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Impact of agriculture on the environment and biodiversity in Luxembourg – A multidisciplinary approach to sustainability

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Abstract

- Farming must not only produce food but also ensure sustainable livelihoods for farmers and protect natural ecosystems and their services.
- Several of the key elements of a sustainable agricultural transition are discussed in this document: National and European policy actions (Chapter 2), interactions between biodiversity and agriculture (Chapter 0), importance of strengthening water resilience (Chapter 4), sustainable use of pesticides (Chapter 5) and the role of Agri-photovoltaics in advancing the energy transition.
- The Common Agricultural Policy (CAP) Strategic Plan 2023–2027 has contributed to improvements in climate, biodiversity, and the quality of water, soil, and air. However, progress remains insufficient. Enhancing the measurement and reporting of clear benchmarks will enable a more accurate evaluation of policy effectiveness. At the same time, it is crucial to ensure that these measures do not add unnecessary administrative burdens on farmers.
- Approximately half of all European animal and plant species depend on agricultural habitats but are also threatened by both agricultural intensification and land abandonment. At the same time, all forms of agriculture rely on biodiversity and ecosystem services. To counter biodiversity loss, several national and international policy initiatives promote the sustainable use of ecosystems and aim to restore ecological balance with limited success so far.
- Agriculture is the largest net water consumer in Europe and a significant contributor to surface and groundwater pollution, particularly due to the excessive use of agro-chemicals, i.e. mineral fertilizers such as nitrogen and phosphorus and pesticides. To address these challenges, expert committees on agriculture and water are currently discussing a series of national action plans.

- While pesticides help minimize crop losses and reduce labour demands, their use can pose significant risks to human health and the environment. Various policy measures aim to regulate and reduce pesticide use, but several challenges remain. These include the vast diversity of active substances, their environmental persistence, the risk of importing pesticide-contaminated food and feed, and ensuring their availability and affordability, particularly amid political crises.
- Agri-photovoltaic installations enhance land use efficiency by integrating agricultural production with solar energy generation. They have the potential to play a contributing role in ensuring energy security and reducing greenhouse gas emissions. Various system designs can be tailored to Luxembourg's context, minimizing impacts on crop yields and biodiversity while remaining compatible with existing farm machinery.
- Innovative strategies are crucial for the transition to sustainable and resilient agriculture. However, their successful implementation requires active collaboration among policymakers, key institutions, farmers, food chain operators, and civil society.

Les documents de recherche, établis par les membres de la Cellule scientifique de la Chambre des Députés, ainsi que par des experts externes sollicités par la Chambre des Députés, relèvent de la seule responsabilité de la Chambre des Députés. Toutes les données à caractère personnel ou professionnel sont collectées et traitées conformément aux dispositions du Règlement n° 2016/679 du 27 avril 2016 (RGPD). Les informations contenues dans ces documents sont estimées exactes et ont été obtenues à partir de sources considérées fiables. Le caractère exhaustif des données et informations ne pourra être exigé. L'utilisation d'extraits n'est autorisée que si la source est indiquée.

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1. General context, Objectives and Strategies

1.1 – The Agricultural Sector Amid the Triple Planetary Crisis

Agriculture and food supply chains are vulnerable to political and economic tensions, as well as the triple planetary crisis of climate change, biodiversity loss, and pollution (1). The frequency of heavy precipitation extremes and droughts has increased in Western and Central Europe and many studies estimated the impacts of climate change on crop productivity and food security (2,3).

The global agricultural growth and intensification is a major driver of biodiversity loss and ecosystem degradation across Europe (4,5). It will exacerbate the environmental impact of agriculture by increasing the use of fertilizers, pesticides and irrigation (Chapters 4 and 5). On the other hand, nature conservation is not possible without agriculture and agriculture is crucial to maintain and restore biodiversity (Chapter 0).

Significantly enhancing energy independence would strengthen Luxembourg's resilience to geopolitical shocks and natural disasters. Renewable energy technologies such as photovoltaic modules and wind turbines enable energy to be produced in the country, potentially reducing its fossil fuel dependence, lowering its greenhouse gas emissions and enabling Luxembourg to fulfil its European climate commitments (Chapter 6).

National and European policy actions steer the transition toward sustainable, competitive, and resilient agriculture. Key objectives of the 2023-27 Common Agricultural Policy include improving environmental quality, promoting ecological balance, and ensuring fairer incomes for farmers (Chapter 2). Farming must not only produce food, safeguard natural ecosystems and their services, but also secure sustainable livelihoods for farmers and safeguard natural ecosystems and their services. To ensure a successful transition toward more resilient, sustainable, and competitive agriculture, shared responsibility is crucial. This requires active cooperation among all stakeholders: farmers, key institutions, civil society, and political leaders (Chapter 7).

This document aims to:

- Highlight the current challenges in agriculture and the complexities involved in transitioning to sustainable practices.
- Examine the environmental impacts of agricultural activities.
- Explore agriculture's potential role in achieving climate goals and how this relates to food security.
- Showcase practical strategies for balancing economic growth with environmental sustainability.
- Review existing policy measures and their effectiveness in supporting sustainable agriculture

1.2 – Key sustainable agricultural practices

Sustainable agricultural practices that improve productivity, while supporting environmental conservation already exist in Luxembourg, but could be further developed (Table 1). Some practices can have positive impacts on biodiversity, water and soil preservation while also reducing pesticide and fertiliser use**.** For instance, crop diversification improves both yields and biodiversity (6), benefiting several ecosystem services, such as water and soil quality, as well as pest and disease control. Similarly, organic farming is both in the interests of agricultural diversification and the protection of nature and biodiversity.

Due to time and space constraints, several essential elements were either only briefly discussed or omitted in this document, but they remain critical for a comprehensive approach to sustainable farming. Strengthening these practices through well-structured regulations, incentives, and subsidy reforms will further support their adoption (Chapter 2).

Table 1 Elements of a sustainable agricultural transition

ELEMENT	EXAMPLES	EXAMPLES OF IMPLEMENTATION IN LUXEMBOURG AND EUROPE	RELATED RISKS AND CHALLENGES
Adapting sustainable agronomical practices (Chapters 3, 4, 5)	Encouraging crop rotation and diversification, buffer strips, mechanical weeding, sustainable management of livestock effluents, regulation of livestock numbers, systematic use of rainwater	ADAPT -Smart Cropping to Adapt Luxembourg Agriculture to Climate Change;	Impact on soil erosion, fuel consumption and food security
Digital transformation	Smart or precision farming to help farmers increase the quantity and quality of agricultural production while using fewer inputs	Lux5GCloud -Luxembourg 5G Smart Country Data Cloud Digital Pilot Farms - Towards a network of pilot farms for demonstrating, evaluating and implementing innovative techniques and decision support tools in crop protection Partnership with Luxinnovation	Excessive workload for IT support services, digital divide, significant time for setup
Monitoring biodiversity, as well as intrant use and occurrence in the environment (Chapters 3, 4, 5)	Research on the productivity and profitability of agricultural practices, on the risk of intrant use for the environment, farmers and society, on the effectiveness of policy actions	European regulation on "Statistics on agricultural input and output (SAIO) " aims at providing statistics for the evaluation of the agricultural EU policies Service d'économie rurale	Challenges in measuring long-term impacts, increase in administrative burden for farmers
Exploiting renewable energy sources (Chapter 6)	Biogas production from agricultural waste, Agri-photovoltaics	Ongoing and second call for tenders for Agri-photovoltaics projects in Luxembourg.	Potentially in competition with food and feed production
Promoting organic farming practices (Chapters 3, 4, 5)	Advancing organic farming practices as a sustainable alternative or complement to conventional agriculture helps reduce the use of antibiotics, thereby lowering the risk of antimicrobial resistance.	PanBio 2025: increase the proportion of organically farmed land in Luxembourg to 20% by 2025;	Food security concerns, access to organic foods for low-income populations

Table 1 (continued)

ELEMENT	EXAMPLES	EXAMPLES OF IMPLEMENTATION IN LUXEMBOURG AND EUROPE	RELATED RISKS AND CHALLENGES
Economic Viability, Supporting local production and the next generation of farmers (Chapter 7)	Strengthening local markets to foster community-based economies, Addressing challenges and opportunities for young farmers.	Flat-rate payment for young farmers	
Conservation covenants (Chapter 3)	Tailored contracts with farmers to implement biodiversity-friendly measures	Biodiversity contracts: Top-up for management of ecologically valuable habitats classified as biotope[1] Nature genéissen by SICONA: Contracts with local farmers to distribute their products when complying with conservation standards.	No long-term solutions

[1] Règlement grand-ducal du 24 juillet 2024 relatif aux aides en faveur de la sauvegarde de la biodiversité en milieu rural

1.3 – Opportunities and challenges for Agriculture and Rural Development in Luxembourg

In 2023, agricultural land and meadows made up approximately 50% of Luxembourg's total surface area and was managed by 1,822 farms, with approximately half of these farms exceeding 50 hectares in size (7). The number of farms is decreasing (~-30% between 200 and 2023), while the total utilized agricultural area remains relatively stable, leading to an increase in the average farm size. Livestock numbers are stable or decreasing, except for poultry (7). Similar changes have been observed across the EU-28 (8). In addition to the global challenges in agriculture, Luxembourg's agricultural sector faces distinct challenges and opportunities on the path to sustainability (Table 1).

Table 2 Specific challenges and opportunities for sustainable agriculture in Luxembourg

CHALLENGES RELATED TO	OPPORTUNITIES RELATED TO
Agricultural development (7): Ongoing decline in the number of farmers, difficult access to farmland for new farmers, lengthy procedures; cross-border farmland	Small country size: Small number of well-connected players and proximity between economic centres
Difficult climatic situation : periods of water stress or excessive rainfall due to climate change, which remain insufficiently addressed by adaptation measures	Knowledge and innovation system : Excellent access to high-speed internet do develop digital farming
Organic farming: While on the increase, organic farming is struggling to meet the ambitious targets set by the government (9)	Landscape: High landscape diversity
Greenhouse gas (GHG) emissions from a high livestock population : driven by relatively high meat consumption among Luxembourg residents	Funding : direct aid from the Common Agriculture Policy made up 24.0% of annual farm income, compared to an EU-wide average of 18.8%.

2. Advancing sustainable agriculture in the EU via the Common Agricultural Policy

- *What are the main objectives of the Common Agricultural Policy (CAP) 2023–2027?*
- *How does CAP combine mandatory and voluntary initiatives to achieve its goals?*
- *How is the effectiveness of CAP evaluated, and what improvements are suggested for the post-2027 CAP?*

2.1 – Key objectives and strategic approach of the CAP 2023–2027

The Common Agricultural Policy (CAP) 2023–2027 shifted its focus towards policy performance and tangible environmental benefits across key areas such as climate, water, soil, biodiversity, and animal welfare (10)**.** This approach aims to enhance the sustainability and resilience of the agricultural sector in the EU, aligning with the ambitious targets established by the EU Green Deal and the Farm to Fork strategy. A core priority includes ensuring fairer incomes for agricultural producers while simultaneously boosting the competitiveness of agricultural and agri-food businesses (11). Under CAP, farmers receive payments through two main funds: (1) European Agricultural Guarantee Fund (EAGF) and (2) European Agricultural Fund for Rural Development (EAFRD)[2].

All farmers receiving CAP support must adhere to EU standards on Good Agricultural and Environmental Condition of land (GAEC) (12)**. CAP combines mandatory conditionality with voluntary initiatives to comprehensively achieve its objectives** (13) (Figure 1). Examples of conditionality under CAP include crop rotation improving soil health, buffer strips along watercourses reducing nutrient runoff and soil management practices improving soil organic matter. Voluntary schemes include eco-schemes (Section 2.2 –), which lead to environmental benefits. For example, support for organic farming helps reduce chemical inputs, improves biodiversity and provides farmers with higher product prices. National priorities and strategies aligning with EU-wide objectives are discussed in Section 2.3 – .

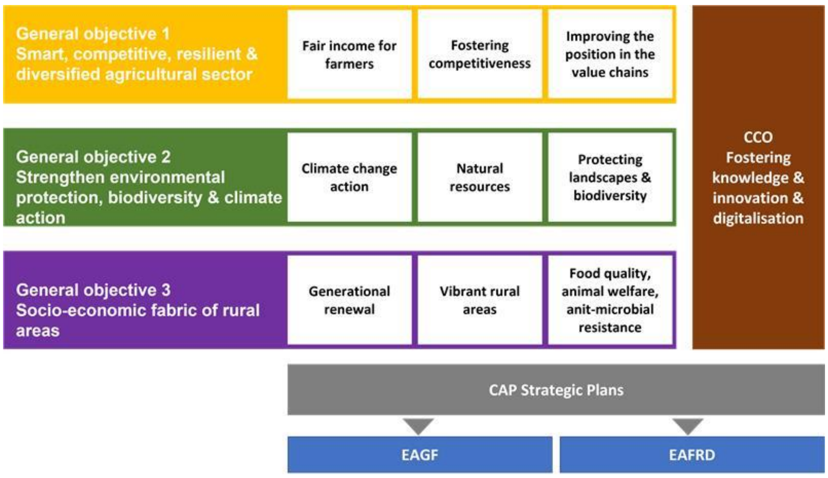

Figure 1 Showing ten objective of CAP 2023-27 under general, specific and cross cutting objectives (data from (14)

[2] *Luxembourg has lowest contribution to EAFRD 20%, EU average is 60%*

2.2 – Eco-schemes and carbon farming enhance sustainability in agriculture

Eco-schemes are designed to support farmers in the following areas of action: climate mitigation or adaptation, water management, soil management, biodiversity, animal welfare and anti-microbial resistance (15). These schemes are tailored to the specific needs identified at national and regional levels. The national strategic plan of Member States must cover at least two of these areas through their eco-schemes. Importantly, their ambitions should exceed baseline requirements while contributing to the EU Green Deal targets.

To bring real-world impact and concrete achievements, 25% of direct payments are allocated to eco-schemes. Income support under eco-schemes also compensates for lost income resulting from farmers commitment to environmentally friendly practices. To mobilise the support for organic farming (16), an additional stream of funding is provided through eco-schemes, which includes technical assistance, knowledge exchange, and innovation sharing using Agricultural Knowledge and Innovation Systems (AKIS).

Farmers can combine different eco-schemes, leading to a holistic transition of their farms while maximizing environmental benefits. For example, agroecology can be integrated with Carbon farming to enhance the productivity and biodiversity of degraded land, improving resilience to climate change (17). Carbon farming is a land management practice that rewards farmers for enhancing carbon capture in soil or reducing carbon emissions to the atmosphere (18). To ensure climate change mitigation, only carbon sequestration beyond business-as-usual levels is eligible for compensation. However, farms that have long embraced agroecological practices may face challenges in demonstrating further improvements to earn carbon credits. To address this, a normative baseline is suggested to fairly recognize the efforts of sustainable farms while maintaining the integrity of carbon farming initiatives (19).

Points-based eco-schemes can be designed to assign different weightings to various practices based on their expected positive impact. This approach encourages farmers to adopt practices that are most relevant to the environmental and climate-related needs of their farms and regions. Examples of such practices include pesticide management, organic farming, nutrient management through precision agriculture, and water management. **Luxembourg has implemented eco-schemes for climate change mitigation, water, soil, biodiversity, and pesticide use; however, it currently lacks eco-schemes for climate change adaptation and animal welfare.**

2.3 – National strategic plan and performance monitoring in the CAP

Each Member State has elaborated its own CAP strategic plan to ensure coherence across CAP instruments and the strategic, complementary use of resources. These plans aim to improve farmers' income and food security (20), drive climate action, safeguard natural resources, enhance biodiversity (15) and strengthen socio-economic aspects of rural areas. This is achieved through a mix of conditionality (GEACs) and voluntary interventions including. Standardized indicators that track environmental benefits (21) are used in the Performance Monitoring and Evaluation Framework to produce annual reports (14).

Performance is measured by a set of 44 indicators mostly represented as payments per hectare and per livestock unit (22)**.** For a holistic outcome, farmers should integrate various eco-schemes with national schemes prioritizing ambitious conditionality standards. The initial situation of each Member State in terms of aid distribution must be considered, explaining the choices made. **Luxembourg, for example, supports 49% of its farmers** (23) **through basic income support for sustainability and 25% using eco-schemes** (14).

Table 3 The strategic planning of Luxembourg for each CAP objectives (23)

CAP OBJECTIVES (25)	SCHEMES IN LUXEMBOURG
To ensure a fair income for farmers (24)	• 19% of farmers received investment to modernize livestock buildings, integrating biogas production or photovoltaic panels • Special attention is given to the beef and veal production sectors • Support is directed towards medium-sized family farms
To foster competitiveness	• Fostering agriculture modernization by supporting the digital transition on farms and in the agri-food sector. • Developing technological and institutional infrastructure to produce and exchange data, while also supporting agricultural investments in digitalization and technical innovation, such as aquaponics and vertical farming.
To improve farmers position in value chain (25)	• Diversifying agri-food value chains by supporting programmes, knowledge, finance, technology, equipment, infrastructure, networks, markets, and business opportunities for the agri-food sector (Betrib 2030) • Support will be provided for farms in the poultry, fruit & vegetable sectors • Livestock reduction will be encouraged through payments under eco-schemes
To take climate change action	• Reducing greenhouse gas emissions, ammonia, and improving manure management per livestock unit • Modernizing livestock buildings with low-emission techniques • Providing financial support to farmers willing to raise livestock in a less intensive manner • Integrating renewable energy to support the production of beef, veal, fruits, vegetables, and cereals (Chapter 6)
To protect natural resources	• Promoting the sustainable use of permanent pasture • Requiring all farms receiving CAP payments to maintain a portion of farmland with ecological importance • Rewarding farmers who refrain from using pesticides (50% reduction by 2030), (Chapter 5)
To protect landscape and biodiversity	• Maintaining permanent grasslands, ecological focus areas, and traditional landscapes to enhance biodiversity. • Farmers managing ecological interest areas will receive financial support, contributing to ecosystem services and habitat conservation (Chapter 3)
To support generational renewal	• Addressing Luxembourg's ageing farming population and ensuring sector sustainability. • Providing start-up grants of up to €100,000 to incentivize young farmers • Offering financial aid for 132 young farmers.
To foster vibrant rural areas	• LEADER initiative benefiting 72% of rural population to promote social inclusion (185) • Restoring, preserving, & enhancing ecosystems related to agriculture & forestry (25)
To protect food quality, animal welfare and anti-microbial resistance	• Investment support is provided only if organic farming rules are respected. • Aiming to reduce antimicrobial use by 50% by 2030 • Increasing land dedicated to organic farming by 20% (currently at 6%)
To foster knowledge and innovation	• Collaborating with Luxinnovation to boost agri-food competitiveness & sustainability through innovation, digitalisation, & partnerships with research players • Providing financial support to improve farmers' expertise in managing bee diseases and pests • Further advancing digitalisation in the agricultural sector • Creating an interface between researchers, farm advisors and farmers to improve the quality and effectiveness of agricultural advice • Developing the Agricultural Knowledge and Innovation System (AKIS) and participating in European Innovation Partnership for organic farming, alternative production, and related initiatives.

2.4 – Evaluation of the CAP 2023-2027 effectiveness

The evaluation of CAP's success in achieving its environmental and climate objectives depends on the actual implementation of eco-schemes and Agri-environment-climate Measures (AECM) (26)**, their uptake by farmers, and the application of conditionality.** AECM payments are linked to the achievement of defined environmental outcomes through land management practices, allowing flexibility in choosing the most suitable practices to meet those results. The European Commission will conduct an interim evaluation by December 2026 with ex-post evaluation in 2031 (27) to assess the effectiveness, efficiency, relevance, coherence, and EU added value of the EAGF and EAFRD funds.

The AECM evaluation requires sufficient scientific knowledge and data on the causal relationship between desired outcomes and land management, as well as a clear method for measuring and monitoring farm-level indicators (28). Enhanced measurement and reporting, leveraging diverse data sources such as satellite imagery, ground research, and farmer-reported practices are required to ensure the environmental benefits (29).

Payments should be tied to verified environmental outcomes rather than merely adopting new technologies. Instead of flat-rate payments, eco-schemes should provide financial support proportional to the environmental benefits delivered by farmers (30).

For future CAP reforms, priority should be given to transitioning toward extensive, regenerative livestock systems promoting pasture-based feeding, rotational grazing, and reduced livestock densities over minor improvements in intensive farming systems. Developing methodologies for seamless data sharing among stakeholders through a mobile application can further enhance monitoring while ensuring farmer privacy is protected (31).

To assess the fairness of CAP (Regulation 2021/2115) in ensuring a more equitable distribution of income support among farmers through direct payments —particularly through capping and degressivity—social conditionality should also uphold the social and labor rights of agricultural workers.

2.5 – Future outlook: post-2027 CAP and the Bioeconomy

By the end of the current CAP, the integration of bioeconomy principles is expected to drive significant progress in sustainability, resource efficiency, and rural development. **Achieving these goals requires dedicated research efforts to support contextual bioeconomic systems, evaluate bioeconomic transitions, and identify effective implementation strategies** (26).

Looking beyond 2027, the upcoming Bioeconomy Strategy will likely further promote carbon sequestration, the replacement of fossil-based products with bio-based alternatives, and the enhancement of waste valorisation. Biogas production from agriculture waste is instrumental in preventing methane emissions from waste decomposition through anaerobic digestion. It also reduces reliance on fossil fuels by integrating into gas grids, while its by-product, the digestate (32), can serve as a biofertilizer, supporting circular agriculture. The use of digestate also supports the EU Biodiversity Strategy 2030 by reducing nitrogen and phosphorus pollution from chemical fertilizers (33,34).

Continued government support through attractive feed-in tariffs and investment aid for decentralized biogas plants will facilitate energy recovery from organic waste streams, enhancing circularity in the agricultural sector (35).

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In Luxembourg efforts are focused on fostering a circular economy by leveraging synergies across various sectors for sustainably managing biodiversity, water, food, health and climate change. By integrating urban and rural resources, key focus areas include converting food waste into energy and developing sustainable construction materials through regional biomass value chains that can also contribute to carbon storage. To foster a sustainable bioeconomy, Luxembourg can build on insights from ongoing research in biomaterials, circular practices, and sustainability assessments conducted by national research institutes such as the University of Luxembourg, LIST, and LISER.

3. The role of agriculture in biodiversity & nature conservation

- *Why is biodiversity important for agriculture?*
- *Why is farmland so important for biodiversity conservation?*
- *What are the major drivers of biodiversity loss in farmland?*
- *How can we improve the status of farmland biodiversity?*

3.1 – Biodiversity is essential to agricultural land use and human health

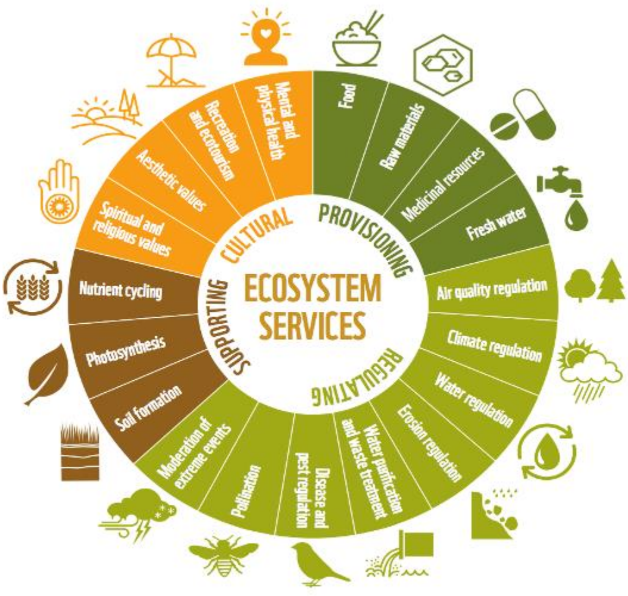
All types of agriculture depend upon biodiversity and ecosystem services (Figure 2**).** These services include provision of soil health, nutrient cycling, pollination, biocontrol, suppression of pathogens, water supply and purification, as well as climate regulation (36). With its ecosystem services, biodiversity is a precondition for the long-term viability of farmland production (37). Nature's contributions to people are not fully replaceable, and some are irreplaceable (38).

Biodiversity increases the stability of ecosystem functions through time (36)**.** Species-rich ecosystems, including meadows, are known to have a higher resistance against climatic extremes (39) as well as against invasions of non-native alien species (40).

Diverse species communities are also more productive. This is caused by differences in functional traits among organisms which increase total resource capture (36). Plant species diversity in grasslands enhances the production of fodder and resilience against climatic fluctuations.

Soil organisms enhance agricultural productivity and sustainability. They improve crop yield, nutrient uptake and reduce nitrogen leaching losses (41). Soil is an essential, non-renewable resource for agriculture, providing the basis for the production of food, fibre, and other resources for a circular bioeconomy (42). Nutrient mineralization and soil organic matter increase with plant richness (36).

Dung- and carrion-feeding organisms help to prevent spread of pathogens (43)**.** Coprophagous and necrophagous insects, as well as soil bacteria help to reduce the risk of human pathogens. On the soil surface, a diverse dung beetle community is capable of removing >90% of animal waste over several days. Organic farms maintain species-rich bacterial communities the effectively suppress persistence of pathogenic *E. coli* (44).



Source: WWF Living Planet Report 2016

Figure 2 Ecosystem services. "*Provisioning services are the products obtained from ecosystems, regulating services are the benefits obtained from the regulation of ecosystem processes, cultural services are the nonmaterial benefits people obtain from ecosystems and supporting services are those services that are necessary for the production of all other ecosystem services.*"(45)

More than three quarters of global food crops rely to some extent on animal pollination. The vast majority of pollinators are wild insect species (46). The most important pollinator groups in Luxembourg are wild bees, flies, moths and beetles. Many of these insect groups are poorly studied and neglected in biodiversity monitoring and conservation.

Biodiversity loss leads to a decline of ecosystem services. There is unequivocal evidence that biodiversity loss reduces the efficiency by which ecological communities capture biologically essential resources, produce biomass, decompose and recycle biologically essential nutrients (36).

3.2 – Agricultural ecosystems maintain a large proportion of Luxembourg's biodiversity

About half of all European animal and plant species rely on agricultural habitats (47)**.** Agriculture shapes habitats and supports a wide variety of species among plants, animals, fungi and microorganisms. These species have co-evolved with large wild herbivores, which were later replaced by livestock grazing and other types of agricultural land use (48).

More than half (55%) of the native plant species in Luxembourg are associated with agricultural ecosystems (Figure 3**).** In agricultural ecosystems, such as dry and wet grassland, heathland, fallow land and arable fields, 688 native species have been reported, while forests maintain 363 species (29%) (49). These species require agricultural land-use and are threatened by both abandonment and intensification of agricultural practices.

Livestock grazing increases structural diversity of grassland habitats (50), The increasing structural complexity caused by livestock grazing promotes a higher diversity and abundance of invertebrates. More complex and species-rich grasslands allow greater opportunities for selective feeding. The impact of livestock on biodiversity is determined by the grazing livestock species and type, livestock density as well as the growth characteristics of the plant species. Too high livestock densities decrease structural heterogeneity of grassland habitats.

Traditional farming systems have a high conservation value (26). Farming practices that have changed relatively little over long periods of time maintain a high biodiversity.

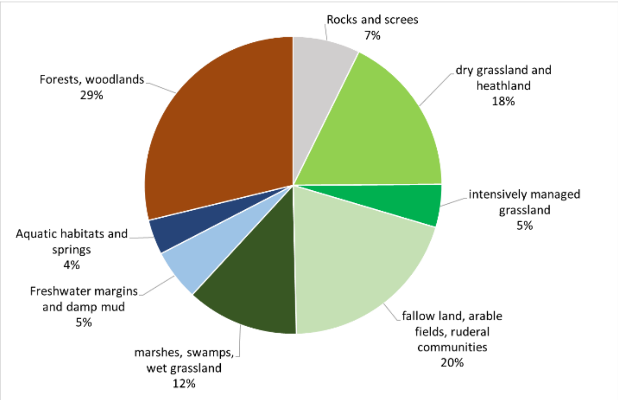


Figure 3 Major habitats of plant species in Luxembourg (data from (49)**).**

3.3 – Changes in agricultural land use are a major driver of biodiversity loss

Due to the large extent of farmland in Luxembourg, any changes in agricultural land use have vast consequences for biodiversity, this includes abandonment as well as intensification of land use. Larger farm sizes lead to a loss of diversity in agricultural land-use and larger fields, which translates to a loss of biodiversity (51–53), while smaller crop fields maintain a higher biodiversity (53). Land abandonment is, therefore, a major threat to biodiversity.

A total of 48,500 species of animals, plants and fungi (out of 163,040 assessed species globally) are threatened by changes in agricultural land-use (54)**.** These changes include homogenization of agricultural practices, larger plots, larger and heavier machines, loss of field margins and similar structures, use of fertilizers and pesticides (Chapters 4 and 5), decreasing crop diversity, higher livestock densities, earlier and more frequent mowing, drainage, irrigation (Chapter 5), plowing, rolling, abandonment of historical management techniques, but also land abandonment coupled with rural exodus (55).

In Luxembourg, about half (47%) of the plant species associated with dry grasslands, heathlands, arable fields, wet grassland, fallow land and ruderal habitats are either threatened or extinct (Figure 4**)** (49)**.** Species associated with dry grasslands are often adapted to nutrient-poor conditions and low livestock densities (49). Species associated with arable fields are threatened by the use of pesticides, fertilization, larger fields and large machines. Species in wet grassland are threatened by drainage, frequent mowing, high livestock densities. 13% (87 plant species) associated with these habitats are already extinct (49)

About half (52%) of all threatened or extinct bird species in Luxembourg are associated with agricultural areas (64% among the extinct bird species) (56). Extinct bird species include species living in wet meadows (corncrake, common snipe, whinchat), orchards (woodchat shrike, hoopoe), arable fields & fallow land (crested lark, corn bunting, tawny pipit), and vineyards (wheatear). Several, formerly common species, are highly threatened, such as grey partridge, northern lapwing, great grey shrike, common grasshopper-warbler, meadow pipit, common quail, common barn-owl, western yellow wagtail, Eurasian tree sparrow, Eurasian wryneck, little owl, red-backed shrike, and Eurasian skylark. The European Farmland Bird indicator has decreased by 61% between 1980 and 2022 (

Figure 5**)**.

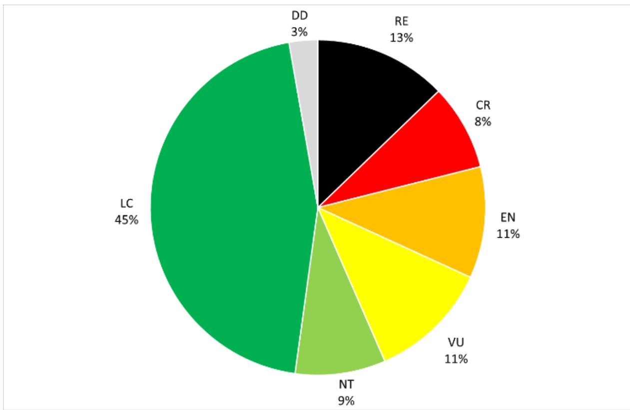


Figure 5 Development of European Common Bird Indicators from 1980 to 2023 (57)**.**

RE = Regionally Extinct; CR = Critically Endangered; EN = Endangered; VU = Vulnerable, NT = Near Threatened; LC = Least Concern; DD = Data Deficient

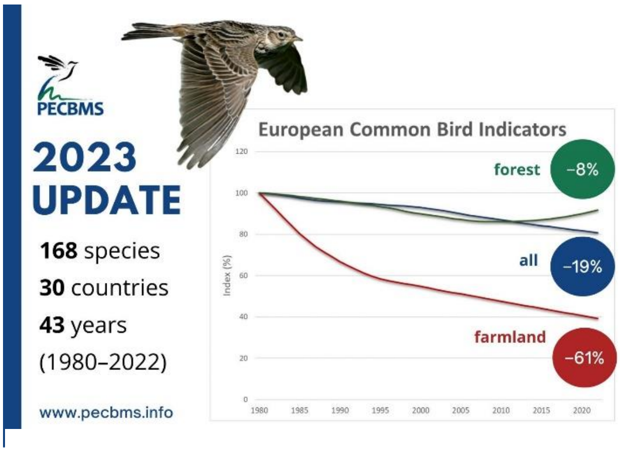


Figure 4 Percentage of threatened plant species in Luxembourg (49)**.**

Agricultural intensification has been identified as the major driver of butterfly declines in Luxembourg (58)**.** Major threats to butterflies are introduction of moto-mechanisation, chemical fertilizers, large-scale plots, loss of crop diversity, loss of hedges and fringes, earlier mowing of meadows, higher livestock densities, conversion of wetland and heathlands into forests, as well as abandonment of marginal sites.

In Luxembourg, agriculture is the major threat to species protected under The Habitats Directive , affecting almost nine out of ten species (59)**.** 85% of the protected species and 64% of the protected habitats are threatened by agricultural land use changes. 83% of grassland habitats and 100% of heathland habitats in Luxembourg have a deteriorated status (49).

High use of fertilizers has negative effects on biodiversity (60)**.** Nitrogen and phosphorous influx in particular lead to eutrophication of grassland and freshwater habitats. This has led to a massive decline of plant species and associated insects (61) (Chapter 4).

Current agricultural practices promote erosion, leading to a decline of freshwater biodiversity (Chapter 4)**.** Lack of field margins and riparian strips fosters erosion and lead to an accumulation of sediments (siltation) in Luxembourg's running waters (62). This destroys microhabitats of freshwater organisms and prevents restoration of freshwater habitats, such as restoration of the Our river for threatened freshwater mussels.

Homogenization of agricultural practices promotes biotic homogenization (63)**.** Ecosystems become spatially more similar, often by replacement of locally adapted specialist species with more widespread species. This is the consequence of global cultural homogenization, including similar agricultural techniques, similar crop types and livestock breeds. A higher diversity of crops promotes biodiversity.

Drainage and regulation of water courses has massively reduced biodiversity in wetlands (64) (Chapter 4)**.** Wetland species are particularly threatened in Luxembourg, with 44% of plants associated with marshes, swamps and wet grassland, and 61% of the plants associated with freshwater margins, and 58% of the plants associated with aquatic habitats being threatened (49).

Intensification of grassland management has a strong impact on biodiversity (65)**.** Higher livestock densities, earlier and more frequent mowing, as well as rolling impacts plants, birds and insects.

Land abandonment is a major threat to biodiversity (66)**.** As a consequence of decreasing numbers of farms, marginal sites are often abandoned, leading to succession by shrubs and trees. This is a particular threat to sites which do not provide any economic benefits.

3.4 – Improving the status of farmland biodiversity through policy actions

Recreating habitat heterogeneity is key to restore farmland biodiversity (67). Blanket solutions are not suitable for biodiversity restoration. Any restoration approaches must be adaptive and able to respond to requirements of both farmers and biodiversity. Restoration of wetlands in combination with extensive cattle grazing leads to an increase in biodiversity (68). A restoration project at the Syr river had positive effects on plant diversity (68).

Luxembourg is a member state of several international conventions aiming at reversing the decline of biodiversity. The Kunming-Montreal Global Biodiversity Framework of the convention for biological diversity includes several international goals, including the target to restore 30% of all degraded ecosystems by 2030, the target to effectively conserve 30% of all areas, the target to halt human induced extinction of threatened species, the target to reduce pollution to levels that are not harmful to biodiversity, and the target to enhance biodiversity and sustainability in agriculture. UN Sustainable Development goal 15 aims at protecting, restoring and promoting sustainable use of terrestrial ecosystems and halt and reverse land degradation and biodiversity loss.

The new EU restoration law makes it mandatory to put in place restoration measures to enhance biodiversity in agricultural ecosystems. The law also includes the obligation to restore at least 30% of threatened habitat types, including semi-natural dry grasslands, species-rich *Nardus* grasslands, and lowland hay meadows. Article 10 of the Restoration Law makes it mandatory to improve pollinator diversity and reverse the decline of pollinator populations by 2030.

Luxembourg's biodiversity strategy (PNPN3) aims at restoring farmland ecosystems. It also contains goals to restore freshwater habitats and soil ecosystems, reduce pollution and re-establish habitat connectivity.

Some CAP direct payment requirements, notably greening, and cross-compliance, have potential to improve biodiversity. However, the Commission and Member States have often favoured low-impact options (69) (Chapter 2).

Financial instruments exist to promote biodiversity-friendly measures. In Luxembourg, the "Règlement grand-ducal du 24 juillet 2024 relatif aux aides en faveur de la sauvegarde de la biodiversité en milieu rural" provides an additional payment for sites under the biodiversity contract (70). This payment increases with higher conservation status of the site and provides funding for a wide range of measures, including biodiversity-friendly management and restoration of grassland, orchards, hedgerows, flower strips, and other elements supporting biodiversity.

4. Agricultural challenges for water resilience

- *How have societal and economic transformations in Europe over the 20th century impacted water resources?*
- *What are the main sources of water pollution in Luxembourg and Europe?*
- *How does agriculture contribute to water quality issues in Luxembourg?*
- *What policies and strategies are in place to manage agricultural water use and improve water quality?*

4.1 – Water – a resource under intense and increasing pressure

Over the 20th century, Europe has undergone profound societal and economic transformations that have significantly impacted its water environment (71). The continent's demographic growth, agricultural intensification, rapid industrialisation, urban development and energy production, among many others, have exerted mounting pressures on rivers, lakes, transitional waters, coastal waters and groundwaters (71).

The proportion of humanity's demand for freshwater used to meet agricultural and food production needs is estimated at around 80% (72). Agriculture is also by far the largest net water consumer in Europe and, without changes in practices, demand from irrigated agriculture is likely to increase with climate change (71). Water resources are thus globally vulnerable to pollution from human activities. European countries report that the main pressures on **surface waters** are related to pollution from diffuse sources such as agriculture (29%), changes to the physical features and natural flow of waterbodies (51%) and pollution from point sources such as from wastewater discharges (13%) and excessive abstraction leading to increased pollutant concentrations (8%) (71). The main pressures on **groundwater** are reported to be diffuse pollution, especially from agriculture (32%), and abstraction (18%), including agriculture, public water supply and industry (71).

Soil erosion and degradation also leads to microbial and chemical contamination of water bodies and loss of biodiversity (73). It also increases the risks of diffuse runoff, soil fertility decline, nutrient and crop productivity loss, landslide, and most importantly sediment accumulation in waterways and reservoirs. This leads to increased risk of flooding, clogging and disturbance of ecosystems and degradation of water quality (73).

4.2 – Luxembourg's water and agriculture landscapes bear specific characteristics

In contrast to most European countries, most of the water used in Luxembourg is dedicated to domestic purposes and the service and industrial sectors (74–76). The agricultural pressure on water is of qualitative rather than quantitative concern. After all, agriculture uses only about 8% of the total volume of water in Luxembourg (77). Water usage for irrigation is also relatively low, with less than 1.5% (<0.5 million m^3) of total surface water and groundwater being abstracted annually by the agricultural sector (76).

Luxembourg's water bodies are not exempt from diverse pollution

Today, more than 90% of Luxembourg's physical agricultural areas are covered by agri-environment-climate measures (AECM) programmes, placing it in the 1st place among the EU-27 Member States (data from 2017) (78). However, this does not prevent the country's water resources from suffering from point and diffuse pollutions of various origins and magnitudes. Recent surface water quality data for Luxembourg indicate that none of the national and transboundary surface water bodies are in a very good or good state, 42% having satisfying quality, whereas 59% are of insufficient (20%) or bad (39%) quality (79). Groundwater quality was evaluated as 50% good and 50% poor, with groundwater quantity being 100% good.

The most widespread pollutants of agricultural origin are nitrates, phosphates and pesticides (Chapter 5) (71). This leads to the contamination of groundwater and surface water sources and threatens our water resources, biodiversity and soil quality. On average, more than 100 notified water pollution incidents occur annually in Luxembourg of which a significant and increasing proportion are of agricultural origins (leakages, technical problems, accidents, etc.) (Question parlementaire 5583/2022).

Out of Luxembourg's 250 groundwater resources, around 100 are currently unusable because of pollution (77). These locations of poor condition have a cumulative flow rate of about 13 million litres per day, which corresponds to the drinking water needs of around 65,000 people (based on a consumption of 200 litres/inhabitant/day) (Question parlementaire 5937/2022).

4.3 – Nutrient input fosters water quality issues

Nitrogen (N) and phosphorus (P) are essential inputs that promote soil fertility and support plant growth. However, excessive nutrient inputs, can lead to surpluses that can contribute to groundwater and surface water pollution and eutrophication (80).

Nitrogen issues in Europe's and Luxembourg's water bodies

Despite reduced nitrogen balances per hectare and reduced nitrate concentrations in rivers (minus 20 % since 1990; (81)), EU27 levels still exceed critical limits and pose risks of acidification and eutrophication of freshwaters, reduced richness in plant and animal species, and atmospheric emissions such as ammonia and greenhouse gases (82).

Of the 114 parameters regularly measured in Luxembourg's groundwater sources, nitrate is among the 4 that regularly exceed threshold values (83). **Luxembourg has the highest percentage of nitrate concentrations in drinking water, ranging from 10 to 50 mg/L (89% of sources; with the remaining 11% even above the threshold value of 50 mg/L)**, while the vast majority of European countries measure nitrate concentrations below 10 mg/L in at least 50% of their drinking water resources (84).

Nitrogen inputs from urban wastewater have been halved since 2004, thanks to investment in wastewater treatment (85). **In the agricultural sector, measures related to drinking water protection zones and agri-environmental programmes are bearing fruit, even though the long-term effect still needs confirmation due to the long infiltration times in the water column and turnover in the water cycle.** Nevertheless, more needs to be done to achieve the objectives of the Nitrate Directive (85). Efforts also need to continue in the urban sector (85). Changes are mainly driven by the decrease in manure excretion due to reduced livestock numbers and reduced use of mineral fertiliser, while the adoption of agricultural practices has only a minor impact (82,86).

4.4 – Phosphorus issues in Europe's and Luxembourg's water bodies

Phosphorus issues in water, particularly in relation to agriculture, can be significant. **Even though the phosphorus surplus at EU level decreased by 70% between 2004 and 2015, excess phosphorus from fertilizers can run off into water bodies** (87). (*Sustainable agricultural practices and methods – Agriculture and Rural Development*). This leads to excessive growth of algae, which depletes the oxygen in the water and harms aquatic life. The filtering capacity of soils generally results in an efficient retention in soils, except during major rainfall events in winter or spring.

In Luxembourg, soil samples are taken every 5 years at farm level and analysed for the presence of phosphorus and other elements that determine soil fertility. At national level, median phosphorus concentrations have decreased in the 2016-2024 reference period compared to the 2008-2016 reference period (from 16 to 14 mg P_2O_5/100 g dry soil in arable land and from 13 to 10 mg in permanent grassland) (Question parlementaire 1080/2024).

Regulatory measures are intended to prevent agricultural phosphorus inputs into the tributaries (88). Restrictions on grazing and feeding, together with the maximum levels of phosphate (particularly in maize) and nitrate fertilisers, limit potential leakages into water protection zones, specifically in the catchment area of the Upper-Sûre reservoir. Wastewater treatment projects will further reduce the discharge of phosphorous into watercourses (Question parlementaire 1080/2024). Specific agricultural advice aims at reducing phosphate inputs in animal feed (83). The LAKU – "Landwirtschaftlech Kooperatioun Uewersauer" - cooperative has set up a specialised farm advisory service, backed up by a programme of measures and budgetary resources, to promote water protection techniques.

4.5 – Agriculture-centred levers for water resilience in Luxembourg

Efforts to improve water use efficiency and to manage water resources in a sustainable way are needed on many levels, especially with regard to agriculture, climate change and its potential impact on water availability (76). National water policies need to be adjusted to local contexts in a geographically and climatically diverse European Union (82).

The coalition agreement of the current government in Luxembourg foresees several strategic measures aim at bridging agricultural and water related issues (89):

- Drawing up a national strategy for water in agriculture
- Involvement of farmers, winegrowers and horticulturalists in the development of national climate, environmental and water protection objectives, according to scientific criteria
- A national water strategy for groundwater and surface waters under increasing pressure from climate change, prolonged droughts and irregular rainfall, in addition to strong demographic and economic growth, to avoid water allocation conflicts
- Creation of retention basins and underground water reservoirs into which water can drain in the event of heavy rainfall, thus preventing flooding during the winter. These water reserves can subsequently be used during periods of drought for irrigation purposes, for example

A number of action plans are currently being discussed in the expert committees for agriculture ("Landwirtschaftsdësch") and water ("Waasserdësch"):

- Instauration of an "Ammonia taskforce" considering adaptation of urea-based fertilisers, addition of additives when spreading and storing slurry, optimisation of nitrogen feed for cattle and herd management
- Reduction in ammonia emissions with a national target of -22% by 2030
- Modification of the drinking water protection zones and nitrates regulations
- Preparation of a guide to best practice for water protection in agricultural areas

The development of horticultural production is an important issue in meeting the growing public demand for home-grown fruit and vegetables, with the necessity to provide access to the required quantity and quality of water.

The new law on drinking water, transposing the EU Drinking Water Directive of 2020, provides for the adoption of a risk-based approach in water protection zones and water supply infrastructures through Water Safety Plans (Lux-WSP) and the “Drëpsi” excellence certificate from 2023 (83).

4.6 – Agricultural policies at EU-level guide water management actions

According to the European Court of Auditors (ECA), EU policies are failing to ensure that farmers use water sustainably. Less than 40% of surface water currently meet the requirement of good quality (71). This raises concerns about the potential for policy changes to counteract the increasing scale of production and consumption, in terms of impacts on water quality (90). Some of the Farm to Fork targets, such as reducing the overall use of pesticides, fertilisers and antimicrobials, are directly related to water quality. At the same time, the Farm to Fork does not seem to systemically address the sustainable management of water resources (82).

Potential of joint agriculture-water initiatives and research

Addressing agricultural water pressures will require going beyond the strict remit of water policy (91). **Sustainable management practices have multiple benefits, helping to reduce the magnitude of pressures on water, while also reducing greenhouse gas emissions, improving the long-term resilience of agriculture to climate pressures and benefiting biodiversity** (91). Together they pave the way to a non-toxic environment, set multiple targets for input reduction and promote more sustainable agricultural production overall.

The main strategies for increased water resilience through agricultural action include (72,92–97):

- Practices to increase water availability for crops and livestock
- Farm resilience to water scarcity
- Adapting agricultural practices to local conditions
- Developing innovative solutions for the use of alternative water sources in agriculture
- Developing economically viable on-farm water recycling and implementing grey/black water reuse strategies
- Evaluation of vertical closed-loop systems that use little land and water
- Eco-schemes to support farmers who introduce or maintain farming practices that contribute to EU environmental and climate goals
- Investment measures that can be used to cover the costs of capital-intensive changes, e.g. non-productive investments such as the restoration of wetlands and peatlands or the creation of landscape features
- Conservation of natural resources that benefit to the public and are not reflected in market prices
- Transboundary water cooperation and funding of basin-scale research projects aimed at introducing modern, environmentally friendly agricultural practices and reducing the deposition of nutrients and pesticides from international sources
- Promoting the digitisation and analysis of agricultural data to improve water quality assessment, including the identification of possible correlations, and to optimise the early detection of new pollutant loads

Finally, the Water Framework Directive requires Member States to take into account of the principle of cost recovery for water services, including environmental and resource costs, in line with the polluter-pays-principle. Resilient water pricing will also ensure that the right incentives for water use, and conservation are in place (82).

5.Sustainable use of pesticides

- *What are the benefits and drawbacks of pesticide use in agriculture?*
- *How can pesticide use in other regions impact European agriculture, particularly in the context of trade agreements like the EU-Mercosur Free Trade Agreement?*
- *What challenges arise in regulating pesticide use, especially regarding PFAS-containing pesticides and Glyphosate, in Luxembourg and other countries?*

5.1 – The downsides of rising pesticides use

Agricultural intensification came along with an increasing use of pesticides[3] and fertilizers[4]. The advantages of using those intrants in agriculture encompass minimizing crop loss, reducing workload, extending the shelf life of agricultural products and lessening soil disruption (98,99) (Figure 6).

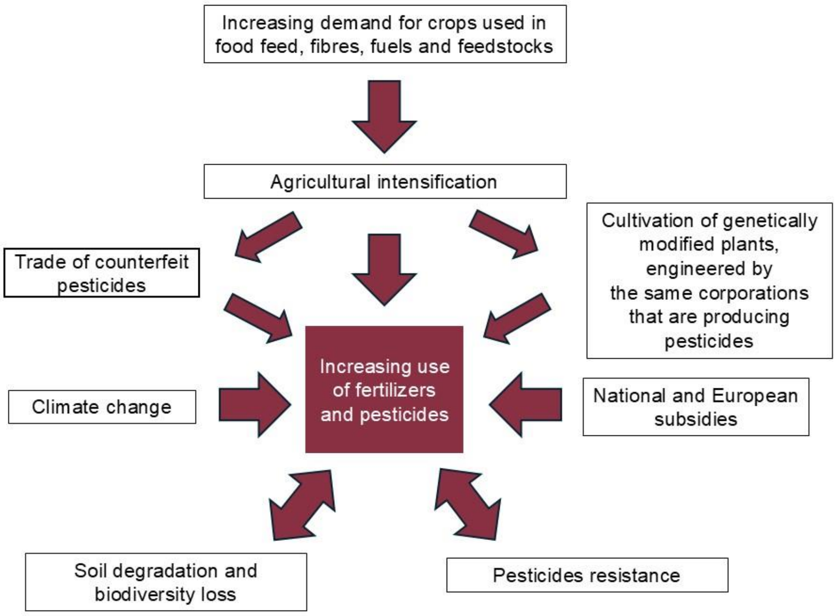


Figure 6. Drivers for the use of fertilizers and pesticides

Inappropriate use of pesticides may however represent a risk to human health and the environment (98,100). The environmental and health risks associated with a specific pesticide depend on the characteristics of its active substance(s), e.g. the toxicity and persistence of residues in the environment and the application method, volume and timing. Environmental pollution can occur through various pathways, such as wind drift, surface runoff, and infiltration (99). Short (acute) and long-term (chronic) effects of occupational and unintended (e.g. dietary) exposure to pesticides potentially include various diseases, e.g. childhood leukaemia (101), Parkinson's disease (102) and hormone/endocrine disruption (103), congenital abnormalities (104) and adverse birth outcomes (105). Moreover, accumulation in non-target organisms and

[3] *"A 'pesticide' prevents, destroys, or controls a harmful organism ('pest') or disease, or protects plants or plant products during production, storage and transport"(197). They can be grouped into different categories, depending on their target (herbicides against weeds, insecticides against insects, etc.), the origin of their active substances (chemical or non-chemical), or their hazard to health and the environment (134).*

[4] *A 'fertiliser' compensates the deficit in key nutrient thereby supporting healthy plant growth and enhancing the production of biomass in the plant. Without replenishing these nutrients, the soil's fertility diminishes with each harvest. The primary components of fertilizers are nitrogen, phosphorus, and potassium (98,198).*

decrease in biodiversity have also been linked to pesticides, e.g., decline in European bird populations (106), insects (107,108) and pollinators (109)

5.2 – The global energy, food and intrant supply chains are interconnected

Food production and security is depending on the availability and affordability of essential inputs like pesticides and mineral fertilizers, whose costs are closely tied to energy prices (110)[5]. As Russia and Ukraine play a major role in global crop and fertiliser supply, Russia's invasion of Ukraine in 2022 has led to a price rise and consumption drop of mineral fertilizers consumption affecting farmers in Luxembourg and elsewhere in Europe (111–116). Markets for agricultural products and inputs stabilized during 2023.

Consumption of pesticides and fertilizers remains stable or decreases in Luxembourg and other Western European countries (117–119). Nevertheless, nearly a quarter of all pesticides continue to be sold within the European Union (120) and detection frequencies of pesticides continue to increase in surface waters in Europe (121).

EU-Mercosur Free Trade Agreement (FTA) and European Agriculture

On December 6, 2024, the European Commission and Mercosur's four founding members (Argentina, Brazil, Paraguay, and Uruguay) finalized negotiations on the EU-Mercosur Free Trade Agreement (FTA) (122). This agreement, decades in the making (123), aims to enhance trade by eliminating customs duties on 91% of EU goods exports to Mercosur and 92% of import duties on Mercosur exports to the EU (124). While the FTA would create the largest free trade zone ever established by the EU, it also introduces trade restrictions for sensitive agricultural sectors, such as beef, through tariff rate quotas. Additionally, more than 350 EU products will be protected by a geographical indication (125). Currently, multiple ratification scenarios for the FTA are under consideration (126).

The agreement is expected to have significant economic implications, benefiting key European industries, while providing Mercosur's agribusiness sector with expanded market access. However, concerns were risen regarding its environmental and sanitary impacts, including deforestation, emissions, soil contamination, and the use of pesticides (123,127–131).

Despite several amendments to protect the environment in Mercosur countries and the agricultural sector in Europe, the FTA still permits Mercosur exports to enter the EU under existing import standards without adhering to EU production standards (123,125,132). Critics from agricultural associations (among others) fear that the agreement could encourage increased trade and use of hazardous pesticides, including those banned in the EU (123). Although many developed countries have reduced or banned the use of Highly Hazardous Pesticides (HHPs)[6], HHPs are exported by European companies to developing countries where pesticides are less strictly regulated (120).

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[5] The cost for natural gas represents 60-80 % of the operating costs for producing nitrogen-based fertiliser, which is the most used fertiliser in the EU in volume. Natural gas is used as source of hydrogen, with the remainder employed to power the synthesis process (199).

[6] *Highly Hazardous Pesticides are "pesticides that are acknowledged to present particularly high levels of acute or chronic hazards to health or environment according to internationally accepted classification systems such as WHO or GHS or their listing in relevant binding international agreements or conventions. In addition, pesticides that appear to cause severe or irreversible harm to health or the environment under conditions of use in a country may be considered to be and treated as highly hazardous"*

5.3 – Challenges in regulating pesticide use at national and global levels

Many policy elements attempt to reduce the production and use of pesticides (Figure 7)**.** Under the Farm to Fork strategy (part of the European Green Deal), the European Commission announced two non-legally binding pesticide reduction targets by 2030: a 50 % reduction in the overall use of and risk from chemical plant protection products, and a 50 % reduction in the use of more hazardous pesticides (133). The proposal for the Sustainable Use Regulation attempted to set legally binding reduction targets at EU level, but was rejected by the European Parliament in November 2023, and officially withdrawn by the European commission in May 2024 (134).

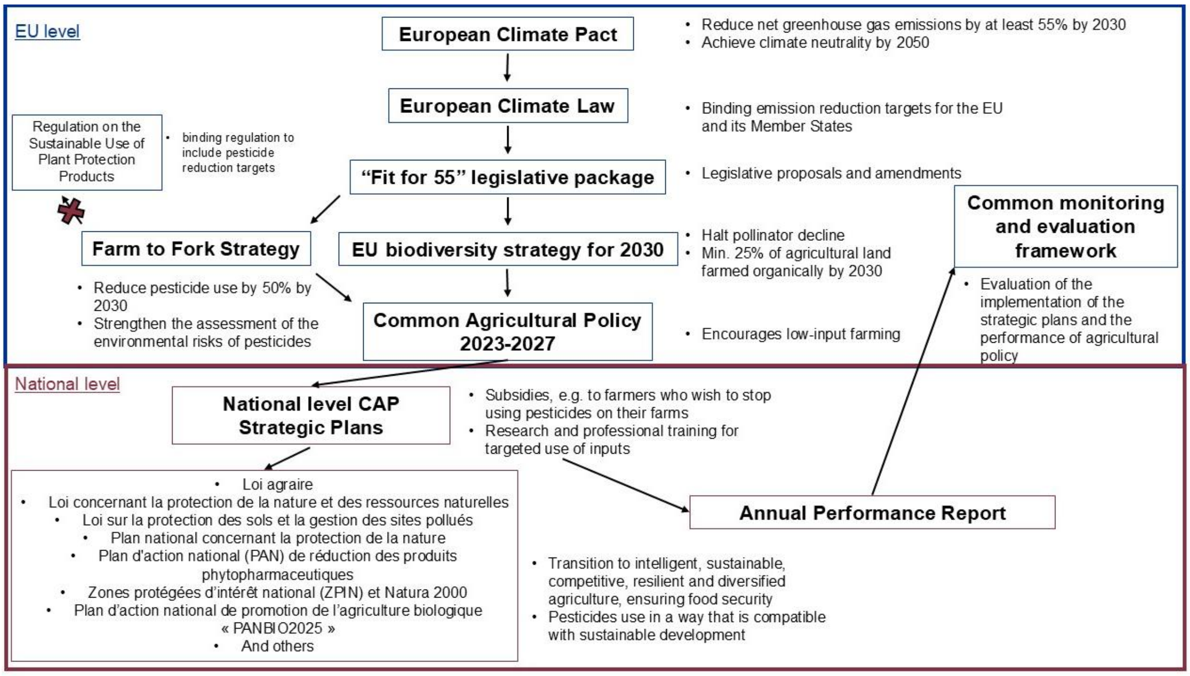

Figure 7 National and European policy actions steering the transition to a sustainable use of plant protection products

Extensive EU legislation governs the marketing and use of plant protection products and their residues in food[7] (134). "*Plant protection products are pesticides that are mainly used to keep crops healthy and prevent them from being destroyed by disease and infestation*"(135). Every active substance in a plant protection product undergoes a dual authorisation process: it must receive approval from the European Commission before it can be authorised at national level. The European Food Safety Authority (EFSA) is tasked with conducting pesticide risk assessments (135,136). Member States remain however responsible for national authorisation of plant protection products. Moreover, Member States are required to control whether food items sold in the market comply with legal limits ('maximum residue levels'). An annual report assessing the pesticide residue levels in foods on the European market is published by EFSA (137).

In 2022, 19.1% from the 634 food samples analyzed in Luxembourg originated from domestic sources. The remaining samples were either imported from EU or third countries or their origin was unknown. Notably, pesticides remained undetectable in 54.1% of the samples. Pesticides were detected in the remaining 45.9% with 37 samples (5.8%) exceeding legal limits. The majority of these

[7] *a listing of European and international instruments in the field of chemical management, environmental and health protection, sustainable development and international trade can be found in the Report on Proceedings of the Workshop on Alternative Business Models for Pesticide Reduction* (195) *and the Annex I of The International Code of Conduct on Pesticide Management* (200)

samples remained non-compliant even after accounting for analytical uncertainty; the origin of these samples was not communicated. At EU-level, organic food was less likely to be contaminated than conventionally produced food (138). This also applies to Luxembourg, as highlighted by an analysis of the Mouvement écologique. The same report shows that in some samples of imported food active substances that are banned in the EU could be detected. It is worth noting that the current maximum residue levels are based solely on absorption through the digestive tract and focus on a single active ingredient at a time, without accounting for combined exposure or other exposure pathways (120).

Per- and polyfluoroalkyl substances (PFAS)

PFAS (139) are widely recognized for their persistence, environmental mobility and potential toxicity (28). PFAS are primarily used as additives in pesticide formulations to enhance the spread and adhesion of plant protection agents on insect and plant surfaces(140). Despite the European Union's intent to ban all PFAS chemicals (141), pesticides containing PFAS are exempt from the REACH Regulation, designed to safeguard human health and the environment from chemical risks. Instead, they are classified as registered plant protection products, with their active ingredients regulated under Regulation (EC) 1107/2009 (142). One example is the active substance Flufenacet (143), which is present in 13 plant protection products authorized in Luxembourg for professional use (144).

Several organizations, including the German Umweltbundesamt, have highlighted regulatory shortcomings in assessing PFAS in pesticides, particularly regarding their degradation products, such as trifluoroacetic acid (TFA). Due to their persistence and accumulation in the environment, some experts advocate for binding regulatory actions to reduce emissions of TFA and its precursors, improved risk assessment methodologies, and continued surveillance of PFAS contamination in food and the environment (145).

According to the coalition agreement 2023/2028, the Luxembourgish government is promoting the sustainable use of plant protection products and the phasing out of glyphosate at European level [8]. Since 2009, the "Ouni Pestiziden" campaign coordinated by Ëmweltberodung Lëtzebuerg and representing partners of the private and public sectors works towards the elimination of pesticides from state, municipal, agricultural and private land (146). Funding from the EU's Common Agricultural Policy provides incentives to farmers for not using plant protection products (147). A Grand-Ducal Regulation bans the use of pesticides in most protected areas of national interest (148). Various plans, directives and agri-environmental measures[9] contribute to the implementation of the Plan d'action national de réduction des produits phytopharmaceutiques (PAN PPP) (149): **between 2017/18 and 2021/2022, a decrease of the use of the big movers[10] by 47% and of all PPP by 27% was recorded. The amount of glyphosate used has even decreased by 91%** (150,151). **Since 2021, Luxembourg has successfully met the Farm to Fork strategy's target of reducing the use of plant protection products by 50%.**

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[8] *Accord de coalition 2023-2028 :« …Dans ce cadre, le Gouvernement promouvra une utilisation durable des produits phytosanitaires afin de garantir la préservation de la biodiversité et la protection de nos eaux de surface ainsi que de nos sources. La formation initiale et continue dans le cadre de la réduction des produits phytosanitaires sera développée et la sensibilisation à ce sujet sera renforcée… » et « …le Gouvernement s'engagera en faveur de l'élimination progressive du glyphosate au niveau européen et soutiendra parallèlement l'abandon volontaire de celui-ci par le biais de subventions. …»*

[9] *E.g. La loi de l'eau et la directive cadre sur l'eau, le PAN-Bio 2025, Plan protection des pollinisateurs, Loi agricole, The strategic plan for the CAP 2023-2027*

[10] *« plant protection products that pose a particular risk or are widely used"(201)*

Glyphosate

The controversial broad-spectrum herbicide glyphosate was granted re-approval by the EU at the end of 2023 for another ten years (152,153). While the International Agency for Research on Cancer classified it as “probably carcinogenic” (154,155), the European Food Safety Authority (EFSA) and the Committee for Risk Assessment (RAC) of the European Chemical Agency (ECHA) confirmed that the substance causes serious eye damage and is toxic to aquatic life with long lasting effects, but found no scientific evidence for its specific target organ toxicity, carcinogenicity or mutagenicity (153,156). The Ramazzini Institute highlights that a comprehensive study addressing long-term toxicity, carcinogenicity, and multi-generational effects, conducted independently of industry influence, is currently missing (157). In Luxembourg, the use of all products containing the herbicide glyphosate was banned on agricultural (between 2021-2023) and public (since 2016) land. While the marketing and use of glyphosate is again authorized since 2023, a subsidy encouraging the voluntary abandonment of glyphosate use was introduced.

5.4 – Key considerations on pesticide use in Luxembourg

This chapter provides a broad overview of the benefits and drawbacks of pesticides use in Luxembourg’s agriculture, as well as the potential impacts of pesticide use in other regions of the world. It emphasizes the need to differentiate the different active substances and carefully assess both their acute and chronic risks to the environment and human health. Currently, over 500 plant protection products are approved in Luxembourg (144)**. However, the risks associated with many substances, such as some PFAS-containing pesticides and possibly glyphosate, remain insufficiently studied. The diversity of these substances makes monitoring their presence and identifying their transformation products in surface water particularly challenging** (158,159)**. While some substances could likely be replaced with physical control methods or alternative active ingredients, thorough evaluation is necessary to prevent unintended harm to non-target organisms, the environment, and crop yields if active substances were banned** (160)**.**

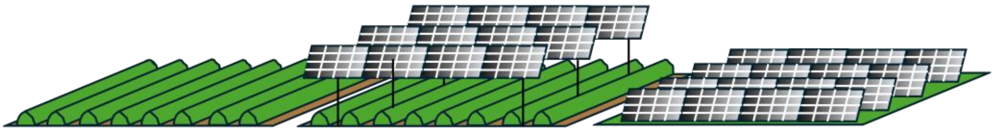
6.Energy transition and the role of Agri-photovoltaics

- *How can farmers benefit from Agri-photovoltaics?*
- *How can Agri-photovoltaics aid the renewable energy transition?*
- *What are the challenges and solutions of using Agri-photovoltaics in a sustainable way?*

6.1 – Agri-photovoltaics combines agricultural production with the generation of clean electricity

Most plants and trees do not use all the sunlight that they receive and sometimes they can even benefit from shade. The excess sunlight can be absorbed by dispersed photovoltaic panels standing on the agricultural land to generate electricity, our most flexible power source. This combination of agriculture and photovoltaics (Agri-PV) has been trialled with high value crops such as salads, through to cereals, fruit bushes and even fruit trees (161).

A pioneering German study found that potato yields in an Agri-PV field surprisingly exceeded those of a normal field and simultaneously the PV panels generated significant energy. Researchers found that the shade of the Agri-PV increased the potato yield by 3% compared to the standard field during the heatwave of 2018 whilst the Agri-PV panels generated 83% of the electricity compared to the ground mounted PV panels completely covering a normal field (Figure 8) (162). Overall, ***the Agri-PV field with potatoes achieved a land use efficiency of 186%***[11], as compared to 100% for the individual potato and PV field use cases.



AREA	POTATOES	POTATOES + AGRI-PV	GROUND MOUNTED PV
Potato yield (%)	100	103	0
Electricity yield (%)	0	83	100
Land use efficiency (%)	100	186	100

Figure 8 In the summer heatwave of 2018 in a test site in Bavaria the potato yield increased under the protective shade of Agri-PV panels and generated considerable electricity.

The diagrams represent the three cases tested, namely a field with just potatoes, a field with potatoes and Agri-PV panels and a field with just PV panels. The Agri-PV panels generated 83% of the electricity as compared to the field of standard PV panels optimised for generating as much electricity as possible. Overall, the dual land use achieved an efficiency of 186%, as compared to 100% of the single use cases *(162).*

Land use efficiencies greater than 100% are demonstrated using Agri-PV in neighbouring European countries with a variety of crops. Lettuce growers in France (163), a pear producer in Belgium (164) and a potato and wheat farmer in Germany (162) all achieved land use efficiencies greater than 100%. Studies on other crops and locations are given in this review paper (161). In most Agri-PV cases the crop yield reduces below 100% but the land use efficiency is above 100% due to the compensating production of electricity.

Agri-PV installations are available in multiple formats to suit the Luxembourg context (Figure 9a). Ground mounted panels can track the sun or hang vertically

[11] Land use efficiency tries to combine the very different outputs of crops and electricity into a singular number. Land use efficiency is often expressed as Land equivalent ratio (LER) in the literature (161). It is the same number as the land use efficiency divided by 100, leading to numbers between 1 and 2. The LER expresses how much of the land would be needed to achieve the same crop yield and electrical power generation if both were done on separate fields.

and are suitable for meadows and cereals which constitute 30% of Luxembourg's agricultural land area (165) as exemplified by the first Agri-PV installation in Kehlen (Figure 9b). Elevated panels of the type installed in Dudelange are suitable for pasture (Figure 9c) which constitute 42% of the agricultural land area (165).

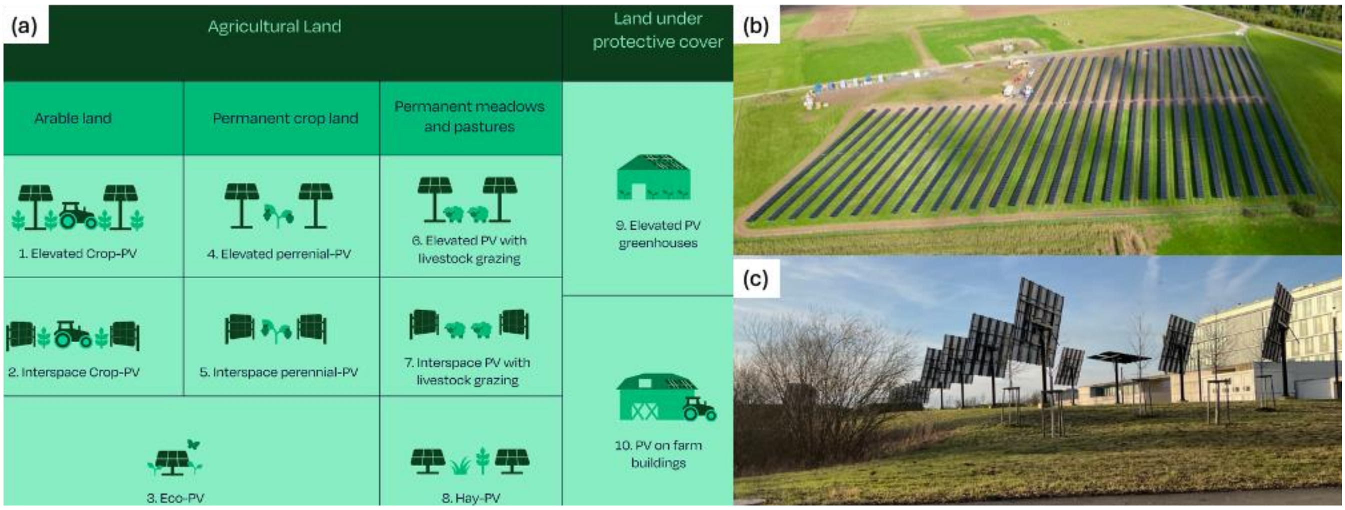


Figure 9 (a) Schematics of the different types of Agri-PV reproduced from (164); (b) Photograph of first Luxembourgish Agri-PV system installed in Kehlen in 2024, reproduced from (166)**, with a capacity of 2 MWp spread of 4.6 hectares leaving 90% of the land free as meadow and generating enough electricity to power between 120 and 500 households (see box below). The PV panels are mounted on a single tracker system that allows the panels to move in an East-West arc during the day to maximise energy yield. The panels may also be rotated vertically to allow farm machinery through to cut and collect the grass between the rows; (c) Photograph of the elevated 0.2 MWp PV tracking system suitable for use with animal livestock, although here installed in the Parc Laboratoire in Dudelange in this case** (167)*.*

Understanding the capacity of photovoltaic installations, how much energy they can produce and the work that can be done.

A photovoltaic installation capacity is the maximum or peak power of electricity it can produce in standard sunny conditions. Since power has units of watts, the peak power is given the symbol of W_p. Depending on the size of the installation different prefixes may be used such as k – kilo meaning ×1.000, M - mega or ×1.000.000, or G – giga or ×1.000.000.000.

1 kW_p of photovoltaic panels has a surface area of ~ 5 m^2. The energy that they produce depends on the number of hours of sunshine that they receive. In one year in Luxembourg this would be around 1000 hours (h) leading to an energy generation of 1000 kWh per year for 1 kWp installed. This amount of energy would allow an average electric car with an energy consumption of 20 kWh / 100 km to drive ~ 5000 km per year.

Note, when describing the energy produced by a photovoltaic installation often the number of family houses per year it could supply is specified. This is done by taking the energy produced by the installation for one year and dividing it by the electrical energy use for a single house, and for 2025 this is given as 4000 kWh (168). The calculated number of houses can be misleading since household consumption varies significantly. The electrical demand of a house using fossil fuel-based heating and transport will be vastly different to a house using an electric heat pump and car. The electrical demand of a heat pump can vary between 3.000 and 9.000 kWh per year depending on the size and insulation of the house (168). An electric car travelling 20.000 km per year would require 4000 kWh. Therefore, the electricity demand of a house can be expected to vary between 4.000 and 17.000 kWh per year. Thus, the use of 4000 kWh per year for a single household will start to overestimate the numer of households powered through the year as electrification accelerates.

6.2 – Agri-photovoltaics offers multiple benefits to farmers beyond the generation of electricity

Agri-PV structures may benefit both plants and livestock and reduce running costs. Photovoltaic panel shading has been found to decrease the amount of water that crops require, reduce daytime temperatures protecting delicate crops such as raspberries (161), and provide shelter to livestock in the middle of the day improving their welfare (169). Other benefits such as larger produce, increased quality, double or extended harvests have been reported for specific crops in certain climatic conditions (161). In some instances, crop yields on Agri-PV are higher than on reference fields but in the majority of cases crop yields decrease to below 80% if the ground coverage of PV panels is higher than 25% (170).

Agri-PV electricity production gives the farmer a second income independent of the success or failure of the agricultural production. The estimated cost of Agri-PV electricity over the lifetime of the installation (levelized cost of electricity) is estimated to be between 5- and 11-euro cents/kwh which compares favourably with the estimated cost of household rooftop solar being between 10- and 16-euro cents/kWh (171). The economics will mainly depend on the balance of the loss of crop yield and its market value, the cost of the Agri-PV infrastructure and the sales price of the electricity.

Combining batteries with Agri-PV installations would enable farmers to maximize their electricity sales price and encourage self-consumption reducing CO_2 emissions. In electricity markets with a time dependent price, farmers can maximise their profit by selling their electricity when prices are highest enabled by storing the energy in batteries. This additionally helps the electrical grid by injecting electricity when it is most needed. On-site batteries would also incentivise self-consumption of energy by electrifying farm vehicles, machinery and power generators on the farm, reducing and eliminating diesel combustion pollution and noise emissions. The overall economics though should be considered on a case-by-case basis (172).

6.3 – Agri-photovoltaics can play a role in providing energy security and reduce greenhouse gas emissions

Covering 1% of the EU's agricultural surface with Agri-PV would lead to a capacity of 1000 GW_p (173), well above the EU 2030 target of 600 GW_p for all photovoltaic installations (174). To achieve the EU's goal of net neutrality by 2050 it is estimated that Europe requires a total of between 2000 and 7500 GWp (175,176) of photovoltaic installations[12]. Agri-PV is nascent with ~3 GW_p of Agri-PV installed (177), which is 1% of all photovoltaic installations in Europe. The first largescale systems were installed in France and Italy in 2011, with the majority of the pioneering research taking place additionally in Germany, USA, China, Japan and South Korea (178).

Covering 1.3% of Luxembourg's agricultural surface with Agri-PV would enable us to reach the 2030 PNEC photovoltaic target of 1236 MW_p[13] (179). This additional 743 MW_p would be added to the country's already existing, predominately building roof mounted, 493 MW_p (180). Luxembourg's largest renewable energy resource is the sunlight that lands on the country's surface and yet the 2030 capacity target of 1236 MW_p would only generate 3.5% of the country's required energy demand[14] (179). By extension, if the national goal is to become near energy independent using photovoltaics in the majority, careful consideration of the energy generated per unit area must be given. As discussed in section 6.1, Agri-PV panels have to allow the sunshine to reach the crop below them and are thus less densely packed than normal PV panels on rooftops or facades. This means that a 1000 m^2 area of Agri-PV panels would generate between 43 and 60 MWh/year [15] whilst closely pack panels would generate 200 MWh/year.

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[12] The large spread of values in the estimation of the required photovoltaic installations by 2050 is because the first study assumes a wind turbine dominated energy transition whilst the second study assumes a photovoltaic dominated transition.

[13] At the time of writing 743 MW_p is required to meet the 2030 power target of PV. If we assume all this demand is met by Agri-PV installations having a power density the same as the Kehlen installation (0.04 kW_p/m^2), 17 km^2 of land would be required, or 1.3% of agricultural land.

[14] The PNEC estimates that Luxembourg's final energy demand in 2030 will be 35.568 GWh. The targetted 1236 MWp of PV installations will generate approximately 1236 GWh, or 3.5%.

[15] The EU estimates 0.06 kWp/m2 is possible, 50% higher than in Kehlen (173). The chosen power density depends on the climate and crop under consideration.

Luxembourg is examining the case for Agri-PV currently. A first call launched by the government in 2022 (181) will install 53 MWp over 74 hectares of land across 14 project sites examining multiple use cases (Figure 10).

Agri-PV installations require timely electrical grid connection to be impactful. The average wait time for PV installations to be connected to the grid in Europe is four years, wasting time, money and resources. Strategic grid extension planning to maximise the number of grid connections of large installations would make economic sense.

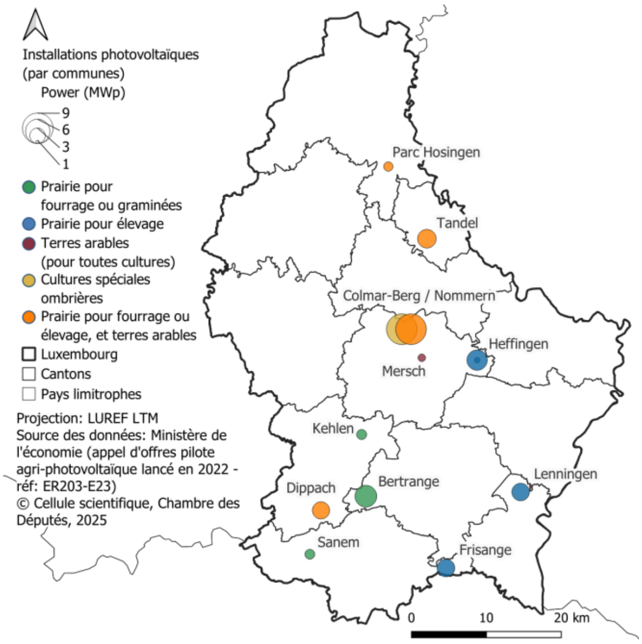

Figure 10 Map of pilot Agri-PV projects in Luxembourg

6.4 – Careful installation of Agri-photovoltaics will avoid reductions in food security, biodiversity and ecosystems

Thoughtless Agri-PV installations may reduce crop yields to unacceptable levels, be incompatible with the farm's current machinery, be a danger to birdlife, and disrupt local wildlife during construction. Below is a table of the most important risks and mitigations (Table 4).

Table 4 List of the most important risks and mitigations for Agri-PV installations.

RISK	MITIGATION
Too great a reduction in light levels or closeness of the panels in combination with a poor choice of crop reduces the yield and quality to unacceptable levels and may even invite weeds and disease	Match the crop to the coverage of photovoltaic panels paying attention to the semi-transparency of the panels, a maximum of ~25% coverage of panels is recommended to keep crop yields of ~80%. Fruits, berries and green leaves tolerate higher levels of shading (170)
Poor choice of panel placement and installation size / height can block or hinder the type of farm machinery used.	Check machinery dimensions to get proper panel placement (182)
Electrical power lines act as obstructions or electrocution risk to birds	Add markers, change design or bury powerlines beneath the earth surface (183)
Biodiversity and soil structure suffer during construction due to heavy machinery and chemicals use, with local wildlife disrupted due to light, noise and vibration.	Implement operational (minimize vehicles, limit roads and pathways, locate facilities away from sensitive areas) and abatement (reduce emissions, chemical and light pollutants, stabilize soil erosion) controls to minimize impacts. Avoid scheduling construction in sensitive time periods (breeding, hibernation, migration) (184)

Food production can be boosted by changing the type of agricultural production to more than offset any loss of yield caused by the implementation of Agri-PV. A meta study of academic research has found that crop yields grown under Agri-PV installations tend to decrease, with some exceptions (170). Legislatively, an Agri-PV installation in France, Japan, and Germany is not allowed if the crop yield falls below 90%, 80%, and 66% respectively of the reference yield without Agri-PV (185). Since the amount of food needed by humans will only increase due to rising population, methods to increase food production or reduce inefficiencies are required. For example, not all animals convert fodder into edible protein with equal efficiency. The protein efficiency of beef (a major product of Luxembourg), pork and poultry is 4, 9 and 20% respectively (186).That means for the same amount of fodder, five times as much poultry protein can be produced as beef protein. This factor of five would more than compensate for any loss of yield in fodder production due to Agri-PV. Viewed differently, the land area required for 100 g of protein from beef, pork, and poultry is 164, 11, and 7 m^2.year (area multiplied by years occupied) respectively. Contrastingly, 100 g of protein from peas which contains all necessary amino acids requires 3 m^2.year (187). If more animals and humans eat legumes, less land area would be required overall to feed the human population.

Agri-PV could be an opportunity to reset current modern monoculture agriculture production. Monoculture crops lead to a reduction in biodiversity and pollinators. In certain contexts, agrivoltaics in combination with planting the right species underneath and around them and applying the right management may lead to improvements in biodiversity and pollinator populations (188)

Successful Agri-PV requires new interdisciplinary relationships both in the field and at the research level. Agri-PV is an emerging field, and new relations are required between photovoltaic companies, farmers, agronomists, engineers, government and researchers. The effect of the photovoltaic installations on crop yield, soil structure and pollinator health and well-being also need to be considered in the local context. Since Agri-PV is still nascent, further research into long term crop yields, sensors, crop types and biodiversity are required. The impact on soil life, microclimate, and biodiversity also is not fully clarified, and the long-term influence on animals remains unclear.

6.5 – Agri-photovoltaics offer benefits, and the pioneer installations should be studied to draw lessons for the improvement of future ones

Agri-photovoltaics offers the opportunity to rapidly expand renewable electricity generation and contribute to the overall demand of Luxembourg whilst boosting the incomes of local farmers. The EU commission is expected to offer guidance on Agri-PV in 2025 (189). Monitoring of the first Luxembourgish 2024-2025 Agri-PV installations (Figure 10) will improve understanding and inform further research and development to widen the crop base, increase biodiversity and resilience of any future installations.

Agri-PV alone does not represent a miracle solution for diversification in agriculture, our challenges in biodiversity, or in the energy transition. However, it represents a building block in the mosaic of solutions for a successful energy transition. With its ability to support adaptation to climate change, to strengthen the income options of farmers and contribute to energy security, Agri-PV is one of the key technologies for a sustainable future.

7.Conclusive remarks daring a glimpse on agriculture policy perspectives

Recently, the global Agriculture Ministers' Conference recognised that **"***sustainable and resilient agriculture and food systems are crucial for global food security and nutrition* **"**.

Innovative strategies and technologies may contribute to the intensification of agricultural production while minimizing environmental impacts. **However, their implementation must be carefully planned, context-specific, and closely monitored through national and European policy measures**.

All EU institutions have recognized that farmers must be active partners in shaping the future of agriculture, as well as partners in environmental and biodiversity protection. Acknowledging the farmer's reliance on EU and state subsidies, as well as the challenges they face regarding financial security, long-term prospects, and social recognition, the EU has taken concrete steps to include farmers' voices. Initiatives such as online surveys and the Strategic Dialogue on the Future of EU Agriculture have been launched to directly involve farmers and key stakeholders from across the agri-food sector.

In December 2024, EU agriculture ministers announced that post-2027 CAP will place greater focus on farmers, guaranteeing stable incomes and robust support for the sector's transition toward more sustainable practices (190). Several drivers to encourage farmers have been identified (120,191–195), such as compensating for yield losses related to the implementation of new approaches, defining pesticide-specific reduction targets and testing and demonstrating new approaches in pilot farms.

In Luxembourg, initiatives like the Landwirtschaftsdësch bring together representatives of Luxembourg's agricultural sector to collaboratively develop solutions for the pressing challenges of agriculture, today and the future. **However, to address these challenges in a truly holistic manner also on national scale, all stakeholders—including food chain operators and civil society—need to be actively involved in the discussion.**

Global food demand is projected to rise by 35% to 56% between 2010 and 2050 (196) driven by population growth. **Policy measures encouraging behavioural change not only among farmers but also consumers are essential.** For instance, promoting the reasonable consumption of animal products would enable a larger share of agricultural land to be dedicated to production of human food rather than animal feed. Moreover, encouraging the consumption of locally produced food that meets sustainable production standards would help ease pressure on water and soil resources—both locally and in regions where inputs are less regulated.

In February 2025, the European Commission unveiled its "Vision for agriculture and food " emphasizing that a successful future for EU agriculture depends on active collaboration with farmers, key institutions, food chain operators, and civil society. The Ministry of Agriculture, Food and Viticulture in Luxembourg launched recently a consultation debate on key topics related to food.

This is certainly promising. However, the current document identifies significant knowledge gaps that must be addressed to enable an evidence-based policy-making for sustainable agriculture and food. It also highlights the essential role of independent researchers in generating context-specific data and developing innovative solutions to enhance agriculture's adaptation to the triple planetary crisis.

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