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BIOPRODUCTS FOR A SUSTAINABLE BIOECONOMY

RESEARCH ARTICLE OPEN ACCESS

# European Biomass Production Systems: Characterization and Potential Contribution to Land Use Diversity

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**Received:** 28 March 2025 | **Revised:** 16 May 2025 | **Accepted:** 3 June 2025

**Funding:** This research received funding from the European Union's H2020 research and innovation programs under the grant agreement no. 101007950 (DecisionES, Marie Sklodowska-Curie) and 101059498 (Eco2adapt), the Research Council of Finland Flagship UNITE (337127) and the SNS research project SYNERGIES. S.P.Z was supported by the Finnish Cultural Foundation, Grant 55232063 (North Karelia Regional Fund).

**Keywords:** biomass production | energy crops | land use diversity index | plantations

## ABSTRACT

The global demand for biomass-based products, including biofuels and biomaterials, is projected to rise significantly in the coming decades, driven by climate change mitigation and the pursuit of energy independence. Expanding biomass production systems, such as short-rotation plantations and energy grasses, offers a promising option to meet this demand. Although these systems deliver environmental benefits, such as carbon sequestration and water purification, their large-scale implementation may lead to landscape homogenization. Conversely, strategically deployed biomass systems can enhance local land use diversity, support biodiversity, and generate mixed income opportunities for farmers. In this study, we present a harmonized analysis of European biomass production systems using spatial data from over 426,783 fields and stands, covering 2,140,568 ha across 17 countries. By integrating empirical data with landscape metrics, we assess the spatial distribution, scale, and land use context of diverse biomass systems ranging from short-rotation plantations to energy grasses. Our results show that depending on their location, biomass production systems have the potential to enhance local land use diversity and support multifunctional landscapes that mitigate the risks associated with large-scale monocultures. Conversely, poorly integrated systems may lead to landscape homogenization and reduced ecological resilience. These findings provide a baseline for crop species selection and spatial planning, thereby informing land use policies that harmonize bioenergy production with environmental sustainability.

## 1 | Introduction

The global demand for biomass-based energy and materials, is projected to rise significantly in the coming decades (OECD 2019; Popp et al. 2021; Scarlat et al. 2015). This growth is largely driven by the need for low-carbon energy alternatives due to concerns over climate change, as well as the support for energy independence, particularly in the European Union (EU) where an increase in bioenergy of 20 exajoules (EJ) is anticipated (Material Economics 2021). As a result, biomass has become a key component of the EU's climate transition strategies, playing a crucial role in reducing greenhouse gas emissions and contributing to global climate targets (Sulaiman et al. 2020).

A viable strategy to meet this growing demand is the expansion of biomass production systems, such as lignocellulosic plantations and energy grasses (Englund et al. 2020; European Environment Agency 2023). Short-rotation plantations are particularly attractive due to their high yields within short time frames (2–20 years) and their potential as low-carbon fuel sources (Djomo et al. 2011; Parra-López et al. 2017). Similarly, energy grasses are valued for their high productivity and minimal input requirements (Jørgensen 2011; Kandel et al. 2016).

However, the sustainability of biomass systems deployment is highly dependent on its spatial distribution and management practices. Large-scale biomass production poses challenges, particularly the risk of homogenizing land use and threatening biodiversity, especially when high-quality habitats are replaced by monocultures (Firbank 2008). Additionally, land use changes linked to biofuel plantations have raised significant concerns about increased greenhouse gas emissions, which can offset the carbon sequestration benefits (Searchinger et al. 2008). While well-integrated biomass systems can contribute to mitigate environmental impacts, large-scale monocultures risk land homogenization, biodiversity loss, and competition with food and feed production (Popp et al. 2014).

Conversely, smaller-scale plantations distributed across homogeneous landscapes can contribute to land use diversification and generate mixed incomes for farmers (Dale et al. 2010; Firbank 2008). In fragmented landscapes, they can also function as dispersal corridors for certain species and enhance connectivity between forest patches, as shown by Müller-Kroehling et al. (2020) and Chiatante et al. (2019). By increasing heterogeneity, biomass systems may support biodiversity in agricultural or conifer-dominated landscapes (Baum et al. 2009; Sage et al. 2006). Evidence suggests that their impacts on avian communities are highly context-dependent, varying with their location and surrounding landscape (Berg 2002; Hanowski et al. 1997). Furthermore, when planted as buffer strips along watercourses, short rotation plantations have the potential to enhance other ecosystem services such as water purification and soil erosion control (Englund et al. 2021; Rosa et al. 2017).

These complexities highlight the importance of strategic policy frameworks guiding sustainable biomass and bioenergy deployment. Although most policies have focused on feedstock production and logistics decisions from a supply chain perspective, the spatial arrangement of biomass systems and their surrounding land uses plays a key role in determining their long-term sustainability and ecosystem service contributions (Dale et al. 2011). As land use activities are dynamic, land management decisions often implicate the inclusion of trade-offs between environmental and economic impacts.

To support more sustainable land management, recent studies have integrated modelling and optimization techniques alongside spatially explicit environmental impacts to identify suitable locations where biomass systems can enhance ecosystem services including soil loss control, water and wind erosion, nitrogen emission to water, and flood control (Englund et al. 2020, 2021; Frank et al. 2014). This presents a key opportunity for decision-makers to implement spatially targeted policies that support the development of biomass systems while enhancing ecosystem services, as well as diversifying farmers' operations (Baumber 2017; Králík et al. 2023).

A major obstacle to fully understanding these opportunities is the lack of comprehensive statistics and centralized records, with data often fragmented across different land agencies, varying by country. To address this, we harmonize data across European countries to assess how representative plantations and energy grasses contribute to local land use diversity. We analyze their location and size distribution to create a detailed profile for each biomass production system based on empirical data. Then, using spatial buffers, we examine their surrounding landscapes and apply a Land Use Diversity Index to identify specific locations and species with the potential to enhance local land use diversity.

Our findings reveal the spatial patterns of biomass deployment in Europe and their potential implications for land use diversity. This study provides a harmonized cross-regional foundation for designing multifunctional landscapes that balance increased biomass production with enhanced land use diversity. Ultimately, our research could further guide the development of spatially explicit policies and help decision makers in promoting a more sustainable deployment of biomass systems.

## 2 | Material and Methods

### 2.1 | Description of Crop Species Representative of Biomass Systems in Europe

The dataset included seven biomass systems representative of fast-growing species distributed in 17 countries in Europe. We grouped these crop species into two main categories. The first group, plantations, encompasses eucalypt (*Eucalyptus* spp.), black locust (*Robinia pseudoacacia*.), radiata pine (*Pinus radiata*), willow (*Salix* spp.), poplar, and hybrid aspen (*Populus* spp.). Radiata pine presents rotation lengths ranging between 18 and 40 years and is mainly used for sawlog and pulp (Mead 2013). Black locust is well known not only for its wood but also for its versatility, being a source of bio-oil and biomass; thus, this crop species can have rotation lengths between 3 and 5 years if grown for biomass energy production and up to 60 years if used for sawlog (Nicolescu et al. 2020). Eucalypt has been used in Europe mainly for paper pulp and biomass (Tomé et al. 2021). In Spain, its rotation length varies between 12 and 14 years (Ruiz et al. 2008). Rotation lengths for poplar and hybrid aspen vary significantly depending on the use and site conditions. For instance, rotation lengths of 5–10 years for hybrid aspen in Germany are considered optimal for biomass production (Liesebach et al. 1999). Hybrid poplar is commonly harvested in rotation periods of 5–13 years in Denmark (Nielsen et al. 2014), and similarly for northern Spain, 12 years have shown the highest productivity for specific clones (Rodríguez et al. 2010). Niemczyk (2021) reported that for stands in more northern geographical sites, optimal biomass production can be reached at rotation lengths above 10 years. Willow normally presents shorter rotation lengths, typically 2–4 years (Baker et al. 2022) and is mainly used for energy production, but is also known for phytoremediation and wastewater treatment (Witters et al. 2009).

The second group, perennial grasses, entails reed canary grass (*Phalaris arundinacea*) and miscanthus (*Miscanthus* spp.). The latter has been widely used for bioenergy production due to its high biomass yield and low input requirements (Lewandowski et al. 2000), it is preferred due to its wide climatic distribution within Europe (Clifton-Brown et al. 2017). Reed canary grass is mainly used as a feedstock for pellets and other solid biofuels or as a source for bioethanol and biogas (Jasinskas et al. 2020; Tilvikiene et al. 2016). It has been cultivated mainly in northern Europe due to its advantage in frost resistance (Mola-Yudego et al. 2021).

The regions where both groups of crop species were documented for our study include Austria, Belgium, Croatia, Czech Republic, Denmark, Estonia, Finland, France, Germany, Italy, Latvia, Netherlands, Portugal, Slovakia, Spain, Sweden, and United Kingdom. For Germany, the regions included were Lower Saxony, Brandenburg, and North Rhine-Westphalia; for the United Kingdom, only England; and for Italy, Toscana and Lombardia.

### 2.2 | Data Sources

Data were mainly collected from each countries' agricultural records and cadastres, using the polygons and reported crops to geolocate all the biomass production systems. It is important to note that for regions in Italy, Germany, Belgium, and the UK, we reclassified the categories labelled as Short Rotation Coppice to specify willow or poplar, as these crop species are widely recognized as the most common in these countries. In the case of Portugal, Spain, Italy, and France data was also collected from national forest inventories, or different cartographic products available (Tables S1, S2; for further details, see: Pineda-Zapata and Mola-Yudego 2025). Data concerning land uses was retrieved from the Corine Land Cover dataset for 2018 (European Environment Agency 2019).

### 2.3 | Characterization of Stands and Fields

Each biomass production system was characterized according to its size, location, and surrounding landscape. The size and location were based on the polygon as reported in each country's data source. Concerning the surrounding landscape, we used spatial buffers of 1 km from the outer edge of each polygon and retrieved the land use area within. Similar distance values have been used in previous studies analyzing spatial patterns of land use (Xu et al. 2023) and spatial characterization of landscapes for multiple purposes (Sprague 2013; Spyra et al. 2019).

Land use classes were aggregated into three main categories: agricultural land, forest, and others, in order to define and simplify the surrounding landscape. These categories were further visualized using ternary diagrams. Additionally, land uses in the buffer areas around each biomass production system were used to estimate a land use diversity index (LUDI), based on a Shannon diversity index (Shannon 1948), defined as:

$$\mathrm{LUDI}_k = \sum_{i=1}^{m} \left(p_i \ln p_i\right) \quad (1)$$

where $p_i$ is the proportion of land use class $i$ inside the buffer for biomass production system $k$. The calculations were performed in R, version 4.3.2 (R Core Team 2024).

We generated density plots showing the relationship between the percentage of agricultural land ($x$-axis) and the LUDI ($y$-axis) for each crop species. For forest plantations, we assume that these are more suitable to enhance land use diversity in homogeneous areas (low LUDI) dominated by agriculture. Conversely, for perennial grasses, the same case would correspond to homogeneous areas (low LUDI) with low percentages of agricultural land. In the figures, we use as reference values: 50% of agricultural land and LUDI = 1.

## 3 | Results

### 3.1 | Location and Area by Country

We documented and characterized 426,783 different fields and stands of biomass production systems (fast-growing forest plantations and energy grasses), distributed in 17 countries and regions in Europe. Among those, poplar plantations presented the widest spatial distribution in south-western Europe as well as in Scandinavia, followed by willow. The latter was located in northern parts of Europe, mainly within Denmark and Sweden, entailing 75% of total stands for the crop species. Radiata pine was documented only in Spain, with stands distributed mainly in the north of the country (Figure 1).

Regarding total area, eucalypt plantations covered the largest area, around 1.5 million ha in more than 60,000 stands distributed in Spain and Portugal, followed by poplar with nearly 400,000 ha and approximately 200,000 fields and stands. For black locust, the largest number of stands was located in France, with more than 40 thousand ha. Concerning energy grasses, miscanthus covered around 25,000 ha, mainly in southern and central Europe, and reed canary grass about 1500 ha, mainly in northern Europe (Table 1).

### 3.2 | Size Distribution by Crop Species

The recorded field and stand sizes showed substantial variability, generally following a log-normal distribution across all crop species (Figure 2). Eucalypt plots had the largest mean area (~20 ha) and exhibited considerable variation, with the largest continuous polygon spanning 53,841 ha in Portugal, while the smallest stand measured less than 0.1 ha. As a reference, in Portugal, the mean agricultural field in the dataset was 9.90 ha (max. 19,178 ha and min. 0.94 ha), and the mean forest stand was 17.66 ha, based on the 2018 Land Use and Occupation map (Table S1) Radiata pine displayed similarly high variability, comparable to black locust, with both species having a mean area of around 5 ha.

In contrast, willow plantations were characterized by much smaller average field sizes, with a mean of 2.6 ha. Although the largest willow field recorded was 100 ha, many fields were smaller than 0.1 ha, making it the plantation system with the smallest average field size. As a reference, the average

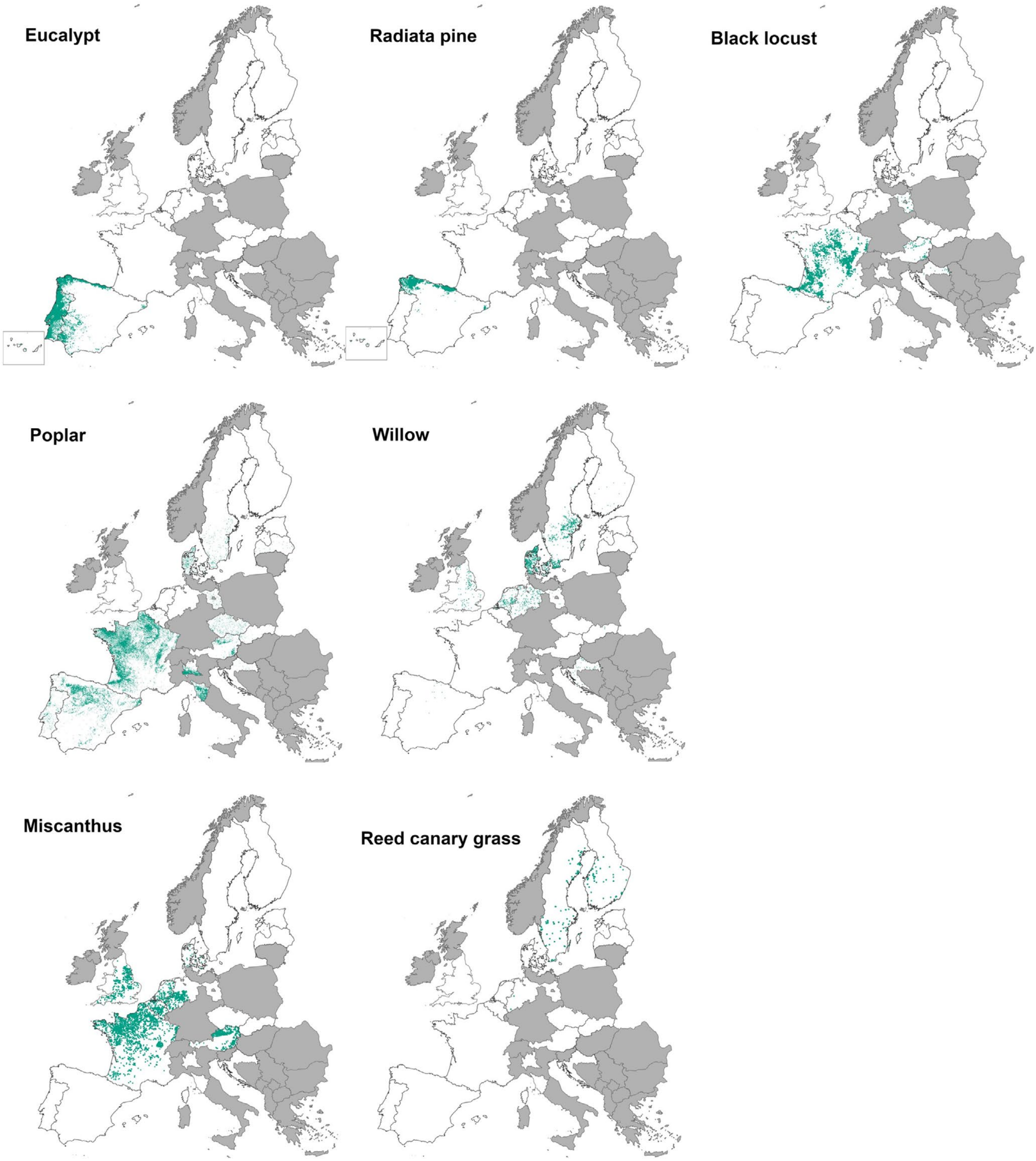


**FIGURE 1** | Areas and locations of the biomass production systems analyzed. In green color, centroids of plantation systems: Eucalypt, radiata pine, black locust, poplar & hybrid aspen, and willow. Perennial grasses: Miscanthus and reed canary grass. Gray areas: No data available.

agricultural field was 4.61 ha, 0.7 ha, and 2.59 ha for Denmark (2022), Netherlands (2023) and Sweden (2018), respectively (see data sources in Table S1). Poplar plantations exhibited a bimodal size distribution, with peaks at 0.05 ha and 0.7 ha, reflecting regional differences in field size patterns and possible reporting criteria. The largest poplar polygon recorded measured 1000 ha. As a reference, the average polygon for forest stands in France was 9.89 ha. Perennial grasses had similar average field sizes, with miscanthus and reed canary grass averaging approximately 2 ha and 3 ha, respectively. The maximum recorded field sizes were 86 ha for miscanthus and 92 ha for reed canary grass.

The size distribution of all biomass production systems investigated followed a logarithmic pattern, indicating that a significant portion of the total area was concentrated within

**TABLE 1** | Biomass production systems included in the analysis.

| Biomass production system | Countries/regions documented | Total area covered | Number of fields/stands | Total agricultural area (×1000 ha) |
|---|---|---|---|---|
| Eucalyptus | Portugal, Spain | 1,449,069 ha | 63,687 | 28,515 |
| Radiata pine | Spain | 259,415 ha | 52,367 | 24,292 |
| Black locust | Austria, Croatia, France, Germany[a], Spain | 46,844 ha | 8381 | 68,110 |
| Poplar | Austria, Belgium, Croatia, Czech Republic, Denmark, Finland, France, Germany[a], Italy[b], Latvia, Portugal, Slovakia, Spain, Sweden | 341,164 ha | 284,887 | 95,399 |
| Willow | Croatia, Denmark, Estonia, Finland, Germany[a], Netherlands, Slovakia, Spain, Sweden, UK[c] | 16,282 ha | 6207 | 59,526 |
| Miscanthus | Austria, Belgium, Denmark, France, Germany[a], Netherlands, UK[c] | 26,365 ha | 10,833 | 59,354 |
| Reed canary grass | Finland, Germany[a], Sweden | 1429 ha | 421 | 13,294 |

*Note:* Forest plantations and energy grasses from 17 countries and regions in Europe, for a total of 2,140,568 ha established in 426,783 fields and stands. Total agricultural area of countries/regions added as a reference (calculated from Corine Land Cover, dataset for 2018).
[a]Germany: Lower Saxony, Brandenburg, and North Rhine-Westphalia.
[b]Italy: Toscana and Lombardia.
[c]United Kingdom: England.

the largest stands or fields. For eucalypt, the largest 20% of stands covered 86% of the total area. The corresponding proportions were 82% for poplar, 70% for Radiata pine, 70% for miscanthus, 64% for willow, 60% for reed canary grass, and 56% for black locust.

### 3.3 | Surrounding Land Use Composition by Crop Species

Each plantation and energy grass system exhibited a distinct profile regarding surrounding land uses (areas 1 km from the edge of each stand/field), reflecting their integration into the broader landscape (Figure 3). Radiata pine plantations and reed canary grass fields were primarily established in conifer-dominated areas (CORINE code 312), accounting for 40% and 30% of the surrounding land uses, respectively. In contrast, eucalypt plantations were predominantly located in areas dominated by transitional woodland-shrub (code 324) and broadleaf forests (code 311), which together comprised 30% of the surrounding landscape.

Black locust buffers displayed a more diverse land use context, with surrounding landscapes characterized by a mix of broadleaf forests (code 311) and non-irrigated arable land (code 211), each representing 23% of the adjacent area. Artificial land uses, such as industrial or urban zones, accounted for a small fraction of the surrounding area, ranging from 0.6% to 4%. Notably, significant water bodies were identified near willow plantations and reed canary grass fields, representing 1% and 4% of the surrounding land uses, respectively.

Poplar and willow plantations, along with miscanthus fields, were predominantly located in agricultural landscapes. Non-irrigated arable land (code 211) made up 24%, 56%, and 53% of the surrounding areas for poplar, willow, and miscanthus, respectively. The ternary diagrams (Figure 3) illustrate the key land use categories shaping the local landscapes where these systems are established. For 20% of willow and miscanthus stands and fields, the surrounding landscapes consisted of more than 90% agricultural land, underscoring their prevalence in intensively farmed regions.

### 3.4 | Land Use Diversity

Eucalyptus and radiata pine plantations exhibited similar spatial profiles, with a substantial proportion of stands located mainly on forest areas with moderate levels of land use diversity. For these two crop species, around 58% and 66%, respectively, of the total number of stands for these species were in areas defined by agricultural land use below 50% of the surrounding areas and land use diversity index above 1, indicating a low contribution to diversifying predominantly forested areas (Figure 4).

In contrast, black locust and poplar plantations showed a distinct pattern, as their location in the landscape was more heterogeneous. Most of these plantations, 43% and 42%, respectively, were located in agriculturally dominated areas, although with moderate levels of land use diversity. In this case, about 19% and 23% of all stands were located in areas where they can be considered to contribute effectively to landscape diversity, introducing forested elements into predominantly agricultural landscapes.

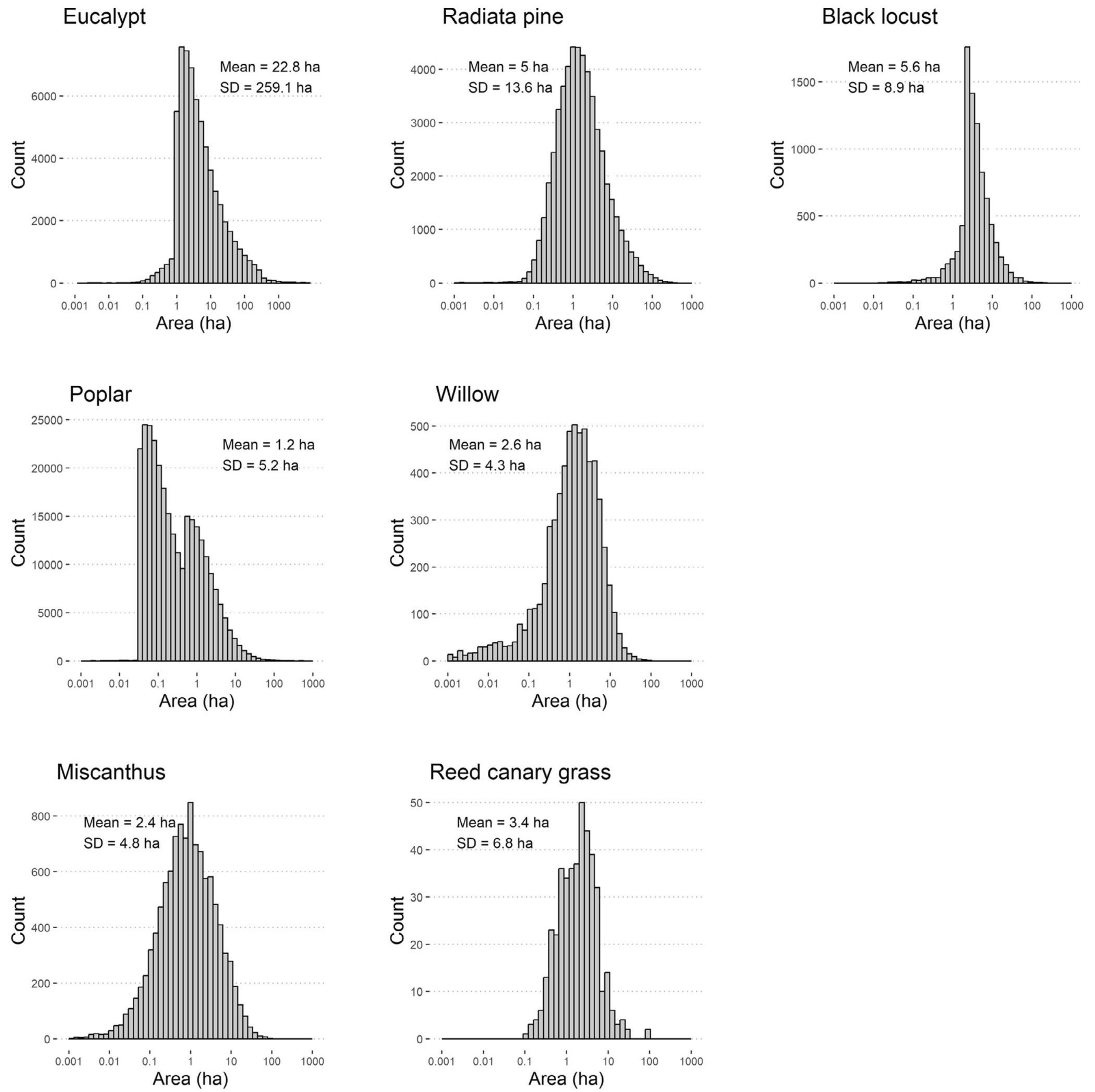


**FIGURE 2** | Stand/field size distribution by biomass production systems in Europe. Field or stand size distribution in ha, the *x*-axis in logarithmic scale, values of area (ha) are truncated in 0.001 and 1000, except for eucalypt.

Willow plantations had the highest effect diversifying the landscape, as 57% of all plantations for the crop species were located on land use homogeneous areas dominated by agriculture, thereby diversifying the land use matrix. The energy grasses showed opposite effects. In the case of miscanthus, 57% of all fields were largely concentrated in agricultural areas with a very low diversity index, reflecting a limited capacity to significantly enhance local land use diversity. Conversely, reed canary grass fields were primarily located in landscapes with less than 50% agricultural land. About 26% of all fields were located in areas with limited agriculture and homogeneous land uses, thus contributing to diversifying these landscapes.

Overall, willow plantations exhibit the highest potential for enhancing landscape diversity (conditional to their suitability in the area), followed by poplar, black locust, and reed canary grass. In other cases, the contribution to land use diversification is moderate.

Regarding landscape dominance, there were 6065 cases of large polygons (over 50 ha) established with the same plantation system, covering a total of 1,157,293 ha (Figure 5). These were most prevalent in Spain and Portugal, primarily involving eucalypt and Radiata pine, though similar cases were also observed for poplar, black locust, and willow. Among these, 2905 stands exceeded 100 ha, encompassing 936,938 ha (43% of the

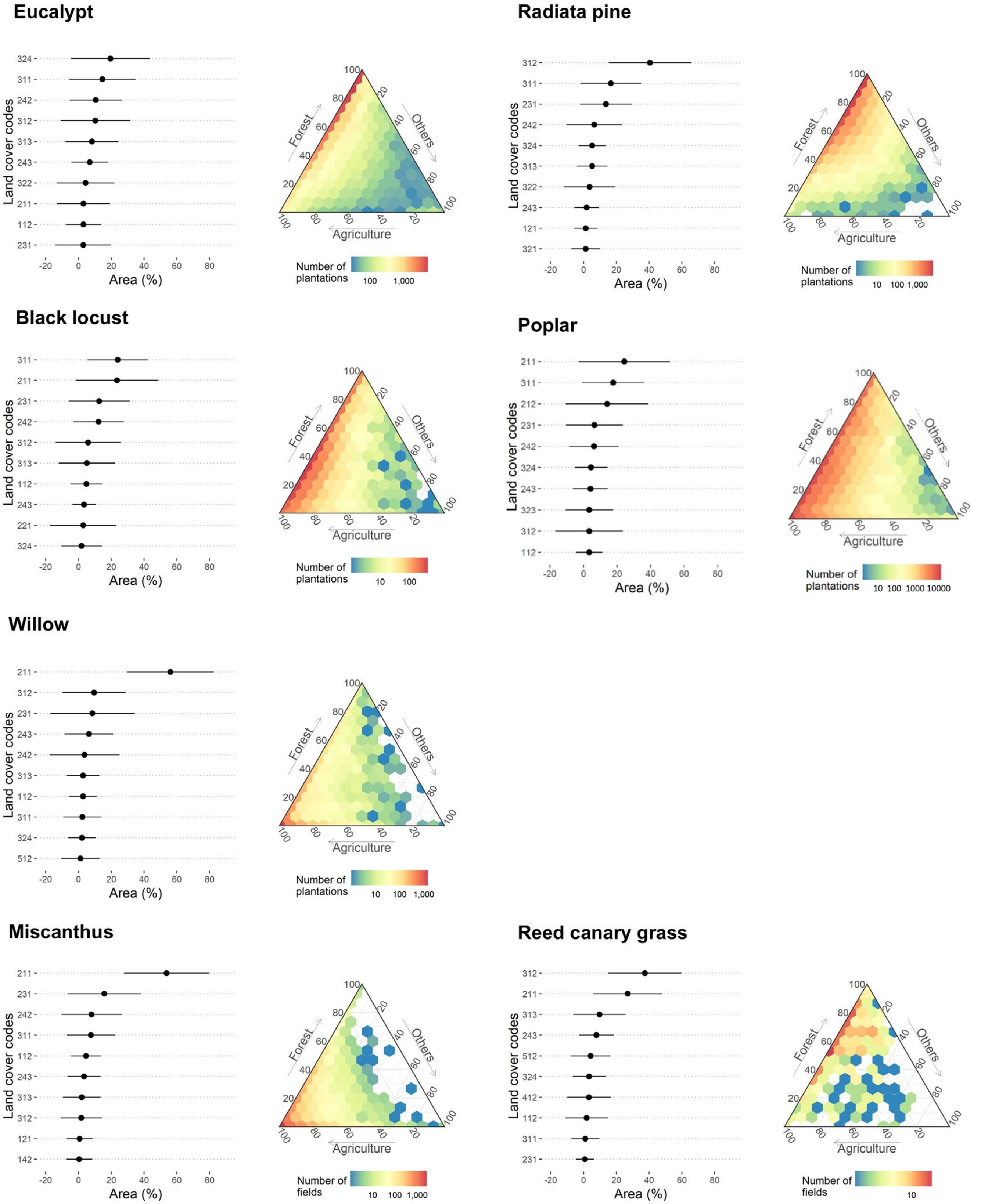


**FIGURE 3** | Surrounding land uses for plantation systems and perennial grasses. In each frame, left: The top ten land uses within a 1 km radius of the recorded fields or stands, categorized using the CORINE Land Cover classification. Points indicate mean values, and error bars represent one standard deviation. Right: Ternary diagrams illustrating the composition of surrounding landscapes for each biomass production system, classified into forests, agriculture, and other land uses. Each hexagon represents fields or stands with identical land use combinations, with hexagon color intensity indicating the density of occurrences.

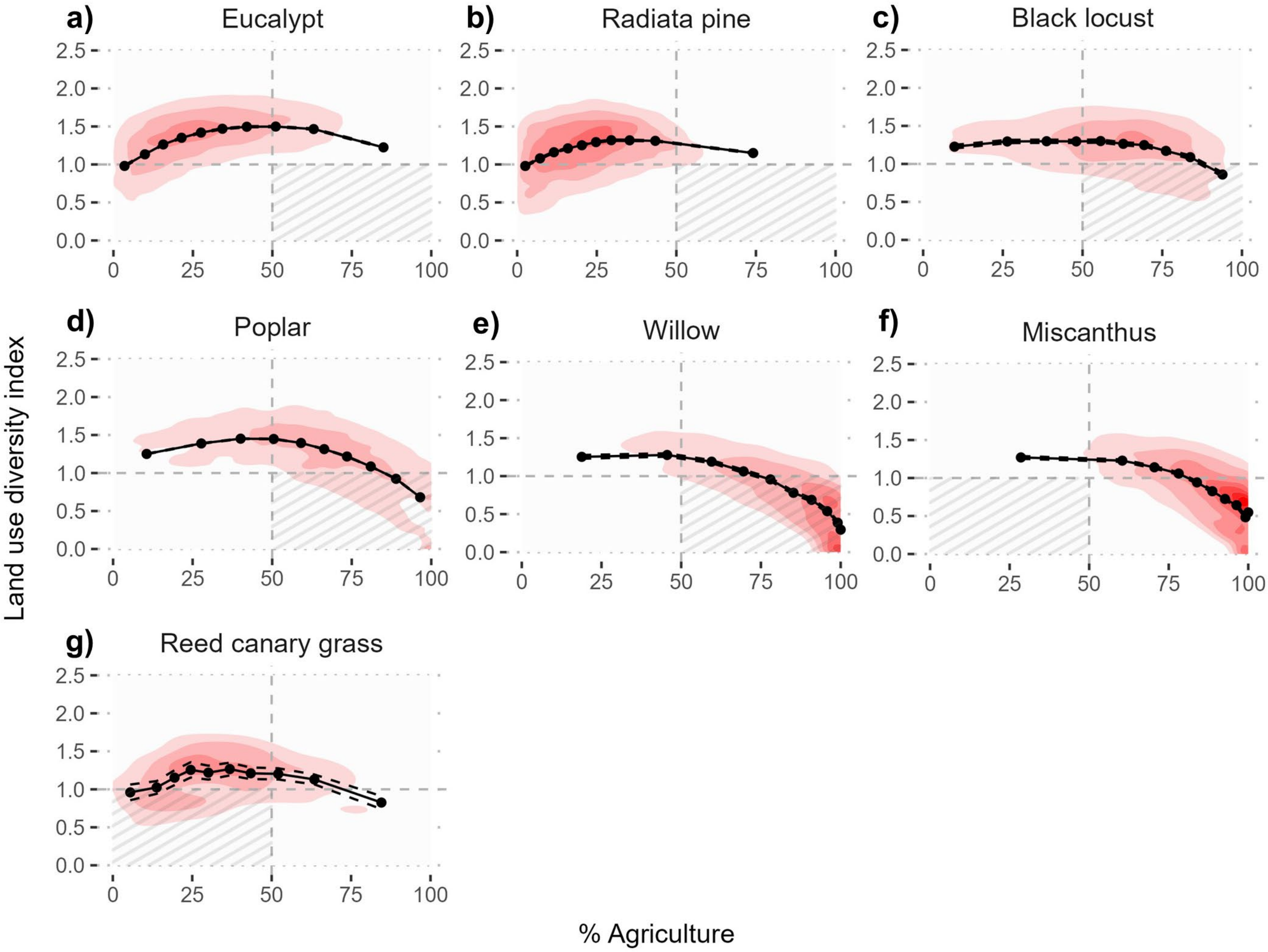


**FIGURE 4** | Land use diversity index (LUDI) in relation to the percentage of agricultural land in the surrounding areas of selected biomass production systems. Surrounding areas entail 1 km from the plantation or field's boundary. The density of observations is represented as filled contour plots, from light to dark color. Black dots represent a 10-tile mean value, and black dashed lines the corresponding standard error. Grey dashed lines defined the contour of a LUDI equal 1 and a percentage of agricultural area over 50% for woody species, and under 50% for grasses.

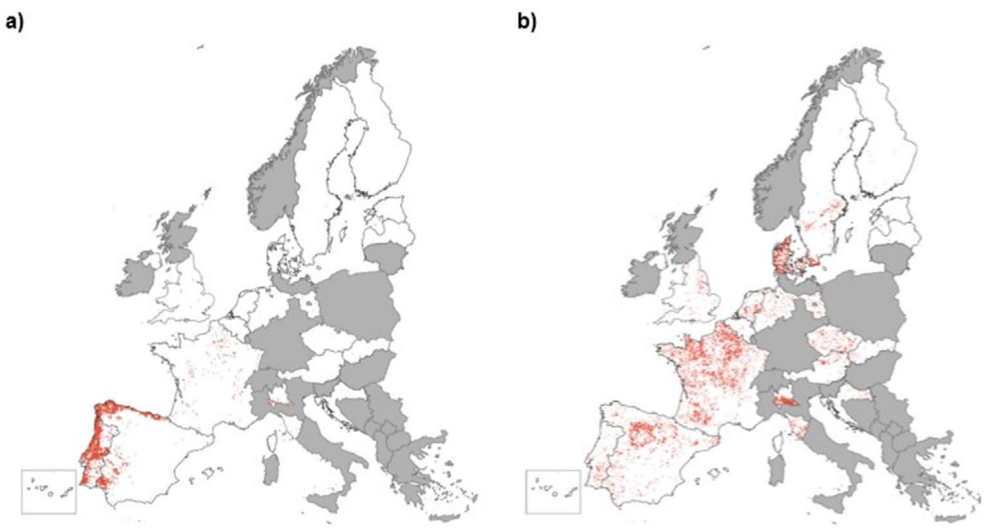


**FIGURE 5** | Identification of biomass stands/fields according to size and land use diversity index. (a) Stands and fields classified by size, with red dots representing large polygons, for all crop species (over 50 ha). (b) In red, biomass production systems that potentially enhance local land use diversity.

total area studied). As an example, the three largest polygons together entailed over 80,000 ha of eucalypt in Portugal. While these represent extreme cases of landscape dominance by a single cultivation, biomass production systems also contributed to land use diversification. Around 70,000 fields and stands (covering 117,766 ha) were located in areas where their contribution to landscape diversity was considered significant. These areas featured largely homogeneous land uses (LUDI < 1), and the criteria included the presence of woody plantations on agricultural landscapes (> 50% agricultural cover) and perennial grasses on forest landscapes (< 50% agriculture).

The spatial distribution of biomass plantations contributing to land use diversity was relevant in France, with over 54,000 ha distributed across 18,120 stands. Spain followed with more than 41,000 stands covering 28,181 ha. Italy had 5029 stands covering 14,366 ha, offering further potential to enhance local land use diversity. Portugal and Denmark each had over 5000 ha of plantation systems, distributed across 1230 and 3012 stands, respectively. For perennial grasses, the numbers were more modest. France had the largest recorded area, with over 169 ha, followed by Sweden with 167 ha, distributed across approximately 134 and 83 fields, respectively, that could contribute to local land use diversification. Overall, the spatial distribution of biomass plantations highlights both the extent of landscape dominance by single crop species and the potential of certain stands and fields to diversify local land use.

## 4 | Discussion

In this study, we document around 2 million ha of forest plantations and energy grasses distributed across more than 400,000 stands and fields throughout Europe. In general terms, data concerning plantation systems remain scattered and lack the standardized collection necessary for comprehensive studies. This limitation has been regarded as an important drawback that affects the development of short rotation plantations (Lindegaard et al. 2016). This work addresses this gap and represents one of the largest efforts to compile, harmonize, and characterize fast-growing plantations and energy grasses across Europe.

Comparisons with previous studies indicate that our estimates for planted areas are generally consistent with the literature. For poplar and willow, our estimates are in line with previous reports (Lindegaard et al. 2016). For Finland and Estonia, the data we retrieved were linked to agricultural subsidies (from 2020 and 2023, respectively), suggesting that the areas we documented might be underestimates compared to national statistics. In England, the Department for Environmental Food and Rural Affairs reported around 8000 ha of Miscanthus and at least 2000 ha of willow in 2020 (DEFRA 2021), while our data, based on The Energy Crops Scheme Agreements, indicate larger areas of 14,000 and 3000 ha, respectively. In most cases, the data made use of official land records or national forest inventory, and thus largely coincided with the national statistics.

Regarding the characteristics of the crop species studied, sizes of fields and stands follow a logarithmic distribution, where a small fraction, approximately 20% of the plantations, accounts for most of the total land area (typically between 60% and 80%). This uneven distribution, following the Pareto principle (Pareto 1897) suggests that larger plantations benefit from economies of scale and reflects the way that land allocation has influenced agricultural landscapes (e.g., Woodhouse 2010). In a comparative study of field size distributions for plantations and energy grasses versus conventional agricultural crops, it was observed that although all systems follow a logarithmic pattern, the effect is markedly more extreme in the case of plantations and energy crops (Xu et al. 2023).

The land use analysis indicates that poplar and willow plantations are primarily surrounded by agricultural land, reinforcing the idea that their presence has the potential enhance landscape compositional heterogeneity. For instance, a significant amount of poplar plantations has potential on contributing to landscape heterogeneity in areas of central Spain, France, Denmark and southern Sweden. In these locations, the land use of the surrounding areas is largely dominated by agricultural crops, and therefore these plantations may have substantial positive impact in terms of biodiversity as well as soil and water (Baum et al. 2012; Dimitriou and Mola-Yudego 2017). The diversification of agricultural landscapes through the inclusion of biomass systems can also provide farmers with additional income sources (Njakou Djomo et al. 2015) and offer new market opportunities for green jobs and the revitalization of marginal lands (Parra-López et al. 2017).

The location of plantations plays a crucial role in biodiversity, as supported by studies on bird communities (Berg 2002), ground beetles (Müller-Kroehling et al. 2020), and butterflies (Haughton et al. 2009). The impacts on biodiversity, however, vary among species and biomass systems. Sage et al. (2006) noted that species dependent on open fields may be displaced by energy crops, while Tarr et al. (2017) argued that the effects of short rotation woody crops depend on whether they are integrated into predominantly forested or grassland-dominated landscapes. These variations underscore the influence of crop heterogeneity in agricultural landscapes, which has been explored with mixed findings. Alignier et al. (2020) suggest that crop heterogeneity benefits plant diversity within fields, whereas Khan et al. (2023) propose that reducing mean field sizes might be more effective in improving biodiversity across taxa. However, the potential of increasing land use heterogeneity to enhance biodiversity is subject to the “area–heterogeneity trade-off hypothesis” (Duelli 1997; Kadmon and Allouche 2007), which predicts that biodiversity is maximized at intermediate levels of heterogeneity, underscoring the need for future studies to focus on locations with intermediate levels of LUDI for more comprehensive assessments. Overall, the influence of surrounding landscapes and land use heterogeneity on biomass systems in Europe remains underexplored, even as the demand for biomass products increases.

Our analysis also shows that reed canary grass, radiata pine, and eucalypt are generally surrounded by forested land uses. In the case of reed canary grass, this pattern aligns with findings from Xu et al. (2023) in Sweden. Additionally, pine plantations tend to be neighbored by other coniferous stands, and eucalypt plantations often occur near broad-leaved tree stands. Notably, eucalypt plantations exhibit some of the largest mean areas among all crop species. It is well established that larger, even-aged plantations are associated with lower biodiversity and reduced habitat complexity. Furthermore, management practices that exacerbate landscape homogeneity may further decrease biodiversity in these landscapes (Calviño-Cancela 2013).

It is important to note that our study captures only a static snapshot of biomass supply systems. The lack of temporal data prevented us from analyzing past land uses, which could shed further light on the impacts of land conversion and bioenergy crop cultivation on landscape heterogeneity and biodiversity (Meller et al. 2015). Moreover, our study's reliance on diverse data sources, from agricultural fields and land use maps to forest maps and crop subsidies, resulted in notable variability in plantation sizes, including outliers such as eucalypt plantations spanning 53,000 ha and poplar plantations covering 1000 ha (Figure S1). These inconsistencies underscore the need for harmonized, cross-regional data systems to support sustainable deployment of biomass systems. Nevertheless, when considering the regional context, our analysis shows that some plantations tend to be larger than agricultural fields within the same datasets, suggesting that these extreme values may reflect land use patterns that require further investigation.

Another key limitation highlighting the need for centralized records is the absence of spatial data for certain biomass systems (e.g., mapped locations, polygon boundaries), despite their documentation in national statistics or specialized literature. For example, in Poland about 6000 ha of fast-growing tree plantations and 500 ha of miscanthus were reported in 2011 (Lewandowski et al. 2016; Szostak et al. 2013), while Hungary reported at least 150,000 ha of predominantly hybrid poplar (IPC 2000) without spatial reference. In Romania, data from the Payments and Intervention Agency for Agriculture (APIA) was available but lacked species-specific details, which prevented their inclusion in the analysis.

Beyond improving consistency, the harmonization of data on biomass systems can also contribute to designing more effective policies. Spatially explicit results, such as those presented in this study, offer valuable insights for implementing targeted subsidies. These subsidies can help establish biomass plantations in optimized areas where additional ecosystem services can be enhanced. Sweden has demonstrated that a combination of subsidies, tax incentives, and investments in district heating infrastructure led to increases in the deployment of willow plantations for bioenergy production. Mola-Yudego and Pelkonen (2008) showed that these financial incentives contributed to an increment of around 70% in adoption rates of willow planting. Furthermore, policies such as the Ecological Focus Areas (EFAs), implemented across all EU member states as part of the Common Agricultural Policy (CAP), have incentivized farmers to dedicate portions of their land to environmentally beneficial practices. While EFAs are not spatially targeted in the strict sense, they do introduce spatially relevant land use requirements at the farm level, which can influence landscape composition and biodiversity outcomes. This illustrates the potential of subsidy mechanisms that incorporate spatial considerations to support more sustainable deployment of biomass systems (Zinngrebe et al. 2017).

Future research should focus on integrating and standardizing cross-regional data that would enable decision-makers to deploy biomass systems in a manner that supports both energy production and environmental sustainability. Additionally, exploring management practices that enhance biodiversity within biomass systems is crucial to develop a more sustainable energy transition. Research has demonstrated that the adoption of practices such as earlier thinning, longer rotations, and retention tree inclusion can have positive effect on biodiversity (Dauber et al. 2010; Hartley 2002).

Our study provides a baseline for more spatially explicit research by integrating data on biomass systems and analyzing their distribution across Europe, along with their land use context. By examining their spatial patterns and their land use profiles, we offer insights into specific locations and crop species that could help enhance local land use diversity. The results of our study can be revisited to inform the development of spatially strategic policies and management practices that contribute to more sustainable biomass and bioenergy development.

## Author Contributions

**Sara Pineda-Zapata:** data curation, formal analysis, methodology, software, visualization, writing – original draft, writing – review and editing. **Blas Mola-Yudego:** conceptualization, data curation, formal analysis, methodology, project administration, supervision, validation, writing – original draft, writing – review and editing.

## Acknowledgements

We thank Marina Peris-Llopis and Miguel Ángel Blanco-Rodríguez for their constructive comments on previous versions of this manuscript. This research received funding from the European Union's H2020 research and innovation programs under the grant agreement no. 101007950 (DecisionES, Marie Sklodowska-Curie) and 101059498 (Eco2adapt), the Research Council of Finland Flagship UNITE (337127) and the SNS research project SYNERGIES. S.P.Z was supported by the Finnish Cultural Foundation, Grant No. 55232063 (North Karelia Regional Fund). Open access publishing facilitated by Ita-Suomen yliopisto, as part of the Wiley - FinELib agreement.

## Conflicts of Interest

The authors declare no conflicts of interest.

## Data Availability Statement

The data that support the findings of this study are available in the Supporting Information material of this article and at the following repository: https://doi.org/10.5281/zenodo.15396453.

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## Supporting Information

Additional supporting information can be found online in the Supporting Information section.