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Temporal changes in diversity of vascular flora accompanying *Salix viminalis* L. plantations

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- The age of energy willow plantation has significant impact on biodiversity.
- With the age of plantation, the total number of species gradually decreases.
- The share of perennial species, woodland and shrub apophytes is increasing.
- The share of therophytes is decreasing.
- *Salix viminalis* crops favour the maintenance of agroecosystem biodiversity.

Abstract: In recent years, there has been increasing interest in the floristic diversity of agroecosystems, particularly for plant conservation. While old plantations claim to be more floristically diverse, little is known about this for *Salix viminalis* L. plantations. The aim of study was to analyse the vegetation accompanying *S. viminalis* and its dynamics as plantations age. The vegetation was identified in 20 plantations, based on 244 phytosociological relevés. For each species, the following were defined: botanical family, geographical and historical groups, origin of apophytes, biological stability, life-form, botanical class and phytosociological class. The relative coverage of major plant groups was statistically processed using the analysis of variance with a linear mixed model. The flora of *S. viminalis* plantations is rich and diverse; in central Poland, it consisted of 193 plant species. These species belonged to many phytosociological classes, of which two dominated: *Molinio-Arrhenatheretea* (46 species) and *Artemisietea vulgaris* (32 species). Perennial species, meadow, woodland, and shrub apophytes, as well as hemicryptophytes, were prevalent. As the plantations aged, the proportion of perennial species, meadow, woodland, and shrub apophytes increased, while therophytes and anthropophytes declined. Photophilous species dominated mainly in young crops (4–5 years old), but their coverage and frequency decreased over time. With plantations age, vascular flora diversity (total number of species) and coverage of ecologically important groups (*Poaceae* family, *Molinio-Arrhenatheretea* class) decreased. These were gradually replaced by mega- and nanophanerophytes and species from the *A. vulgaris* class. The stabilisation of flora occurred after eight years of willow cultivation.

Keywords: anthropophytes, apophytes, botanical families, dynamics of flora, life forms, plantation age

INTRODUCTION

In recent years, scientists have emphasised that the floristic diversity in agroecosystems, which consists of the diversity of crop species and flora accompanying crops, is a valuable part of the agricultural landscape (Feledyn-Szewczyk, 2013; Fehér *et al.*, 2020). The composition of agroecosystem flora is affected by various factors, including the simplification of crop rotations, introduction of new cultivars of crops, the use of seed material that has been well cleaned of weed diasporas, as well as the use of new soil cultivation technologies, fertilisers, and herbicides. Biodiversity of agroecosystems decreases with the intensification of agricultural production and the emergence of large-area monocultures. Kędziora and Karg (2010) emphasise that many species have irretrievably disappeared, for example species characteristic of flax cultivation: *Camelina alyssum* (Mill.) Thell., *Cuscuta epilinum* Wehe ex Boednn, *Spergula arvensis* subs. Maxima (Weihe) O.Schwarz (Siciński, 2003). The number of insects that feed on weed seeds, such as *Polygonum aviculare* L., *Chenopodium album* L. has also decreased (Marshall *et al.*, 2003). The reduction of available food leads to the extinction of not only pest insects, but also many beneficial insects that serve as natural predators of commercial crop pests. Consequently, the populations of many bird species that feed on seeds – and whose young depend on insects for nourishment – have also declined significantly.

Energy crop plantations used as renewable energy source have been cultivated for many years becoming an integral part of agricultural landscapes in many countries, including Canada, the USA, and various countries in Europe. Among the many plant species potentially suitable for biomass production, the following groups can be distinguished. These include fast-growing trees and shrubs such as e.g. *Salix* sp., *Populus* sp., *Robinia pseudoacacia* L.; perennials: *Sida hermaphrodita* (L.) Rusby, *Helianthus tuberosus* L., *Silphium perfoliatum* L., *Reynoutria sachalinensis* (F. Schmidt) Nakai; perennial grasses: *Phalaris arundinacea* L., *Miscanthus* spp., *Pancium virgatum* L., *Spartina pectinata* Bosc ex Link, *Andropogon gerardi* Vitmen. In countries with warmer climates, *Paulownia* Siebold & Zuccarini and *Eucalyptus* L'Hér are also widely used. In Europe, particularly in Poland, the largest areas of energy crops are occupied by *Salix* sp. and *Populus* sp. (Matyka, 2013; Stolarski *et al.*, 2014; Bioenergy Europe, 2019; Feledyn-Szewczyk, Matyka and Staniak, 2019).

In Poland, *S. viminalis* is cultivated on approximately 8,000 ha. While numerous studies focus on the production and economic aspects of willow cultivation (Matyka, 2013; Stolarski *et al.*, 2019), relatively few address the flora associated with *S. viminalis* and its ecological importance (Baum, Weih and Bolte, 2012; Feledyn-Szewczyk, Matyka and Staniak, 2019). The impact of these plantations on agroecosystems biodiversity and changes in flora over time remain insufficiently explored (Winberg, Smith and Ekroos, 2023). The rich biodiversity of energy willow plantations indirectly affects various organisms. These plantations are rich in significant food resources for birds, butterflies, and bees, making them valuable habitats for both fauna and flora. *S. viminalis* crops serve as habitats for many species of migratory and breeding birds, including fieldfare, thornbill, and marsh warbler. Positioned among arable fields, these plantations contribute to the spread of avifauna into neighbouring croplands. Additionally, traces of mammals such as roe deer, red deer, hare, and wild boar have also been observed within willow plantations (Safader, 2014). Furthermore, willow plantations support populations of beneficial insects, such as ladybugs, which play an important role in maintaining environmental resilience.

Climatic, soil, and anthropogenic factors are well known to affect the floristic diversity of agroecosystems, and these factors are also expected to influence the floristic diversity of energy willow plantations. In these plantations, plants such as arable weeds and grassland species, experience different growth conditions compared to typical crop fields. This arises due to a distinct willow cultivation practices, such as 2–3-year harvesting cycle, which limits light availability and affects thermal and humidity conditions. Moreover, the floristic composition of willow plantations depends on the land use prior to the establishment of the plantation and the age of the plantation (Korniak, Hołdyński and Wąsowicz, 2009; Baum, Weih and Bolte, 2012). It is recommended to establish willow crops on soils not used for food production. These plantations are established on arable land, grasslands, fallow fields, or fallow land, making it possible to cultivate willow on poor and light soils. As a result, the flora of these areas includes various plant groups, e.g. species typical of arable land, grasslands, forests, shrub habitats, and ruderal environments (Feledyn-Szewczyk, Matyka and Staniak, 2019).

Understanding the vegetation accompanying willow plantations and its changes over time is important for maintaining agroecosystem biodiversity, which is essential for maintaining healthy ecological functions. Studies conducted in Poland and in other countries, such as Denmark, indicate that short rotation energy crops (SRC), including *S. viminalis*, contribute to the diversification of the agricultural landscape due to different morphology and cultivation technologies, thereby promoting biodiversity. Comparison has shown that willow plantations support a greater richness of agricultural crops than traditional arable land. They also host more bird species, as well as an increased abundance of *Hymenoptera* and larger *Hemiptera* (over 5 mm) compared to both arable land and fallow land (Rowe *et al.*, 2011). Other authors argue that willow plantations can also increase beetle biodiversity. However, the analysis of the literature indicates that invasive species such as *Solidago* sp. and *Conyza canadensis* (L.) Cronquist occur in willow plantations, necessitating ongoing monitoring. Compared to conventional crops, perennial energy crops require fewer plant protection products and fertilisers, creating favourable conditions for the development of various weed species (Feledyn-Szewczyk, 2013). Additionally, our previous studies have identified the presence endangered species within the willow plantations (Janicka, Kutkowska and Paderewski, 2020).

The vegetation of *S. viminalis* plantations in Poland has primarily been studied in young plantations (1–5 years old) and analysed as a whole (Ziaja and Wnuk, 2009). The flora of older energy willow plantations (over 5-year-old) remains particularly unexplored. Moreover, no studies have systematically compared the flora of younger and older plantations to track changes occurring with the age of the plantation. The research hypothesis assumes that the floristic diversity of energy willow crops is determined by a various factors: climatic, soil, anthropogenic, as well as the age of the plantation. The aims of the study were: (1) identification and multifaceted analysis of vascular flora accompanying energy willow plantations, and (2) analysis of the dynamics of flora changes with the age of the plantation.

MATERIALS AND METHODS

STUDY LOCATION AND CHARACTERISTICS OF ENERGY WILLOW PLANTATIONS

The study was carried out in 2011–2015 and in 2018 involving 20 plantations of *S. viminalis*, in eight locations in the Łódź Region, in central Poland (Tab. 1). Plantations of different age, soil conditions (soil agricultural complex) and land use before their establishment were selected for the study.

The study area was characterised by a relatively flat surface. The plantations were established in 2004–2008 (Tab. 1), so during the study period they were 3–14 years old. Before the establishment of the plantations, the land had been used as permanent grasslands (ML), arable lands (AR), and part of it was fallow (FA) for several years. The cultivated area of *S. viminalis* varied significantly, ranging from approximately 0.3 ha to approximately 9.8 ha (Tab. 1). In accordance with the applicable methodology, the number of research plots per plantation was determined based on whether the combination of subsequent relevés was sufficiently large and whether new species important for the characterisation appeared. The relevés were made every year in the same plantation, ensuring consistency. Consequently, they were carried out in the most numerous plantations, i.e. with an area of 0.51–2.0 ha – 122 relevés (49% of all relevés), in 0.3–0.5 ha – 31 relevés (12%), in 2.01–4.0 ha – 34 relevés (14%) and in 4.01–9.8 ha – 57 relevés (24%).

Since most plantations (except one) had an area of ≤5 ha, they were classified as small in size. Willow harvesting was usually carried out in a 2–3-year cycle (Tab. 1). *S. viminalis* plantations were neither fertilised and nor treated with pesticides.

SOIL CONDITIONS

The energy willow plantations were established on the soils of seven different agricultural soil complexes: 2z, 4, 5, 6, 7, 8, and 9 (Tab. 1). According to Polish soil classification (Kabała *et al.*, 2019) and WRB classification (IUSS Working Group WRB, 2015), most of the plantations were established on Cambisols (10 plantations). The remaining plantations were established on Gleyic/Stagnic Phaeozems/Chernozems (2), Fluvisols (4), and Podzols (4).

The soil reaction ranged from very acidic to acidic, except Phaeozems, which contained silt in the upper part of the soil profile and had a neutral pH (one plantation). The soils were characterised by a varied content of phosphorus, from very low and low (15.6–43.1 P mg·kg^{-1} soil) – mainly Fluvisols and Podzols, to medium and high (47.0–81.9 P mg·kg^{-1} soil) –

Table 1. Location, area and characteristics of the energy willow plantations

No. of plantation	Locality name	Altitude (m a.s.l.)	Area (ha)	Land use before the establishment of plantation	Year of establishment	Soil agriculture complex[1)]
1	Dmosin	157	3.30	arable land	2005	5, 6, 7
2	Okołowice	164	5.00	fallow land	2008	2z
3	Okołowice	164	2.00	fallow land	2008	2z
4	Okołowice	180	9.87	fallow land	2008	6, 7
5	Olsza	185	1.23	arable land, fallow land	2007	5, 6, 9
6	Olsza	181	1.00	arable land	2007	5
7	Olsza	195	2.30	arable land	2005	5, 6
8	Olsza	195	1.50	arable land	2005	5
9	Piwaki	224	1.30	arable land	2004	4, 6
10	Piwaki	219	0.30	arable land	2004	8
11	Piwaki	222	1.40	arable land	2004	5
12	Podole	166	0.80	arable land	2004	5
13	Podole	162	1.10	arable land	2004	5, 6
14	Podole	162	0.50	arable land	2004	5
15	Stare Rowiska	145	1.60	arable land	2007	5, 6
16	Świątniki	188	4.80	fallow land	2008	7
17	Świątniki	176	1.40	fallow land	2008	7
18	Świątniki	183	5.00	fallow land	2008	7, 9
19	Wojciechowice Duże	100	0.45	permanent grassland	2005	2z
20	Wojciechowice Duże	100	0.40	permanent grassland	2004	2z

[1)] 2z = alluvial soils in river valleys, periodically too dry or too wet; 4 = heavy clay sands with high humus content and regulated water conditions; 5 = loam sandy and silty soils, slightly sensitive to droughts; 6 = sandy and loam sandy soils, often too dry; 7 = sandy soils, very dry; 8 = medium compact, heavy soils, excessively wet for too long; 9 = silty and sandy soils, too wet or too dry.
Source: own elaboration on the basis of information from plantations owners and Geoportal of Łódź Voivodeship (2019).

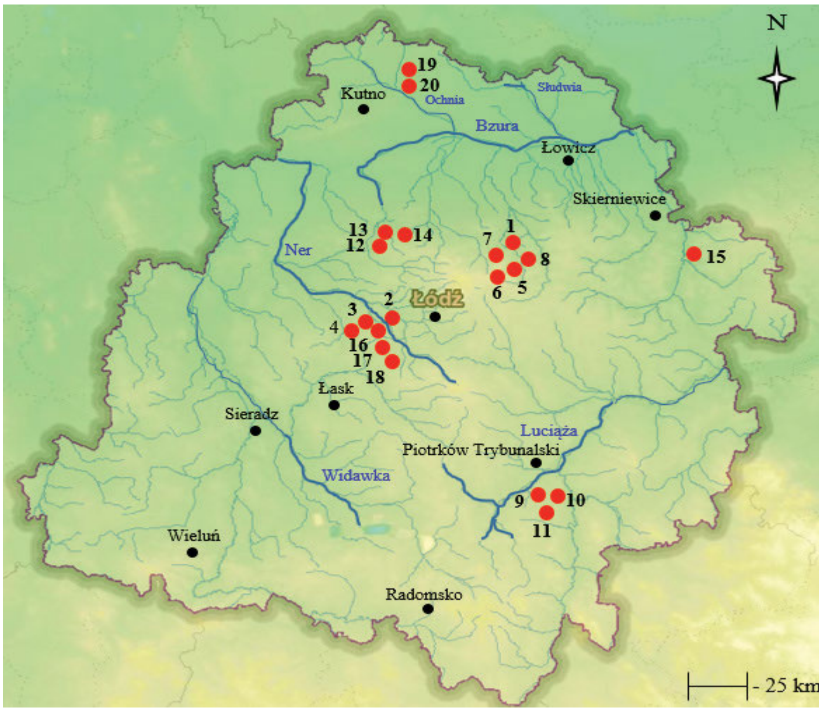

Fig. 1. Location of the study area in Łódź Region; 1–20 = plantation numbering in accordance with the numbering in Tab. 1; source: own elaboration

Cambisols and Gleyic/Stagnic Phaeozems/Chernozems. All soils were generally poor in potassium, while magnesium content varied from very low to very high. The content of organic matter also varied. In Phaeozems, it was 2.78%, while in Fluvisols, it was quite high, ranging from 6.12–7.26%. The lowest content of organic matter was in Cambisols, ranging from 1.88% to 2.28%.

WEATHER CONDITIONS

The total precipitation during the growing seasons was very diverse across the study years, ranging from 270 mm in 2015 to 539.7 mm in 2011 (Tab. 2). The highest rainfall was recorded in July 2011 (106.1 mm; Tab. S1), and the total precipitation during the entire growing season that year was approximately 47% higher than the long-term average. In contrast, the 2015 growing season had total precipitation approximately 26% lower than the long-term average. Mean air temperatures from April to October in 2011 and 2013–2015 were consistent (14.4–14.8°C), and slightly higher that the long-term average. However, in 2012 and 2018, temperatures were notably higher than the long-term average. The 2018 growing season recorded the highest air temperature, exceeding the long-term average by 2.1°C (Tab. 2).

METHODS

The vegetation accompanying willow plantations was identified based on 244 phytosociological relevés according to the Braun--Blanquet method (Braun-Blanquet, 1964). This method allows for the simultaneous recording of the number and degree of coverage of a given species in a so-called phytosociological relevé. The relevé process began with selecting a uniform, typical patch of vegetation, avoiding atypical features such as hills and hollows, and has an area of 100 m^2. Then a short description of the habitat was provided, including the date, location, size of the relevé, and coverage with willow and plants accompanying willow. Subsequently, a list of all plant species present in a given area was

Table 2. Weather conditions in the years 2011–2015 and 2018

Months	Year						
	2011	2012	2013	2014	2015	2018	1990–2010
Average monthly air temperature (°C)							
Apr–Oct	14.8	15.0	14.4	14.7	14.4	16.4	14.3
Jan–Dec	9.0	8.8	8.4	9.5	9.8	9.9	8.7
Sums of monthly precipitation (mm)							
Apr–Oct	539.7	351.0	474.4	406.3	270.0	409.6	366.3
Jan–Dec	653.4	500.7	650.5	581.5	423.0	535.9	532.1

Source: own elaboration on the basis of Meteorological Station of the Institute of Meteorology and Water Management – National Research Institute in Skierniewice (1990–2015, 2018).

developed and their coverage – defined as the vertical projection of the plants on the ground surface – was estimated using the Braun-Blanquet scale (1–5, +, r). The research was conducted mainly in June and July each year. Phytosociological classes were determined according to Matuszkiewicz (2024), with nomenclature determined after Mirek *et al.* (2020). For each plant species, the following parameters were determined: coverage coefficient (*D*) and constancy class (*S*) according to Pawłowski (1972). The share of individual plant species was determined based on the constancy class (*S*): V – 80–100% of all phytosociological relevés, IV – 60–80%, III – 40–60%, II – 20–40%, I – 0.01– 20%. Braun-Blanquet values, which describe vertical plant projection on the ground surface, were converted into percentages (5 – 87.5%, 4 – 62.5%, 3 – 37.5%, 2 – 17.5%, 1 – 5%, + – 0.1%). The obtained values were scaled to 100% for each relevé. The coverage coefficient was calculated according to the following formula: the sum of the average percentages of species cover that occurred in all phytosociological relevés, divided by the total number of phytosociological relevés and multiplied by 100 (Pawłowski, 1972).

For each species, the following attributes were determined: botanical family, historical and geographical group, origin of apophytes, life form, biological stability, botanical class, and phytosociological class based on the following sources: Anioł-Kwiatkowska (1974), Szafer, Kulczyński and Pawłowski (1986), Korniak (1992), Zajac and Zajac (1992), Rutkowski (2008), Mirek *et al.* (2020). Anthropophytes – these are species of foreign origin, apophytes are species of local origin. Among life form occurred: herbaceous chamaephytes – with buds <25 cm above the ground; hemicryptophytes – herbaceous, perennial plants, with buds near the ground, protected against freezing with a layer of litter and soil; geophytes – often with storage organs (rhizomes, tubers, bulbs) with buds within the soil, nanophanerophytes – shrubs and small trees, megaphanerophytes – trees (over 5 m high) therophytes – short-lived, annual plants, that completes its life cycle (from germination to the production of seeds) within one growing season, hydrophytes – aquatic plants, and helophytes – marsh plants with buds that overwinter in the mud below the surface. In addition, the average relative coverage according to Pawłowski (1972) of apophytes and anthropophytes were calculated.

The relative coverage of main plant groups was statistically processed using the analysis of variance with a linear mixed model. This model allows determining the significance of various factors, such as age of plantation, soil-agricultural complex, and forecrop, which are typically not included in PCA analysis. A PCA biplot was also added and used as a complement to linear mixed models. Principal component analysis (PCA) was conducted using standardised variables describing phytosociological relevés. The variables included the total coverage of species belonging to: the *Molinio-Arrhenatheretea* class, the *A. vulgaris* class, the *Poaceae* family, the *Asteraceae* family, apophytes, geophytes, hemicryptophytes, mega- and nanophanerophytes, and woodland and shrub species. Moreover, the mega- and nanophanerophytes were included in these plant species groups because phanerophytes is a group of plants that plays an important role in forest communities and energy willow also belongs to this group. The total relative coverage of a studied group of species was the dependent variable, while plantation parameters such as forecrop and agriculture complex were fixed factors (categorical independent variables). Plantation age (in an inversely proportional relationship) and its age interactions with forecrop were independent continuous variables, whereas plantation localisation was a random factor. The linear model was employed to ascertain whether the independent variables (age of the plantation, agricultural complex, and forecrop) exerted a significant influence on the relative coverage in question, and to estimate the influence of the said variables on the relative species group cover or on the species diversity. Biodiversity of flora was analysed using the following indices: species richness, Shannon–Wiener diversity index (*H'*), Simpson diversity index in terms of the soil agriculture complex. The statistical analyses were conducted using R software (R Core Team, 2020). The linear mixed model and the significance of the factors were calculated using the 'lme4' (Bates *et al.*, 2015) and 'lmerTest' (Kuznetsova, Brockhoff and Christensen, 2017) packages.

RESULTS

FLORISTIC DIVERSITY ACROSS PLANTATION CONDITIONS AND LOCATIONS

The vascular flora of 20 *S. viminalis* plantations consisted of 193 plant species from 43 botanical families (Tab. S2). The families with the largest number of species were: *Asteraceae* (38 species), *Poaceae* (27 species), and *Rosaceae* (17 species). It was found that the largest number of species occurred on silty and sandy soils, particularly those that were either too dry or too wet (complex 9). In contrast, the poorest flora was characterised by willow crops on very dry, sandy soils (complex 7), as presented in detail in an earlier publication (Janicka, Kutkowska and Paderewski, 2020). Older plantations were characterised by a smaller number of species than younger plantations. Mainly light-loving and short-lived species were lost. These species were replaced by new species that occurred only in older plantations. Certain species were present only in younger plantations, including *Anthoxanthum aristatum* Boiss., *Galeopsis bifida* Boenn., *Matricaria maritima* subsp. inodora (L.) Dostál, *Medicago lupulina* L., *Setaria pumila* (Poir.), *V. tetrasperma*, *V. villosa* Roth.

The recorded plant species belonged to many phytosociological classes, of which two dominated: *Molinio-Arrhenatheretea* (46 species) and *Artemisietea vulgaris* (32 species) (Tab. S2). Most species occurred in I and II constancy classes and were characterised by low coverage. Species belonging to the *Molinio-Arrhenatheretea* class dominated in plantations established on land previously used as permanent grassland (ML), located near small rivers (e.g. *Deschamspia caespitosa* (L.) P. Beauv., *Potentilla anserina* L., *Galium mollugo* L.). Moreover, species of this class also occurred in large numbers on soils of complexes 5 and 6, on lands previously used as arable land (AR). The dominance of species from the *Artemisietea vulgaris* class and species from the *Agropyretea intermedio-repentis* class (mainly *Elymus repens* L. (Gould)) was characteristic of plantations established on soils with various soil complexes (4, 5, 6, 7, 9), on lands previously used mainly as arable land (AR). In contrast, in plantations established after fallows (FA), located on various soil complexes (5, 6, 7, 9), species belonging to the classes: *Molinio-Arrhenatheretea* and *A. vulgaris* occurred with the greatest relative coverage. Plantations located on sandy and dry soils (complex 7), established mainly on former fallows (FA), were accompanied by *Agrostis capillaris* L. from the *Trifolio-Geranietea* class (average relative coverage of approximately 60%, constancy class V). Species belonging to the *Molinio-Arrhenatheretea* class (*Daucus carota* L., *Holcus lanatus* L.) had a smaller share in these plantations. Additionally, species in higher constancy classes (III, IV) but with low coverage included *Hieracium pilosella* L. and *Achillea millefolium* L.

Analysis of the share of geographical-historical groups, biological persistence, and life forms showed that, regardless of the type of land use before the establishment of the plantation, the vascular flora of energy willow plantations was dominated by apophytes (79%) (Tab. S2), perennial species (approximately 62%) and hemicryptophytes (approximately 48%). In addition to woodland-shrub apophytes, meadow apophytes dominated in plantations established after arable land (AR) or after grassland (ML), and xerothermic apophytes dominated in plantations established after fallow land (FA). The predominance of hemicryptophytes was confirmed by the analysis of flora coverage (Fig. 2). Notable species of this group included: *Agrostis gigantea* Roth, *Dactylis glomerata* L. – characteristic of grasslands, *Convolvulus arvensis* L. – a ruderal species, commonly found on roadsides, wastelands, and railway areas, and *Geum urbanum* L. – an indicator species of old forests. The species with the greatest coverage and frequency were *A. millefolium* s.str. and *A. capillaris* L. The proportion of geophytes and chamaephytes were lower, averaging 6 and 2%, respectively. Geophytes occurred mainly in older willow plantations, including *Glechoma hederacea* L. and *Calamagrostis epigejos* (L.) Roth.

An important part of the flora among anthropophytes were plants classified as **invasive** on a national scale that are naturalised in Poland. In all studied energy willow plantations, 12 invasive species were found, with different invasiveness categories, including 4 species belonging to invasiveness category IV: *Echinocystis lobata* (Michx.) Torr. et A. Gray, *Padus serotina* (Ehrh.) Borkh., *Solidago canadensis* L., *Solidago gigantea* (Aiton). Other species were included in category I or II of invasiveness (*Antoxanthum aristatum* Boiss., *S. canadensis* L., *Erigeron annus* (L.) Pers., *Galinsoga ciliata* (Raf.) S.F. Blake, *Galinsoga parviflora* Cav., *Setaria pumila* (Poir.) Roem. & Schult, *Setaria viridis* (L.) P. Beauv., *Veronica persica* L.).

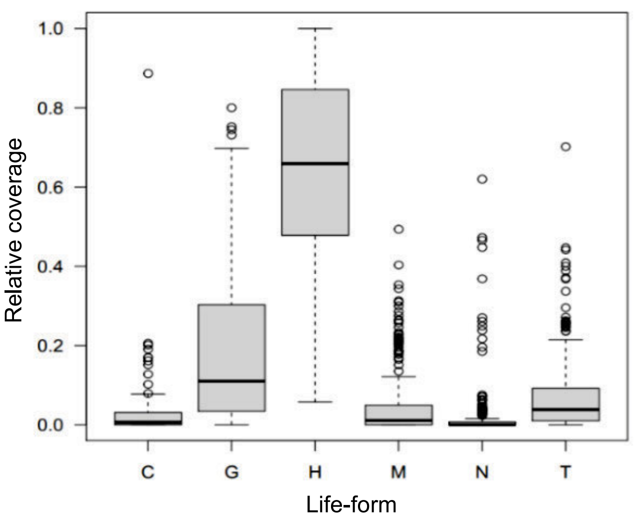

Fig. 2. Relative coverage of life-forms on *Salix viminalis* L. plantations; C = Chamaephytes, G = Geophytes, H = Hemicryptophytes, M = Megaphanerophytes, N = Nanophanerophytes, T = Therophytes; source: own study

Among the flora of willow plantations, **protected and endangered species** were found, though they occurred sporadically. One partially protected species, *Helichrysum arenarium* (L.) Moench, was recorded, valued for its medicinal properties. In addition, two species were recorded listed on the Polish red list (Kaźmierczakowa *et al.*, 2016). These were classified as endangered segetal weeds at the national level: *Agrostemma githago* L. and *Gnaphalium luteo-album* L. The first of them: *A. githago* L. is an archaeophyte, naturalised in the Polish flora, but it is disappearing due to changes in modern cereal cultivation techniques. Its presence was found in the locality of Olsza, in a single site (patch), on silty and sandy soil, either too wet or too dry (soil agricultural complex 9). Its abundance was classified as "+", indicating the presence of only a few specimens. The second species, *G. luteo-album*, is near-endangered and characteristic of *Cyperetalia fusci* communities. Its presence was recorded in a single phytosociological relevé in the locality of Piwaki, on very good rye complex soil, with an abundance classified as "1".

An interesting part of the flora consisted of **herbs and melliferous** plants, which play a vital role in both human and animal health. These plants serve as a source of herbal raw materials, pollen, and nectar for insects, especially bees. In the studied willow plantations, herbs accounted for 30% of the flora, while melliferous plants comprised 17%. Notable species providing valuable medicinal raw material included *A. millefolium* s.str., *Hypericum perforatum* L., *Taraxacum officinale* F.H. Wigg., *Urtica dioica* L., and *D. carota*.

The **Shannon–Wiener biodiversity index** (*H*') varied depending on the soil agricultural complex. The lowest value of *H*' (1.36) was recorded in vegetation accompanying willow on very dry, sandy soils (complex 7). In contrast, significantly higher values (1.75–1.76) were observed in the vegetation of soil complexes 6 and 9 (Fig. 3).

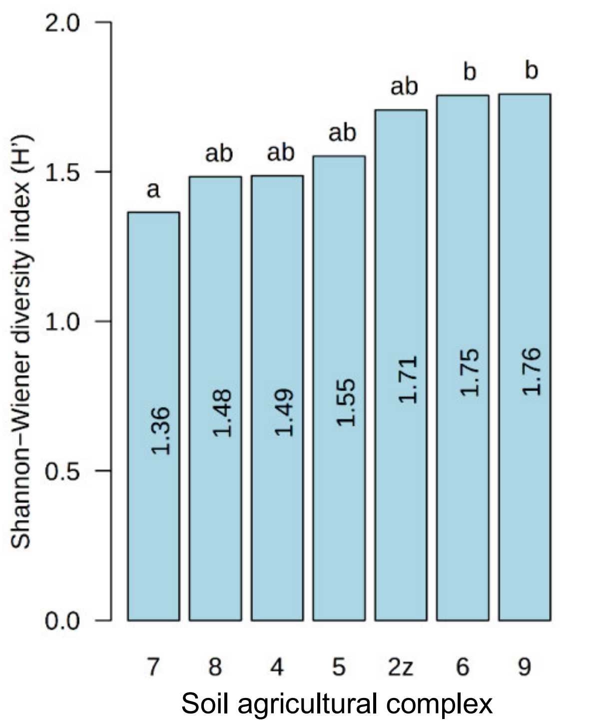

Fig. 3. Biodiversity of *Salix viminalis* L. plantations expressed by the Shannon–Wiener index (*H*') depending on the soil agricultural complex with homogeneity groups according Tukey test; source: own study

Both Simpson values (ranging from 0.779 on 2z to 0.571 on 7) and H' values consistently ranked the floristic biodiversity of willow plantations across different soil complexes. The biodiversity ranking, from highest to the lowest, followed this order: 2z, 9, 6, 5, 7. This indicates a gradient from alluvial, silty, periodically too dry or too wet soils (2z) to very dry, sandy soils (complex 7).

The PCA analysis showed that high dispersion of relevés; however, their quantity was sufficient to draw meaningful conclusions (Fig. 4). The total coverage of hemicryptophytes, species from the *Molinio-Arrhenatheretea* class, and the *Poaceae* family was greater in younger plantations, but decreased over time. In contrast, he relative coverage of the mega- and nanophanerophytes and the woodland and shrub species, which were closely related, increased over time. In terms of species abundance dynamics, there was a progressive increase in the relative coverage of geophytes and species from the *A. vulgaris* class. Notably, these two variables remained relatively independent of each other, suggesting that floral composition may evolve in either direction.

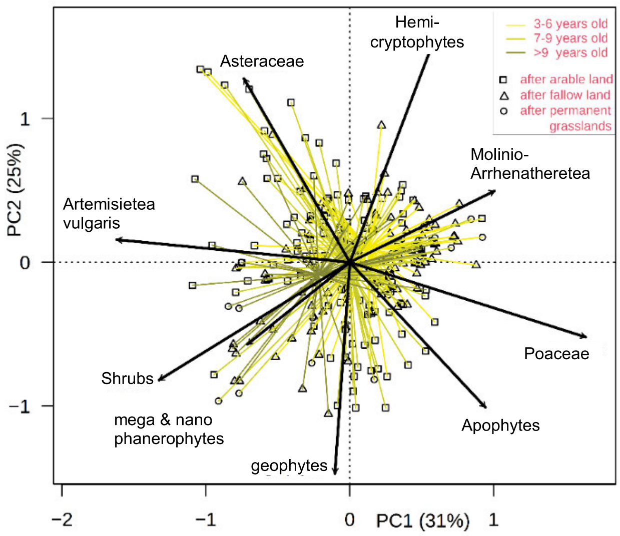

Fig. 4. The PCA analysis based on standardised variables that describe phytosociological relevés; the variables are marked with arrows, while the relevés are marked with squares, triangles and circles (depending on the land use prior to plantation establishment) and connected with lines depending on the age of the plantation during phytosociological analyses; source: own study

FLORA DYNAMICS OVER PLANTATION AGE

The analysis of species dynamics showed a decline in their number with the age of the plantation (3–14 years). For example, in Okołowice, 51 species were recorded in younger plantations (4–5-year-old), whereas older plantations (10-year-old) exhibited a 23.5% decrease, with only 39 species. Because of the high relative coverage of the *Poaceae* family (median about 40%), its distribution was analysed by the use of linear model. The interaction of the age of plantation and forecrop was not statistically significant, indicating the effect of age on the *Poaceae* family coverage. After 14 years, the relative coverage was about 45% (Tab. S3, Fig. 5a). The following grass species decreased their coverage with plantation age, particularly *A. capillaris* L., *E. repens* (L.) Gould, and *H. lanatus* L. (Tab. 3). However, no significant time effect was observed, and only the soil agriculture complex played a significant role in shaping the relative coverage of *Asteraceae* family. It is also important to highlight species from the *Fabaceae* family. These photophilous species were dominant mainly in young plantations (4–5 years old), but their coverage and frequency declined over time, examples include *Trifolium arvense* L. and *Vicia hirsuta* (L.) Gray (Tab. 3).

The analysis of variance using the linear model showed a significant interaction between plantation age and previous land use, affecting the coverage of the following plant classes: *Molinio-Arrhenatheretea* which showed a declining trend (Tab. S3, Fig. 5b) and *Artemisietea vulgaris* class which exhibited an increasing trend (Tab. S3, Fig. 5c) regardless of the forecrop. Thus, the age influence on the relative coverage was diverse. In plantations established after permanent grasslands, the coverage of the *Molinio-Arrhenatheretea* class rapidly decreased within about 8–9 years of willow cultivation (Fig. 5b). After 14 years, its relative coverage stabilised at about 25%. In plantations established on arable land and fallow land, the coverage with this class has remained relatively stable over the years. However, the coverage of *A. vulgaris* species increased rapidly in plantations established on arable land and permanent grassland, while in those established on fallow land, it remained at a similar level (Fig. 5c). After 14 years, the relative coverage of *A. vulgaris* on the arable land was about 45%. Moreover, with the age of the plantation, the constancy class and coverage coefficient of species accompanying the willow declined.

Over the years, there was a notable increase in the coverage of apophytes (native species) and gradual decline of anthropophytes (species of foreign origin). The mean relative coverage of apophytes was 82–100% (except for 11-year-old plantations) and was the highest in the oldest plantations (12–14 years old) (Tab. S4). However, no significant impact of time on the total apophyte dynamics was observed in this study. Instead, soil complex was found to be the most influential factor (Tab. S3).

The increase in the proportion of woodland and shrub apophytes with plantation age occurred regardless of prior land use (Fig. 5f). In plantations established after arable (AR) and fallow land (FA), the coverage of this plant group reached approximately 25% and 20%, respectively, by the time the plantations were 8 year old. In contrast, plantations established after permanent grassland (ML) reached 25% coverage of woodland and shrub apophytes at around 13 years of cultivation (Tab. S3, Fig. 5f).

Considering the life forms of plants in willow plantations, it was found that therophytes – annual species that overwinter as seeds and are characteristic of arable land – occurred mainly in younger willow plantations (4–5 years old), where their share was about 25%. In older plantations (10 years old), their presence decreased by half (about 12%). Some of species were absent in older willow plantations, for example, in 4–5 year old crops, species such as *Apera spica-venti* (L.) P. Beauv. and *Myosotis arvensis* (L.) Hill. The share of hemicryptophytes showed only minor changes with the plantation age. For example, in Okołowice, their share increased slightly from 51% to 59%. Among the hemicryptophytes in younger plantations (4–5 years old), species such as *Hypochoeris radicata* L., *Poa pratensis* L., *Vicia cracca* L. were present but not found in older (10-year-old) plantations. In older (10-year) crops, *Senecio jacobaea* L. increased its constancy classes (from I to III). The analysis of

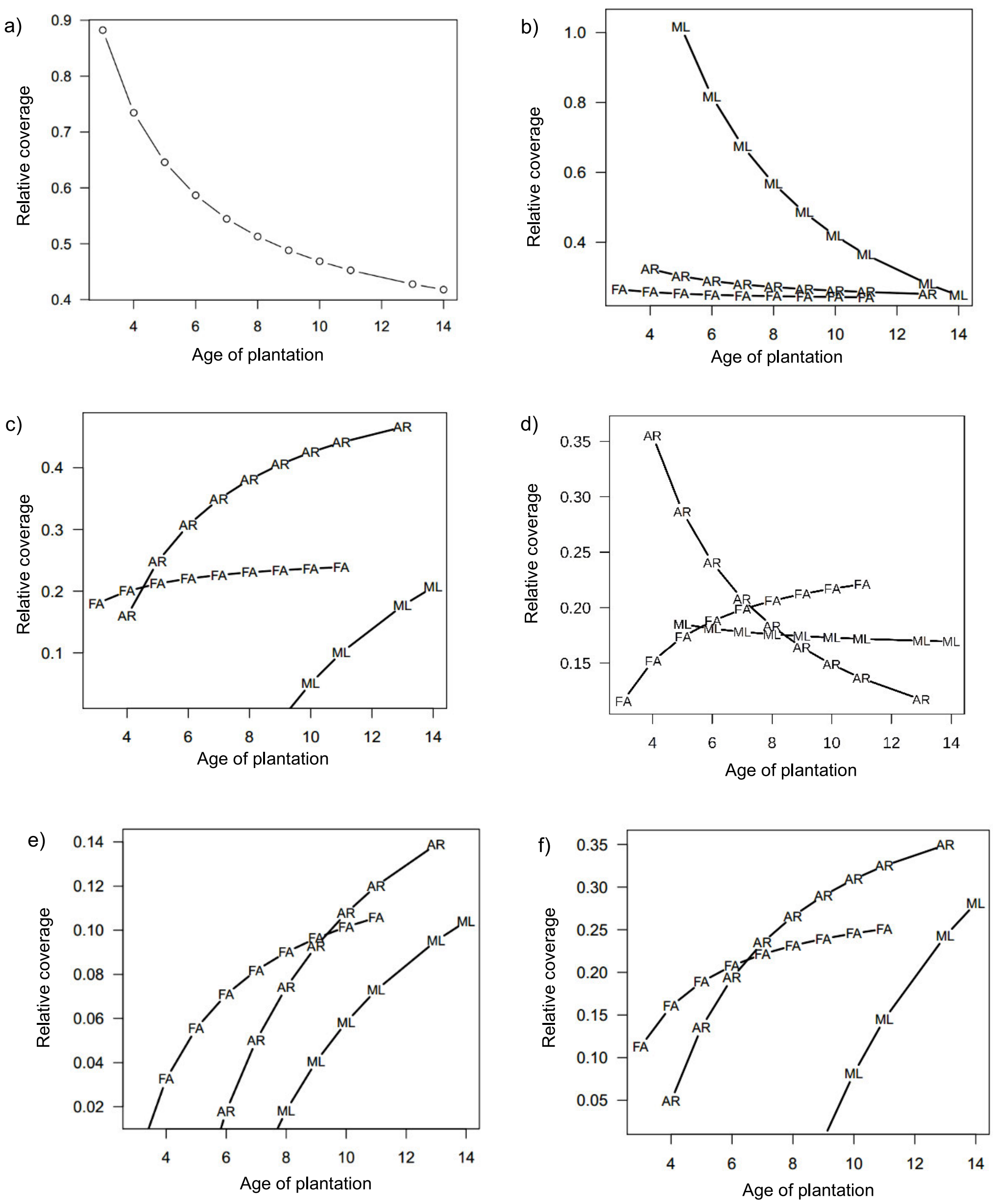

Fig. 5. Relative coverage of species of: a) *Poaceae* family depending on the age (3–14 years), b) the *Molinio-Arrhenatheretea* class depending on the land use before establishing the plantation and their age (3–14 years), c) the *Artemisietea vulgaris* class depending on the land use before establishing the plantation and their age (3–14 years), d) geophytes depending on the land use before establishing the plantation and their age (3–14 years), e) mega and nanophanerophytes depending on the land use before establishing the plantation and their age (3–14 years), f) woodland and shrub species depending on the land use before establishing the plantation and their age (3–14 years); *Salix viminalis* L. plantations estimated by linear mixed model; FA = plantations established on fallow land, AR = plantations established on arable land, ML = plantations established on permanent grasslands; source: own study

variance showed no significance in the total coverage of hemicryptophytes.

The share of geophytes and chamaephytes numbers gradually increased with the age of the plantation. The total relative cover of geophytes was lower than hemicryptophytes (mean 19% vs. 61%). However, its dynamics was significant (Tab. S3) and depended on prior land use (Fig. 5d). The total relative cover of geophytes increased in plantations established on fallow land and decreased in plantations established on arable land. Among geophyte species, only *C. epigejos* (L.) Roth – an expansive grass in nutrient-poor, acidic soils, sandy habitats, abandoned meadows, and arable land – increased its coverage significantly over time.

The analysis of variance showed a significant interaction effect between plantation age and prior land use on the total coverage of mega- and nanophanerophytes. As plantations aged, the total coverage of these plant groups increased, reaching approximately 10% after 9–10 years of cultivation in plantations established on arable land and fallow land. Similar levels were reached after 14 years in plantations established on permanent grasslands (Tab. S3, Fig. 5e). Among the mega- and nanophanerophytes in willow plantations, species commonly found in forests were noted, such as: *Betula pendula* Roth, *Pinus sylvestris* L., *Quercus petraea* (Matt.) Liebl., and *Quercus robur* L. These species occurred both in younger (4–5 years old) and older (10 years old)

Table 3. Mean coverage (%) and frequency (%) of selected plant species on the *Salix viminalis* L. plantation in Okołowice

Species	Mean coverage		Frequency	
	plantation age in years			
	4–5	10	4–5	10
Achillea millefolium L. s.str.	10.41	7.93	90	56
Agrostis capillaris L.	14.95	4.52	60	67
Artemisia vulgaris L.	1.33	0.50	50	67
Betula pendula Roth	0.62	1.62	20	44
Calamagrostis epigejos (L.) Roth	5.95	36.48	70	100
Daucus carota L.	2.14	3.32	70	89
Elymus repens (L.) Gould	10.39	4.45	80	44
Erigeron annus (L.) Pers.	1.34	0.22	50	22
Holcus lanatus L.	2.88	0.72	40	56
Hypericum perforatum L.	0.45	0.07	40	11
Jasione montana L.	0.55	0.37	50	11
Leontodon autumnalis L.	0.19	0.13	20	11
Oenothera biennis L.	1.67	2.18	60	67
Padus serotina (Ehrh.) Borkh.	0.95	13.71	90	100
Pinus sylvestris L.	1.52	3.63	70	56
Rumex acetosella L.	1.77	0.87	70	33
Solidago canadensis L.	3.51	3.97	60	67
Quercus petraea (Matt.) Liebl	0.16	0.62	10	33
Quercus robur L.	0.21	0.48	50	22
Tanacetum vulgare L.	2.97	1.69	70	67
Taraxacum officinale F.H. Wigg.	0.41	1.20	40	33
Trifolium arvense L.	4.61	0.19	70	22
Vicia hirsuta (L.) Gray	1.30	0.07	50	11
Invasive species				
Antoxanthum aristatum Boiss.	0.00	0.07	0	11
Conyza canadensis (L.) Cronquist	0.40	0.00	50	0
Erigeron annus (L.) Pers.	1.34	0.22	50	22
Padus serotina (Ehrh.) Borkh.	0.95	13.71	90	100
Setaria viridis (L.) P. Beauv.	0.26	0.00	20	0
Solidago canadensis L.	3.51	3.97	60	67

Source: own study.

energy willow plantations, with a gradual increase in their coverage and frequency over time (Tab. 3).

Two **invasive** species: *P. serotina* (Ehrh.) Borkh. and *S. canadensis* L., which pose a significant ecological threat, were found in both younger (4–5 years old) and older (10 years old) energy willow plantations. Their occurrence frequency ranged from 60 to 100% (Tab. 3). One of them: *P. serotina* (Ehrh.) Borkh., a species that re-grows quickly after cutting, spreads easily as birds consume its fruits and disperse seeds over long distances. It coverage increased significantly with plantation age (from 0.95 to 13.71%). Other species classified in the low invasiveness category, not causing ecological threat, e.g. *A. aristatum* Boiss., *Solidago canadensis* L., occurred rarely and quite often, respectively, and with low coverage (up to 1.34%). Coverage with these two species remained at a similar level over the years of willow cultivation.

Coverage of partially **protected** species, i.e. *H. arenarium*, remained at a similar level during the following years of willow cultivation (0.05–0.08%). A large share of **herbs** was found both in younger (4–5 years) and older (10 years) willow crops, i.e. 31% and 41%, respectively. With the age of willow crop, some herb species decreased their coverage, for example: *H. pilosella* L. (from 16.72 to 6.26%), *H. perforatum* L. (from 0.45 to 0.07%), and others slightly increased, e.g.: *T. officinale* F. H. Wigg. (from 0.41 to 1.20%). The species richness of **melliferous** plants was similar regardless of the age of the plantations. Among them, the most common species were: *Jasione montana* L. – and *Rumex acetosella* L. The coverage of these plant species decreased with the age of the plantation (from 0.55 % in 4–5-year-old plantations to 0.37% in 10-year-old plantations). However, the coverage of *Oenothera biennis* L. slightly increased with the age of the plantation (from 1.67% to 2.18%) (Tab. 3).

DISCUSSION

FLORISTIC DIVERSITY ACROSS PLANTATION CONDITIONS AND LOCATIONS

The conducted studies aimed to understand plant biodiversity trends, knowledge of which can be helpful for better management of the *S. viminalis* L. agroecosystem. Our study showed that the vascular flora of the *S. viminalis* plantations in central Poland, comprising 193 plant species, is rich and diverse compared to the energy willow flora found in other areas (Korniak, Hołdyński and Wąsowicz, 2009; Trąba, Majda and Wolański, 2009). Such a large floristic richness results, among others, from the great diversity of soil conditions in the studied plantations and their location in the landscape. An important role was also played by a large number of surveyed plantations. Furthermore, it should be emphasised that our study covers the entire flora, which has not been previously shown in the literature. The results of our study confirmed the hypothesis that the floristic diversity of energy willow plantations is determined by soil conditions (Janicka, Kutkowska and Paderewski, 2020). A greater number of plant species on wet soils than on periodically too dry soils was also noted by Skrajna *et al.* (2009) and Wróbel, Wróbel and Gregorczyk (2011).

The high share of species belonging to two phytosociological classes, *A. vulgaris* and *Molinio-Arrhenatheretea,* is primarily due to the age of the assessed plantations, prior land use, and their location. Siciński (2009) and Trąba, Majda and Wolański (2009) found that *S. viminalis* L. communities constitute a system composed of species belonging to various phytosociological classes, without the presence of specific species. Therefore, they do not form classic phytocenoses, which was confirmed by the results of our own studies. The small share of species in higher constancy classes indicates that plant communities occurring in willow plantations are transient and unstable. The lack of flora stabilisation results from the systematic cutting of willow (Trąba, Majda and Wolański, 2009).

The flora of energy willow is dominated by native species. The low share of foreign-origin species is probably due to the method of willow cultivation (long-term no-till monoculture). This method does not favour the development of anthropophytes, as also noted by Anioł-Kwiatkowska, Kącki and Śliwiński (2009). By the second year of cultivation, light conditions in energy willow plantations favour the emergence of shade-tolerant species, commonly found in forests and shrubs, e.g. *Galium aparine* L., *G. hederacea* L., *Sambucus nigra* L., *Calystegia sepium* (L.) R.B. Therefore, among the apophytes, the majority of species were of woodland-shrub and meadow origin, especially in willow plantations established after permanent grassland. This trend was also highlighted in our previous study (Janicka, Kutkowska and Paderewski, 2019).

The large share of perennial species and hemicryptophytes, as shown in the analyses of biological persistence and life forms, results from the age of the plantation and their succession towards forest communities. A similar dominance of these plant groups was previously noted by Skrajna *et al.* (2009), Baum, Weih and Bolte (2012), Janicka, Kutkowska and Paderewski (2020) for perennial species, while by Welc *et al.* (2017) for hemicryptophytes.

The presence of invasive species is considered an unfavourable aspect of the flora in energy crops, as emphasised by Fehér, Halmová, and Končeková (2013) and Feledyn-Szewczyk, Matyka, and Staniak (2019). Conversely, the occurrence of protected species in willow plantations has been noted by only a few authors, e.g. Korniak, Hołdyński, and Wąsowicz (2009), as well as Siciński (2009). Discussing the presence of medicinal, melliferous, and poisonous plants remains difficult, as their presence has not been analysed in studies on the composition and structure of flora accompanying energy willow plantations. The presence of various species in the studied energy willow plantations plays an important role in supporting biodiversity in agricultural areas. This is especially significant in the era of intensive plant protection product use in agriculture, as previously pointed out by Grimau *et al.* (2014) and Kwiatkowski, Haliniarz and Harasim (2020).

In terms of species richness, energy willow crops fall between forest ecosystems and crops. The *H*' index values observed in our studies were higher than those recorded for crops such as winter rape and spring wheat, which had an average *H*' index of approximately 1.5 (Feledyn-Szewczyk, 2013).

FLORA DYNAMICS OVER PLANTATION AGE

The results of the research confirmed the hypothesis that the floristic diversity in energy willow plantations is determined by the age of the plantation. Over time, the branching of willow stools increases soil shading and intensifies competition among plants. As a result, as plantation ages, the number of species accompanying willow declines, as previously indicated by Korniak, Hołdyński, and Wąsowicz (2009). *S. viminalis* L. plantations are communities related to forest and shrub ecosystems, forming a system composed of various phytosociological classes. As the dynamics show, they are subject to visible changes over time.

The analysis of flora dynamics showed that as willow plantations mature, the share of short-lived species declined while the share of perennial species increased. The share of anthropophytes decreased and the share of apophytes increased. Over the years, there is a notable rise in the coverage of woodland-shrub apophytes, as well as mega- and nanophanerophytes. The seedlings of native tree species found in willow plantations originate from nearby mixed forests. The presence of tree seedlings in willow plantations has also been noted by other authors, including Cunningham *et al.* (2006) and Welc *et al.* (2017).

For the first time in Poland, the presence of protected, endangered, and melliferous species has been assessed in willow plantations older than five years. In the Łódź Region protected and endangered, species occurred sporadically in energy willow plantations. Their presence enriches the flora of agricultural areas and plays a crucial role in maintaining biodiversity of agroecosystems, especially during intensive plant protection product use. However, the presence of invasive species, while important, is an undesirable aspect. Despite their presence in different constancy classes (I–IV), ongoing monitoring is necessary. Changes in the value of the Shannon-Wiener index with the age of the plantation has been presented in greater detail in previous studies (Janicka, Kutkowska and Paderewski, 2019; Janicka, Kutkowska and Paderewski, 2020). The analysis of flora dynamics shows that after a period of rapid changes in the first 6–8 years of willow cultivation, the flora begins to stabilise. The stabilisation occurs in terms of life-form, origin of apophytes, and its gradual equilibrium with the habitat. It should be noted that in literature there are only few studies on the dynamics of flora changes in older *S. viminalis* crops (over five years) (Korniak, Hołdyński and Wąsowicz, 2009; Feledyn-Szewczyk, Matyka and Staniak, 2019). The results presented in the literature usually concern younger plantations (1–5 years old), where vegetation shows greater changes than in older plantations (9–10 years old). Additionally, discussions of these results are often complicated by the fact that many authors do not specify the age of the studied willow plantations – an essential factor for analysing vegetation dynamics.

According to Vanbeveren and Ceulemans (2019), *S. viminalis* crops can enrich biodiversity when introduced into an agriculturally dominated landscape. However, in a landscape dominated by forests, their impact may be negative. The size of energy plantations also plays a crucial role, so their introduction into the landscape should be approached with caution (Vanbeveren and Ceulemans, 2019). Small-scale energy willow plantations (up to 5 ha) have a better impact on biodiversity than large-scale plantations (over 10 ha). In addition, the establishment of short-rotation alley cropping systems – incorporating fast-growing trees such as energy willow – can increase protection against wind erosion while offering ecological and possible long-term economic benefits for agricultural sites (Böhm, Kanzler and Freese, 2014).

CONCLUSIONS

The flora of *S. viminalis* L. plantations is rich and diverse. Over a 6-year study conducted in 20 small-scale plantations, 193 species of vascular plants belonging to 43 botanical families were recorded. The dominant groups include perennial species, meadow, and woodland-shrub apophytes, and hemicryptophytes. As the willow plantations age (3–14 years), the number of species declines, the share of therophytes (short-lived species) decreases, and the coverage with species of *Poaceae* family diminishes. As the willow plantations age, the coverage with *Molinio-Arrhenatheretea* class decreases, especially in the plantations established on permanent grasslands. The *Artemisietea vulgaris* class coverage increases, especially in plantations established on arable land. With the age of the willow plantation, the mega- and nanophanerophytes coverage increases. However, the coverage with geophytes increases in the plantations established on fallow land but decreases in the plantations established on arable land.

The presented analyses provide valuable insights into the flora of small-area *S. viminalis* L. plantations and its dynamics in "older" plantations (over 5 years old) in central Poland. Moreover, the findings indicate that the floristic composition of energy willow plantations and its changes over time are of great importance for the biodiversity of agricultural ecosystems. The flora accompanying the energy willow plantations is characterised by a significant share of plant groups important for biodiversity, including melliferous (17%), medicinal (30%), protected (1 species), endangered (2 species), and invasive (12 species), the share of which should be monitored. Small-area energy willow plantations (up to 5 ha) contribute to maintaining the biodiversity of the agroecosystem in the Łódź Region. Furthermore, the results confirmed the hypothesis that the diversity of plant species accompanying the willow is primarily influenced by the plantation age (3–14 years). However, a gradual decrease in the floristic diversity of the willow flora over time (reduced number of species, lower constancy class, and lower coverage coefficient) may indicate a potential deterioration in the ecological function of the ecosystem. Therefore, further multifaceted research in this area, especially on plantations over a dozen years old, is necessary to develop better plantation management.

SUPPLEMENTARY MATERIAL

Supplementary material to this article can be found online at https://www.jwld.pl/files/Supplementary_material_Janicka1.pdf.

CONFLICT OF INTERESTS

All authors declare that they have no conflict of interests.

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