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Grower perspectives on perennial wild plant mixtures for biogas production in Germany

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ABSTRACT

'Perennial wild plant mixtures' (WPM) cultivation is a novel approach to combine biomass provisioning for biogas production with biodiversity enhancement at field scale in Germany. But the methane yield is about 40% lower compared with silage maize. Therefore, the cultivation of WPM is incentivized with about 250–927 Euro per hectare and year. However, agronomic and best management practices of WPM cultivation are unclear, so that large parts of the yield potential of WPM are likely to remain untapped. Hence, this study aims to shed light on farmers' current perspectives and experiences with WPM cultivation by carrying out a nationwide survey in 2021. The feasibility of inferential statistics was examined in detail, but was not possible due to an insufficient number of responses. Nevertheless, the descriptive analysis revealed valuable information on farmers' experiences with and their motives for cultivating WPM such as biodiversity enhancement and landscape beauty. Generally, WPM were proven to be much less productive compared with common biogas crops such as maize. Nevertheless, 59% of the farmers cultivated WPM on less favorable soil, and 67% of the farmers used nitrogen fertilization rates of less than or equal to 50 kg ha^{-1}, resulting in generally higher yields compared with results from unfertilized areas. However, while there is common agreement on the positive effects of WPM cultivation on agrobiodiversity, more agronomic research on best management practices is required to make WPM more competitive to common biogas crops without additional subsidies.

1. Introduction

The cultivation of biomass crops for bioenergy production is regarded as a supporting pillar for the development of a sustainable bioeconomy by the European Commission (European Commission, 2017; Scarlat et al., 2018, 2013). However, when growing biomass numerous requirements need to be met to reduce land use conflicts, for example with food or feed production (Alexopoulou et al., 2023; Loew et al., 2024). In Germany, subsidies have increased farmers willingness to expand cultivation of silage maize (*Zea mays* L.) to maximize area-based bioenergy yields since 2000 (Proplanta, 2023; Witt et al., 2012). This triggered a major public debate about the perceived neglect of biodiversity in the German agricultural sector. Several studies showed that insect biomass and diversity especially of wildbees is dramatically declining in Germany (Hallmann et al., 2017; Van Dyck et al., 2009; Westrich et al., 2011).

The intensification of agriculture, with its use of chemical plant protection products, the loss of habitats through the removal of structural elements and the expansion of fields, seems to be one of the main causes for the decline of insects in agricultural areas (Brühl and Zaller, 2021; Emmerson et al., 2016; Raven and Wagner, 2021; Robinson and Sutherland, 2002; Sánchez-Bayo, 2021). In addition, the large-scale establishment of monocultures such as wind-pollinated cereals and maize which do not rely on pollination by insects make them unattractive to pollinators (Nicholls and Altieri, 2013) going along with a decline in species number and abundance in such areas (Alignier et al.,

Abbreviations: BW, Baden-Württemberg; CO_2, carbon dioxide; EU, European Union; ha, hectare (1 ha = 10,000 m^2); L, liter, when used as a unit; L, Linnaeus, when used in botanical names; Mg, megagram; N, nitrogen; DM, dry matter; WPM, perennial wild plant mixtures.

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2020; Hass et al., 2018; Sirami et al., 2019). Although some arable crops like oilseed rape offer feed sources (e.g., nectar and pollen), they are primarily frequented by generalist pollinators, have a short flowering period (Diekötter et al., 2010), and could induce negative mass flowering effects on agrobiodiversity (Holzschuh et al., 2016). As a result, vast, homogeneous agricultural landscapes provide less habitat, shelter and food resources for insects, leading to higher yields but at the expense of biodiversity (Landis, 2017; Landis et al., 2000).

However, pollinator decline will not only negatively impact natural vegetation, but also crop production and thus human food security and well-being, as 88% of all wild plants and 70% of economically important plant species depend on animal pollination (Klein et al., 2006). This underlines the crucial role of pollinators in the reproductive cycle of plants and highlights human kind's dependence on pollination services for food production (Klein et al., 2006). As a result, for almost 20 years, research has been conducted into alternative biogas cropping systems that, in addition to the economic provision of biomass, place greater emphasis on other ecosystem services such as habitat provision (Tscharntke et al., 2021), soil carbon storage (Martani et al., 2023), erosion control (Cosentino et al., 2015) and landscape cultural value (Huth et al., 2019) than maize cultivation (Herrmann et al., 2016; Kaltschmitt et al., 2005; Krimmer et al., 2021). In this context, silage maize should by no means be replaced, but rather usefully supplemented, for example through targeted habitat connectivity, at sites prone to erosion or leaching, and in areas close to settlements to create beneficial land use change effects (Englund et al., 2020; Von Cossel, 2020).

To address this challenge, alternative cropping systems are urgently required that deliver high yields while preserving biodiversity, especially in light of the decrease in available agricultural land due to urbanization, water scarcity and land degradation (Bossio et al., 2010; MIDAS, 2023; Rosegrant et al., 2009; Zimmermann et al., 2021). One particularly alternative biogas cropping system is 'perennial wild plant mixtures' (WPM) (Von Cossel, 2020) (Fig. 1). These are seed mixtures consisting of a total of about 25 annual, biennial, and perennial plant species, predominantly wild and native to Central Europe, that have been selected and combined based on their suitability for biogas production as well as their biodiversity benefits and other ecosystem services (Vollrath et al., 2012). The integration of WPM in landscapes dominated by monocultures such as maize could provide pollinating insects with a long-lasting food source, given the different flowering times of the various WPM species (Von Cossel et al., 2024a). Especially in fall and winter, when agricultural land offers little habitat and shelter, perennial WPM remnants may compensate for this deficiency (Von Cossel, 2020).

Existing studies have mainly focused on yield performance (Janusch et al., 2021; Von Cossel et al., 2019), species composition dynamics (Von Cossel and Lewandowski, 2016), life cycle assessment (Lask et al., 2020), and monetary value of the ecosystem services (Brander et al., 2024) of WPM (Kiefer et al., 2023). However, there is a lack of more far-reaching information on the practical experience of farmers that have grown WPM to date, as well as relationships between agronomic factors (tillage, site quality, etc.) and biomass yield performance or the overall outcome of WPM cultivation. Therefore, the aim of this study was to ascertain the prospects for the practical application of WPM cultivation in Germany. To do so, the following research questions were addressed: Which WPM was grown where and for what reasons? What successes and failures have the farmers experienced, and what were the reasons? What conclusions can be drawn for the future, and what questions remain open for research and practice for the time being?

2. Material and methods

To achieve this goal, a nationwide survey was conducted in 2021 in Germany to provide information on the motives driving WPM cultivation and the requisite framework for their implementation. However, WPM were cultivated in 9 federal states only. A standardized questionnaire based on questions from surveys of previous WPM-related projects carried out in 2013 (Janusch et al., 2021) and 2017 (Paltrinieri and Schmidt, 2020), supplemented with more detailed questions, for example on the soil quality and the seedbed preparation before and after sowing, was used (Table S1). Table S1 provides the English translation of the original questions (in German), together with selection options, if these were applicable.

As there was no official information on how much WPM cultivation area exists, and how many/which farmers cultivated WPM, existing networks of WPM projects, in which farmers were informed about the WPM cultivation concept, were used as contact points. The farmers were approached via email notification, which contained a request preformulated by the authors of this study (Table S1). The emails were sent by the project coordinating companies or associations to the email distribution lists of the projects at the time (Deutsche Wildtier Stiftung, Hamburg, Germany), and 'Bienenstrom' (Stadtwerke Nürtingen GmbH, Nürtingen, Germany). The number of farmers who were growing or had grown WPM at the time of the survey were estimated at around 500. Further, it was assumed that half of this number was reached via the emails sent. Despite the Covid pandemic in 2021, the online survey received a guessed response rate of 20% (n=51). However, WPM

Fig. 1. On-farm impressions of perennial wild plant mixture cultivation in Althengstett (A, first year of cultivation) and Wolfschlugen (B, second year of cultivation), southwest Germany.

cultivation is not being carried out in almost half of the German states (i.e., 9 out of 16 Federal States). In addition, not all questionnaires were completed, resulting in missing data of 0–92.2%, depending on the question (on average 49 ± 22% missing data per question). The reasons for the absence of answers were not specified. The data quality control was carried out by the authors. No unrealistic, contradictory, and therefore unusable information was found in the responses.

Data were analyzed by descriptive statistics only. Due to the low response rate and missing data, potential influencing factors were partly confounded. Therefore, inferential statistics was not used to avoid miss-interpretation of data. All analyses were conducted in R, version 4.3.1 (R Core Team, 2024), using the packages “ggplot2” (Wickham, 2009) and “gt” (Iannone et al., 2020) to display the results graphically.

3. Results and discussion

Due to the sample generation methods, most responses are coming from BW (Fig. 2). Further, several forms were not filled out completely which impeded the statistical analysis. It is rather unusual to achieve a high response rate with low completion rates. This could be due to the fact that many farmers took part in the survey because they wanted to help with the study, even if they could not answer all the questions. The reason for some missing data could also be that the information requested (e.g. the age of the seed) was either no longer known to the farmers or had never been known.

The farm sizes ranged between 2.5 and 1060 ha, with WPM cultivation areas of 0.7–24 ha, and a share of WPM cultivation area of total arable area per farm of 1.7–19.8% (Table 1).

Most farmers (43%) used seed mixtures from Saaten Zeller (Saaten Zeller GmbH & Co. KG, Eichenbühl-Guggenberg, Germany), while two farmers used seed mixtures from Rieger-Hofmann (Rieger-Hofmann GmbH, Blaufelden-Raboldshausen, Germany), and 54% of the farmers did not answer this question.

Thirty-two of the 51 respondents reported starting the cultivation of WPM in 2020 due to the start of the project “Bunte Biomasse” the year before (Table S1). The remaining 17 farmers stated that they had already started cultivating before 2020, with two of them began cultivation prior to 2010. Twenty-five farmers stated that they acquired knowledge about the cultivation of WPM through various channels such as acquaintances (30%), hunting community (22%), the WPM network (15%), media (11%), as well as governmental bodies like the department of agriculture (15%) and regulations (7%).

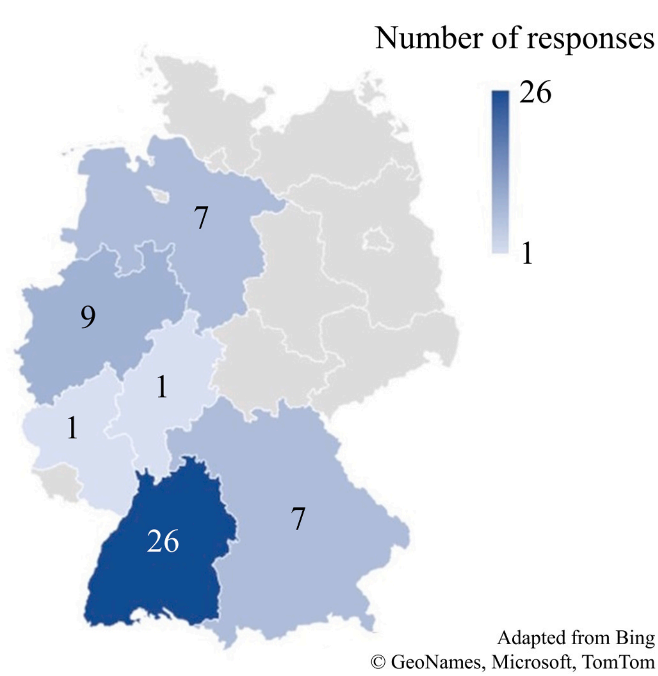

Fig. 2. Number of respondents of the survey, sorted by federal state.

These diverse sources have provided them with valuable insights into the benefits of incorporating wild plant mixtures into their farming practices. This dissemination of information underscores the importance of collaborative networks and accessible resources in fostering innovation and sustainable agricultural practices within farming communities. Networks facilitate the exchange of knowledge, best practices and experiences among farmers, researchers, government agencies and other stakeholders. Through accessible resources such as press, workshops and online platforms, farmers can access information on emerging techniques and initiatives related to sustainable agriculture. Utilizing these resources enables farmers to make informed decisions to adapt to changing environmental conditions and contribute to the long-term resilience and viability of agricultural systems.

3.1. Farmers’ motivation for growing WPM

Of the 26 farmers who stated their reasons for growing WPM (question number 24, Table S1), 84.6% cited the promotion of biodiversity in the agricultural landscape as the main motivation (Fig. 3A). “Biodiversity” and “Landscape beauty” were most mentioned motivations for the farmers to cultivate WPM (Fig. 3A). This is in accordance with findings of Paltrinieri and Schmidt (Paltrinieri and Schmidt, 2020) and Huth et al. (Huth et al., 2019). However, without subsidies, most farmers see no future in WPM cultivation due to the low dry matter (DM) (and methane) yields.

In a question on changes in soil structure through WPM cultivation (“How would you describe the change in soil structure, e.g. better rootability of the soil, erosion?”, selection options: Positive; Negative; No change), 88.9% selected positive changes in soil structure. Additionally, 13 farmers mentioned further reasons for growing WPM that were largely in line with the points highlighted above but offered more detailed insights. Among the reasons specifically related to soil, one farmer mentioned the efficient use of marginal arable land and another one the improvement of soil organic matter accumulation through the cultivation of WPM. However, if farmers grow WPM on poor marginal arable land and maize on more favorable land, then a meaningful comparison between the performances of these biogas crops is not possible. In future, it should therefore be investigated if WPM could perform better on marginal arable land compared with common biogas crops such as silage maize. This would enable a realistic comparison of the performance of WPM and conventional biogas crops, from which more appropriate cultivation recommendations and support models can be derived.

In addition, farmers emphasized the potential of WPM cultivation as a strategic approach to extensify intensively farmed agricultural land. Some farmers noticed that growing WPM could improve their public image and increase landscape quality for the community. In a further question, 76.2% of the farmers stated that they had received positive feedback on WPM cultivation from, for example, neighbors, acquaintances and above all passers-by. Only 14.3% had experienced no reactions and only 9.5% negative reactions. Most of these motivational reasons for growing WPM can also be found in the paper by Paltrinieri and Schmidt (Paltrinieri and Schmidt, 2020), as well as in other studies that have already dealt in particular with ecosystem services such as the improvement of the landscape (Huth et al., 2019).

3.2. Aspects of biodiversity with emphasis on pollinators

When asked whether farmers noticed changes in the abundance of different animal groups in fields with WPM cultivation, 90% of the farmers reported an increase in insect numbers, and 80% even reported an increase in pollinator abundance (as indicated by "Bee flight") on WPM fields (Fig. 3B). However, changes of pollinator abundance over

Table 1
Overview of average arable land per farm per Federal State (Statista, 2022), average farm sizes of the respondents of the survey and wild plant mixture (WPM) acreage sorted by federal state and number of responses.

	Average arable land per farm per Federal State (ha) (Statista, 2022)	Average total arable land per farm (ha)	Average WPM cultivation area per farm (ha)	Average share of WPM area of total arable area per farm (%)
Baden-Wuerttemberg	37.0	249.3	2.1	1.7
Bavaria	36.9	159.2	4.1	5.9
Lower Saxony	73.9	64.8	2.4	19.8
North Rhine-Westphalia	46.3	230.0	6.6	3.3
Hesse	50.4	n.a.[a]	n.a.	n.a.
Rhineland-Palatinate	44.8	n.a.	n.a.	n.a.

[a] n.a. = not available.

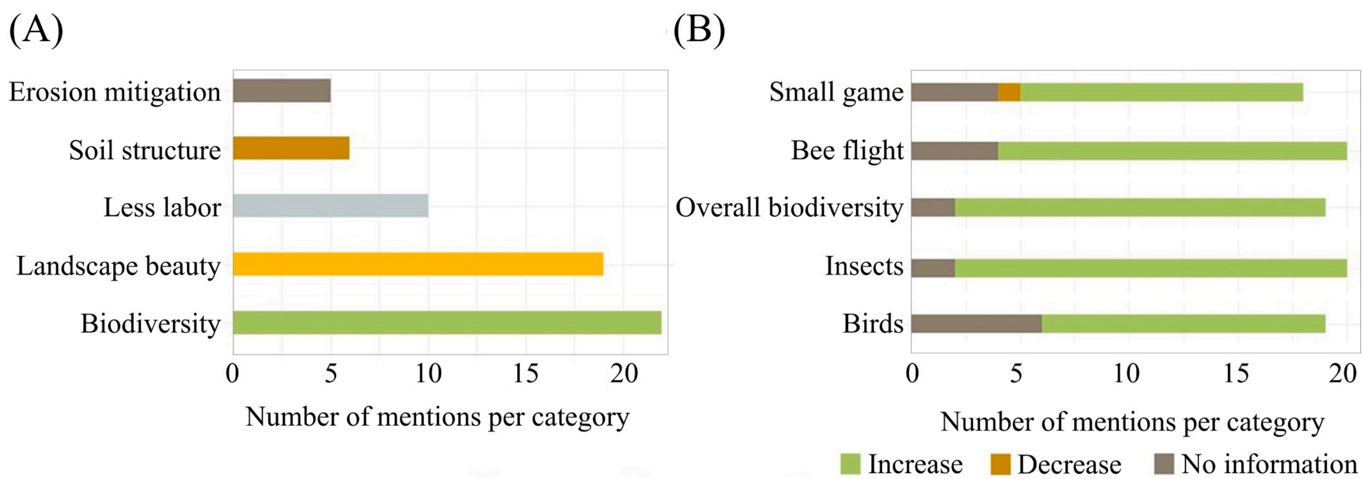

Fig. 3. Farmers' (n=26) responses to the question "Why did you decide to start growing WPM?" with the selection options: Erosion mitigation; Improvement of soil structure; Less labor required (over the entire duration of the stand); Improvement of landscape beauty; Promotion of biodiversity; and an empty text field for farmers to describe other reasons (A). Farmers' responses to the question "Have you noticed changes in the number of species (bees, insects, small game, birds)?" with the selection options: Number of small game; Flight intensity of bees; Total species diversity; Number of insects; Number of birds; (n=21) (B). For both questions (A and B), the selection of multiple motivations and changes, respectively, was possible.

time remain unknown. Regarding small game, 78.0% observed an increase, while only 5.6% reported a decrease. Concerning bird numbers, 68.4% noted an increase. None of the farmers who answered this question observed a decrease in the number of birds or insects, particularly of bees ('bee flight') in the WPM fields (Fig. 3B). A further examination of the responses regarding the changes observed in certain species groups on the WPM fields underlined the biodiversity aspect (Fig. 3B) which is in line with reports from other projects on WPM (Table S1). WPM therefore appeared to have a positive effect on the abundance of these animal groups in agricultural landscapes.

Nevertheless, the farmers' statements on the biodiversity effects are subjective impressions that require further investigation (Vollrath et al., 2016). It further remains to be clarified what indirect land use change (e.g., true costs and benefits (Wagner et al., 2022)) the lower biomass yields of WPM compared to maize and other crops on the practice areas trigger. A life cycle assessment carried out by Lask et al. (Lask et al., 2020) based on WPM field trial results helped better understand the performance gaps between WPM and silage maize. However, their approach should be supplemented and re-examined with data from large-scale field trials to allow for more profound conclusions on the overall ecosystem service performance of WPM. This could also help derive more reliable information on both the best possible funding models and best management practices for WPM cultivation.

3.3. Soil quality and soil management techniques

Like other perennial biomass crops (e.g., miscanthus (*Miscanthus* Andersson) (Winkler et al., 2020), Virginia fanpetals (*Sida hermaphrodita* L. Rusby) (Von Cossel et al., 2024b)), WPM cultivation in the year of establishment is heavily dependent on appropriate soil conditions and low weed pressure. The soil quality across the WPM fields considered for this work exhibits a notable variation, ranging from 'very good' to 'very poor' conditions according to the farmers, with 41% rated as 'good' or 'very good' (Fig. 4A). This shows that it would be inappropriate to compare WPM biomass yields directly with those of conventional biogas crops such as maize, since the latter ones are usually grown on favorable soil. However, WPM field trials on favorable arable land have provided evidence that high yields (> 20 Mg DM ha^{-1}) from WPM such as common tansy are possible even in adverse (e.g., dry) production years (Von Cossel and Lewandowski, 2016).

Further results indicate a potential correlation between soil quality and yield, as evidenced by the observation of higher yields on fields classified as having good soil quality compared to those classed as satisfactory (Fig. 4B). This relationship is substantiated by the statistical characteristics of the soil quality categories. Specifically, fields classified as having good soil quality exhibited a mean yield of 15.0 Mg DM ha^{-1}, with a standard deviation of 6.0 Mg DM ha^{-1}, and a median of 13.5 Mg DM ha^{-1}. In contrast, fields categorized as satisfactory demonstrated a markedly lower mean yield of 11.0 Mg DM ha^{-1}, coupled with a higher standard deviation of 8.3 Mg DM ha^{-1} and a median of 9.0 Mg DM ha^{-1}.

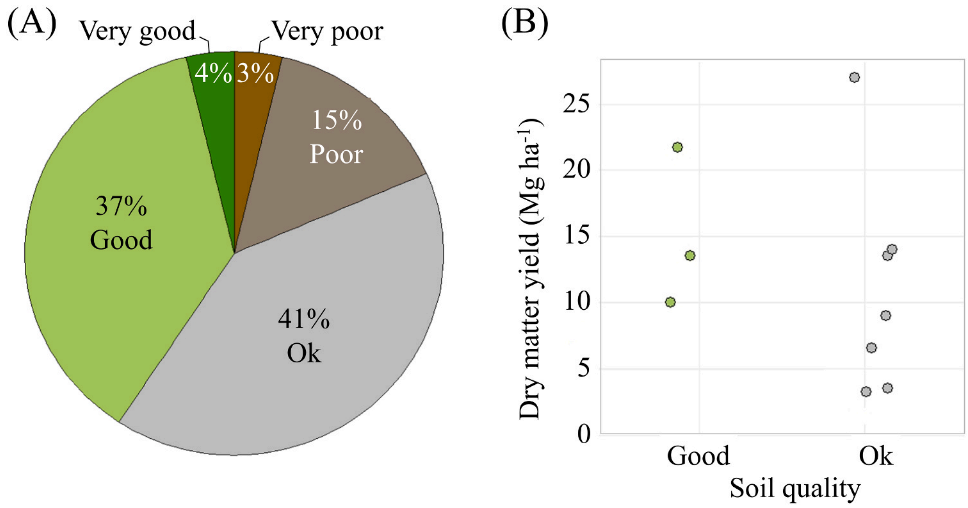

Fig. 4. Farmers' responses to the question "How do you rate the site where you grow WPM?" with the selection options: Very good; Good; Ok; Poor; Very poor (n=27) (A). Farmers' responses to the question "What was the average annual dry matter and biomass yield in tons per hectare?" for the soil quality categories 'good' (n=3), and 'ok' (n=12) (B). For the other soil categories ('very good', 'poor', and 'very poor') no data was provided by the farmers.

It is important to note that this comparison could not be tested for significance due to data limitations, preventing the execution of linear regression models with additional variables that could potentially influence the DM yield. Generally, the findings suggest that soil quality could play a crucial role in determining the DM yield (Fig. 4) which is in line with findings of Fürst-Preiß and Von Cossel (Fürst-Preiß and Von Cossel, 2024).

Out of the participating farmers, a total of 38 specified their applied soil preparation techniques (Fig. 5). The variation in soil preparation techniques among farmers can be attributed to a combination of factors including regional climate, soil type, agricultural traditions, and available resources. The use of rolling before sowing helps to create a smooth seedbed and improve seed-to-soil contact, which can enhance germination and crop establishment (Vollrath et al., 2012). By combining ploughing and rotary harrowing, farmers can effectively prepare the soil for WPM cultivation, optimizing soil structure, fertility, and moisture retention while minimizing weed competition and facilitating successful establishment of diverse plant species (Kuhn et al., 2014). Additionally, the adoption of no-tillage practices reflects a growing trend towards conservation agriculture, aimed at preserving soil structure and biodiversity (Cadel et al., 2023; Kan et al., 2020; Renwick et al., 2021). Lower Saxony, characterized by its extensive plains and relatively uniform soil types, may have less need for complex soil preparation methods

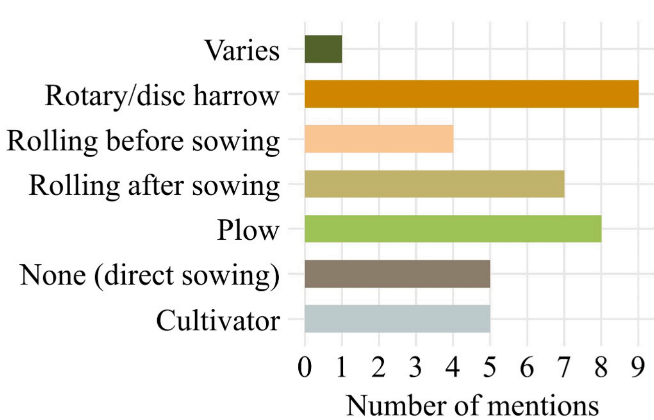

Fig. 5. Farmers' responses to the question "Which seedbed preparation did you use?" with the selection options: None (direct sowing); Plow; Cultivator; Rotary/disc harrow; Rolling after sowing; Rolling before sowing; Varies. Multiple answers per farmer (n=23) were possible.

compared to regions like Bavaria and Baden-Württemberg, which feature diverse landscapes and soil conditions (BfN, 2024). Overall, there is not yet sufficient information on best management practices for tillage before WPM cultivation, farmers seem to act on instinct or in comparison with experience from grassland and forage farming.

Transitioning from soil quality and preparation to fertilization, the focus shifts to the impact of different nitrogen fertilizer application rates ($> 20 \leq 50$ kg ha^{-1}, and $> 50 \leq 80$ kg ha^{-1}) on DM yield in WPM cultivation. For fields receiving $> 20 \leq 50$ kg ha^{-1} of fertilizer, the mean yield was 6.8 Mg DM ha^{-1}, with a standard deviation of 4.6 and a median of 6.8 Mg DM ha^{-1}. In contrast, fields receiving $> 50 \leq 80$ kg ha^{-1} of fertilizer exhibited a higher mean yield of 13.6 Mg DM ha^{-1}, with a standard deviation of 7.8 Mg DM ha^{-1} and a median of 13.8 Mg DM ha^{-1}. The disparity in DM yield between the two fertilizer application ranges can be attributed to the differential nutrient availability and uptake by WPM species at varying fertilizer levels, considering that only two farmers who applied $> 20 \leq 50$ kg ha^{-1} made their data available. While fields receiving lower amounts of fertilizer may adequately meet the nutrient requirements of many flowering wild plant species such as bladder campion (*Silene vulgaris* (Moench) Garcke), yellow bedstraw (*Galium verum* L.), and oregano (*Origanum vulgare* L.), higher fertilizer application rates can provide additional nutrients essential for robust growth and biomass accumulation of other wild plant species such as common tansy (*Tanacetum vulgare* L.), mugwort (*Artemisia vulgaris* L.), and common knapweed (*Centaruea nigra* L.) (Fürst-Preiß and Von Cossel, 2024; Von Cossel and Lewandowski, 2016). Due to the small data set on biomass yields and the different soil qualities, however, no reliable statements can be made on the significant effects of the fertilizer level. However, fertilization rates of more than 50 kg ha^{-1} would seem legitimate when one considers that other perennial biomass crops suitable for biogas production, such as cup plant (*Silphium perfoliatum* L.) and miscanthus, also require nitrogen fertilizer applications exceeding 50 kg ha^{-1} (Song et al., 2023; Von Cossel et al., 2020; Winkler et al., 2020).

It was observed that WPM fields with weed control and without seedbed preparation as well as with conservation tillage techniques such as plowing tended to have higher DM yields than fields without weed control. However, further analysis with significance tests could not be carried out due to lacking data.

3.4. Challenges in the use of WPM for biogas production

In view of the challenges of cultivating WPM for biogas production, it was often noted in the 12 responses to the last open question for other comments, that the DM (and methane) yield of WPM is significantly lower compared to maize. Thus, from an economic point of view, WPM are only seen as a limited alternative by farmers (Table S1) (Baum, 2019; Fürst-Preiß and Von Cossel, 2024; Janusch et al., 2021). The high lease prices in particular were therefore emphasized several times as a reason for choosing the poorer (because cheaper) areas for WPM cultivation. Consequently, the majority of respondents (59%) rated their WPM cultivation sites as ranging from 'okay' to 'very poor'. When comparing DM yields between farmers growing WPM on 'good'-rated sites versus those on 'sufficient'-rated sites, differences in their average DM yields were observed. Regardless of farmers' differing views on what is 'good' and what is 'poor' soil, this highlights the trade-off farmers must consider either utilizing WPM on marginal sites, but with lower DM yields, or utilizing sites with good qualities and obtaining higher DM yields accordingly. However, local differences in climate, precipitation and soil moisture have not been considered here but could be additional yield-influencing factors.

Regarding the biogas substrate quality, most farmers pointed out that WPM biomass cannot compete with silage maize. One farmer reported that WPM biomass had a negative impact on the fermentation stability of the biogas production. However, another farmer stated that there were no notable problems in ensilaging WPM and processing the WPM silage in the biogas plants. It can be assumed that these contradictory observations could be due to different weight proportions of WPM biomass in the substrate mix, but this requires further investigation. One useful question for future research could be how the species composition of the WPM biomass and its weight proportion in the substrate mix affects the process stability of biogas production. The results could help to reduce the economic loss caused by the utilization of WPM biomass in the biogas plant and in this way convince more farmers to grow WPM.

Despite the lower DM (and methane) yields compared to maize, it was often stated that WPM cultivation contributed to biodiversity and landscape beauty. Thus, it was approved that WPM benefits the community, justifying governmental support to compensate for the losses (Table S1) (Fürst-Preiß and Von Cossel, 2024; Paltrinieri and Schmidt, 2020).

Other problems identified by farmers include seed dispersal of WPM crops into adjacent fields, costly and labor-intensive harvesting, and difficulties in determining the appropriate seed quantity due to the varying sizes of seeds (Table S1). This variability is evident in our survey, with farmers strongly differing in their sowing rates, ranging from 5 to 15 kg ha^{-1}.

Not only in adjacent fields but also within WPM areas, weeds appear to pose a major challenge. Fifteen farmers reported issues with weeds such as cereals (via remaining seeds in the soil from the previous years), grasses, and millets, as well as a significant presence of pigweeds and thistles. When asked if they could envision cultivating WPM as a long-term complement to maize, despite the challenges and concerns, 45% were not averse to this, while only 20% believed WPM could not be a long-term complement. This underlines the importance to highlight the environmental benefits, as farmers should actually take the economically more rewarding path (without WPM) as entrepreneurs. The remaining 35% of the farmers stated that they could only envision WPM cultivation on marginal sites, as a means of crop diversification, or as cover for small game and overall biodiversity enhancement.

Nevertheless, in 2024, four federal states already supported the cultivation of WPM for biogas production. For instance, in Baden-Wuerttemberg subsidies of 500 EUR per ha and year are provided through the Agricultural Environmental, Climate, and Animal Welfare Support Program (FAKT II) (FNR, 2024; MLR, 2024), while in North Rhine-Westphalia there is an available subsidy of 460 EUR per ha and year through Agricultural Environmental Measures (FNR, 2024). Additionally, WPM cultivation is now supported within the framework of Agricultural Environmental and Climate Measures (AUKM) in Lower Saxony, with a subsidy of 685 EUR (conventional) and 927 EUR (organic) per ha and year (FNR, 2024), and in Bavaria with a subsidy of 450 EUR per ha and year through the Cultural Landscape Program (KULAP) (FNR, 2024; StMELF, 2023). These subsidies could be the key to popularizing WPM cultivation among a broader range of farmers and landowners, thereby circumventing structural losses in maize-dominated landscapes and contributing to halting insect decline. However, further improvement in the performance of WPM as a biogas substrate is necessary so that in the long term no more subsidies for WPM cultivation (than for maize) are needed to convince farmers to grow it. Addressing these challenges necessitates a comprehensive approach that integrates scientific research, agricultural policy, and practical farming strategies (Clifton-Brown et al., 2023; Reinhardt et al., 2021).

4. Conclusions

This study collected information from farmers across Germany, who cultivated WPM, in order to elucidate the multifaceted challenges faced by farmers in the cultivation of WPM. Thereby, this study was intended to contribute towards a better understanding of how to improve the competitiveness of WPM compared to common biogas crops. It was shown that the complexity of WPM cultivation goes beyond agronomic considerations and comprises environmental sustainability aspects, including maintenance of biodiversity and thereby ensuring ecosystem services and functions. The profitability of WPM cultivation is notably hindered by several factors, and many farmers would not start cultivating WPM without receiving higher subsidies than they receive for maize cultivation. These include the tendency to grow WPM on marginal arable land, resulting in lower biomass yields compared to more conventional crops like maize which are preferably grown on favorable (non-marginal) arable land. Therefore, further agronomic research on the cultivation of WPM for biogas production is urgently needed to improve the competitiveness of WPM compared to conventional biogas crops such as silage maize. In this regard, some of the important questions for future studies are: (i) When to control the weeds? (ii) On which soil to grow? (iii) How much fertilizer should be applied?

Moving forward, comparative quantitative studies between WPM and maize under controlled and similar site conditions are necessary to provide a more robust understanding of their respective agronomic performance and economic viability. Long-term-studies spanning multiple growing seasons are essential to capture the dynamics of perennial plant systems inherent to WPM cultivation. Such studies can offer valuable insights into the long-term effects of WPM on soil health, biodiversity, and rentability.

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CRediT authorship contribution statement

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

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