by 12 days compared to the previous year (Teagasc, 2024). The average herd size in 2023 was 95 cows, reflecting ongoing consolidation within the sector. Notably, 37% of dairy farms comprised over 100 cows, accounting for 63% of total milk production (Teagasc, 2024). This trend indicates a shift towards larger-scale operations in the Irish dairy industry. The economic viability of dairy farms was significantly challenged in 2023. Approximately 40% of dairy farms reported an average income of less than €30,000, highlighting the financial pressures within the sector (Teagasc, 2024). This situation underscores the need for strategic interventions to enhance the sustainability and profitability of dairy farming in Ireland.

These findings predominately effect the southern region where dairy farming is most prevalent, particularly in counties in Cork, and to a lesser extent in Tipperary, Limerick and Kerry (see Table 4).

Sheep Farming

The average Family Farm Income (FFI) for sheep farms saw a significant decrease, falling by 22% to approximately €12,625 (Teagasc, 2024). This decline was primarily due to a 5% reduction in the gross output value, attributed to lower lamb prices and a drop in production volumes. While the costs for concentrate feed increased by 4%, overall production costs remained relatively stable as declines in other areas offset this increase (Teagasc, 2024).

In terms of technical performance, key metrics also showed a downturn. The stocking rate, which measures the number of animals per hectare, declined by 4%, marking its lowest level in over a decade, though it remained close to an average of seven ewes per hectare (Teagasc, 2024). Similarly, the weaning rate—critical for productivity—decreased by 5% compared to the previous year, leading to an 8% reduction in lamb carcass output per hectare (Teagasc, 2024). Interestingly, the distribution of flock sizes indicated a shift toward smaller operations, with flocks of fewer than 100 ewes producing the majority of lambs, reflecting a departure from the dominance of larger flock sizes in the previous decade. From a social sustainability perspective, the economic pressures on sheep farming households were evident. The proportion of economically viable sheep farms dropped to 16%, a reduction of 12 percentage points compared to the previous year (Teagasc, 2024). This highlights the growing challenges farmers face in maintaining profitability and sustainability within the sector.

Such results are particularly important for the NW region where sheep farming is most prevalent, particularly in counties Donegal, Mayo and Galway (see Table 5).

Tillage Farming

According to Ireland's National Farm Survey 2023, the average Family Farm Income (FFI) for tillage farms fell sharply by 71%, dropping from €73,523 in 2022 to €21,399 in 2023 (Teagasc, 2024). This dramatic decline is attributed to a combination of lower crop prices and higher production costs. Global market conditions caused cereal prices to fall by 30% to 35%, while gross output value on tillage farms decreased by 20% (Teagasc, 2024). Concurrently, production costs increased by 8%, driven by rising land rental rates and other input expenses. The operational challenges faced by tillage farmers were exacerbated by unfavourable weather conditions. Delays in planting and reduced crop yields were common, with crops like spring barley experiencing yield declines of up to 23% (Teagasc, 2024). These factors not only reduced production volumes but also heightened costs as farmers managed adverse conditions impacting crop health and harvesting.

Economic viability in the tillage sector suffered significantly in 2023. Only about 34% of tillage farms were considered economically viable. Direct support payments, which averaged €451 per hectare, were critical to sustaining these farms, as they accounted for 154% of the income generated per hectare, underscoring the sector's reliance on subsidies for financial stability (Teagasc, 2024). Structurally, tillage farms tend to be larger in size compared to farms in

other agricultural sectors. The survey represented approximately 6,246 tillage farms with an average size of 73 hectares (Teagasc, 2024). The income per hectare was €292, comparable to cattle rearing and sheep enterprises, which reported incomes of €220 and €286 per hectare, respectively (Teagasc, 2024).

These findings are particularly relevant for the Southern region where tillage farming is most prevalent, particularly in counties Wexford, Cork, and Tipperary, but also the EM region, particularly in counties Meath, Kildare and Louth (see Table 3).

Implications for developing regional bioeconomy strategy

The sharp decline in farm incomes across all systems highlights the urgent need for innovation and diversification to sustain rural economies and enhance resilience in the face of global market fluctuations, environmental challenges, and high production costs. A regional approach to bioeconomy development offers the opportunity to tailor solutions to the specific strengths and needs of different areas, fostering economic stability and environmental sustainability.

Beef and dairy farming present significant opportunities for bioeconomy initiatives. Regions such as Galway, Mayo, Roscommon, Cork, Clare, and Kerry, where beef farming is prevalent, face financial challenges that could be alleviated by integrating bioeconomy solutions. The use of manure and animal by-products for biogas production can provide an income source while reducing greenhouse gas emissions and energy costs (Yazan et al., 2018). Cooperative models could enable smaller farms to share resources and benefit from shared infrastructure, such as bio-refineries for processing waste into fertilisers, bioplastics, or bioenergy (Bento et al., 2024).

In counties like Cork, Tipperary, Limerick, and Kerry, where dairy farming is concentrated, declining incomes and technical inefficiencies suggest the need for investments in bioeconomy technologies. Dairy by-products such as whey could be utilised in high-value food, pharmaceutical, or bio-based industries, diversifying income streams (Mukherjee et al., 2023). Precision farming and waste-to-energy systems could improve milk quality and production efficiency while addressing sustainability challenges (Taner, 2024). The shift toward larger herds in these regions supports the scalability of bioeconomy initiatives, making them more feasible and impactful.

Sheep farming, concentrated in Donegal, Mayo, and Galway, faces pressures from low lamb prices and declining productivity. Regional bioeconomy strategies could focus on utilising wool and other non-meat products for sustainable textiles or bio-composite materials (Udrea et al., 2021). This diversification would provide additional revenue streams for smaller-scale farmers, helping them maintain viability. Establishing value-added processing facilities in these regions would further strengthen rural economies while reducing waste and promoting innovation.

Tillage farming, which has been significantly impacted by falling cereal prices and yield reductions, offers strong potential for bioeconomy applications. Regions such as Wexford, Cork, Tipperary, Meath, Kildare, and Louth could focus on converting crop residues into bioenergy, bioethanol, or bioplastics. Enhancing soil health through bio-fertilisers and carbon sequestration initiatives could improve long-term sustainability while generating new revenue streams (Kumawat et al., 2021). The relatively larger size of tillage farms provides a strong foundation for implementing regional-scale projects and technologies.

Across all regions, declining technical efficiencies and economic viability emphasise the need for innovative approaches. Investments in advanced technologies, such as precision farming and circular agricultural models, can optimise resource use, reduce waste, and improve productivity. Encouraging the use of locally grown high-protein crops as feed alternatives could reduce reliance on imports, addressing both economic and environmental concerns (Rauw et al., 2023). Agroforestry and integrated crop-livestock systems could enhance biodiversity, sequester carbon, and diversify income streams while fostering resilience against climate variability (Chappa et al., 2024).

The reliance on subsidies and the limited economic viability of many farms underscores the importance of policy and financial support for a bioeconomy transition. Regional strategies should prioritise creating local markets for bio-based products, investing in renewable energy infrastructure, and developing cooperatives and knowledge-sharing platforms to enable farmers to adopt bioeconomy innovations. By aligning with the distinct agricultural profiles of each region, Ireland can build a resilient and sustainable bioeconomy that addresses current challenges while ensuring the long-term prosperity of rural economies.

Natural Capital Profile: Air quality, geology, soil and biodiversity

Air quality

Ireland's air quality is generally considered good by European standards, but there are notable regional and localised issues, especially in urban areas and during colder months due to solid fuel burning and traffic emissions (EPA, 2023; O'Dwyer et al., 2023). The Air Quality Index for Health (AQIH) and particulate matter (PM2.5) levels are the main indicators used to assess air quality across Ireland's regions (see Table 7) (EPA, 2024a; O'Dwyer et al., 2023; EPA, 2021). The NW region, encompassing counties such as Donegal, Mayo, and Sligo, typically experiences the cleanest air in Ireland. PM2.5 levels are lowest here, with Mayo recording averages as low as 5.8 µg/m³, well below both EU and WHO thresholds (see Table 7). However, local hotspots do occur, particularly in towns where solid fuel use is common (Goodman, 2023; O'Dwyer, 2023). The Southern region, including Cork, Kerry, and Waterford, generally maintains good air quality, but certain urban centres like Limerick and Waterford cities experience higher PM2.5 concentrations. Limerick City, for example, recorded one of the highest annual averages at 11.1 µg/m³ (see Table 7). Rural areas in this region fare better, but wintertime solid fuel use does cause short-term spikes (*ibid*). The EM region, which includes Dublin and surrounding counties, faces the greatest air quality challenges. Dublin, as the capital and largest urban area, regularly records PM2.5 levels around 10.6 µg/m³, with winter peaks due to traffic and home heating (see Table 7). While still within EU legal limits, these values exceed the latest WHO guidelines (WHO, 2021). Other counties in this region show moderate levels, with urbanisation and transport being the main contributors to pollution (EPA, 2024a; Goodman, 2023; O'Dwyer, 2023). In summation, while Ireland's air quality is generally good, the EM region, especially Dublin, faces the most significant challenges due to urbanisation and traffic, whereas the NW region enjoys the cleanest air, with the Southern region falling in between (see Table 7). he primary pollutant of concern is fine

Table 7: Air Quality by Region and County (Representative 2019–2022 Data)

	Avg. PM2.5 (Mg/m³)	Typical AQIH Range
REGION		
NW	5-8 – 8.0	1-3 (Good)
Southern	8.5 – 11.1	2-4 (Good-Fair)
EM	10.0 – 12.0	3-5 (Fair-Moderate)
COUNTY		
Donegal	6.0	1-2
Sligo	6.5	1-2
Leitrim	6.2	1-2
Cavan	7	2
Monaghan	7.2	2
Galway	6.8	2
Mayo	5.8	1
Roscommon	7.5	2
Clare	8.5	2-3
Tipperary	9	3
Limerick	11.1	4
Waterford	10	3-4
Kilkenny	9.2	3
Carlow	9.5	3
Wexford	9	3
Cork	10.5	3-4
Kerry	8.8	2-3
Dublin	10.6	4-5
Wicklow	9.8	3-4
Kildare	10	3-4
Meath	10.2	3-4
Louth	10.5	3-4
Longford	9.5	3
Westmeath	9.8	3
Offaly	10	3-4
Laois	9.7	3

** PM2.5 values are annual averages; AQIH is on a scale from 1 (best) to 10 (worst).*

particulate matter, especially from solid fuel burning and traffic. Levels are highest in cities during winter and lowest in rural western counties during summer (EPA, 2024a; EPA, 2023; Goodman, 2025). In respect to nitrogen dioxide (NO_2), concentrations are highest in urban areas, particularly Dublin, due to road traffic (EPA, 2023; O'Dwyer, 2023), while pollutants such as ozone (O_3) and sulphur dioxide (SO_2) remain below EU limits but can occasionally approach WHO guideline values (WHO, 2021), especially in urban and industrial areas (EPA, 2023; O'Dwyer, 2023).

Geology

Ireland's geology is the result of over 1.7 billion years of geological evolution, with a landscape shaped by ancient mountain-building, sedimentation, volcanic activity, and glaciation (see Table 8). The country's rocks cover nearly every geological period, leading to distinct regional and county-level patterns in bedrock, landforms, and mineral resources (GSI, 2025a; Holland, 1981). The NW region is dominated by ancient metamorphic and igneous rocks (GSI, 2025a; Holland, 1981). The region exhibits some of Ireland's oldest rock formations, including Precambrian metamorphic schists, gneisses, and granites, especially in Donegal and Mayo (see Table 8). These rocks are remnants of early tectonic events and are often overlain by glacial deposits, resulting in rugged mountains and thin, acidic soils (GSI, 2025). The Southern region is characterised by folded Devonian sandstones and Carboniferous limestone, producing dramatic mountain and karst landscapes (Feehan, 2013; The Geological Society, 2018). Extensive Devonian Old Red Sandstone forms the prominent east-west ridges of Cork and Kerry and Variscan orogeny has resulted in strongly folded mountain ranges (see Table 8). Carboniferous limestone is widespread in valleys, particularly in Clare and Limerick, where classic karst landscapes like the Burren are found (Feehan, 2013; The Geological Society, 2018). The EM region is largely underlain by Carboniferous limestone, creating broad central lowlands covered by glacial deposits, bogs, and lakes (see Table 8). Granite uplands are found in Wicklow and Dublin, while fertile soils and extensive peatlands dominate the lowland areas (GSI, 2025a;

Table 8: Geology by Region and County

	Dominant Bedrock Type	Main Geological Features	Notable Landforms
REGION			
NW	Metamorphic, granite	Precambrian, Paleozoic	Derryveagh, Glenveagh
Southern	Sandstone, limestone, slate	Variscan orogeny, karst	Burren, Cliffs of Moher,
EM	Limestone, granite, shale	Limestone, granite, bogs	Eskers, drumlins
COUNTY			
Donegal	Metamorphic, granite	Schist, quartzite, granite	Mountains, rugged coast
Sligo	Carboniferous, limestone	Limestone & quartzite	Caves, karst, drumlins
Leitrim	Quartzite, shale, limestone	Folded rock, glacial valley	Upland bog, lakes
Cavan	Limestone, shale	Limestone, glacial	Eskers, drumlins
Monaghan	Limestone, shale	Rolling lowland, glacial	Bogs, lakes
Galway	Granite, limestone	Granite, limestone	Connemara, Burren
Mayo	Metamorphic, quartzite	Glacial mountains	Croagh Patrick, Clew Bay
Roscommon	Limestone	Glacial features	Bogs, lakes
Clare	Carboniferous limestone	Karst, limestone	Burren, Cliffs of Moher
Tipperary	Sandstone, limestone	Folded strata	Galtee Mountains
Limerick	Limestone, shale	Limestone, river valleys	Shannon Estuary, caves
Waterford	Sandstone, limestone	Folded mountains,	Comeragh Mountains,
Kilkenny	Limestone	Glacial features	River Nore valley
Carlow	Granite, limestone	Granite, limestone	Blackstairs Mountains
Wexford	Granite, shale, limestone	Granite	Hook Peninsula
Cork	Sandstone, limestone	Folded ridges, limestone	Mountains, valleys, coast
Kerry	Sandstone, slate	Mountains, folded rocks	MacGillycuddy's Reeks
Dublin	Granite, limestone, shale	Granite, limestone	Dublin Bay
Wicklow	Granite, quartzite	Granite, glacial valleys	Glendalough, bogs
Kildare	Limestone	Glacial deposits	Bog of Allen
Meath	Limestone	Glacial features	River Boyne valley
Louth	Limestone, shale	Coastal lowlands	Cooley Mountains
Longford	Limestone, Shale	Limestone, glacial	Bogs, lakes
Westmeath	Limestone	Drumlins	Lough Ennell, peatlands
Offaly	Limestone	Bogs, glacial features	Bog of Allen
Laois	Limestone, Sandstone	Lowlands, upland ridges	Slieve Bloom Mountains

** Bedrock types and features are simplified for clarity.*

2025b). Ireland's geology is the result of ancient continental collisions, tropical seas, volcanic activity, and glaciation (see Table 8). Each region and county displays distinct geological characteristics, which influence the landscape, soils, and natural resources, underpinning Ireland's variegated natural capital profile and ecological diversity (GSI, 2025a; Holland, 1981).

Soil

Ireland's soils are shaped by a combination of glacial history, underlying geological (parent) material, climate, and land use, resulting in a rich diversity of soil types across the country (see Table 9) (EPA, 2024b; Teagasc, 2011; Ryan, 1963). National soil surveys and geochemical atlases provide a detailed classification and mapping of these soils, which are critical for agriculture, land management, and environmental protection (EPA, 2024b; Teagasc, 2011). The NW region is dominated by soils developed on ancient metamorphic and igneous rocks, with extensive areas of peat and gley soils due to high rainfall and poor drainage (Teagasc, 2011; Ryan, 1963). Blanket peat is widespread in uplands, while drumlin areas feature heavy, poorly drained clay soils (EPA, 2024b; Teagasc, 2011), while brown earths are less common but occur in some lowland pockets (Ryan, 1963). The Southern region features a mix of fertile brown earths, especially on limestone and sandstone, and significant areas of gleys and peats in poorly drained lowlands and uplands (Teagasc 2011; Ryan, 1963). Valleys and lowlands, particularly in Cork, Limerick, and Tipperary, are characterised by deep, well-drained mineral soils, while upland areas in Kerry and Waterford have more acidic, peaty soils (EPA, 2024b; Teagasc, 2011). The EM region is characterised by extensive brown earths and grey-brown podzolic soils, especially in the central limestone lowlands (EPA, 2024b; Teagasc, 2011). The Midlands are notable for large expanses of raised bog (peat soils) and gleys in poorly drained areas (Teagasc, 2011), with well-drained mineral soils common in the east, while peat and gley soils dominate the central boglands (EPA, 2024b). Ireland's soils are a product of complex interactions between climate, glaciation, and the underlying parent material. Understanding these soils is essential for sustainable agriculture, land management, and the

Table 9: Soil Types by Region and County

	Dominant Soil Type	Main Soil Features	Notable Land Uses
REGION			
NW	Peat, gley, podzol, brown	Bog, gleys, acidic, clays	Grazing, forestry, peat
Southern	Brown, gley, peat, podzol	Mineral, peaty, acidic	Tillage, pasture, forestry
EM	Brown, gley, peat, podzol	Mineral, raised bogs	Tillage, pasture, peat
COUNTY			
Donegal	Peat, gley, podzol	Bog, gleys, acidic soils	Grazing, forestry, peat
Sligo	Gley, peat, brown earth	Clay, waterlogged soils	Pasture, limited tillage
Leitrim	Gley, peat, clay	Clay, waterlogged, acidic	Grazing, forestry
Cavan	Gley, brown earth	Heavy clay, drumlin soils	Pasture, some tillage
Monaghan	Gley, Brown Earth	Clay, poorly drained	Pasture, limited tillage
Galway	Peat, gley, brown earth	Bog, limestone soils	Grazing, peat cutting
Mayo	Peat, gley, podzol	Bog, upland peats	Grazing, peat cutting
Roscommon	Brown earth, gley, peat	Limestone soils, bogs	Pasture, peat extraction
Clare	Brown earth, gley, peat	Limestone, karst, peaty	Pasture, tillage, peat
Tipperary	Brown earth, gley	Mineral soils, some peats	Tillage, pasture
Limerick	Brown earth, gley	Mineral soils, some peats	Tillage, pasture
Waterford	Brown earth, podzol, peat	Acidic, fertile lowlands	Tillage, pasture, forestry
Kilkenny	Brown earth, gley	Mineral soils, some clays	Tillage, pasture
Carlow	Brown earth, gley	Well-drained mineral	Tillage, pasture
Wexford	Brown earth, gley	Sandy soils, some peats	Tillage, horticulture
Cork	Brown Earth, gley, Peat	Fertile valleys, peaty	Tillage, pasture, forestry
Kerry	Peat, Podzol, Brown Earth	Bog, acidic uplands	Grazing, peat cutting
Dublin	Brown Earth, gley	Mineral soils, some peats	Urban, tillage, pasture
Wicklow	Podzol, peat, brown earth	Acidic uplands, bog	Forestry, grazing
Kildare	Brown earth, gley, peat	Fertile lowlands, bogs	Tillage, pasture, peat
Meath	Brown earth, gley	Mineral soils, some clays	Tillage, pasture
Louth	Brown earth, gley	Mineral soils, some peats	Tillage, pasture
Longford	Gley, peat, brown earth	Bogs, poorly drained soils	Pasture, peat extraction
Westmeath	Brown earth, gley, peat	Fertile lowlands, bogs	Tillage, pasture, peat
Offaly	Peat, gley, brown earth	Raised bog, poor drain	Peat extraction, pasture
Laois	Brown Earth, gley, Peat	Fertile lowlands, peats	Tillage, pasture

** Soil types and features are simplified for clarity.*

conservation of Ireland's natural landscapes (Teagasc, 2011; EPA, 2024).

Biodiversity

Ireland's biodiversity is shaped by its variegated landscapes, climate, and land use, with each region and county supporting unique habitats, species, and conservation priorities (NPWS, 2023). National and county-level Biodiversity Action Plans (BAPs) provide the most comprehensive published information on the distribution and management of biodiversity across the country (NPWS, 2023; CBD, 2009). The NW region is a stronghold for rare and threatened species, with extensive peatlands and coastal habitats supporting specialised flora and fauna (NPWS, 2023) (see Table 10). The Southern region is rich in karst, woodland, and wetland habitats, supporting a wide variety of plant and animal species, but faces pressures from habitat fragmentation and agricultural intensification (NPWS, 2023) (see Table 10). The EM region includes important lowland grasslands, bogs, and rivers, with urbanisation and land use change posing significant threats, but also benefits from large protected areas and active restoration projects (CBD, 2009) (see Table 10). Ireland's regional and county biodiversity patterns reflect the interplay of geology, climate, and land use, with each area presenting unique conservation opportunities and challenges. County Biodiversity Action Plans are essential for identifying local priorities and guiding effective conservation action across the country (NPWS, 2023; CBD, 2009).

Implications for Developing a Regional Bioeconomy Strategy

Ireland's natural capital profile, including air quality, geology, soil, and biodiversity, offers critical insights for developing regionally tailored bioeconomy strategies. Regional variation in these environmental attributes directly affects the feasibility, sustainability, and direction of bioeconomy development, with implications for sectoral specialisation, land use planning, environmental protection, and socio-economic opportunity.

Table 10: Biodiversity by Region and County

	Dominant Habitats & Features	Conservation Focus
REGION		
NW	Blanket bogs, peatlands, coastal	Corncrake, hen harrier, pearl mussel
Southern	Karst, woodlands, wetlands, coast	Horseshoe bat, chough, orchids, otter
EM	Lowland grasslands, bogs, rivers	Curlew, otter, pollinators, bats
COUNTY		
Donegal	Blanket bog, mountains, coast	Corncrake, golden plover, pearl mussel
Sligo	Coastal dunes, bogs, woodlands	Chough, otter, rare plants
Leitrim	Bogs, lakes, woodlands	Marsh fritillary, otter, bats
Cavan	Lakes, drumlins, wetlands	White-clawed crayfish, marsh fritillary
Monaghan	Drumlin lakes, wetlands, woodlands	Marsh fritillary, otter, bats
Galway	Limestone pavement, turloughs, bogs	Turloughs, freshwater pearl mussel, bats
Mayo	Blanket bog, peatlands, rivers	Corncrake, otter, salmon, rare mosses
Roscommon	Turloughs, bogs, lakes, woodlands	Turlough species, otter, bats
Clare	Karst limestone, coastal dunes	Horseshoe bat, orchids, rare butterflies
Tipperary	Grasslands, woodlands, rivers	Kingfisher, bats, pollinators
Limerick	River valleys, woodlands, wetlands	Kingfisher, otter, wetland birds
Waterford	Coastal cliffs, estuaries, woodlands	Chough, otter, rare plants
Kilkenny	River Nore, woodlands, grasslands	Kingfisher, otter, bats
Carlow	River Barrow, woodlands, wetlands	Otter, kingfisher, bats
Wexford	Coastal dunes, woodlands, wetlands	Brent goose, otter, bats
Cork	Coastal cliffs, estuaries, woodlands	Chough, otter, bats, rare plants
Kerry	Mountains, peatlands, coast	Chough, hen harrier, otter, rare mosses
Dublin	Urban parks, coastal habitats	Brent goose, bats, pollinators, rare plants
Wicklow	Upland woodlands, bogs, rivers	Red grouse, hen harrier, otter, bats
Kildare	Bog of Allen, rivers, woodlands	Curlew, bats, pollinators
Meath	River Boyne, woodlands, grasslands	Kingfisher, bats, pollinators
Louth	Cooley Mountains, coast, rivers	Brent goose, otter, bats
Longford	Raised bogs, lakes, woodlands	Curlew, snipe, bog mosses, bats
Westmeath	Lakes, bogs, woodlands	Otter, bats, pollinators
Offaly	Raised bogs, callows, woodlands	Curlew, snipe, bog mosses, bats
Laois	Slieve Bloom, bogs, grasslands	Red grouse, snipe, bats

Air quality patterns indicate significant regional disparities with clear implications for siting biobased industries and biomass processing facilities. The North-West (NW) region, with the cleanest air (PM2.5 as low as 5.8 µg/m³ in Mayo), presents opportunities to promote low-impact biobased industries such as organic farming, eco-tourism, or peatland-based carbon sequestration initiatives. In contrast, Eastern and Midland (EM) counties, particularly Dublin and surrounding commuter counties, face higher PM2.5 levels and nitrogen dioxide from traffic and domestic heating. Bioeconomy strategies here must prioritise low-emission technologies, sustainable transport, and urban greening. The Southern region, with mixed air quality, suggests a hybrid approach that balances industrial development with strong air pollution mitigation in urban areas like Limerick. Air quality also serves as a co-benefit indicator for bioeconomy actions; for example, substituting solid fuel with biogas could deliver measurable improvements in urban PM2.5 concentrations.

Geological diversity across regions strongly influences biomass availability, land use potential, and infrastructure planning. The NW region's ancient metamorphic and igneous geology underlies rugged uplands and thin acidic soils, limiting intensive agriculture but supporting extensive forestry, upland grazing, and carbon-rich peatlands. These conditions align with a bioeconomy focused on ecosystem services, habitat restoration, and high-value niche products like wild foods and medicinal plants. Conversely, the Southern region's Devonian sandstones and Carboniferous limestones underpin fertile valleys and distinctive karst systems, offering potential for biomass-intensive activities such as anaerobic digestion (AD), sustainable forestry, and high-value horticulture. The EM region, dominated by Carboniferous limestone and glacial lowlands, is well suited for integrated agri-food and energy systems, leveraging existing infrastructure and more favourable logistics for feedstock distribution and circular economy hubs.

Soil characteristics are pivotal in determining biomass productivity and environmental resilience. The NW region has extensive peat and gley soils, with low drainage and limited arability but high carbon storage potential. This necessitates a bioeconomy strategy focused on protecting and restoring peatlands rather than exploiting them, alongside extensive grazing systems and forestry. In contrast, Southern and EM regions contain fertile brown earths and well-drained mineral soils ideal for tillage, pasture, and biomass cropping. These areas could support biorefinery development, sustainable feedstock cultivation (e.g., grass, cereals, oilseeds), and nutrient recycling initiatives. However, the prevalence of peaty soils in low-lying areas across all regions underscores the need for soil-sensitive planning to avoid degradation or greenhouse gas emissions from inappropriate land conversion.

Biodiversity profiles introduce both constraints and opportunities. The NW region, home to priority habitats like blanket bogs and rare species, is conservation-sensitive. Here, bioeconomy strategies should reinforce biodiversity goals through habitat-based services, nature-based tourism, and eco-certification. The Southern region supports species-rich karst and woodland systems that must be protected from fragmentation due to industrial-scale bioeconomy development. The EM region, with threatened grasslands and pollinator-dependent systems, must integrate biodiversity considerations into urban-rural biomass loops, for instance through green infrastructure and pollinator-friendly cropping systems.

In summation, Ireland's natural capital base provides a scientifically grounded basis for developing regionally differentiated bioeconomy strategies. These must align sectoral focus with ecological realities, supporting biodiversity, air quality, and soil health while enabling rural diversification, emissions reduction, and circular economy goals. Regional planning should move beyond a 'one-size-fits-all' approach, adopting place-based bioeconomy strategies that capitalise on each region's ecological strengths and socio-environmental needs.

Application of Circular Sustainability and the Cascade Principle in Irish Agriculture and Land-Use Policy

Introduction

Ireland is beginning to transition towards circular sustainability, the application of circular economy principles to use resources efficiently and reduce waste, within its agriculture and land-use policies. A key concept in this respect is the cascade principle, which prioritises the use of biological resources in higher-value applications first (like food or materials) before lower-value uses (like energy) (DBEI, 2019). Together, these approaches aim to make Irish agriculture more sustainable by closing resource loops (nutrient recycling, waste valorisation) and maximising value from biomass (Walsh et al., 2017). This section provides an overview of how these concepts are embedded in Ireland's national policies and on-the-ground practices, as well as the influence of EU frameworks.

National Policy Initiatives Aligning with Circular and Cascade Principles

National Bioeconomy Policy and Action Plan

Ireland's policy framework for the bioeconomy explicitly incorporates circular and cascade principles. The National Policy Statement on the Bioeconomy 2018 outlined guiding principles including sustainability, a "food-first" approach, and the cascading use of biomass (i.e. using biomass for food, feed and bio-based materials before energy) (DBEI, 2019). Building on this, the government released its first National Bioeconomy Action Plan 2023–2025, which contains 33 actions to accelerate the sustainable bioeconomy (Government of Ireland, 2023a). This Action Plan emphasises environmental sustainability and circularity, explicitly listing *"Cascading"* as a core principle: *"Higher value applications (e.g. food or bio-based materials) are derived [from biomass] prior to their use in energy and fuel generation."* (Government of Ireland, 2023a, p.8) It also adopts a *"Food First"* principle to ensure food security is prioritised in biomass use (O'Riordan et al., 2024). By embedding these principles, the Bioeconomy Action Plan seeks to "do more with less", extracting maximum value from Ireland's biological resources while avoiding waste (DBEI, 2019). For example, it supports development of biorefineries and bio-based products from agricultural by-products and wastes, in line with cascade utilisation (*ibid*). A Bioeconomy Implementation Group coordinates this across government, and a forthcoming National Bioeconomy Strategy will further integrate circular bioeconomy goals (Government of Ireland, 2023a).

Climate Action Plan (Agriculture and Land Use)

Ireland's Climate Action Plan is another key policy incorporating circular sustainability in agriculture. The Climate Action Plan 2023 (Government of Ireland, 2023b) sets ambitious targets for the agriculture and land-use sector to help achieve climate neutrality by 2050. Alongside emission reduction measures, the plan highlights the role of the circular economy and bioeconomy in reaching climate goals (DECC, 2023). Notably, it calls for implementing circular bioeconomy models at scale and emphasises the cascade principle in biomass use. The plan states that the bioeconomy *"seeks to cascade the use of our biological resources, and harness waste and natural capital"* as part of a climate-solutions toolkit (Government of Ireland, 2023b, p.125). In practice, this means promoting actions like nutrient recovery, anaerobic digestion of agricultural residues, and use of wood products to store carbon. The Climate Action Plan includes actions to "unlock the full potential of the bioeconomy" and references the forthcoming Bioeconomy Action Plan as key to climate

targets (Government of Ireland, 2023b). For example, it supports a major scale-up of anaerobic digestion for biogas (with a target for 5.7 TWh of indigenous biomethane by 2030), which will use organic farm wastes and grass silage to produce renewable gas while returning nutrient-rich digestate to soils (Government of Ireland, 2023b). It also encourages increased organic farming (with incentives under the CAP Strategic Plan) and better fertiliser use efficiency – measures that contribute to nutrient cycling and reduced "linear" inputs (Department of Agriculture, 2022). Overall, the Climate Action Plan embeds circularity by linking waste reduction and resource reuse with climate mitigation in agriculture.

Food Vision 2030 – Agri-Food Strategy

Food Vision 2030: A World Leader in Sustainable Food Systems is Ireland's ten-year strategy for the agri-food sector (DAFM, 2021). This strategy explicitly endorses circular economy principles as part of achieving environmental sustainability and resilience. Food Vision 2030 signals a shift toward a more diversified and circular agri-food system, including targets for nutrient recycling, water reuse, and waste reduction (DAFM, 2021). It notes that Ireland's agri-food sector must *"operate within planetary boundaries"* and calls for the sector to be *"based on circular economy principles"*, for instance through reducing food waste by 50% by 2030 and recycling nutrients and resources within the system (DAFM, 2021; UNFSS, 2021). The strategy sets an objective of a climate-neutral food system by 2050, with verifiable progress by 2030 on emissions, water quality, and biodiversity (DAFM, 2021). Achieving this involves measures like greater use of organic manure and anaerobic digestion, valorisation of co-products, and expansion of nature-based farming that improves soil health (UNFSCH, 2021). Food Vision 2030 also emphasises improving soil and grassland management to recycle nutrients more efficiently, and expanding forestry and organic production, aligning with circular bioeconomy goals (DAFM, 2021). In summary, at the national level Ireland's core strategies – from the Climate Action Plan to Food Vision 2030 and the Bioeconomy Action Plan – all integrate circular sustainability concepts. They promote a regenerative model of agriculture that recirculates resources (e.g. nutrients, biomass) and apply the cascade principle to favour the highest-value, most sustainable use of biological resources before lower-value uses (DBEI, 2019). This alignment in policy provides a supportive framework for implementing circular practices on the ground.

Influence of EU-Level Frameworks on Ireland's Policy

Ireland's approach is strongly shaped by broader EU frameworks that prioritise sustainability, circularity and efficient resource use in agriculture.

European Green Deal (2019)

The EU Green Deal set the direction for climate neutrality and a sustainable economy in Europe, and Ireland's commitments mirror this ambition. Under the Green Deal's *Farm-to-Fork Strategy* and *Biodiversity Strategy*, the EU introduced targets such as reducing nutrient losses by 50%, cutting chemical pesticide use by 50%, and expanding organic farming to 25% of land by 2030. These targets influenced Ireland's policies: for example, Ireland significantly increased supports for organic farming (aiming to reach ~10% of land in organic by 2030, from a low base), and strengthened nutrient management rules in line with the EU Nitrates Directive and Farm-to-Fork goals (European Commission, 2020). The Green Deal's emphasis on circular nutrient use and sustainable food systems is reflected in Food Vision 2030 and Ireland's Climate Act commitments (O'Riordan et al., 2024). Moreover, the EU Biodiversity and Forestry strategies (as part of the Green Deal) encourage afforestation and the sustainable use of biomass, reinforcing Ireland's push for nature-based solutions and wood-based products in a cascade approach.

Common Agricultural Policy (CAP) 2023–2027

The reformed CAP integrates environmental and circular economy objectives more than ever before, which has guided Ireland's national CAP Strategic Plan. The CAP now requires that 40% of spending contribute to climate and environmental goals. Ireland's CAP Strategic Plan (approved 2022) includes Eco-Schemes and Agri-Environment Climate Measures that reward farmers for actions like nutrient management planning, use of cover crops to improve soil health, precision fertilisation, manure recycling, and planting trees or hedgerows (Department of Agriculture, 2022). Such measures promote on-farm circular practices (e.g. recycling organic nutrients and protecting soil) as part of income supports. Additionally, Ireland has introduced a results-based *Agri-Climate Rural Environment Scheme* (ACRES) and supports for farm renewable energy (solar, biogas) under Pillar II, influenced by CAP's sustainability focus. The CAP also supports innovation via European Innovation Partnerships (EIP) – in Ireland, EIP projects have included initiatives on grassland nutrient recycling and cooperative approaches to biomass use. In short, the CAP provides financial incentives and regulatory impetus for Irish farmers to adopt circular sustainability measures (European Commission, 2021). Ireland's push for an "agricultural transition" is thus backed by CAP funding conditioned on improved resource efficiency and circular use of inputs.

EU Circular Economy Action Plan (2020)

The EU's Circular Economy Action Plan (as part of the Green Deal) has spurred national action on waste and resource use. A notable element is the focus on nutrient recycling in farming: the plan calls for an Integrated Nutrient Management Action Plan to promote the reuse of nutrients and reduce fertiliser waste (European Commission, 2020). Ireland has responded through its national Circular Economy Strategy 2022 and Waste Action Plan for a Circular Economy 2020, which include measures on valorising agricultural wastes (e.g. promoting composting and anaerobic digestion) and reducing food waste (Government of Ireland, 2021). The Circular Economy and Miscellaneous Provisions Act 2022 in Ireland transposed aspects of EU policy, establishing a general framework for circular economy practices and setting a national goal of 50% food waste reduction by 2030 to match EU ambitions. In agriculture, this means greater recovery of agricultural by-products (like animal manures, crop residues) into secondary resources (fertilisers, biogas, bio-materials) rather than treating them as waste. The cascade principle is also embedded in EU bioeconomy policy – the updated EU Bioeconomy Strategy (2018) and the EU Forest Strategy (2018) both stress cascading use of biomass (Olsson et al., 2016). Ireland has adopted this principle via its bioeconomy policy as noted, ensuring consistency with EU recommendations (Government of Ireland, 2018; O'Riordan et al., 2024).

Overall, EU frameworks like the Green Deal and CAP have provided both the vision and concrete tools (regulations, funding) that shape Ireland's policies. Ireland's national strategies are closely aligned with EU objectives: for instance, Food Vision 2030's targets on emissions and waste parallel Green Deal targets (UNFSCH, 2021), and the Climate Action Plan's agricultural measures contribute to EU Effort Sharing Regulation targets for emissions cuts. This alignment ensures that circular sustainability and cascading principles are not just national ideals but part of a broader EU-driven transition.

Implementation in Key Areas: Bioeconomy, Soil, Nutrients, Forestry, and Waste

Ireland's policy commitments are increasingly being translated into practical implementations across various domains of agriculture and land use. This section highlights how circular and cascade principles are being applied on the ground, through pilot projects, programs, and changes in practices, in areas such as the bioeconomy, soil health, nutrient management, forestry, and waste valorisation.

Circular Bioeconomy Initiatives and Waste Valorisation

A core application of circular sustainability is in the agricultural bioeconomy: finding new uses for biological resources and wastes through innovation. Several pilot projects in Ireland demonstrates this approach. For example, the CircBioCityWaste project (launched 2021) is developing a biorefinery process that uses the *cascading principle* to convert organic waste streams into value-added products. In this project, sludge and digestate from dairies and municipal waste are first processed into bio-based products like biostimulants, biofertilisers, and soil conditioners; then the remaining residue is thermochemically converted to biochar and renewable energy (CAP Network Ireland, 2024). This cascade use ensures maximum value extraction (nutrients and soil amendments) before the final energy recovery, and it exemplifies circular nutrient cycling. The socio-economic impact spans farmers (who could use the biofertiliser), waste managers, and the environment, demonstrating a win-win for sustainability (CAP Network Ireland, 2024). Another example is the CircoVal project, which focuses on *circular valorisation of bovine and ovine co-products* – essentially turning animal by-products from the meat industry (like hides, fats or other waste parts) into new products or bioenergy, rather than disposing of them. By treating such outputs as feedstocks for other processes, these initiatives reduce waste and create new income streams, aligning with Food Vision 2030's call for diversification and circularity (DAFM, 2021).

The Irish government and research agencies are actively supporting bioeconomy pilots. Through mechanisms like the Disruptive Technologies Innovation Fund and EU Horizon projects, companies and researchers are exploring uses for farm and food waste – from mushroom compost turned into biodegradable packaging, to brewing by-products being used in animal feeds and biogas. An example in practice is the Carbery Group (a dairy cooperative) which operates an anaerobic digester treating cheese-production effluent (whey) along with pig manure to produce biogas for energy and a nutrient-rich biofertiliser that farmers apply back to land (Murphy et al., 2021). This closed-loop system illustrates circular economy in agri-food: waste from one process becomes a resource for others, reducing reliance on synthetic fertilisers and fossil fuels. Likewise, Ireland's dairy industry more broadly has begun to adopt on-farm anaerobic digesters to manage slurry and generate renewable heat or electricity, supported by grants and a planned feed-in tariff for biomethane (Government of Ireland, 2023b). These digesters exemplify cascade use by extracting energy after the primary agricultural production, and returning nutrients to soils as digestate.

Importantly, Ireland has instituted networks and hubs to drive the circular bioeconomy. The Irish Bioeconomy Foundation (IBF) operates a Bioeconomy Innovation Centre in Co. Tipperary (at Lisheen) to pilot biorefinery technologies, including extracting biochemicals from grass, converting agri-residues to biogas, and producing fiber products from waste straw. Annual events like Bioeconomy Ireland Week raise awareness and showcase successful projects.

Soil Health and Nutrient Cycling

Healthy soils and closed-loop nutrient use are fundamental to circular agriculture. In Ireland, there is growing emphasis on soil health initiatives and nutrient management programs that embody circular principles. One major step has been the launch of a comprehensive National Soil Sampling and Analysis Programme (2021–2022) led by Teagasc (the agriculture research authority) to map soil nutrient status on Irish farms. By identifying exactly what nutrients are needed (or present in excess), this program helps farmers optimise fertiliser use – avoiding over-application of chemical inputs and promoting the use of organic manure where feasible. This improves nutrient recycling (using what's already in the farm system) and reduces nutrient waste and runoff (Lalor et al., 2022). The government's Climate Action Plan also highlights soil carbon sequestration and health: farmers are encouraged (and incentivised via CAP eco-schemes) to adopt practices like cover cropping, minimum tillage, and mixed-species pastures, which enhance soil structure, retain nutrients, and even fix nitrogen naturally (Government of Ireland,

2023b). These practices reduce the need for external inputs by cycling nutrients within the soil-plant system, exemplifying circular sustainability at farm level.
Ireland's regulatory framework for water and nutrients, primarily the Nitrates Regulations (aligned with the EU Nitrates Directive), has tightened limits on inorganic fertiliser and promotes slurry management. To comply, many Irish farmers have invested in improved manure spreading technology (like low-emission slurry spreading) that increases nutrient uptake by crops and decreases loss to water or air (DACM, 2021). The government also supports nutrient recycling innovations. For example, pilot projects are treating cattle slurry to separate the liquid (high in nitrogen and potassium, which can be used as fertiliser) from solid fractions (which can be composted or used for energy), effectively turning manure into standardised, transportable fertiliser products. Additionally, Ireland is exploring use of recovered phosphorus from wastewater or manure in fertiliser blending, in line with the EU Circular Economy Action Plan's push to substitute virgin mineral fertilisers with recycled nutrients (European Commission, 2020).

Soil health is also being tied to carbon farming initiatives. Ireland is participating in EU-wide programs to reward farmers for building soil organic carbon, which inherently promotes practices like returning crop residues to soil, use of farmyard manure/compost, and diversifying rotations, all of which close nutrient loops and improve soil fertility. By valuing soil carbon (through possible carbon credits or results-based payments), policy incentivises farmers to treat plant biomass and organic waste as valuable soil inputs rather than waste. For instance, straw or hedge clippings that might have been burned or discarded are now seen as resources for mulching or composting to enrich soil.

In summation, circular nutrient cycling is increasingly evident in Irish agriculture through better nutrient planning, the recycling of manures and organic wastes as fertilisers, and farming practices that regenerate soil. These efforts not only reduce pollution and input costs but also reinforce the cascade principle, nutrients are used and reused in the system rather than lost. As Food Vision 2030 notes, Irish farmers are evolving into providers of ecosystem services like carbon sequestration and water protection alongside food, by adopting such circular practices (DAFM, 2021). This represents a practical realignment of agriculture with natural nutrient loops.

Forestry and the Cascade Use of Biomass

The forestry sector provides a clear illustration of the cascade principle in action. Ireland has a relatively small but growing forest resource and a strong policy drive to expand afforestation (with targets of 8,000 hectares of new forests per year) to meet climate and bioeconomy goals (DAFM, 2022). In managing and utilising forest biomass, Irish policy emphasises "cascade use", using wood for the highest value products first, and only using residues or end-of-life wood for energy (Olsson et al., 2016). This approach is aligned with EU recommendations and is reflected in Ireland's forestry and climate strategies.
In practical terms, this means that timber from Irish forests is ideally used in long-lived products such as construction timber, furniture, or engineered wood products (which store carbon for decades). The COFORD Forest Bioeconomy report explains that wood used in buildings displaces more carbon-intensive materials like concrete or steel, and stores sequestered carbon, providing a climate benefit (COFORD, 2017). After these products reach end-of-life (potentially after reuse or recycling if feasible), the remaining wood waste can be used as biomass fuel for energy, thus substituting fossil fuels (COFORD, 2017). This cascade (material -> reuse -> energy) maximises the carbon and economic value from each unit of wood. For example, wood off-cuts from sawmills in Ireland are first used to make products like particleboard or wood pellets (materials use); only the lowest-grade fines or post-consumer scraps are burned for heat. Even in energy use, these wood residues contribute to renewable energy targets (biomass boilers are used in some industry and heating systems, supported by incentives like the Support Scheme for Renewable Heat). In this respect, the cascade principle aims to avoid the inefficient scenario of freshly harvested wood being immediately burned for energy without first contributing to higher value uses.

The cascade approach in forestry is supported by R&D and innovation projects. NexGenWood (Next Generation Wood) is a research collaboration funded by DAFM to develop new wood products and processing methods in Ireland (CAP Network Ireland, 2024). Its aim is to create high-value bioproducts from wood, such as biochemicals, novel bio-based materials, or advanced composites, thereby diversifying the uses of forestry biomass beyond traditional lumber (*ibid*). Such innovations aim to ensure that more of the tree is used, (for example extracting compounds from bark for biopolymers, or using cellulose for textiles), aligning with circular economy thinking (*ibid*). Likewise, Ireland is exploring wood cascading in construction: initiatives are underway to promote timber construction in public projects and to establish deconstruction practices that allow wood recovery from demolished buildings. By keeping wood in circulation longer (through reuse or recycling into panel board), the need for virgin material is reduced (*ibid*). This reflects the circular economy maxim of keeping materials at their highest utility for as long as possible.

In essence, sustainable forestry in Ireland operationalises the cascade principle: policy and practice aim to "cascade" wood through various lifecycles, from forest, to product, to recycled product, to energy – extracting maximum economic and environmental value (COFORD, 2017). This not only supports circular sustainability but also strengthens rural economies by creating new value chains in the bioeconomy (e.g. wood product innovation, biomass energy industries).

Examples of On-the-Ground Projects

Ireland's transition toward circular agriculture is illustrated by a number of real-world pilot projects and local initiatives beyond those already mentioned. These serve as learning sites for broader adoption.

Farm Eco-Platforms and Demonstration Farms

The Teagasc Signpost Farms programme has established dozens of demonstration farms nationwide to showcase climate-smart and circular practices (Teagasc, 2025). Participating farms implement measures like nutrient budgeting, multi-species swards, renewable energy installations, and enhanced slurry management (*ibid*). These farms have reported significant reductions in synthetic fertiliser use by substituting with clover N-fixation and recycled manures, thus validating circular nutrient use in commercial farming (*ibid*). They also trial composting farm waste (like grass cuttings or pig bedding) into organic fertiliser (*ibid*). The knowledge from Signpost Farms is being disseminated to thousands of farmers through open days and advisory services, accelerating uptake of circular methods (*ibid*).

Bioeconomy Demonstration Initiatives

Under the Bioeconomy Action Plan, a flagship initiative is to create a network of regional bioeconomy demonstrators (Government of Ireland, 2023a). One example is the Midlands Bioeconomy Pilot in County Offaly, which is repurposing a former peat harvesting site into a bioeconomy hub (Bord na Móna, 2022). There, trials are ongoing on growing biomass crops (like willow, miscanthus) on cutaway peatlands and converting them, via cascading processes, into bioenergy, biochar, and even building materials (*ibid*). The project is designed to find sustainable alternatives for peat (formerly used in energy), create rural jobs, and use marginal land for productive circular application (*ibid*). Early results show that with the right technology (pyrolysis and biorefining units), a cascade of products can be derived from these biomass crops, from vinegar and tar (chemical extracts) to char (soil amendment) to syngas (energy), illustrating a local circular economy in action (Bord na Móna, 2022).

Food Waste to Bioenergy

In line with the national Food Waste Prevention Roadmap, local authorities and companies have started initiatives to capture food waste and agricultural by-products for valorisation (Rajendran et al., 2019). One notable project is in County Cork, where a collaboration between pig farmers and a food processor is collecting food processing waste (e.g. spent grains from a brewery and dairy waste) to feed into an anaerobic digester co-located on a farm (XDS Sustainable Energy Consulting Ltd., 2022). The biogas produced is used to generate electricity for the processor and heat for the farm, while the digestate returns to farmers' fields as fertiliser (Fagerström et al., 2018). This closed-loop system, supported by an SEAI community energy grant, aims to reduce waste disposal needs and fossil energy use simultaneously (SEAI, 2017).

Conclusion

Ireland's policy landscape demonstrates a notable integration of circular sustainability and cascade principles within agricultural and land-use strategies. National initiatives such as the Climate Action Plan, Bioeconomy Action Plan, and Food Vision 2030 articulate a clear rhetorical alignment with EU circular economy ambitions, aiming to enhance resource efficiency, reduce dependency on linear inputs, and valorise biological by-products. However, while the policy intent is robust, implementation on the ground remains uneven and fragmented. Many of the examples cited, from anaerobic digestion systems to nutrient recycling and bio-based product development, are still confined to pilot stages, reliant on targeted funding and lacking systemic scalability. Structural challenges persist, including limited infrastructure for biorefining and waste processing, inconsistent market development for secondary bio-products, and regulatory ambiguity surrounding biomass use prioritisation (O'Riordan et al., 2024). Moreover, the cascade principle, though referenced in policy, is often more aspirational than operational, with few mechanisms ensuring biomass flows adhere to high-value hierarchies in practice (Pender et al., 2024). Ireland's relatively small forestry base, persistent nutrient imbalances, and dependence on imported inputs further complicate circularity goals (O'Connor et al., 2023; O'Flaherty et al., 2021). To advance beyond rhetorical commitment, there is a need for stronger governance instruments, coordinated cross-sectoral implementation, and long-term investment in decentralised technologies and farmer support schemes. Evaluative frameworks that monitor not just outputs (e.g., number of anaerobic digesters) but systemic impacts (e.g. reductions in nutrient losses or fossil input substitution) is critical (O'Connor et al., 2023). As such, although Ireland is laying important conceptual and policy foundations for a circular agricultural transition, realising this vision at scale will require bridging persistent gaps between strategy, infrastructure, and everyday farming practice.

Regional Profile: Informing a Co-Designed Bioeconomy Development Strategy

The Northern and Western (NW) Region

The Northern and Western region is characterised by its small-scale farming systems, rugged landscapes, and abundant natural ecosystems. With 57% of the land farmed, the lowest proportion nationally, and an average farm size of 27 hectares, the region demonstrates a high density of smaller farms, especially in counties like Monaghan, Cavan, and Leitrim. This predominance of fragmented agricultural systems aligns with the region's potential for decentralised and community-driven bioeconomy initiatives.

Wetlands and peatlands cover 27% of the landmass, primarily in counties like Donegal, Mayo, and Galway, making the NW region a critical area for biodiversity conservation and carbon sequestration. These ecosystems present opportunities for sustainable practices such as rewetting drained peatlands and introducing paludiculture (Ziegler et al., 2021). Biomass crops compatible with wetlands, such as reeds and sphagnum moss, could be cultivated for use in bio-based industries, including construction and horticulture (Younis et al., 2022). The region also features significant heterogeneous agricultural areas, constituting 11% of its land, which could support agroforestry systems that enhance biodiversity, improve soil health, and provide diversified income streams.

Livestock production in the NW region focuses on beef and sheep farming. Counties like Donegal, Mayo, and Galway are hubs for sheep farming, with an average of 67 sheep per farm. Beef farms, with 30 cattle per farm, tend toward extensive systems that could benefit from sustainable grazing practices. Initiatives that emphasise biodiversity-friendly livestock management and carbon farming could leverage the region's natural capital while aligning with circular economy principles (Tiwari et al., 2024). Community-based cooperative models, including small-scale anaerobic digestion facilities for agricultural residues, would further support economic viability and resource efficiency (Rahman et al., 2019).

Given the region's extensive peat and gley soils, low PM2.5 levels, and intact biodiversity corridors, bioeconomy strategy should prioritise low-impact, nature-based models. These may include carbon farming, ecosystem services, and wetland-compatible biomass cultivation, rather than industrial-scale biomass extraction. The cascade principle reinforces this by favouring non-extractive, high-value uses of biological resources, such as biobased construction materials and peatland restoration products, before energy application.

The Southern Region

The Southern region, encompassing 69% farmland, is the most agriculturally intensive area in Ireland. Larger average farm sizes of 40 hectares and high livestock densities of 54 livestock units per farm underline the region's focus on large-scale dairy and beef farming. Counties such as Cork, Tipperary, and Kilkenny dominate in dairy and beef production, supported by extensive grasslands, including the highest proportions of pasture (35%) and grass silage (19.9%). The region also boasts significant forestry resources, covering 12% of the landmass, concentrated in counties like Kerry and Clare.

Dairy farming, particularly in Cork, serves as a key economic driver, with opportunities to valorise by-products such as whey into high-value products like bioplastics and nutritional supplements. Meanwhile, the region's livestock density offers potential for integrating circular economy practices through advanced manure management systems, converting livestock waste into biogas and bio-based fertilisers (Khoshnevisan et al., 2021). Forestry resources provide additional pathways for bioeconomy development, including biomass energy, bio-based products, and biodiversity-friendly reforestation initiatives (Singh et al., 2023).

Given its focus on intensive agricultural systems, the Southern region's bioeconomy strategy should prioritise scaling up renewable energy projects, such as large-scale, possibly grass-based, biorefineries and precision agricultural technologies. Practices such as conservation tillage and precision nutrient management could mitigate environmental impacts while enhancing productivity (Pramanick et al., 2022). Investments in industrial symbiosis, where by-products from dairy and beef farming are repurposed for bio-based materials, would further integrate sustainability into high-output farming systems (Dammer et al., 2023).

However, regional air quality data, particularly PM2.5 levels in Limerick and Waterford, highlight the need for siting bioprocessing facilities with consideration of cumulative emissions. Applying the cascade principle ensures that livestock by-products and forestry biomass are directed first toward high-value reuse (e.g. bio-based materials, feed supplements) before being combusted for energy. This supports both emission reduction and resource efficiency goals embedded in the Climate Action Plan and Bioeconomy Action Plan.

The Eastern and Midlands (EM) Region

The Eastern and Midlands region, with 65.9% farmland and the largest average farm size of 41 hectares, is defined by its emphasis on arable and cereal production. Cropland, accounting for 11.1% of the landmass, is concentrated in counties like Wexford, Carlow, and Louth, which lead in cereal production. This makes the region well-suited for crop-based bioeconomy initiatives, including bio-based materials, biofuels, and high-value products derived from cereal residues.

The region’s fertile soils and established agricultural infrastructure present opportunities for integrating renewable energy systems, such as bioethanol production from cereals, and advancing precision agriculture technologies (Sikiru et al., 2024). Additionally, its larger farms provide the scale needed for large biorefineries and efficient resource recovery systems, reducing waste and environmental impact (Awasthi et al., 2022). Smaller areas of wetlands (8%) and forestry (9%) also provide opportunities for biodiversity-focused initiatives, though they are less prominent than in other regions.

The EM region’s proximity to urban centres creates synergies between rural and urban areas, supporting urban agriculture and bio-based industries. However, challenges such as nutrient runoff and greenhouse gas emissions from intensive farming practices require targeted interventions. Policies promoting conservation tillage, precision fertilisation, and crop diversification into high-value products and agroforestry systems would enhance the region’s resilience to environmental and market pressures (Hussain et al., 2024).

Regional natural capital data show moderate-to-high PM2.5 exposure and significant biodiversity pressure in lowland grasslands and water catchments. These vulnerabilities call for urban–rural circularity strategies that prioritise nutrient recycling, wastewater-based fertiliser recovery, and green infrastructure development. The cascade principle provides a useful framework here: cereal residues and urban food waste should be valorised through biobased materials, compost, or fermentation products prior to energy recovery, thereby maximising resource value while minimising emissions.

Integrated Regional Strategy for Bioeconomy Development

Each region of Ireland offers unique opportunities for bioeconomy development, shaped by its agricultural systems, natural resources, and socio-economic conditions. The NW region’s focus on small-scale, biodiversity-enhancing practices contrasts with the Southern region’s potential for scaling up intensive agricultural systems integrated with renewable energy. Meanwhile, the EM region is poised to lead in crop-based bioeconomy initiatives leveraging its extensive arable land and larger farms. To guide sustainable development, regional strategy must also reflect variations in natural capital, such as air quality, soil characteristics, and habitat sensitivity,

and align with circular sustainability and cascade principles embedded in national and EU frameworks.

To achieve a cohesive national bioeconomy framework, these regional strategies must align with international sustainability objectives, such as the European Green Deal and the UN Sustainable Development Goals. Policies and investments should reflect the specific strengths and challenges of each region, ensuring equitable and sustainable growth. Collaborative stakeholder engagement, targeted funding, and innovative technologies will be critical to fostering a bioeconomy that balances economic productivity with environmental stewardship. By leveraging regional assets, Ireland can build a resilient, inclusive bioeconomy that supports rural communities while contributing to global sustainability goals.

Conclusion

The findings of this research underscore the critical need for regionally tailored bioeconomy strategy that harnesses Ireland's diverse agricultural landscape while aligning with sustainability goals. Each region presents unique opportunities: the Northern and Western region should prioritise biodiversity-driven initiatives and community-based models; the Southern region holds promise for scaling intensive agricultural systems with integrated renewable energy and circular economy practices; and the Eastern and Midlands region is well-positioned to advance crop-based bioeconomy innovations. These approaches must be rooted in environmental protection, such as peatland conservation, soil health, air quality thresholds, and biodiversity protection, and guided by the cascade principle to ensure efficient, sustainable resource use. By leveraging these regional strengths, addressing challenges such as environmental sustainability, and fostering policy support and technological innovation, Ireland can create a robust bioeconomy. Such an approach not only offers pathways for economic resilience in rural communities but also contributes to achieving national and international sustainability objectives. The integration of tailored regional insights into a cohesive national framework is essential for ensuring Ireland's leadership in sustainable agricultural development and global bioeconomy advancements.

APPENDIX

Table 1: CORINE Land Cover Database 2018

Authors' Classification	CORINE Classification		
1. Urban Fabric	Artificial Surfaces	Urban Fabric	Continuous urban fabric Discontinuous urban fabric
		Industrial, commercial and transport units	Industrial or commercial units Roads and rail networks and associated land Port areas Airports
		Mine, dump and construction sites	Mine extraction sites Dump sites Construction sites
		Artificial, non-agricultural vegetated areas	Green urban areas Sport and leisure facilities
2. Arable land	Agricultural areas	Arable land	Non-irrigated arable land Permanently irrigated land Rice fields
3. Permanent crops		Permanent crops	Vineyards Fruit trees and berry plantations Olive groves
4. Pastures		Pastures	Pastures

5. Heterogeneous agricultural areas		Heterogeneous agricultural areas	Annual crops associated with permanent crops Complex cultivation patterns Land principally occupied by agriculture, with significant areas of natural vegetation Agroforestry areas
6. Forest and seminatural areas	Forest and seminatural areas	Forest	Broad-leaved forest Coniferous forest Mixed forest
		Shub and/or herbaceous vegetation associations	Natural grassland Moors and heathland Sclerophyllous vegetation Transitional woodland/shrub
		Open space with little or no vegetation	Beaches, dunes, and sands Bare rock Sparsely vegetated areas Burnt areas Glaciers and perpetual snow
7. Wetlands and Peatlands	Wetlands	Inland wetlands	Inland marches peatbogs
		Coastal wetlands	Salt marshes Salines Intertidal flats
8. Water Bodies	Water Bodies	Inland waters	Water courses Water bodies
		Marine waters	Coastal lagoons Estuaries Sea and ocean

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