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Renewable Energy from Wildflowers—Perennial Wild Plant Mixtures as a Social-Ecologically Sustainable Biomass Supply System

Moritz von Cossel

A growing bioeconomy requires increasing amounts of biomass from residues, wastes, and industrial crops for bio-based products and bioenergy. There is much discussion about how industrial crop cultivation could promote social–ecological outcomes such as environmental protection, biodiversity conservation, climate change adaptation, food security, greenhouse gas mitigation, and landscape appearance. In Germany, maize (*Zea mays* L.) is the main biogas substrate source, despite being associated with problems such as erosion, biodiversity losses, an increase in wild boar populations and lowered landscape diversity. The cultivation of perennial wild plant mixtures (WPM) addresses many of these problems. Despite being less developed than maize, WPM cultivation has received notable attention among scientists in Germany over the past decade. This is mainly because WPMs clearly outperform maize in social–ecological measures, despite their methane yield performance. This review summarizes and discusses the results of 12 years of research and practice with WPMs as a social-ecologically more benign bioenergy cropping system.

1. Introduction

With the aim of a fossil-free future, a growing bioeconomy requires biomass for both bio-based products and bioenergy pathways.[1–7] There are several biomass sources such as wastes from agriculture and wood industry,[8–10] macroalgae,[11–15] microalgae[16,17] and industrial crops[1,18,19] although, not all these biomass sources are equally useful:

i) Wastes from agriculture and the timber industry are limited by the production capacity of agriculture and the wood industry.[1,20]
ii) Macroalgae plantations are not easy to operate (requiring artificial platforms) and their production areas are limited to coastal regions.[13,15]
iii) The cultivation of microalgae for biofuel production is very cost-intensive and not yet suitable for large-scale implementation.[21]

Against this backdrop, industrial crop cultivation, is far more promising.[20] There exists a wide range of industrial crops, many of which with well documented and researched cultivation techniques and utilization pathways (**Table 1**).[19,22–29] Second, the potential cultivation area for industrial crops reaches from the tropics to the northern Atlantic and continental zones.[19,30–34] Furthermore, industrial crop cultivation can mitigate greenhouse gas (GHG) emissions through bio sequestration[35] and through bioenergy to carbon capture and storage (BECCS) strategies.[1] This is because the below-ground fraction of the crop (the root system) remains in the soil and contributes to humus accumulation.[1,24,36–39] In the long-term, humus accumulation even promises to rehabilitate degraded land and make it suitable for food crop cultivation again.[38,40–43] For both algae cultivation and the use of residues from agriculture and wood industry, neither BECCS nor the recovery of degraded land is practicable. Consequently, biomass supply from industrial crops seems a more reasonable solution from a broader perspective—but how can industrial crop cultivation be expanded without compromising environmental and social needs?

From an ethical perspective, industrial crop cultivation should generally not compete with other land uses such as food crop cultivation and natural successions, so that neither food security nor biodiversity conservation are threatened.[147–154] Both food security and biodiversity conservation are high on the agenda of the United Nations' sustainability development goals.[155,156] These can be realized through both land saving and land sharing approaches.[151,152] The utilization of favorable agricultural land for industrial crop cultivation should be restricted to social-ecologically sustainable land sharing concepts, e.g., wide crop rotations including both food crops and industrial crops.[23,157–162] The land saving concept, i.e., cultivating industrial crops on unfavorable agricultural land—so-called "marginal agricultural land"[163]—thus saving the favorable agricultural land for food crop cultivation, is limited by biophysical constraints such as adverse rooting conditions and climatic conditions or economic challenges such as inconvenient field shapes and long field-farm distances.[19,25,88,89,164–167] Additionally, the intensive (industrial) cultivation of common cash crops such as sugar cane, oil palm, rape seed, and maize often requires high off-farm inputs such as nitrogen (N) fertilizer herbicides, or insecticides.[1,153,168–170] Intense usage of these

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off-farm inputs can have both environmental and social consequences which conflict with the goal of better social-ecological outcomes.[150,167,171]

In light of this, the low-input cultivation of industrial crops on marginal lands has received increasing attention in the literature over the past two decades.[19,150,168,171,172] The approach of combining low-input agricultural practices and marginal agricultural land utilization for industrial crop cultivation was recently introduced as marginal agricultural land low-input systems for biomass production (MALLIS).[19] MALLIS are defined as being both i) noncompetitive with food crop cultivation, and ii) environmentally sustainable through erosion mitigation, groundwater protection and low external (off-farm) input demands.[19] Technically, the development of site-specifically adapted MALLIS also includes cropping principles of agroecology mainly based on traditional knowledge of subsistence farming.[149,173,174] Agroecosystem efficiency can be increased by applying site-specifically adapted crop rotations,[22,175,176] intercropping strategies,[161,177–181] catch crop cultivation,[182–185] through tillage management,[186,187] and agroforestry.[188,189] Legumes can add biologically fixed atmospheric N to the nutrient cycle and thus reduce external inputs such as synthetic N fertilizer.[26,105,131,132] In addition to MALLIS, low-input high-diversity mixtures of perennial species, e.g., from conservation areas and roadsides, are predicted to play a vital role in biomass supply in the future.[106,169,190]

The most relevant parts of industrial crops suitable for MALLIS are the lignocellulosic components: hemicellulose, cellulose and lignin, because they can be used in numerous utilization pathways to produce both bio-based products[191] and bioenergy.[1,2,90,192] Further, lignocellulosic crops suitable for MALLIS are potentially relevant for a growing bioeconomy regardless of the lignocellulosic composition of the crops (e.g., rich in lignin or rich in hemicellulose, etc.).[19,167] And the use of lignocellulosic industrial crops offers a more sustainable biomass supply compared with the reference scenario based on conventional (1st generation) industrial crops such as maize, oil palm and rape-seed.[193] One reason for this is that the use of lignocellulosic industrial crops grown on marginal agricultural land does not compete with human nutrition, because i) food crops are rather unprofitable to grow on marginal agricultural land[19] and ii) lignocellulosic crops such as miscanthus and switchgrass are not edible like maize, wheat, and sugar beet.

Several crucial further aspects need being considered for holistically more sustainable implementations of MALLIS into existing agricultural systems.[167] The most important of which being the need for biodiversity conservation.[151,194,195] Biodiversity conservation is seen to be essential and indispensable for maintaining, and potentially increasing, the resilience level of agroecosystems.[179,196,197] High resilience levels reduce the susceptibility of agroecosystems against biotic disturbances such as droughts and heavy rain events.[196,198] This becomes even more important considering the expected effects of severe climate change on agriculture.[33,199–203] Biodiversity conservation is also crucial for supporting pollinator populations.[204–206] Both the diversity and the abundances of pollinators have been found to decrease significantly due to monotonous industrial agriculture.[204,205,207–210] It is well-known that pollinators should be protected and supported, because they are necessary for pollinating the food crop.[195,208,209,211–215] One outstanding example for this phenomenon is the rapid increase in the cultivation of maize (*Zea mays* L.) (**Figure 1**) for biogas production in Germany since the early 2000s which in terms of agrobiodiversity and environmental protection was often associated with negative land use change effects.[216–218]

Maize is a fast growing annual cereal crop which is used worldwide as a major source for food, feed and bioenergy.[219–221] Thanks to its C4-metabolism[222,223] and intensive breeding efforts,[67,84,224–226] it generates high biomass yield levels in temperate climates and it is very well suited to anaerobic digestion.[86,157,227,228] If cultivated correctly, maize can be integrated into existing crop rotations and provide ecosystem services such as habitat functioning. Maize also produces pollen that can be used by pollinators, though it is of poor quality and it is produced only over a short period of time in summer when many other sources of nectar and pollen are available from other crops and wild plant species.

There is also a significant risk of negative environmental impacts in maize cultivation, such as erosion, N leaching, declining agrobiodiversity, promotion of wild boar populations and decreasing aesthetic landscape appearance.[207,216,229–233] This is particularly the case if good agricultural practices are not adhered to and inappropriate political conditions are created.[234] For decades, debate has raged on how to counteract the monotonization of agricultural landscapes caused by intensive maize cultivation (in combination with short and conventionally managed crop rotations), and which compromises are more sensible than the current maize-dominated agricultural systems and under which conditions.[27,103,157,228,235,236]

The expansion of the range of plant species used as biogas substrates is an important step in this process, as it can once again increase agricultural biodiversity. Herrmann et al.,[23] for example, list a whole range of alternative biogas crops that are available for the development of further crop rotations with

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Table 1. Overview of some common lignocellulosic industrial crops and cropping systems.

Common name	Botanical name	Life cycle	Photosynthetic pathway	Reference
Agave	*Agave tequilana* F.A.C.Weber	Perennial	CAM	[44–47]
Biomass sorghum	*Sorghum bicolor* L. Moench	Annual	C4	[48–50]
Black locust	*Robinia pseudoacacia* L.	Perennial	C3	[51,52]
Cardoon	*Cynara cardunculus* L.	Perennial	C3	[53–55]
Cup plant	*Silphium perfoliatum* L.	Perennial	C3	[27,28,56–58]
Giant reed	*Arundo donax* L.	Perennial	C3	[59–66]
Hemp	*Cannabis sativa* L.	Annual	C3	[67–73]
Kenaf	*Hibiscus cannabinus* L.	Perennial	C3	[67,74–76]
Lupin	*Lupinus mutabilis* Sweet.	Biennial	C3	[77–80]
Maize	*Zea mays* L.	Annual	C4	[81–87]
Miscanthus	*Miscanthus* ×*giganteus* Greef et Deuter	Perennial	C4	[59,65,66,87–97]
Pencil tree	*Euphorbia thirucalli* L.	Perennial	CAM	[98–101]
Permanent grassland	-	Perennial	C3	[102–114]
Poplar	*Populus* spp.	Perennial	C3	[115–118]
Prickly pear	*Opuntia ficus-indica* (L.) Mill.	Perennial	CAM	[119,120]
Reed canary grass	*Phalaris arundinacea* L.	Perennial	C3	[121–123]
Siberian elm	*Ulmus pumila* L.	Perennial	C3	[19]
Switchgrass	*Panicum virgatum* L.	Perennial	C4	[59,87,96,124–129]
Tall wheatgrass	*Thinopyrum ponticum* (Podp.) Z.-W. Liu & R.-C. Wang	Perennial	C3	[19,130]
Virginia mallow	*Sida hermaphrodita* L. Rusby	Perennial	C3	[58,131–139]
Willow	*Salix* spp.	Perennial	C3	[140–146]

annual crops (**Figure 2**). Such crops can be combined with one and other as well as with food crops—resulting in short or long crop rotations, whereby the length refers to the number of crops or the number of years it takes to fulfill one rotation of all crops of the crop rotation (Figure 2). Long crop rotations with annual crops are better for soil fertility than short crop rotations because long crop rotations are less likely to allow the natural pests and diseases of the plants to accumulate over time, and because wide crop rotations increase the resilience of the agroecosystem.[179] The integration of legumes in crop rotation can also help to reduce the use of synthetic N fertilizer, thus reducing GHG emissions.[26,131,132,182,237–241] Nevertheless, long crop rotations—just like short crop rotations—require high labor and material costs. Here, perennial biomass crops (Table 1) offer the advantage that they only need to be established once over a period of 5 to over 20 years. Soil cultivation, sowing or planting of perennial biomass crops therefore only needs to be carried out once which is assessed very positively in life cycle assessment, and is associated with considerable savings in fuel, pesticides and fertilizer.

Figure 1. Monocropped maize in a field trial near University of Hohenheim in August 2019.

In the literature perennial biomass crops grown in monocultures are mostly mentioned (Table 1), except for grassland[110–114] and agroforestry.[188,189] As with very short crop rotations or monocultures with annual crops (e.g., monocultivated maize), these carry the risk of i) a decrease in agrobiodiversity,[242–244] ii) an increase of the susceptibility to crop-specific pests and diseases,[245–247] and iii) a monotonization of the landscape appearance.[232] An alternative perennial biomass cropping system that has been tested in practice for about twelve years but has not yet achieved a breakthrough is the cultivation of perennial wild plant mixtures (WPM) (**Figure 3**).

WPMs are mixtures of over 20 different flowering and predominantly wild (i.e., not bred) plant species native to Central Europe. Among these plant species are annual, biennial and perennial species, selected and combined in such a way that they are overall well suited as a biogas substrate (high biomass yield and good biogas substrate quality).[248] The aim was to

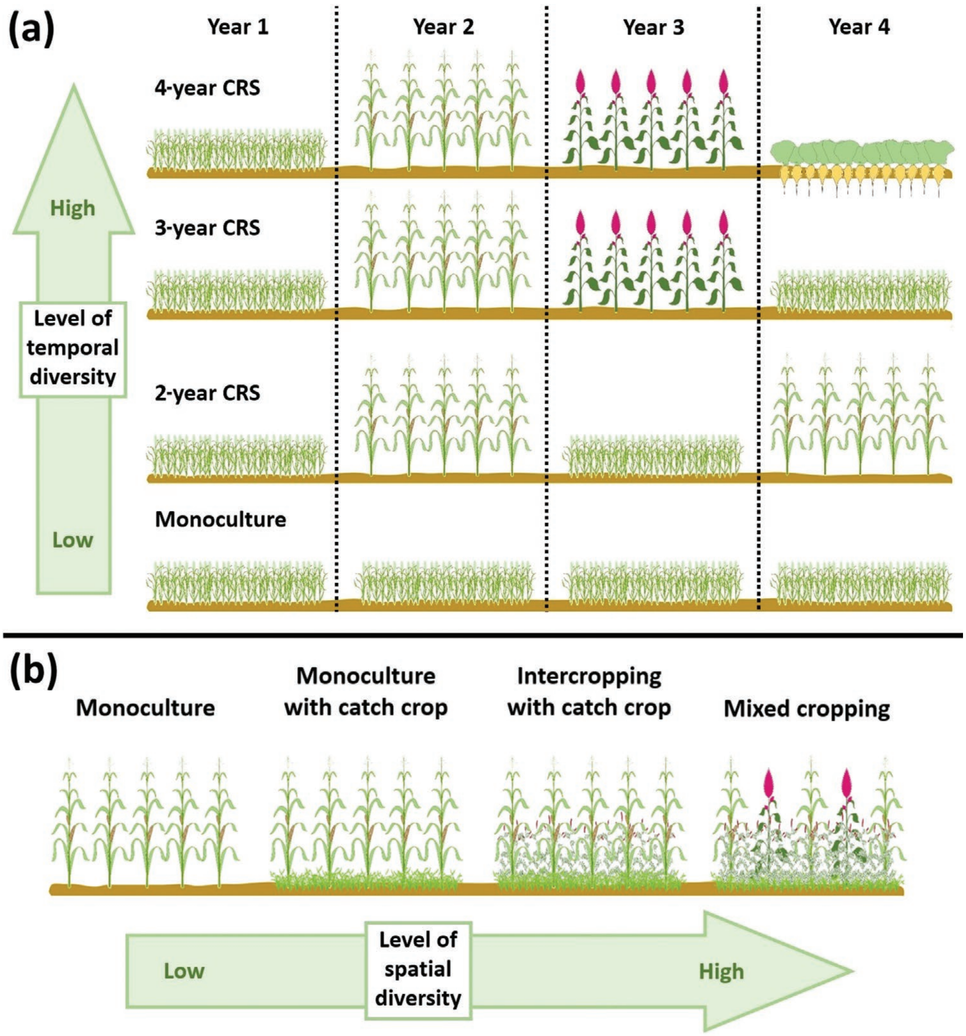

Figure 2. Schematic description of a) temporal diversity and b) spatial diversity of agricultural systems (CRS, crop rotation system).

develop a dynamic perennial polyculture, which in comparison with perennial monoculture emphasizes the aspect of biodiversity conservation and at the same time offers a high biomass potential.[248] This should be achieved by temporal diversification on the one hand (annual, biennial and perennial species alternate with time) (Figure 2a) and by spatial diversification (every year several species are present as mixed cultures in the plant stand) (Figure 2b) on the other hand.[216]

Figure 3. A wild plant mixture in a field trial near University of Hohenheim in Summer 2015.

This review examines the state of current knowledge on the cultivation of WPMs as a new bioenergy cropping system (BCS) for biogas production. To this end, a comprehensive review was conducted with a focus on i) the history of WPMs, ii) the intentions of the developers, and iii) the first experiences of practitioners implementing WPMs. Additionally, the technical practice guidelines[249] are explained to communicate how to establish and manage WPM cultivation—including basic information on chances and challenges of WPM cultivation for BCS. Then, the suitability of WPMs as a biogas substrate will be elaborated and discussed, whereby the biomass substrate quality for both ensilage and anaerobic fermentation will be reviewed separately. Based on this information, the potential contribution of WPMs to future BCS in comparison with annual energy crops such as maize is presented and discussed from an economic perspective. The ecosystem services of WPMs are examined and also compared with annual energy crops. Potential implementation strategies are

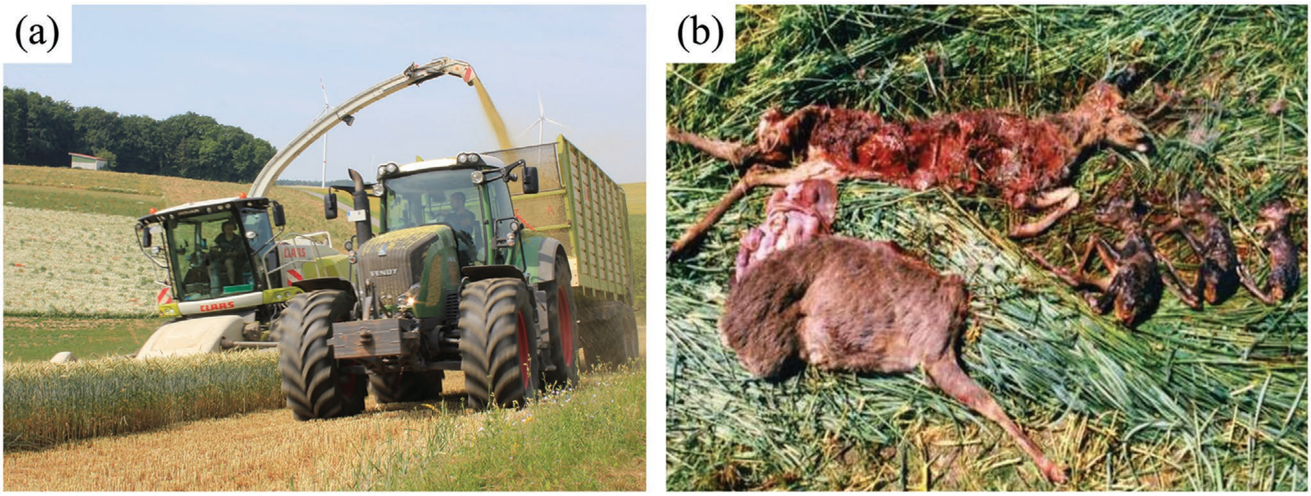

Figure 4. a) Harvest of rye for whole crop cereal silage (WCCS) and b) wild game losses caused by the harvest of cereals for WCCS (Image credit: Werner Kuhn, (4 a), and Christoph Hildebrandt (4 b)).

discussed, with the research question, how could WPMs best fit into existing BCS for biogas production, since there are several limitations that must be considered. In this context, it is then discussed, how the awareness of the public can be raised, and how the public can contribute to a faster practical implementation of WPMs. The final section provides an outlook on potential future developments, new types of income for WPM farmers and further promising utilization pathways for WPM biomass.

2. Wild Plant Mixtures for Biomass Supply—How it all Began

The concept of developing mixtures of flower-rich, wild and native plant species for biogas production was first brought up by Barbara Kuhn, a hobby farmer and herbalist in Hubertushof, Germany.[250] Her husband, Werner Kuhn, a passionate farmer, hunter and conservationist, soon realized that this may be a good idea. Werner Kuhn then began developing a conceptual design within the collaborative network entitled "Netzwerk Lebensraum Feldflur" (NLF).[251] Werner Kuhn and his partners from the NLF soon discovered that WPM could potentially have several advantages over monocropped maize or whole crop cereal silage (WCCS), in addition to the dynamic colorful landscape appearance they provide. The most important proposed ecosystem services comprise the provision of food and shelter for open land animals.[249] This ecosystem service has become more and more relevant with the increased monotonization of agricultural systems.[232] For instance, the cultivation area of silage maize (Figure 1) has almost doubled in Germany since the 1990s due to governmental incentives promoting biogas production.[252,253] The result was an even more homogenous landscape with decreased habitat functioning for open land animals such as Northern lapwing (*Vanellus vanellus* Linnaeus, 1758), European roe deer (*Capreolus capreolus* Linnaeus, 1758) and brown hare (*Lepus europaeus* Pallas, 1778).[254]

Another economically highly feasible biogas substrate is the biomass from cereals harvested at late milk-ripening stage (WCCS). Both dry matter yield and specific methane yield are similarly high when compared with silage maize. The ensilage quality is also high and thus, it seems to be a perfect biogas substrate—but only from an economic perspective. On the contrary, the increasing use of WCCS for biogas production[218,255] (**Figure 4**a) prompted ethical debates on the social–ecological effects. This was because of the losses in wild animals and ground breeders due to WCCS harvesting during the breeding, setting and rearing periods (Figure 4b).

The proposal of an officially funded project received a great deal of support, especially from the hunting sector (**Table 2**)—the biogas sector had previously not been represented but was added later.[256] A few years later, a BMEL-funded project (Research Project No. 22005308) was launched in which the first WPMs were developed.[257] Since it primarily concerns wild plants that should be used in the mixtures, it was less a matter of breeding than agronomic research work, e.g., determining which plant species work well in conjunction with one another. In the year of publication of the final report on the first phase of the WPM project (**Table 3**),[257] a feasibility study was published in which the economic performance potential of WPM was analyzed by an independent party.[258]

3. Agricultural Practices of WPM Cultivation

WPM cultivation does not require special agricultural practices that would otherwise not be found on conventional farms. Generally, much less labor, material and fuel is required to cultivate WPMs (**Figure 5** and Tables A1–A5).[265] However, several important things need to be considered for a site appropriate and successful WPM implementation, especially during the sowing phase. These and all other necessary measures in cultivation and harvesting are presented in the following subsections.

3.1. The Selection of a Suitable Site

The first step for successful WPM cultivation is the selection of an appropriate site.[248] The area should not be contaminated

Table 2. Affiliations involved in the initial project "Energetic utilization of herb-rich seeds in agricultural landscapes and settlements—an ecological and economical alternative for biogas production." Taken from Vollrath et al.[248]

Affiliation type	Name	Role	Website
Government department	German Federal Ministry of Food and Agriculture	Funder	https://www.bmel.de/EN
State institute	Bayerische Landesanstalt für Weinbau und Gartenbau	Coordinator	https://www.lwg.bayern.de/
Nonprofit organization	Deutscher Verband für Landschaftspflege e.V. (DVL)	Partner	https://www.lpv.de/
Foundation	Deutsche Wildtier Stiftung (DeWiSt)	Partner	https://www.deutschewildtierstiftung.de/
International nongovernmental and nonprofit organization	Internationaler Rat zur Erhaltung des Wildes und der Jagd (CIC)	Partner	http://www.cic-wildlife.org/de/
Breeding company	Saaten Zeller GmbH & Co. KG	Partner	https://www.saaten-zeller.de/
Nonprofit organization	Bayerischer Jagdverband e.V. (BJV)	Partner	https://www.jagd-bayern.de/
Nonprofit organization	Deutscher Jagdverband e. V. (DJV)	Partner	https://www.jagdverband.de/
Collaborative network	Netzwerk Lebensraum Feldflur	Partner	https://lebensraum-brache.de/

with problem weeds,[248] as these could otherwise proliferate and reduce both the biomass yield and the biogas substrate quality of the WPM in the long term.[57,259] In order to increase the potential contribution of WPM cultivation to biodiversity conservation through habitat networking, several small areas should be cultivated with WPM rather than fewer large areas to avoid negative mass-flowering effects on pollinator populations.[266] The distribution of these small WPM areas should also aim to fulfil other potential environmental goals such as erosion protection, groundwater protection, habitat networking and field shape optimization.[89,267]

3.2. Seedbed Preparation

The tillage required for WPM cultivation is similar in principle to the cultivation of maize. The topsoil should be loosened very gently, without the addition mulch or other material (**Figure 6**). However, experience with direct sowing of WPMs after cereal harvested as WCCS in summer[57] shows that if no weeds are present, direct sowing is also possible and can lead to the successful establishment of WPMs.

3.3. Weeding Measures

Weeding measures are of decisive importance for a successful WPM establishment, especially during the first year. As De Mol et al.[243] reported, no relevant weed propagation is to be expected in the first years of establishing WPMs similar to those investigated by Von Cossel et al.[57,259] Although the number of WPM species decreases significantly from the third year of cultivation onward (it drops to about 3 species), the stocking density remains comparable to the first two years of cultivation.[243] This puts WPMs in a good position to manage the weed potential independently via competition, i.e., without herbicide or mechanical weed control measures.[243] However, in addition to choosing a location that is relatively weed-free,[248,249] three principles must also be considered:

1. Seedbed preparation should be as fine as possible according to the given soil conditions[268] so that the WPM can germinate optimally. The faster and denser the WPM growth, the better the competitiveness of the wild plant species against weeds.
2. The germination of existing weed seeds within the topsoil can be initialized by a false seedbed—an additional very early—seedbed preparation. Shortly before the main seedbed preparation, the weeds are then cut back. This serves to reduce the amount of weed seeds that germinate during WPM cultivation.
3. Results from the LAZBW have shown that early WPM sowing is usually more promising than late sowing.[269] According to Stolzenburg,[269] this is probably because late sowing of WPM gives weeds a competitive edge over wild plant species.[269] Hence, late WPM sowing can increase weed pressure compared to early WPM sowing.

From the second year onward, WPMs are generally highly competitive against weeds.[248] Should weeds nevertheless be observed, a pruning should be carried out in spring.[249] If this measure fails, the WPM should not be continued on the respective area to avoid increasing weed pressure over subsequent years. Excessive weed infestation could also have a very negative impact on the image of WPM cultivation as a provider of biomass for biogas production, as weed areas are generally considered unprofitable and aesthetically undesirable.[270]

Another important aspect is the weed potential that emerges from the WPM itself. This is because many wild plant species, such as yellow melilot, knapweed or common tansy, reach seed maturity by the time they are harvested in the autumn, thus introducing seeds into the biogas process chain. Such wild plant species seeds that survive the three process steps of ensiling, fermentation and storage of the digestate could then become weed species on non-WPM fields, which artificially increases the weed pressure and hence the necessary herbicide use or weeding intensity in the respective arable crops. However, it was found that only a few hard-shelled seeds, for example those of yellow melilot or common mallow, survive the biogas process chain.[271,272] It should therefore be ensured that these species do not reach full seed maturity, in order to keep the potential

Table 3. Bibliographic overview of reports and scientific (peer-review) research articles about perennial wild plant mixtures as biogas substrate.

Year of publication	Document type	Title/topic	Reference
2012	Official report	Energetic utilization of herb-rich wild plant mixtures in agricultural landscapes and settlements—an ecological and economical alternative for biogas production (Phase I)	[248]
2013	Report	Wild plant mixtures as biogas substrate	[257]
2014	Research article	Impact of land-use change towards perennial energy crops on earthworm population	[244]
2016	Official report	Energetic utilization of herb-rich wild plant mixtures in the agricultural landscape—an ecological and economical alternative for biogas production (Phase II)	[254]
2016	Research article	Perennial wild plant mixtures for biomass production: Impact of species composition dynamics on yield performance over a five-year cultivation period in southwest Germany	[259]
2016	Research article	Wild plant silage suitability for bioethanol production	[260]
2016	Research article	Wild flower mix—Methane production in comparison with other crops	[176]
2017	Research article	Perennial species mixtures for multifunctional production of biomass on marginal land	[261]
2017	Research article	Impact of newly introduced perennial bioenergy crops on soil quality parameters at three different locations in W-Germany	[262]
2018	Research article	Biochemical methane potential (BMP) of six perennial energy crops cultivated at three different locations in W-Germany	[263]
2018	Research article	Optimization of specific methane yield prediction models for biogas crops based on lignocellulosic components using nonlinear and crop-specific configurations	[264]
2019	Dissertation	Agricultural diversification of biogas crop cultivation	[216]
2019	Research article	Methane yield and species diversity dynamics of perennial wild plant mixtures established alone, under cover crop maize (*Zea mays* L.), and after spring barley (*Hordeum vulgare* L.)	[57]
2019	Research article	Bioenergy and its effects on landscape aesthetics—A survey contrasting conventional and wild crop biomass production	[232]
2019	Research article	Marginal agricultural land low-input systems for biomass production	[19]

weed pressure caused by the application of these seeds within the digestate as low as possible. However, as yellow melilot shows a relatively continuous seed maturity from the beginning of flowering, early harvesting would be recommended to reduce the potential amount of mature seeds in the fermentation substrate. This, in turn, is questionable because it considerably shortens the flowering period. Especially for yellow melilot, the flowering period is potentially very long (May-September) and, due to the high quality of the nectar, of great importance for the ecosystem functions of WPM cultivation. Despite this, the weed potential from hard-shelled wild plant species seeds may also be rather low on the farm, as WPM cultivation has been and for the foreseeable future will only constitute a small part of the biogas substrate mix (besides manure, maize, and others). In addition, yellow melilot and common mallow are biennial species that reach their greatest growth potential only in the second year of vegetation after sowing. Biennial wild plant species within a crop rotation from annual crops are unlikely to reach this second year of growth. According to reports from farmers, the spread of hard-shelled wild plant species such as yellow melilot and common mallow is not a serious problem.[273]

3.4. Sowing

WPMs do not require any specialized sowing techniques or technology. Pneumatic seed drills can easily handle the small seed rate of 10 kg ha^{-1}.[248] However, the sowing material should not be mixed within the tank of the sowing machine to avoid segregation of the seeds by size (large and small grain seeds).[248] This is important because the WPM seeds are of many different sizes, and their thousand kernel weights vary between <1 and >200 g (**Figure 7**).[259]

For sowing of WPMs, it is extremely important to place the seed loosely on top of the topsoil (**Figure 8**).[249] If the seed is worked in even one centimeter, most wild plant species will not germinate; most wild plant species are light responsive germinators and have a very small seed size (Figure 7).

The optimum sowing time is between April and mid-May, when the risk of late frost, which could potentially damage sensitive wild plant species is low.[248] An early sowing time should be chosen, especially on sites with light soils.[248] In order to suppress the development of weeds, a quick emergence of the wild plant seeds is advantageous.[248] For this reason sowing should not take place during a dry period.[248] Field trials in Hohenheim have shown that weeds can propagate vigorously in the event of drought after WPM sowing, which can lead to a total failure in the long term.[57]

In very loose sandy soils, it is advisable to consolidate the area by rolling prior to sowing to prevent the seed from being placed too deeply.[248] In this case, rolling after sowing (at first) may have to be omitted to avoid "burying" the seed for previously stated reasons.[248]

3.5. Establishment Procedures

Numerous studies have looked at possible variations of WPM establishment.[57,254,257] The main establishment procedures

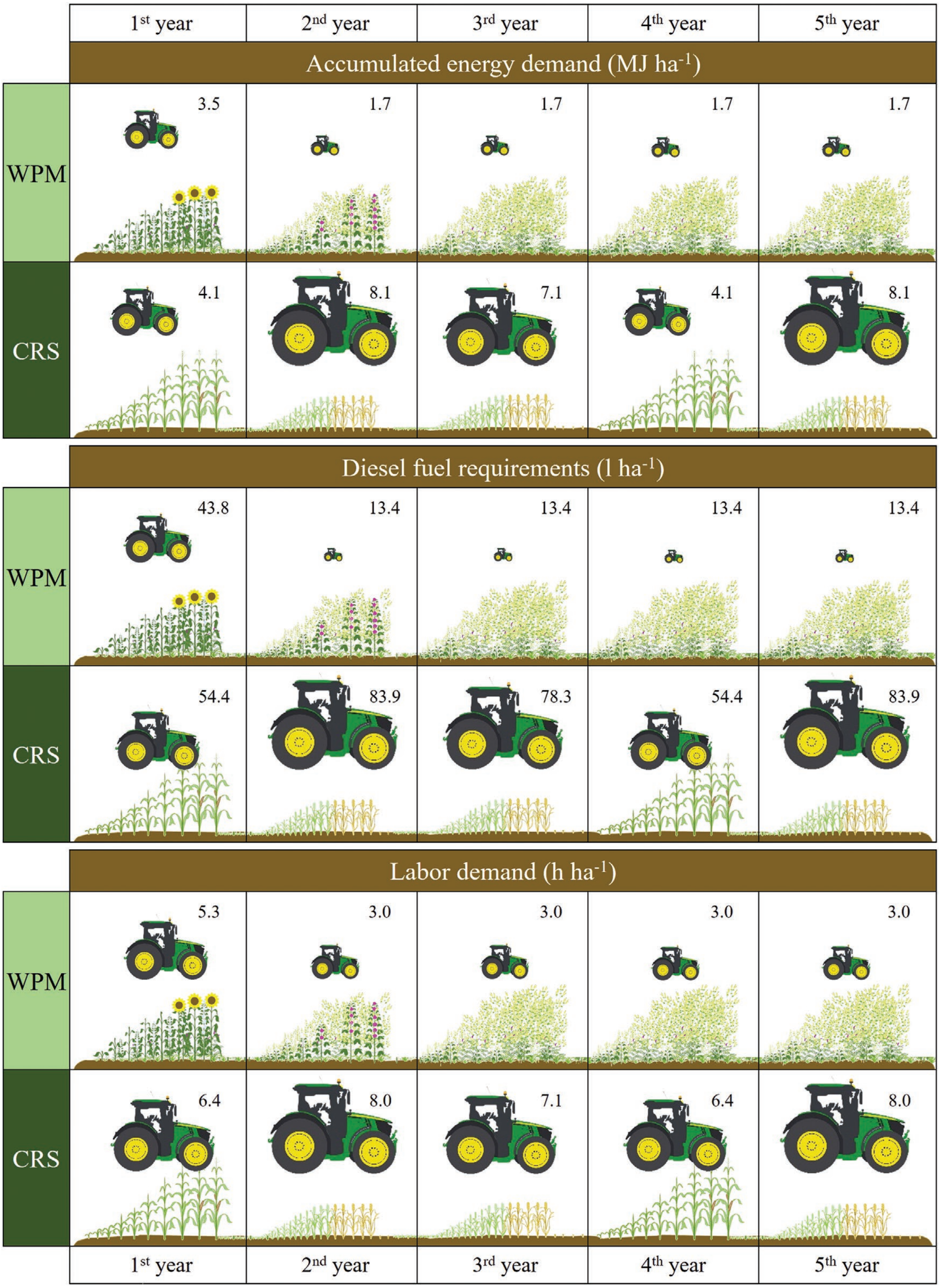

Figure 5. Schematic overview of diesel fuel, labor and accumulated energy requirements for wild plant mixture cultivation (WPM) and a random three-year crop rotation of maize, winter wheat and winter rye (CRS) during five years of cultivation (calculated). The size of the tractors represents the proportion of maximum value per category across years.

Figure 6. Impression of the intensive seedbed preparation for successful WPM cultivation: topsoil cultivation using a rotary harrow in combination with a roller (Image credit: film-webfabrik Heilbronn).

studied are i) alone, ii) under maize, and iii) after cereals harvested as WCCS (**Figure 9**). The following subsections explain and discuss the first experiences with these establishment procedures.

3.5.1. The Establishment of WPM Alone

The standard procedure for establishing WPM is to sow (E1) WPM seed alone (Figure 9a–c). This procedure is described sufficiently well by Kuhn et al.:[249]

1. selecting a site with low weed pressure;
2. fine soil preparation;
3. shallow sowing (“the seeds must see the sun”);
4. rolling.

A seed mixture frequently used for this purpose in practice is “BG70” (Saaten Zeller GmbH & Co. KG, Eichenbühl-Guggenberg, Germany) (Figure 7a). However, there are other suppliers who offer wild plant seed mixtures for similar purposes, such as Rieger-Hofmann (Rieger-Hofmann GmbH, Blaufelden, Germany) (Figure 7b).

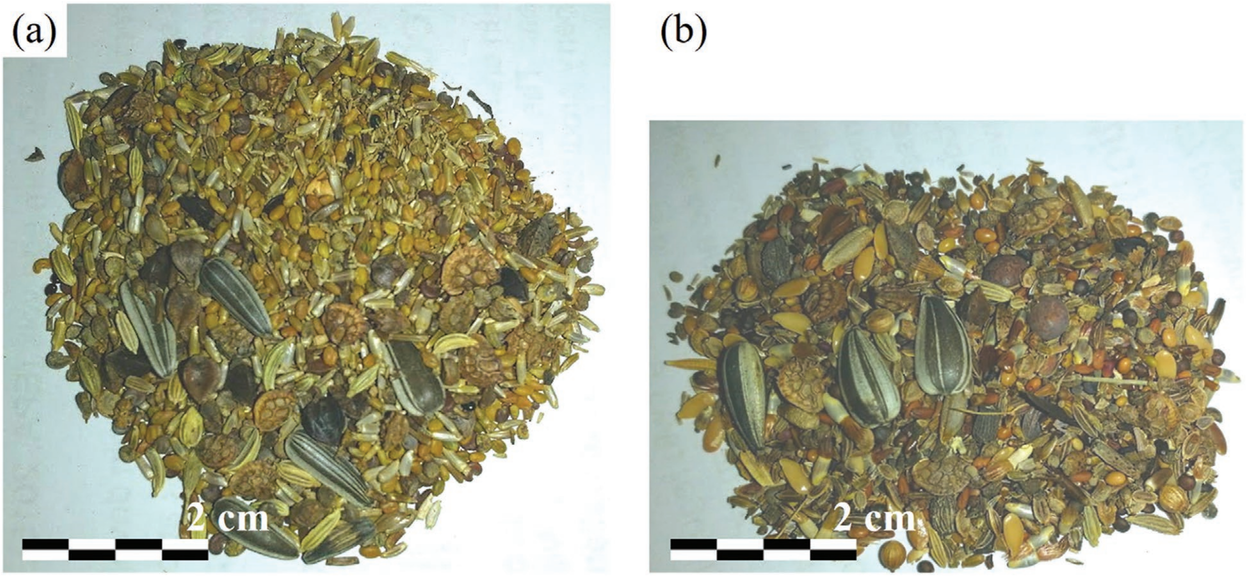

Figure 7. Seeds of the wild plant mixtures a) “BG70” (Saaten Zeller GmbH & Co KG, Eichenbuehl-Guggenberg, Germany) and b) “22 Wildacker – Wildaesung – Wilddeckung” (Rieger-Hofmann GmbH, Blaufelden-Raboldshausen, Germany).

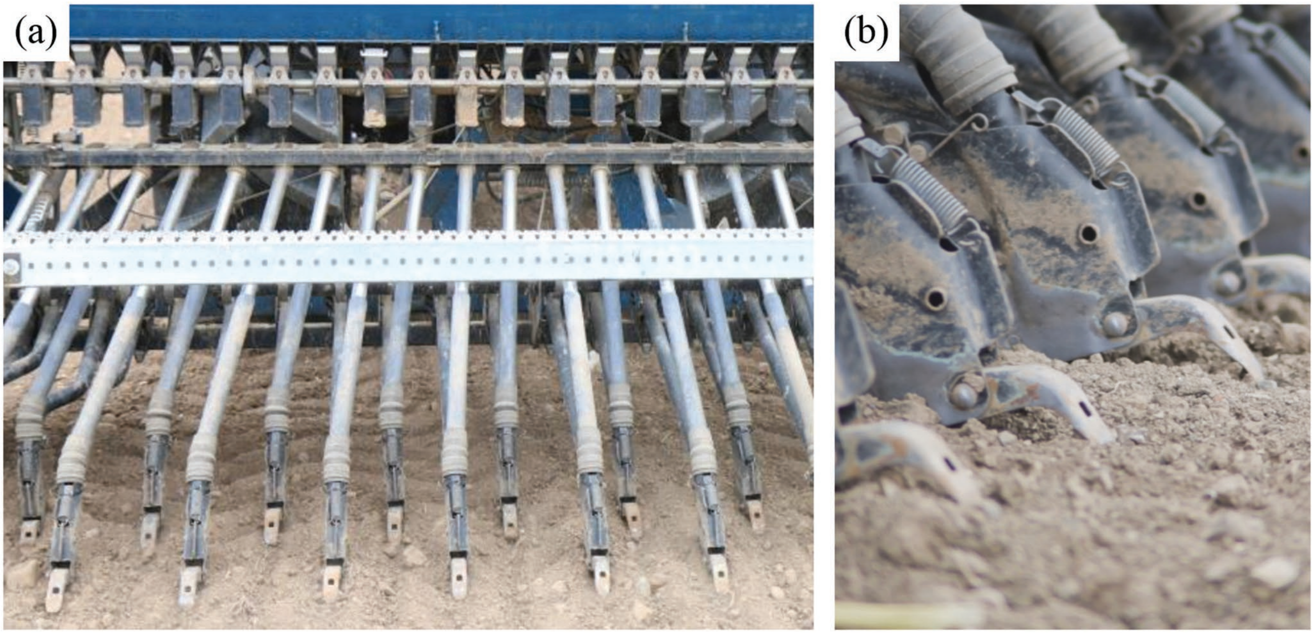

Figure 8. Sowing technique as recommended by Vollrath et al.[248] and Kuhn et al.:[249] pneumatic seed drill a) sowing the seeds of the wild plant mixtures in 15 cm row distances. b) The seeds are laid on top of the seedbed (Image credit: film-webfabrik Heilbronn).

In general, this establishment procedure is considered to be the safest in terms of establishing success under dry weather conditions in the early summer months. As such conditions are more frequent in southern Germany than in northern Germany,[167] the establishment procedure E1 will be more suitable for southern Germany than other establishment variants (see below), where the WPM young plants are more susceptible to water-limiting weather conditions.

3.5.2. The Establishment of WPM under Maize

The establishment of WPM under maize has, among other things, the advantage that the dominant annual species emerges safely (because it is deeply sown) (Figure 9d–f), which is not the case with pure seed, since sunflower seeds, if laid superficially, can be easily discovered and eaten by birds (predators).[243] Vollrath et al.[248] also reported that the WPMs which were established under maize performed well until the third year of cultivation after establishment. This is in line with the findings of Von Cossel et al.[57]

Results of a life cycle assessment study on WPM cultivation, currently under review, indicate that the yield of maize in the first year is very important for the overall sustainability of WPM cultivation on a financial basis.[274]

3.5.3. The Establishment of WPM after Whole Crop Cereal Silage

WPMs (without annual main yielders such as sunflower or amaranth) are often sown after a winter or summer cereal harvested as WCCS (Figure 9g–i). It should be noted that this is contrary to the philosophy of WPM cultivation, since, as mentioned above, during the June harvest, it cannot be ruled out that either the nests of ground-nesting birds are destroyed or highly pregnant wild animals or the young may be killed by machinery during the harvest.

Nevertheless, an agronomic advantage of WPM's sowing following WCCS is that the cereal transfers an area of low weed pressure to WPM, where the wild plant species can also establish much better because there is no competition with main yield contributors such as sunflower and maize, i.e., for light, nutrients or water. In the case of WPM seeding after WCCS, the physical properties of the soil are also already much more resistant to wind and water erosion compared to WPM establishment alone or under maize. This is because of direct sowing (Figure 9g).

3.6. Plant Protection

The cultivation of WPM does not require any type of plant protection measure except for weeding (see above).[248,249]

3.7. Fertilization

The optimal amount of fertilizer depends on the site-specific yield level, which depends not only on soil quality and the expected precipitation, but especially on the respective condition and the wild plant composition of the WPM stock.[248] In general, a N fertilization level of 100 kg ha^{-1} (minus N_{min}) is recommended.[248] However, less fertilization should be applied if the WPM stock has a lower stock density or if high yielding wild plant species do not predominate. However, in a dense stock of common tansy or common knapweed, more than 100 kg N ha^{-1} may be applied.

As far as the type of fertilizer is concerned, WPM are not demanding, i.e., synthetic or organic fertilizer can be used.[249]

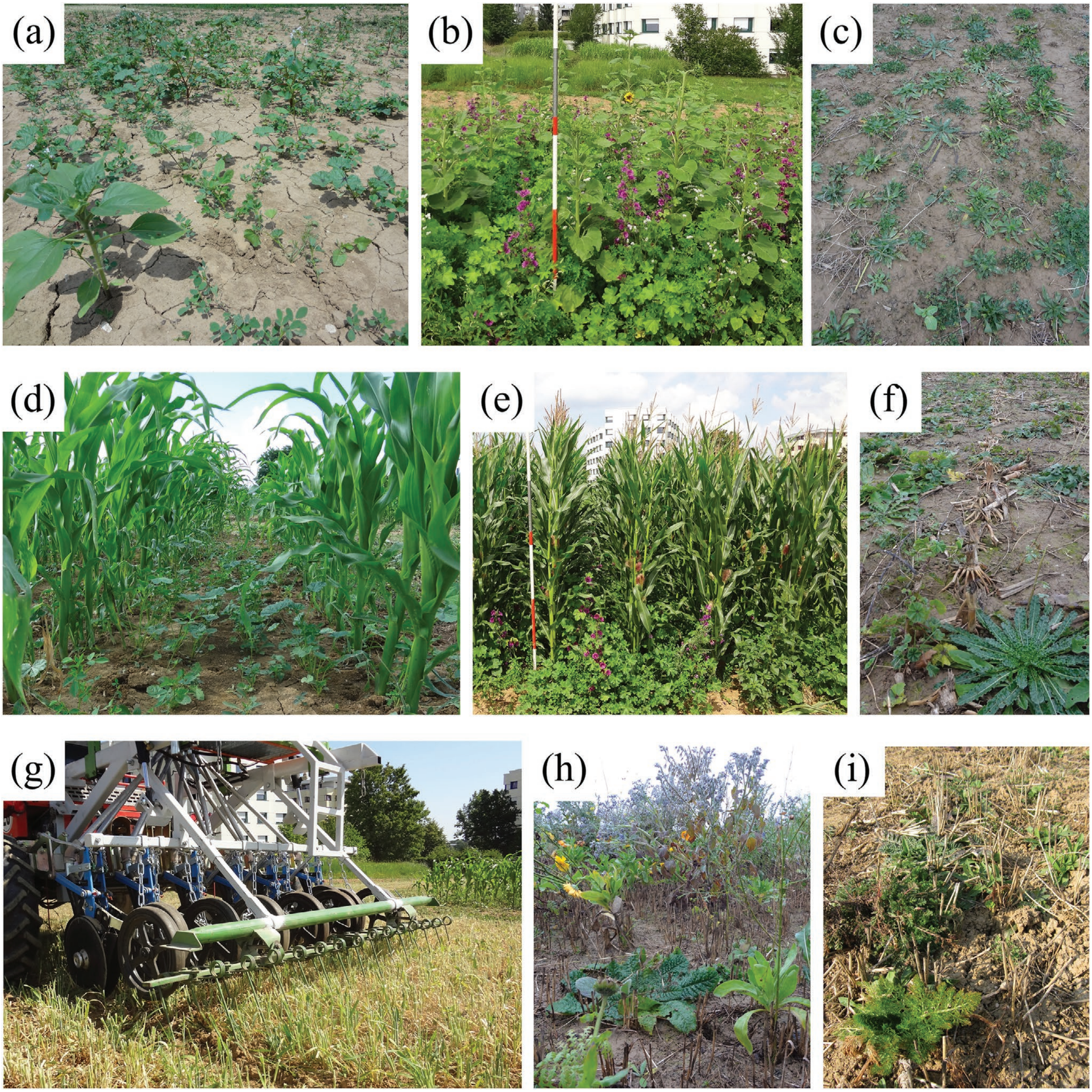

Figure 9. Impressions of three WPM establishment procedures: a–c) alone, d–f) under maize, and g–i) after cereal harvested as WCCS in summer. For each establishment procedure the start, the middle and the end of the first vegetation period is shown (from left to right).

It makes most sense to cover the N requirement with digestate—the residue produced in biogas production. This can also ensure the return of organic matter, which helps closing nutrient cycles and stabilizing both soil carbon contents and soil fertility—provided that a suitable application method is used.[275,276]

From a nature conservation point of view, there is something to be taken into account when it comes to the timing of fertilizer application. The fertilizer should be applied as early as possible (as late as necessary) to maximize the breeding period for ground-nesting open land bird species in which they can breed undisturbed.[254] This is especially important when the winter was mild and the birds start breeding relatively early.[254] If a second fertilization is considered during the vegetation phase,[249] it should be carried out at a correspondingly late stage (toward the end of the breeding and settling period).

3.8. Harvest, Logistics, Conservation, and Storage

In principle, all wild plant species can be harvested with the same harvesting technique as maize (**Figure 10**) and the

Figure 10. Harvest of wild plant mixtures after the second vegetation period in Schelklingen (southwest Germany) in Summer 2019 (source: Petra Stapf, 2019).

storage of the freshly harvested biomass in so-called mobile silos (**Figures 11** and **12**) does not pose any particular challenges.[248,249,273] It is however recommended that sideknifes or crop dividers be used, as they are used for example in rapeseed cultivation,[277,278] to mitigate the effect of lodging. This is especially necessary for WPMs when the wild plants easily become entangled or begin lodging,[279–281] as has often been observed in yellow melilot, common tansy, and common knapweed.[57,273] By using sideknifes or crop dividers it can be avoided, that plants and their roots are torn out and contaminate the crop material with soil.[273] Sideknifes or crop dividers also improve harvest productivity by reducing the number of stops needed to clean the cutterbar.[273]

When determining the optimal harvest time, a compromise between biogas substrate quality and ecosystem services must be made, especially from the second vegetation period onward. This is because the biogas substrate quality of the WPM is highest during mid-July to mid-August. From an overall operational point of view, this can initially be seen as positive, as no other harvesting work needs to be carried out at this time. However, at the end of July, high-yielding wild plant species such as yellow melilot, common tansy or common knapweed are still in the main flowering phase (full flowering).[57,282] A later harvest would therefore have great social–ecological advantages, because important ecosystem services could be provided for longer, such as support for pollinating insects, the provision of food and habitat for open land animals and the aesthetic enhancement of the landscape. However, a later harvest would result in a lower biogas substrate quality than an early harvest, and thus land use efficiency would be lower in case of a delayed harvest. This would require an even larger area to feed the biogas plant than is already required for WPM cultivation compared to maize cultivation. Nevertheless, it should be taken into account that the cultivation or combination of WPM can be further optimized, as described in Section 4.1.1.

The storage density of the freshly harvested plant material of WPMs remains unclear. If it is lower than for maize, the assessment of harvest productivity must take into account that WPMs cause higher weight-related transport costs than maize. In addition to a lower biomass yield level, this could also worsen the chopper's acreage output and thus increase its costs per WPM harvest unit. This problem can be avoided by harvesting WPMs during the same period as maize (Figure 12), in which case other factors must of course be taken into account. For example, it has yet to be investigated whether WPM's fresh biomass, which is relatively dry (35-45% dry matter content, DMC) compared to maize (30–35% DMC),[26,57,259,264] can improve the overall storage performance. It is conceivable that WPM biomass could act like a sponge in the mobile silo (Figures 11b and 12) by absorbing the leachate escaping from maize biomass and thus preventing it from being washed out.[283] A similar phenomenon was recently reported with the

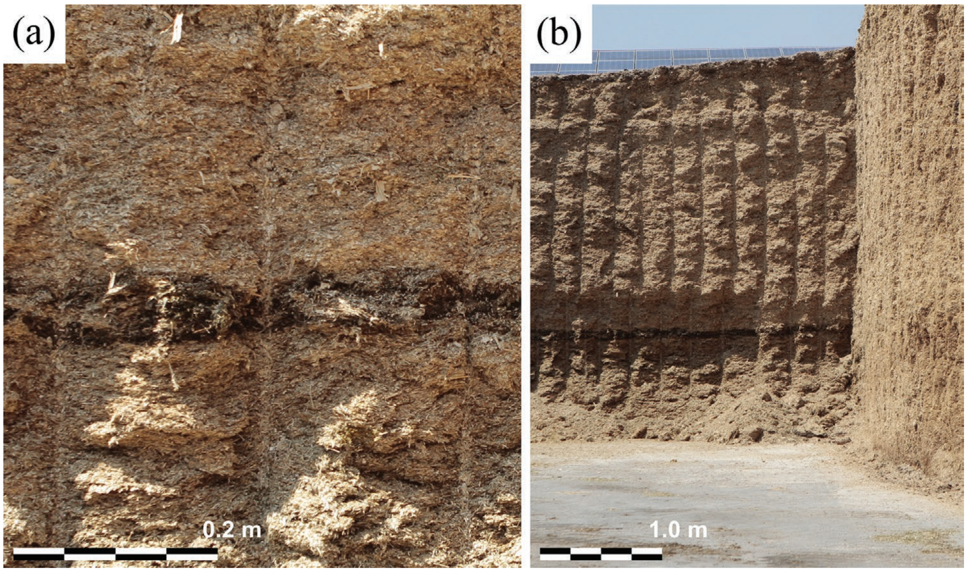

Figure 11. Illustration of a 10 cm thick layer of biomass from wild plant mixtures within a mobile silo a) from closer look, and b) from a distance (source: Petra Stapf, 2019).

Figure 12. Impression of a mobile silo getting filled with fresh harvested biomass from a) wild plant mixture (WPM) and b) maize. Behind this, both c) a biogas plant and d) another mobile silo are shown. The other silo contains ensiled biomass from the previous year (source: film-webfabrik Heilbronn).

use of cup plant (*Silphium perfoliatum* L.) as a biogas substrate in a large biogas plant.[283] Although the stems of some yield relevant wild plant species such as common tansy and mugwort (*Artemisia vulgaris* L.) are not as thick as those of cup plant,[28] they have a similar morphological structure, i.e., the stems are internally marrowy.

However, during the storage of the biogas substrate a conservation process, the so-called "ensiling," must take place, where within a few days the lactic acid and acetic acid contents increase to 5–10% and 2–4% respectively.[227] The main purposes of ensiling are to i) maintain the mass of the feedstock,[227,284–287] ii) to reduce energy losses through aerobic degradation,[288] and iii) to ensure that the biogas substrate quality of the biomass is maintained over a long period of up to one year.[227,289] Therefore, a distinction must be made between loss of leachate and ensiling quality both of which can be evaluated using certain thresholds (**Table 4**). The storage density of the freshly harvested plant material also plays an important role here.[227,290]

Messner et al.[284] found that the biomass losses are lower during the ensilage of WPM (3.5–4.4% of dry matter) compared to maize (3.9–6.3% of dry matter). They further reported that the fermentability coefficient of WPM (40–52) lies within the optimal range for successful ensilaging (Table 4). In contrast, the quotient of sugar content to buffering capacity (QSB) of WPM ranges between 1 (Aulendorf) and 1.8 (Forchheim) which is far below the optimal range (Table 4). However, farmers have reported no difficulties with the ensilaging of WPM biomass.[273]

4. Biomass Yield and Biomass Quality of WPM

4.1. Biogas Production

WPMs provide numerous benefits from both an economic, and an environmental perspective and are therefore highly likely to play a vital role in the future of biogas production, as in Theuerl

Table 4. Thresholds for good ensilage quality (adapted from Messner et al.[284]).

Parameter	Unit	Formula	Optimum range
Dry matter (DM) content	% of fresh matter (FM)	DM/FM	≥30
Quotient of sugar content (SC) to buffering capacity (BC) (QSB)	–	SC/BC	3–8
Fermentability coefficient (FC)	–	FC = DM % + (8 × QSB)	≥45

et al.[291] This section focuses on aspects of biogas substrate quality, biomass yield and methane yield.

4.1.1. Biogas Substrate Quality and Overall Suitability for Anaerobic Digestion

In this subsection, the suitability of WPM for fermentation in biogas plants is presented and discussed. An important indirect parameter is the substrate-specific methane yield (SMY). In the first part of this subsection, literature data on SMY are listed and discussed. However, since the determination of the SMY is a very time-consuming and material-intensive process, prediction models have been developed for specific biogas crops, including some wild plant species.[264] The potential application of these prediction models for the further improvement of WPM is presented and discussed in the second part of this subsection.

Specific Methane Yields and Overall Suitability of WPM Biomass for Anaerobic Digestion: Following Vollrath et al.,[248,257] from both the native wild shrubs and the cultivated shrubs, only those species were filtered which were expected to produce a high methane yield if harvested as late as possible. Across all life cycles, the wild plant species investigated by Vollrath et al. reached a SMY of 175–350 l_N (kg VS)$^{-1}$.[248] The highest SMY is achieved by the perennial wild plant species mugwort with 346 l_N (kg VS)$^{-1}$, which rarely dominates the plant stands. The perennial wild plant species common tansy and common knapweed, which dominate the plant stands much more frequently, only reach 233 and 271 l_N (kg VS)$^{-1}$, respectively.[248] These values are more or less within the lower range of those presented by Herrero Garcia et al.[292] for energy crops in common, but they are higher than those presented by Triolo et al. who found an average SMY of 214 l_N (kg VS)$^{-1}$ for various herbaceous wild plant species[293] none of which are included in the WPM developed by Vollrath et al.[248] There are also large variations in SMY between different genotypes of wild plant species such as brown knapweed (*Centaurea jacea* L.). For six different genotypes of brown knapweed, Seppälä et al. reported an SMY ranging from 168 to 362 l_N (kg VS)$^{-1}$.[294] However, these examples show that wild plant species have the potential to achieve similarly high SMY as established plant cosubstrates such as maize or triticale. This is due to the fact that most wild plant species have not yet been bred or even selected as intensively as maize or triticale. It therefore seems reasonable for Vollrath et al.[248] to conclude that initial breeding successes with wild plant species can be achieved within a very short time.[248]

Furthermore, the biogas substrate quality of lignocellulosic biomass from wild plant species may be increased by adding enzymes to the main fermenter of the biogas plant.[295] These enzymes can help degrade cellulose and hemicellulose and thus, reduce the retention time of the substrate within the fermenter.[292] However, the use of enzymes as a pretreatment approach during anaerobic digestion may not only increase the productivity of the biogas plant fed with WPM but also increase the SMY of wild plant species. This can be derived from a study by Herrero Garcia et al.[292] who found that using lignocellulosic biomass more or less similar to that of wild plant species, the addition of enzymes can increase biogas yield by up to 30%. Another type of pretreatment would be the use of 3% potassium hydroxide (KOH).[296] In experiments with switchgrass, this pretreatment led to a methane yield almost four times higher than that of untreated biomass.[296] Since WPMs have a very similar lignocellulose composition to Switchgrass,[57,262,297] it is possible that a pretreatment based on 3%-KOH could also significantly increase the methane yield of WPM. However, it remains an open question how this could be implemented in an economically practicable way, especially if only small amounts of WPM biomass are produced for biogas production (Figures 11 and 12).

As WPMs are currently occur only in rather small quantities as a second or third choice cosubstrate (Figures 11 and 12)[256] for the foreseeable future, it is still necessary to consider how the WPM biomass could influence the biogas substrate quality of the other cosubstrate types. It has already been mentioned that the WPM biomass may reduce leachate losses during ensiling. However, in the fermenter, the nutrient composition of the WPM biomass plays a particularly important role.[298] In principle, synthetic additives are required in biogas production if a high proportion of plant biomass is used as a cosubstrate.[227,299–301] These additives ensure that the microorganisms are supplied with sufficient macro and micro nutrients.[300,302,303] This is necessary because the plant-based cosubstrate with the highest mass percentage is usually maize – which contains relatively small amounts of trace nutrients.[300,304] Wild plant species, on the other hand, contain relatively high levels of macro- and micronutrients,[298] as evidenced by their high ash content.[264,305] Fahlbusch et al.[298] found, that such high proportions of trace elements within the WPM mixtures can help reducing the need for synthetic additives within the biogas production process. The reduction of the use of synthetic additives is considered desirable from environmental sustainability angle, e.g., lower accumulation of heavy metals in the environment, and social sustainability, e.g., less support for the mining of heavy metals under socially questionable working and living conditions in developing countries.[298,306]

SMY Predictability: The prediction of the SMY can make it possible to estimate the biomethane potential of a biogas plant or a whole region.[264] Depending on the knowledge of the biomass composition this can be done by more or less extensive models.[264] For maize, it is much easier to predict the SMY than for WPMs.[264,307–309] This is mainly because maize biomass is much more homogeneous than WPM.[264,308] Thus, the variation coefficients of the potential regressors (lignocellulosic fractions, minerals, etc.) are much lower for maize than for WPM. However, the number of WPM species peaks in the second year and is comparably low from the third year onward.[259] This means that a system with only a few dominant wild plant species could allow for the use of crop-specific prediction models. Crop-specific models (such as maize-models mentioned above) are generally more precise than across-crop models.[264] However, more research is required to determine whether WPM SMY prediction could be relevantly improved using crop-specific models of the dominant species.

4.1.2. Biomass and Methane Yield Per Hectare

The biomass yields of WPM vary greatly depending on the species composition and establishment success of the site-specific growth conditions[248,259,263] (**Table 5**). Therefore, it is rather impossible to compare the biomass yields of WPM cultivation between years and locations.[263] However, this subsection aims at providing an overview of the potential biomass yield range of WPMs. In order to reduce the varietal effect, only those observations were compiled which are based on WPMs similar to those described as "S2" in Von Cossel et al.[57,259]

As already mentioned, WPM cultivation requires significantly less labor and materials than maize, wheat or rye (Figure 5 and Tables A1–A5). This could be an important selection criterion for those areas that are far away from the farm, because the field-farm-distance is generally a crucial cost factor in crop production.[310] In principle, however, it should be taken into account that the labor and material input for WPM cultivation is only lower than for maize or rye when using the area as a reference (Figure 5). If there are differences between the cultivation methods in terms of productivity, which is the case here (Tables 5 and **6**), then the productivity per unit area must be taken into account, for example the electrical energy (**Figure 13**). This is because both biomass and methane yield of WPM are generally lower than maize, wheat or rye (Table 5).[311] It was shown that WPM, taking productivity per unit area into account, is more efficient than the cultivation of maize or rye only from the second year onward (Figure 13 and Table 6). This means that it is particularly important to establish the perennial wild plant species well, as each additional year in which they achieve good yields improves the overall performance of WPM cultivation. It is still to be seen whether WPM can be productive for as long as miscanthus (20 years), for example.

Another important aspect for assessing the long-term efficiency of the WPM cultivation system is the N use efficiency (NUE). There are no comprehensive studies available yet, but the following can be deduced from the literature: WPM's N-demand is highly dependent on the soil type, the site-specific yield level and the proportion of legumes, which varies over the years.[259] Legumes can fix atmospheric N and make it available to plants, which means that synthetic N fertilizer can be replaced, providing significant GHG emission savings. This means that the better the perennial wild plant species are adapted to the location and the higher the proportion of legumes such as lucerne (*Medicago sativa* L.) and yellow melilot, the better the NUE could be. However, a more precise statement requires further investigation of the relationship between N leaching potential and biomass yield level in WPM cultivation.

4.2. Further Bioenergy Purposes, Bio-Based Products and Coproducts

4.2.1. Additional Bioenergy Purposes

Thermochemical Conversion: The thermochemical conversion of plant biomass is seen as an important option for producing useful biofuel products.[312] If the WPM pant stands are left over winter, they can be harvested dry (water content < 20%) and are then available for conversion pathways other than biogas production such as using biomass to generate heat and electricity.[104,313–315] The most important parameter for combustion is the lignin content, as lignin has the highest heating value.[312,314,316] Most wild plant species contain high amounts of lignin (circa 10% of dry matter), which increase when they are harvested later,[57,259] but there is no specific literature on the heating value of wild plant species. It is known from current research at the University of Hohenheim that the yield-relevant perennial wild plant species such as common tansy and common knapweed are do not lodge during winter and can therefore be harvested in winter. This does however not apply, for example, to cup plant, whose stems start to bend and lodge in rows as early as November. Furthermore, WPM biomass contains a relatively large amount of ash,[264,305] which has a negative effect on its thermochemical properties. In the case of WPM biomass, preliminary results of an ongoing study by the Biobased Products and Energy Crops Department indicate that the ashes show very good melting characteristics.

Bioethanol Production: For the production of bioethanol from plant-based biomass, a high content of cellulose and hemicellulose as well as a low content of lignin is generally advantageous.[317] It was recently found, that annual wild flower (WPM) biomass is not yet suitable for bioethanol production using thermohydrolysis as pretreatment and alteration of the silage-pH. WPMs only achieved <10% ethanol, while miscanthus reached 38.2–72.2%.[260] High contents of lignin are not generally disadvantageous for ethanol production. This is because although the lignin reduces the bioethanol yield, it is used in existing bioethanol refineries to provide the process energy via combustion.[317] Lignin has a very high combustion value, as already mentioned above. Therefore, if a bioethanol refinery plans to switch from a conventional bioethanol crop such as switchgrass or miscanthus[318–320] to WPMs, it should first be determined whether the amount of lignin present in the WPM biomass would still be sufficient to cover the energy demand of bioethanol production.[317] If this is not the case, agricultural systems that do not completely consist of a perennial biomass crop cultivation system but of a mixture, for example WPM and miscanthus, would be recommended. If the separation of lignin from the pretreatment process of biogas substrate is successful, it would be advisable to think about linking the value chains of biogas production and bioethanol production and to calculate their energy and material flows.

4.2.2. Bio-Based Products from WPM

WPMs are nonhomogeneous because they consist of several different crop species with different biochemical compositions (due to differences in physiology, morphology and maturation). Thus, it is expected that WPM would be rather unsuitable for biorefinery.[321] However, it should be investigated whether it would be worthwhile to use WPM from the third growing season onward to provide basic chemicals. From the third year onward, the diversity of WPM decreases sharply, which could lead to sufficient homogeneity in the biomass composition. This would then of course also entail the need for a suitable monitoring protocol, which would help to optimize the harvesting time, for example.

Table 5. Overview of some of the available data on the yield performance of perennial wild plant mixtures.

Source	Location	Dry matter yield [Mg ha^{-1}]	Substrate-specific methane yield [l_N (kg VS)$^{-1}$]	Methane yield [m^3_N ha^{-1}]	Notes
[263]	Klosterklund	5.0$^{a)}$	208	965	–
[263]	Altrich	13.1$^{a)}$	218	2686	–
[248]	Various	5.8	302	1576$^{b)}$	1st year of cultivation; maize: 16.2 Mg ha^{-1}; 338 l_N (kg VS)$^{-1}$
[248]	Various	10.3	291	2697$^{b)}$	Average over four years of cultivation (2nd–5th year, with 4th–5th estimated); maize:16.2 Mg ha^{-1}; 338 l_N (kg VS)$^{-1}$
[254]	Various	7.5	n.a.	n.a.	2013; 1st year
[254]	Various	5.3	n.a.	n.a.	2013; 1st year.; 0 kg N (ha year)$^{-1}$
[254]	Marquardt	10.8	n.a.	n.a.	Average over three years of cultivation (2012–2014); sown in 2012
[254]	Grub	7.1	n.a.	n.a.	Average over three years of cultivation (2012–2014); sown in 2012
[259]	Hohenheim	10.0	n.a.	n.a.	Average over five years of cultivation (2011–2015); 50 kg N (ha year)$^{-1}$
[259]	Renningen	14.8	n.a.	n.a.	Average over five years of cultivation (2011–2015), 50 kg N (ha year)$^{-1}$
[259]	Sankt Johann	12.7	n.a.	n.a.	Average over five years of cultivation (2011–2015), 50 kg N (ha year)$^{-1}$
[57]	Hohenheim	11.3	259	2745	Established alone; average over five years of cultivation (2014–2018), 90 kg N (ha year)$^{-1}$; maize: 20.1 Mg ha^{-1}; 330 l_N (kg VS)$^{-1}$
[57]	Hohenheim	15.3	263	3808	Established under maize; average over five years of cultivation (2014–2018), 90 kg N (ha year)$^{-1}$; maize: 20.1 Mg ha^{-1}; 330 l_N (kg VS)$^{-1}$
[269]	Rheinstetten-Forchheim	9.6	n.a.	n.a.	Average over four years of cultivation (2011–2014), lower soil quality, 160 kg N (ha year)$^{-1}$ from 2nd year onward, maize: 20.2 Mg ha^{-1}
[269]	Oehringen	9.7	n.a.	n.a.	Average over four years of cultivation (2011–2014), 160 kg N year^{-1} from 2nd year onward
[269]	Aulendorf	11.0	n.a.	n.a.	Average over four years of cultivation (2011–2014), 160 kg N year^{-1} from 2nd year onward, maize: 21.1 Mg ha^{-1}
[269]	Krauchenwies	11.9	n.a.	n.a.	160 kg N year^{-1} from 2nd year onward
[284]	Aulendorf	n.a.	223$^{c)}$	2204	Average over three years of cultivation (2012–2014)
[284]	Forchheim	n.a.	236$^{c)}$	2297	Average over three years of cultivation (2012–2014)
[284]	Forchheim	n.a.	221$^{c)}$	2094	Average over three years of cultivation (2012–2014)

$^{a)}$The dry matter yield was calculated using the volatile solid yield and the content of volatile solids; $^{b)}$Calculated using an estimated proportion of volatile solids of dry matter of 90%; $^{c)}$Biogas batch experiments were conducted using ensilage (not dry matter), n.a. = not available.

Other bio-based product categories such as bedding material or feed for pets may become relevant for further farm diversification, because the requirements on the biomass composition are less restrictive. This means, that biomass from WPM could eventually be considered as bedding material as long as the harvested biomass is dry enough to be balled. The same occurs for the use as feed for pets, provided that no toxic plants such as common tansy are within the mixture.[322]

4.2.3. Byproducts of WPM Cultivation

The Use of the Wild Plant's Inflorescences in Floristry: The high number of flower-rich species enables the provision of various coproducts, which contribute to farm diversification and can provide additional income for example the use of flowers in floristry. The flowering shoots of various wild plant species such as wild mallow and knapweed are well suited for cut flower bouquets as they last a long time (>1 week) in flower vases (author's experience). However, their use as cut flowers does not necessarily have to be commercial. Nonmonetary use of wild plant flowers by local residents and tourists can also contribute positively to the farm's image and in the long run to improving the acceptance of bioenergy. Not only inflorescences but also seeds of wild plant species can be collected and provide another coproduct either for commercial or private use.

Honey as a High-Value Coproduct: Furthermore, the flowers attract honeybees and thus, the WPM can provide a high value source of food for honey production.[273] Honey from WPMs looks like dark blossom honey (**Figure 14**), is liquid to viscous-flowing and has an intense aroma. It is not yet known whether WPM honey could be marketed on a large scale. In any case, the first sales figures from the direct marketing of the AG Wildpflanzen-Biogas show that the buying interest has already been aroused.[273] Therefore, the use of honey from WPM cultivation can be regarded as potentially economically feasible. This can contribute to farm diversification and increase the net income of biogas farms. In addition, no pesticides are used in WPM cultivation, so that neither beekeepers nor honey consumers need to worry about chemical-synthetic pesticide residues. Consequently, the honey could be marketed as an organic product which could in turn increase its value.

Table 6. Average yield levels, working time requirements, diesel requirements, and cumulated energy demand of wild plant mixture cultivation and a common biogas crop rotation system. For working time, diesel and energy demand, the values were related once to the area [ha^{-1}] and once to the energy output [MW$_{el}$ h^{-1}].

Cropping system	Fresh matter yield$^{a)}$ [Mg DM ha^{-1}]	Methane yield$^{b)}$ [m^3 CH$_4$ ha^{-1}]	Energy output$^{b)}$ [kWh$_{el}$ ha^{-1}]	Working time requirement$^{c)}$		Diesel requirements$^{c)}$		Cumulated energy demand$^{c)}$	
				[h ha^{-1}]	[h MW$_{el}$ h^{-1}]	[L ha^{-1}]	[L MW$_{el}$ h^{-1}]	[MJ ha^{-1}]	[MJ MW$_{el}$ h^{-1}]
WPM (1st year)	n.a.	2341	8867	5.6	0.63	37.8	4.27	3041	342.93
WPM (2nd–5th year)	n.a.	2341	8867	4.4	0.50	13.6	1.53	1735	195.62
Maize	50	4945	18731	8.4	0.45	54.0	2.88	4106	219.21
WW	40	3846	14568	8.0	0.55	60.9	4.18	4289	294.39
WR	40	3846	14568	7.7	0.53	53.1	3.65	3861	265.05

$^{a)}$For maize, winter wheat (WW) and winter rye (WR), the values were taken from FNR;[311] for wild plant mixture (WPM), see Table 5; $^{b)}$Calculated according to FNR[311]; $^{c)}$Calculated based on KTBL,[310] with field size = 5 ha, mechanization = 67 kW, and field to farm distance = 2 km.

In view of the comparatively low methane yields of WPM, it is therefore important to mention that at least the deficits of WPM in terms of land use efficiency can be somewhat reduced by honey as a coproduct. Additional land requirements for the provision of the required biomass or a lower volume load of the biogas plant (due to lower biomass yields of the WPM compared to maize) cannot of course be compensated by honey as a coproduct. On the other hand, the integration of honey production into WPM cultivation can promote the development of the labor market in rural areas by creating new jobs. Furthermore, the keeping of honeybees provides an important component of natural ecosystems, as bees also pollinate non-WPM plant species and thus contribute to biodiversity conservation.

5. Social–Ecological Benefits of WPM Cultivation

5.1. Nectar—Support for Pollinators

Looking at an area of flowering wild plant species in spring or summer (Figure 3), one immediately notices the large inflorescences, providing large quantities of pollen and nectar to pollinators. As this ecosystem service (the provision of large quantities of nectar and pollen) was a decisive selection criterion in the development of WPM,[248] it is indeed the case that numerous pollinator insect species such as honey bees, wild bees and bumblebees benefit from the flowering WPM plant stands.[57,248,254] Yellow melilot for example provides high quantities of high-quality nectar over a long period (May–September) (Figure 3).[57,248,254] But nectar is not always of the same quality, and it is not only the quantity that is crucial for successful promotion of biodiversity among pollinating insects.

Following Warzecha et al.,[323] four wild plant species are sufficient to provide enough feed for 81% of all pollinator species. Among these highly relevant wild plant species is yellow chamomile (*Cota tinctoria* (L.) J. Gay ex Guss.) (**Figure 15**). This wild plant species is also included in the WPMs.[57] It is most abundant in the wild plant stands during the second vegetation period, but in case of successful seed propagation and field emergence, it may continue to occur in the WPM plant stands in the following vegetation periods. However, as the perennial wild plant species common tansy and common knapweed grow to almost twice the size of yellow chamomile, it is more likely to play the role of a gap-filler or peripheral plant that appears at the edge of the field.

The most important perennial wild plant species which predominate in WPM plant stands from the third year onward, namely common tansy and common knapweed[57] were not covered in the study of Warzecha et al.[323] Nevertheless, preliminary results of an ongoing study have shown that both common tansy and common knapweed are attract numerous pollinators including both honeybees, bumble bees and wild bees.[282] These results are line with observations by Vollrath et al.[248,254] In contrast, the existence of other WPM species which produce less amounts of nectar and pollen are also of great importance for a healthy development of the wild bee larvae because those sources of nectar can be much richer in macronutrients and other essential nutritional components as was recently found by Filipiak.[324] Furthermore, it is also very likely that diverse spontaneous (weed) plant species grow among wild plant species. This can be deduced from the results of Feledyn-Szewczyk et al.,[325] who studied the effect of perennial energy crop species on weed diversity. It was found that perennial dicotyledons had a weak but nevertheless positive effect on the diversity of nonsown species compared to crop rotation systems.[325] Provided that these nonsown species do not gain predominance, they can provide additional food for pollinating insects and open land bird and game species.[325] Thus, WPMs can help increase the agrobiodiversity including both sown and not-sown (weed) species. This can have significant positive effects on the yield of those main crops which require insect pollination.[326,327] Even in the cultivation phase from the third year of vegetation onward, WPMs show a diverse stand composition, although the number of species of the dominant (yield-relevant) species is lower than in the first and second year of vegetation. Accordingly, the so-called mass-flowering effect (negative effects of intensively flowering monocultures such as rapeseed on pollinator populations) would not be expected for WPM.[266,328] However, this still needs to be investigated in large scale field trials.

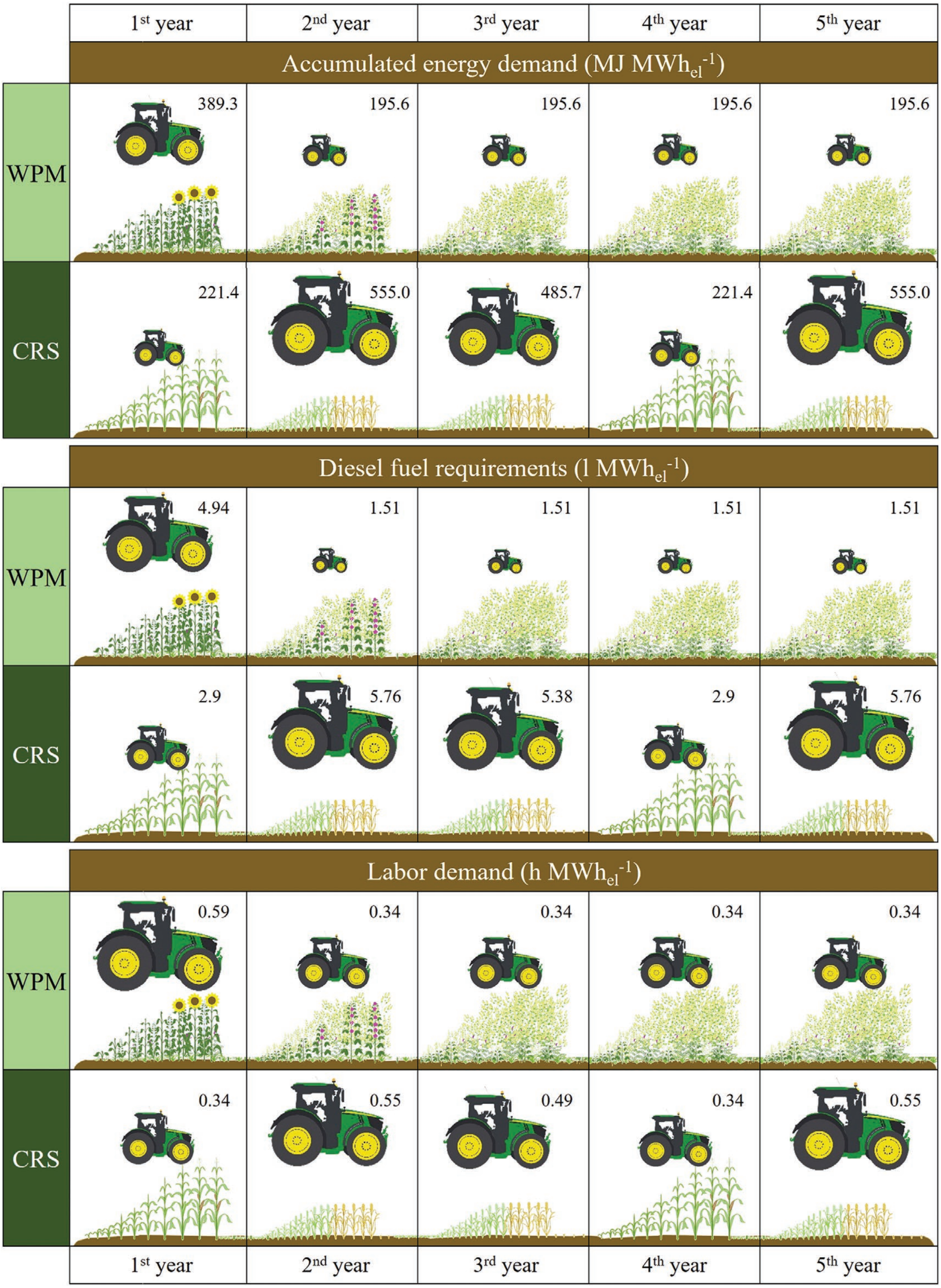

Figure 13. Schematic overview of diesel fuel, labor and accumulated energy requirements per megawatt hour (available as electrical energy) for wild plant mixture cultivation (WPM) and a random three-year crop rotation of maize, winter wheat and winter rye (CRS) during five years of cultivation. The size of the tractors represents the proportion of maximum value per category.

5.2. Soil Organic Carbon Accumulation (CO_2 Sequestration)

Only one study has been conducted on the impact of WPM cultivation on soil organic carbon content. Emmerling et al.[262] have used the example of perennial wild plants, cup plant and maize to investigate how the soil organic C and N pools and the microbial properties of the soil change within five years of cultivation. It was found that even after such a relatively short

Figure 14. Honey produced from perennial wild plant mixtures which were grown by the AG Wildpflanzen-Biogas (Kißlegg, Germany).

period of time, WPM showed an increase in soil organic carbon of 1–2%.[262] WPMs were comparable to other perennial cropping systems in terms of their potential to contribute to CO_2 sequestration. However, for all perennial cropping systems (including WPM) this potential was limited to good sites.[262] On less favorable land, where poorer soil quality and lower rainfall led to lower growth of the perennial cropping systems, lower soil organic carbon contents were found after five years of cultivation than for the annual cropping systems.[262] If GHG emissions are also to be included, Carlsson et al.[261] argue that the yield level is less relevant than the fertilization level. There is certainly room for improvement here, as some field trials have shown that WPM can achieve yields greater than 10 Mg ha^{-1} even with less than 100 kg N ha^{-1}.[57]

Figure 15. Yellow chamomile (*Cota tinctoria* (L.) J. Gay ex Guss. with Apis mellifera Linnaeus, 1758) within a field trial with wild plant mixture BG70 (Saaten-Zeller GmbH & Co. KG).

It can be concluded from this that improved WPM must be developed for comparable types of marginal agricultural land, so that soil organic carbon enrichment can also be achieved there and thus make an important contribution to climate protection via BECCS.[1] It should be considered on a case-by-case basis whether other methods such as natural succession, are more appropriate, which under certain circumstances can contribute better to CO_2 sequestration than the cultivation of energy crops.[154]

5.3. Erosion Mitigation

Wind and water erosion are serious issues that must be considered for more sustainable agricultural systems including biogas cropping systems—especially in the case of intensive maize cultivation.[329] Following Brandhuber and Treisch,[330] intensive maize cultivation can cause soil removal of more than 3 Mg (ha year)$^{-1}$. Such high erosion rates can be reduced through the implementation of practices such as mulching, intercropping and reduced tillage intensity.[331] Perennial biomass cropping systems such as WPM cultivation combine many of these agricultural practices for better erosion mitigation. First, WPMs do not require any soil tillage from the second year of cultivation onward. This reduces the time when the soil is not covered with a mulch layer (living mulch or dead mulch material). This is important for erosion mitigation, because a continuous soil coverage with mulch or living mulch reduces the kinetic energy of the raindrops hitting on the ground ("raindrop erosion") and thereby reduces the surface runoff and both extensive and linear forms of erosion.[331–334] Following Köller et al.,[335] this is the only reason for a better soil water infiltration rate of soils that are not tilled (no-till system) compared with those that are tilled regularly. Against this, neither the increased bioturbation activity by earthworms nor the reduced tillage intensity under no-till systems have substantial effects on the soil water infiltration capacity.[335] Nevertheless, there are a number of benefits deriving from higher earthworm activity and reduced tillage intensity under aspects of soil fertility which are described and discussed in terms of WPM cultivation within Section 5.4.[331]

Based on the fact that WPM cultivation always contains significant amounts of dead biomass (dead branches and leaves of early maturing wild plant species) as well as a lot of emerging young wild plants and spontaneous weed species, WPM cultivation can be associated with a continuously developing mulch layer.[336] Importantly, this also applies during the autumn and winter months when the erosion potential is much higher.[337] Many parts of the wild plants are not caught by the chopper and fall to the ground; furthermore, many perennial wild plant species such as common tansy and common knapweed start to sprout again in autumn, thus forming a patchy mulch layer of living mulch. For maize cultivation, this is only the case if maize is intercropped with a living mulch or otherwise mulched. Typically, the soil in maize cultivation is uncovered during the sowing and establishment period as well as immediately after harvest.

Thus, surface runoff can be reduced much better under WPM cultivation compared with annual cropping system such as maize cultivation. The erosion mitigation potential of WPM cultivation can further be improved, if the rows are aligned at right angles to the slope.[38,329] This can be deduced from results from Cosentino et al.,[38] which confirm that perennial energy grasses can reduce the erosion potential of slopes and in the long run even contribute to the biological soil improvement of the areas.[38]

After harvesting, maize stubbles, if left standing for a while, can reduce wind speed and thus reduce wind erosion, but here too the protective potential of WPM cultivation is much more pronounced, since WPM have a higher plant density than maize. This is because i) WPM are sown in 14.5 cm rows, maize in 75 cm rows, and ii) the sowing density is also much higher for WPM (>700 kernels m^{-2}) than for maize (7–10 kernels m^{-2}).[26,57,259] Consequently, it can be assumed that WPM cultivation contributes better to erosion mitigation on areas exposed to strong winds than maize cultivation.

5.4. Effects on Soil Microbial Communities and Overall Soil Fertility

Studies have shown that the plant diversity of WPM can have a positive effect on soil organisms.[244,262] The exact mechanisms of action remain largely unexplored. However, a high temporal and spatial dynamic in the soil microbial community can be assumed due to the highly dynamic species composition of the WPM stands.[259] In most cases, the precrops of WPM are annual crop rotations.[248] This shift from a tillage- to a no-till system causes a crucial reformulation of the soil microbial community which can take up to four years.[335] In addition, the wild plant species of the WPM mixtures have broad genetic resources, since they are predominantly wild genotypes.[57,248,254,259,338] Wild genotypes generally have a broader spectrum of resistance mechanisms than cultivated high-yielding varieties.[339–341]

Consequently, the resilience of the ecosystem can be increased as well as the resistance of the cultivation system, which is bound to the ecosystem resilience of the agroecosystem, can also be increased. This assumption highlights two potentially future social–ecological advantages: i) the contribution of the biogas crop cultivation system to climate change adaptation, and ii) the importance of WPM cultivation for the recovery of degraded arable land.[342] The latter advantage in particular would help to mitigate the problems of land use conflicts in the cultivation of energy crops already described in the introduction, since marginal agricultural land would be used.

5.5. Habitat Functions and the Protection of Open Land Animals

Active protection of open land animals such as grey partridge (*Perdix perdix* (Linnaeus, 1758)), European hamster (*Cricetus cricetus* (Linnaeus, 1758)), red deer (*Cervus elaphus* Linnaeus, 1758), and European hare (*Lepus europaeus* Pallas, 1778) is only weakly developed in conventional biogas cropping systems.[249,251] This is due to the fact that most biogas crops are annual (or winter-annual), which in combination with moderate to intensive tillage provides hardly any habitat and food for small game – especially in the winter months.[218,249,255] The only exceptions are crop rotation systems in which catch crops are cultivated, which extend the period of vegetative soil cover.[343–346] This helps to improve the supply of food and weather protection for open land animals.[249] Optimal cultivation systems are those that provide year-round soil cover and thus food and weather protection for open land animals.[249] Consequently, the cultivation of perennial crops such as WPM can improve the living conditions for open land animals due to the perennial nature of the cultivation system.[249] WPMs also provide a large number of high quality food sources for the various wild game species[249,273] and open land bird species,[254] as WPMs are wild native plant species that are already part of existing ecosystems.

These positive effects on the habitat conditions of open land bird and wildlife species can likely be significantly enhanced by not harvesting some of the areas cultivated with WPM but leaving them standing over winter (**Figure 16**). This would enable the wild plant species to fulfill a habitat function of great importance for agricultural land, as there is usually little or no cover during the winter months (Figure 16). For the use of biomass as biogas substrate, however, the problem arises that the area must be harvested once a year—otherwise direct payments are reduced. This means that all WPM subareas that are to be left standing over winter must be mulched at least once in the spring of the previous year (in winter the area cannot be harvested, because there is no growth that could be harvested).[347] Thus, the earlier the plant stand is harvested in spring, the more likely it is that a high density of WPM will be established and thus provide relevant cover and food for open land bird and wildlife species over the winter months. However, mulching in the spring is associated with disadvantages that maybe avoided by growing WPMs. On the one hand, the WPMs offer numerous early flowering wild plant species, which provide an important first flowering window for the first insect generations of the year. For bumblebee queens, for example, it is particularly important to find sufficient food after hibernation to complete the exhausting development of their bumblebee colonies.[348,349] For this reason, the suitability of WPM biomass for bioethanol production should be further investigated (as mentioned above). If it were possible to convert the WPM biomass into bioethanol in an economically sustainable way, then the harvest of WPM could be completely shifted to winter, as is the case for Miscanthus.[90,97,122,140,145,350] This winter harvesting method would then very likely also have significant economic advantages in terms of productivity per unit area and workload. On the one hand, a better nutrient circulation within the perennial wild plant species is enabled, which in turn could increase both nutrient use efficiency and biomass yield potential in the long run. On the other hand, the resistance of perennial wild plant species to biophysical constraints such as shallow soil, sandy soil, contaminated soil, and drought events could also be improved. This could help to increase the potential suitability of WPMs for marginal agricultural land. However, similar to the use of WPM biomass for biogas production, it is necessary to investigate how long WPM stocks can be maximally productive if common tansy, common knapweed or other perennial wild plant species are well established.

Figure 16. a) Wild teasel (*Dipsacus fullonum* L.)) and b,c) other wild plant species grown on a stripe-shaped area as a kind of fragmentation within an intensively farmed agricultural area. The wild plants were not harvested in autumn 2019. The pictures were taken in a) Hohenheim and b,c) Plieningen (southwest Germany) in July 2018 and January 2020, respectively.

5.6. Reduction of Spread of Wild Boar Stocks

In conventional maize biogas cropping systems, the expansion of wild boar (*Sus scrofa* Linnaeus, 1758) populations represents a major problem.[351] Wild boar populations are difficult to control in regions with intensive maize cultivation, as hunting in the plant stands of maize is not possible, unless hunting aisles are used in the maize. Wild boar can find food in maize fields that is rich in starch (the corncob) and therefore excellent for their nutrition demands, which further increases population pressure. The consequences of this problem range from the farm level to the social level.[352] Farms suffer high yield losses due to wild boar activity in maize plant stands. These losses are capped by hunting, but for the biogas plant operators, mostly the farm owners themselves, there is a deficit in the provision of biomass, which must be compensated by biomass from additional areas. In this context, land use conflicts are aggravated to the detriment of biogas production, which can have a negative impact on the public image of the bioenergy sector. In addition, growing wild boar populations also increase the risk of accidents on public transport routes.[352,353] The resulting decline in safety in public transport is a serious problem. In addition, the risk of a potential spread of animal diseases such as *African swine fever virus*,[354,355] which can be transmitted from wild boar to domestic pigs, increases proportionally in regions with an increasing wild boar population, which already has serious economic consequences for commercial piggeries on a global scale.[356]

WPM cultivation can help mitigating the spread of wild boar populations.[249,273] This is due wild plant species have no such nutritional value for wild boar. Furthermore, WPM stands are harvested much earlier (end July–mid August) than maize (October) and thus, wild boar populations can be better controlled in areas where WPM are being cultivated.

5.7. Landscape Appearance

Surveys have shown that the attitudes of residents and tourists who are confronted with WPM plant stands appear to be have positive impressions of WPM cultivation.[270,273] This fits in with the findings of Huth et al.,[232] who conclude that perennial crops such as miscanthus and WPMs have a higher aesthetic value than annual energy crops such as maize. Both in near-settlement areas (**Figure 17**) and in recreational areas, WPM can therefore help to defuse the public debate on bioenergy-related land use effects. Information boards can be set up along busy field paths and inform the local population about the purpose of the WPMs and the species they are made up of.[273] The cultivation of WPMs in areas close to settlements can thus also contribute to education by providing an aesthetically appealing demonstration area where the background and interrelationships of bioenergy production can be communicated and explained.

6. Concepts of Public and Political Support for Farmers

The limited area available for primary production is a major reason for the heated debate on whether the economy needs to grow continuously.[357] Limited agricultural area is a problem for economic growth. This is complicated by the "environmental trilemma" of sustainable land use, according to which there will be increasing conflicts of use between economic, social and ecological interest groups worldwide.[195] Consequently, more holistically sustainable biomass cultivation strategies need to address both economic and social-ecological needs. This becomes increasingly important in a world, where pollinator populations have been declining rapidly for decades, and in which the sixth mass extinction has begun. If no radical changes in

Figure 17. Wild plant mixture grown on a near-settlement area in southwest Germany in 2014.

public attitudes take place, resulting in a holistically sustainable bioeconomy then human civilizations clearly risks reaching he boundaries of planetary resources.[358,359] Both the planetary boundaries and the natural nonanthropocene systems need to be taken into account within market strategies, regardless of the ethnological driving force (liberal, socialistic, communist).[360] This is a key element of Goepel's Transformative Literacy in which "5 P's" (paradigms, people, purpose, processes, and the planet) map the socioecological–technological systems.[360]

As far as biogas crop cultivation is concerned, WPMs provide numerous benefits for the community excluding their lower land use efficiency on good soils compared with maize and WCCS. These public benefits are worth almost nothing for the farmers who are cultivating the WPM, while a lowered income is significant hindrance. Thus, farmers must be compensated for the public benefits they obtain by growing WPMs, and there is an ongoing debate on how to realize this compensation, for example through implementing a so-called "public good bonus."[361–363] However, there exists so far no such public good bonus so far—the WPMs are not even recognized as a EU greening measure.[347] Therefore, in this section, it is explored how the cultivation of WPM could be embraced by the community (Section 7.1) and which economic solutions could substitute for the lower net-profit for the farmers (Section 7.2), respectively.

6.1. Public Approaches

One approach to compensate for the additional expenditure of farmers growing WPMs is to pass on the costs to the electricity customer. This concept is explained and discussed here using the example of the brand "Bienenstrom" (Stadtwerke Nürtingen GmbH, Nuertingen, Germany). The brand "Bienenstrom" means "bee power" and stands for a special electricity product for household and small business customers, which creates habitats for plants and insects—especially pollinating insects. The participating farms, which have so far used conventional biogas crops such as maize and triticale as biogas substrates, first cultivate some of their farmland with WPMs (instead of maize or triticale). The electricity generated from the biomass of these WPM cultivation areas is then sold to interested electricity customers as "Bienenstrom" via an Internet platform (www.bienenstrom.de). With every kilowatt hour of "Bienenstrom" sold, one Eurocent (gross) flows into the project for the cultivation and expansion of the WPM cultivation areas. This makes it possible to pay the farmers involved in the project a fixed annual amount per hectare of WPM cultivation area. This makes the "Bienenstrom" concept also interesting for farmers, because this calculable payment compensates for the increased cultivation costs and lower revenues from the use of WPMs as biogas substrate compared to conventional biogas crops.

The "Bienenstrom" model is still relatively young, but in 2019, 14 farms have already participated and cultivated WPM on about 20 ha. Due to growing consumer demand, the area under WPM, the biomass of which is used to provide "Bienenstrom," will be expanded to about 30 ha in 2020. All over Germany farmers have shown interest in participating in the project. The farmers benefit not only from the compensation payments but also from the positive media coverage associated with WPM cultivation.

In the short to medium term, it therefore looks promising to promote the cultivation of WPMs through special products such as "Bienenstrom." In the long term, however, it remains to be seen what will happen when state-regulated feed-in tariffs for biogas electricity[364] are abolished.[283] It could be that the use of maize or triticale as biogas substrate would then no longer be worthwhile, so that many biogas farms that currently cultivate WPMs on the side would tend to abandon their biogas production in the long term[283] and would also no longer cultivate WPM. It is likely that completely new land use concepts will then be needed, in which the cultivation of WPM for biogas production will certainly still play a role, but in a completely different way—for example, only in conjunction with government support measures, such as greening measures, which compensate ecosystem functions even more extensively than before through strategically optimized WPM cultivation concepts. A stronger financial involvement of the rural population or tourism companies, which have a direct share in the positive effects of WPM cultivation, would also be conceivable.[273]

6.2. Political Approaches

First of all, it should be considered whether WPMs could be added to the EU greening measures as has been done for cup plant and miscanthus (*Miscanthus* × *giganteus* Greef et Deuter).[347] This could increase the flexibility of farmers to develop suitable implementation strategies considering both farm-specific social–ecological demands and the technical options. However, the potential shift from common greening measurements such as catch crops, legumes, etc., to WPMs as greening measures needs careful consideration. This means that in a worst case scenario, WPMs could replace other environmentally friendly greening measurement and thus, reduce the environmental sustainability within other farming sectors such as the cultivation of food and forage crops. Against this, in a best case scenario, the other agricultural practices of the prior greening measures could be continued after WPM have been declared as a new type of greening measure.

Another important area of responsibility for policy makers includes improving the accessibility and comprehensibility of applications needed for WPM cultivation. This should reduce the bureaucratic burden for farmers who intend to grow WPM.

This concerns not only the correct declaration of the crop type but also a clear regulation to ensure that fields cultivated with WPM do not lose their arable status after five years. This is because, as described above, WPM stocks can be productive for much longer than five years.[57,259,273] Each additional year is also extremely important in order to further reduce the high establishment costs in the first year.[265]

7. The Potential Role of WPM for Marginal Agricultural Land

In the previous sections, it has been shown and discussed how WPM are cultivated, what advantages and disadvantages they have in terms of biomass production and biomass quality, what other ecosystem services can be provided by WPM cultivation and how the cultivation of WPM has been promoted to date. However, the question now arises as to the areas on which WPM should be predominantly cultivated in future in order to avoid conflict with food crop cultivation. This basic question applies to industrial crops in general, and the use of marginal agricultural land is being discussed and already applied in science and practice as a promising solution.[19,25,167] There are two main types of marginal agricultural land: i) biophysically limited via poor growth suitability for food crops, and ii) economically limited due to logistical difficulties in the field management (i.e., shape). In this section, it will be briefly assessed for both of these types of marginal agricultural land whether WPMs could play a relevant part in MALLIS for biomass production in the future.

7.1. The Growth Suitability of WPM Under Biophysical Constraints

The biophysical constraints most strongly represented in Europe (EU28) are i) adverse rooting conditions such as shallow rooting depth and unfavorable texture (156 000 km²), ii) adverse climatic conditions such as low temperature, high temperature or dryness (112 000 km²), and iii) adverse soil water conditions such as limited soil drainage or excess soil moisture (108 000 km²).[19,365] If such areas are now to be used for biomass cultivation,[19,167] the question arises as to what extent WPM would be suitable for this purpose. This is because on such areas, WPM cultivation would rather not compete with food crop cultivation.[167] It was found that wild plant species similar to those of the WPMs can be used for revegetation of degraded land under certain circumstances.[342] In principle, the wild plant species of the WPM also appear to be very promising for such purposes, showing a broad tolerance spectrum to biotic and abiotic stress factors. This is particularly true for biennial and perennial wild plant species, which are much less susceptible to drought due to their deep root system from the second year of planting than annual biomass plants, whose root system can hardly develop under drought conditions. Field experiments have shown, that young plantlets of wild plant species such as common mallow (*Malva sylvestris* L.) (**Figure 18**) are very tolerant of biophysical constraints such as drought conditions or heavy rain events. Promising perennial wild plant species are for example greater knapweed (*Centaurea scabiosa* L.) and common tansy (**Figure 19**), which are well established under field test conditions as well as in practice on rather unfavorable sites and can achieve reliable yields.[57,273] However, these observations contradict results from Brauckmann et al.,[366,367] who found WPM unsuitable for cultivation on sandy soils during drought conditions.

It is therefore necessary to further investigate the types of marginal agricultural land on which WPM can be economically cultivated, what risk is involved for farmers, and what possible support measures should be provided. The same applies to adverse soil water conditions. It will probably not be a good idea to choose an autumn harvesting method such as WPM's for sites where there is a high probability that the soil will be saturated in autumn and therefore difficult to drive on without damaging the soil through compaction.[368] There are no further investigations available yet. It would be conceivable for such sites to harvest WPM in winter, which would be associated with a different type of use of WPM biomass as biogas substrate, for example thermochemical conversion or bioethanol production (see above).

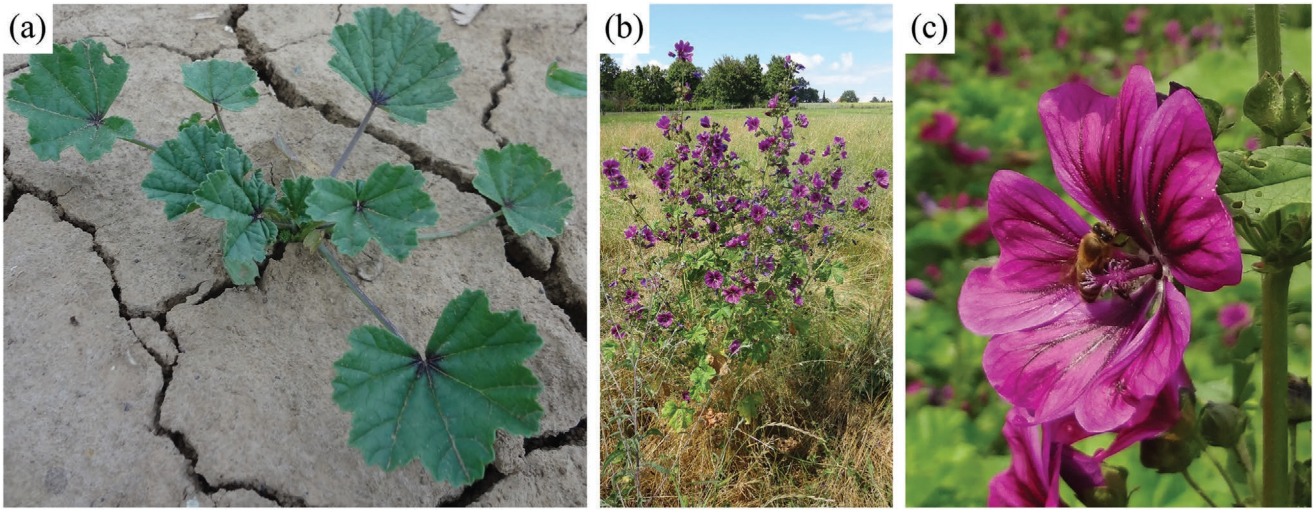

Figure 18. Young plant of common mallow (*Malva sylvestris* L.) establishing under drought conditions at a field trial near a) University of Hohenheim, b) habitus, and c) inflorescence of fully developed common mallow.

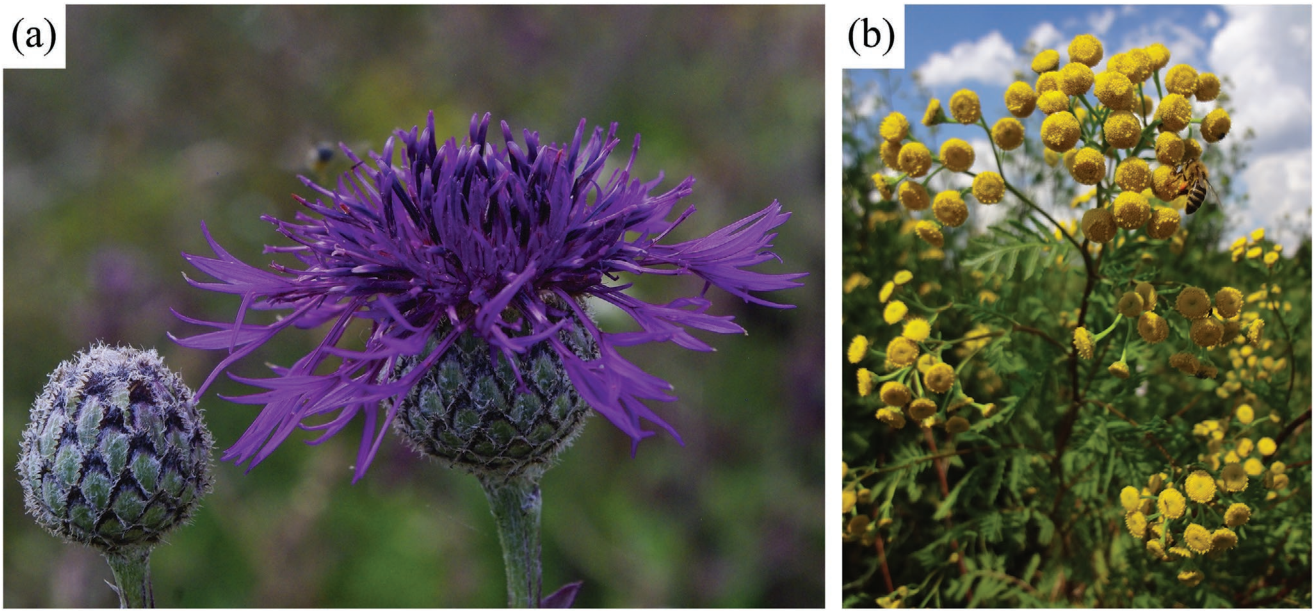

Figure 19. Impression of the inflorescences of a) greater knapweed (*Centaurea scabiosa* L.) and b) common tansy (*Tanacetum vulgare* L.).

7.2. Improving the Economic Performance of Existing Productive Areas

Following Feldwisch[267] the economic productivity of existing productive sites can be improved through field shape optimization.[267,369] The idea is to grow perennials in the field corners, so that the remaining well-shaped field can be easily managed and used for annual crop cultivation.[267,369] There are some suggestions in the literature for perennial crops and cropping systems such as willow, miscanthus and grassland. The multiannual nature of these crops and cropping systems not only improves the management of the remaining well-shaped field, but also increases the habitat availability for beneficial insects.[248,370] This provision of food and habitat directly adjacent to the cultivated arable land can help to significantly reduce pesticide use on the adjacent arable land while maintaining yield levels. With WPM cultivation this effect could be much more pronounced than with other crops and cropping systems. This can be assumed because, WPMs have a higher number of species than willow and Miscanthus and thus also provides nectar species that are essential for the reproduction of various pollinating insect species (see above).[323] Additionally, it can be assumed that the lower intensity of cultivation and the higher growth has a more positive influence on the insect and bird fauna than intensively managed grassland (which is usually used to improve the shape of the field, especially within the greening measures).[347]

8. Conclusions

This review provides an overview of the first experiences with WPM cultivation from research and praxis. WPMs are a perennial cropping system that can provide biomass for biogas production. WPMs offer a dynamic and diverse species composition of flowering and predominantly wild plant species, which significantly increases agrobiodiversity compared to conventional biogas crops. It has been shown that WPM cultivation offers great social-ecological advantages over conventional biogas crop rotation systems, but the average methane yield of WPM is still significantly lower. This results in negative land use change effects, i.e., more land is needed to produce the same amount of bioenergy (in the form of biogas and heat) as for example in the cultivation of maize or triticale. However, continued improvement and practical application of the existing WPM cultivation system can still be recommended under special circumstances. A further development of the cultivation system seems to be reasonable, as it is not only a very young cultivation system in terms of its development status, but also because the range of fluctuation of the biomass yield potential of WPM reaches a level of competitiveness with conventional biogas crops such as maize or triticale in several studies. Furthermore, the additional social-ecological benefits of WPM cultivation can be so significant under certain local conditions that the still relatively low economic performance of the cultivation system can be ignored. This could be, for example, the proximity of the field to residential, recreational or nature conservation areas. Also, unfavorable geometry of the fields cultivated with food crops can make it possible to cultivate WPM because, apart from improving the management of the remaining primary field, the species-rich WPM area can have a positive effect on the pesticide requirements of the primary field. However, a complete replacement of the conventional biogas crops by WPM cannot be recommended at present, because the overall sustainability of the biomass supply would very probably be significantly lower than in the current situation due to enormous land use change effects. A meaningful addition of WPM to the range of conventional biogas crops can very likely enhance the overall sustainability of biogas cropping systems. Only then would it appear reasonable in the long term to cultivate biomass for bioenergy and thus, at least in the energy sector, help significantly toward achieving a transition to a fossil-free and social-ecologically sustainable bioeconomy.

Appendix

Table A1. Data basis for the calculation of diesel demand, labor and energy consumption in wild plant mixture cultivation in the first year of cultivation (adapted from KTBL (https://www.ktbl.de/webanwendungen/pflanzenbauverfahren/)).

Work process	Frequency	Amount		Working time requirement [h ha^{-1}]	Diesel requirements [L ha^{-1}]	Machine costs [€ ha^{-1}]						Accumulated energy demand [MJ ha^{-1}]		
		Value	Unit			Amortization	Interest cots	Others	Repairs	Operating materials	Services	Operating materials	Machinery, plant and buildings	Total
Soil sample	0.2													
Removal by hand; driving with pick-up truck				0.03	0.01	0.05	0.01	0.02	0.01	0.01	0.00	0.60	0.25	0.85
Ploughing with reversible plough	1													
4 shares, 1.4 m, mounted; 67 kW				1.67	22.79	14.04	4.04	1.79	22.13	17.09	0.00	1120.00	130.04	1250.04
Harrowing with seedbed combination	1													
4 m; 67 kW				0.45	5.34	6.66	2.00	1.21	6.98	4.01	0.00	262.00	66.22	328.22
N_{min} sampling	1													
Removal by hand; drive with pick-up truck				0.47	0.12	0.40	0.06	0.16	0.12	0.09	0.00	6.00	2.09	8.09
Sowing of 3 m strips with seed drill	0.2	10	kg ha^{-1}											
3 m; 45 kW				0.44	1.28	1.96	0.57	0.24	2.42	0.96	0.00	63.00	16.53	79.53
Weed bonitur	1													
Visual bonitur; rides with pick-up				0.12	0.12	0.36	0.05	0.15	0.08	0.09	0.00	6.00	1.91	7.91
Stock bonitur	1													
Visual bonitur; rides with pick-up				0.11	0.06	0.23	0.03	0.09	0.05	0.05	0.00	3.00	1.21	4.21
Digestate application, from the farm with pump tanker, drag hose	1	20	m^3 ha^{-1}											
5 m^3, 7.5 m; 45 kW				2.16	7.20	19.36	4.69	2.60	19.31	5.40	0.00	354.00	154.07	508.07
Chopping, transporting and compacting	1	50	Mg ha^{-1}											
Service				0.00	0.00	0.00	0.00	0.00	0.00	0.00	400.00	0.00	789.01	789.01
Limestone application off the field	0.33	3	Mg ha^{-1}											
Front loader, 1500 daN; mineral fertilizer shovel, 0.55 m^3; 45 kW				0.03	0.17	0.19	0.05	0.04	0.23	0.13	0.00	8.58	2.11	10.69
Trailed spreader, 4 m^3; 67 kW				0.07	0.75	1.64	0.39	0.30	0.91	0.56	0.00	36.63	17.66	54.29
Interest costs (3%, 3 months)									0.66	0.30	3.00			
Total				5.55	37.84	44.89	11.89	6.60	52.90	28.69	403.00	1 859.81	1 181.10	3 040.91

Table A2. Data basis for the calculation of diesel demand, labor, and energy consumption in wild plant mixture cultivation from second year of cultivation onward (adapted from KTBL (https://www.ktbl.de/webanwendungen/pflanzenbauverfahren/)).

Work process	Frequency	Amount		Working time requirement [h ha^{-1}]	Diesel requirements [L ha^{-1}]	Machine costs [€ ha^{-1}]						Accumulated energy demand [MJ ha^{-1}]		
		Value	Unit			Amortization	Interest cots	Others	Repairs	Operating materials	Services	Operating materials	Machinery, plant and buildings	Total
Soil sample	0.2													
Removal by hand; driving with pick-up truck				0.03	0.01	0.05	0.01	0.02	0.01	0.01	0.00	0.60	0.25	0.85
N_{min} sampling	1													
Removal by hand; drive with pick-up truck				0.47	0.12	0.40	0.06	0.16	0.12	0.09	0.00	6.00	2.09	8.09
Digestate application, from the farm with pump tanker, drag hose	1	12	m³ ha^{-1}											
5 m³, 7.5 m; 45 kW				1.40	5.18	11.98	2.91	1.61	12.19	3.89	0.00	255.00	96.49	351.49
Weed bonitur	1													
Visual bonitur; Rides with pick-up				0.12	0.12	0.36	0.05	0.15	0.08	0.09	0.00	6.00	1.91	7.91
Stock bonitur	1													
Visual bonitur; rides with pick-up				0.11	0.06	0.23	0.03	0.09	0.05	0.05	0.00	3.00	1.21	4.21
Digestate application, from the farm with pump tanker, drag hose	1	20	m³ ha^{-1}											
5 m³, 7.5 m; 45 kW				2.16	7.20	19.36	4.69	2.60	19.31	5.40	0.00	354.00	154.07	508.07
Chopping, transporting and compacting	1	50	Mg ha^{-1}											
Service				0.00	0.00	0.00	0.00	0.00	0.00	0.00	400.00	0.00	789.01	789.01
Limestone application off the field	0.33	3	Mg ha^{-1}											
Front loader, 1500 daN; mineral fertilizer shovel, 0.55 m³; 45 kW				0.03	0.17	0.19	0.05	0.04	0.23	0.13	0.00	8.58	2.11	10.69
Trailed spreader, 4 m³; 67 kW				0.07	0.75	1.64	0.39	0.30	0.91	0.56	0.00	36.63	17.66	54.29
Interest costs (3%, 3 months)									0.66	0.30	3.00			
Total				4.39	13.61	34.21	8.19	4.97	33.56	10.52	403.00	669.81	1 064.80	1 734.61

Table A3. Data basis for the calculation of diesel demand, labor, and energy consumption in maize cultivation (adapted from KTBL (https://www.ktbl.de/webanwendungen/pflanzenbauverfahren/)).

Work process	Frequency	Amount		Working time requirement [h ha^{-1}]	Diesel requirements [L ha^{-1}]	Machine costs [€ ha^{-1}]						Accumulated energy demand [MJ ha^{-1}]		
		Value	Unit			Amortization	Interest cots	Others	Repairs	Operating materials	Services	Operating materials	Machinery, plant and buildings	Total
Soil sample	0.2													
Removal by hand; driving with pick-up truck				0.03	0.01	0.05	0.01	0.02	0.01	0.01	0.00	0.60	0.25	0.85
Ploughing with reversible plough	1													
4 shares, 1.4 m, mounted; 67 kW				1.67	22.79	14.04	4.04	1.79	22.13	17.09	0.00	1120.00	130.04	1250.04
Harrowing with seedbed combination	1													
4 m; 67 kW				0.45	5.34	6.66	2.00	1.21	6.98	4.01	0.00	262.00	66.22	328.22
N_{min} sampling	1													
Removal by hand; drive with pick-up truck				0.47	0.12	0.40	0.06	0.16	0.12	0.09	0.00	6.00	2.09	8.09
Digestate application, from the farm with pump tanker, drag hose	1	12	m^3 ha^{-1}											
5 m^3, 7.5 m; 45 kW				1.40	5.18	11.98	2.91	1.61	12.19	3.89	0.00	255.00	96.49	351.49
Precision seeding	1													
4 rows, 3 m; 45 kW				0.71	3.22	22.15	4.20	1.10	12.04	2.42	0.00	158.00	97.70	255.70
Plant protection measure	1	300	L ha^{-1}											
Crop protection sprayer, 15 m, 1000 L; 45 kW				0.25	0.94	3.76	0.88	0.29	1.98	0.71	0.00	46.00	18.02	64.02
Weed bonitur	1													
Visual bonitur; rides with pick-up				0.12	0.12	0.36	0.05	0.15	0.08	0.09	0.00	6.00	1.91	7.91
Plant protection measure	1	300	L ha^{-1}											
Crop protection sprayer, 15 m, 1000 L; 45 kW				0.25	0.94	3.76	0.88	0.29	1.98	0.71	0.00	46.00	18.02	64.02
Stock bonitur	1													
Visual bonitur; rides with pick-up				0.11	0.06	0.23	0.03	0.09	0.05	0.05	0.00	3.00	1.21	4.21
Digestate application, from the farm with pump tanker, drag hose	1	20	m^3 ha^{-1}											
5 m^3, 7.5 m; 45 kW				2.16	7.20	19.36	4.69	2.60	19.31	5.40	0.00	354.00	154.07	508.07
Chopping, transporting and compacting	1	50	Mg ha^{-1}											
Service				0.00	0.00	0.00	0.00	0.00	0.00	0.00	400.00	0.00	789.01	789.01
Limestone application off the field	0.33	3	Mg ha^{-1}											
Front loader, 1500 daN; mineral fertilizer shovel, 0.55 m^3; 45 kW				0.03	0.17	0.19	0.05	0.04	0.23	0.13	0.00	8.58	2.11	10.69
Trailed spreader, 4 m^3; 67 kW				0.07	0.75	1.64	0.39	0.30	0.91	0.56	0.00	36.63	17.66	54.29
Stubble working, flat, oblique (30°)	1													
2.5 m; 67 kW				0.68	7.12	6.08	1.76	1.18	9.57	5.34	0.00	350.00	59.48	409.48
Interest costs (3%, 3 months)									0.66	0.30	3.00			
Total				8.40	53.96	90.66	21.95	10.83	88.24	40.80	403.00	2651.81	1454.28	4106.09

Table A4. Data basis for the calculation of diesel demand, labor and energy consumption in winter wheat cultivation for whole crop cereal silage (adapted from KTBL (https://www.ktbl.de/webanwendungen/pflanzenbauverfahren/)).

Work process	Frequency	Amount		Working time requirement [h ha^{-1}]	Diesel requirements [L ha^{-1}]	Machine costs [€ ha^{-1}]						Accumulated energy demand [MJ ha^{-1}]		
		Value	Unit			Amortization	Interest cots	Others	Repairs	Operating materials	Services	Operating materials	Machinery, plant and buildings	Total
Soil sample	0.2													
Removal by hand; driving with pick-up truck				0.03	0.01	0.05	0.01	0.02	0.01	0.01	0.00	0.60	0.25	0.85
Ploughing with reversible plough	1													
4 shares, 1.4 m, mounted; 67 kW				1.67	22.79	14.04	4.04	1.79	22.13	17.09	0.00	1120.00	130.04	1250.04
Harrowing with seedbed combination	1													
4 m; 67 kW				0.45	5.34	6.66	2.00	1.21	6.98	4.01	0.00	262.00	66.22	328.22
Seeding with rotary harrow and seed drill	1	180	kg ha^{-1}											
2.5 m; 67 kW				1.11	12.29	13.01	3.41	1.48	16.88	9.22	0.00	604.00	96.33	700.33
Weed bonitur	1													
Visual bonitur; rides with pick-up				0.12	0.12	0.36	0.05	0.15	0.08	0.09	0.00	6.00	1.91	7.91
Plant protection measure	1	300	L ha^{-1}											
Crop protection sprayer, 15 m, 1000 L; 45 kW				0.25	0.94	3.76	0.88	0.29	1.98	0.71	0.00	46.00	18.02	64.02
N_{min} sampling	1													
Removal by hand; drive with pick-up truck				0.47	0.12	0.40	0.06	0.16	0.12	0.09	0.00	6.00	2.09	8.09
Digestate application, from the farm with pump tanker, drag hose	1	5	m³ ha^{-1}											
5 m³, 7.5 m; 45 kW				0.74	3.41	5.52	1.35	0.74	5.96	2.56	0.00	168.00	46.12	214.12
Stock bonitur	1													
Visual bonitur; rides with pick-up				0.11	0.06	0.23	0.03	0.09	0.05	0.05	0.00	3.00	1.21	4.21
Spread mineral fertilizer, loose fertilizer	1	100	kg ha^{-1}											
Fertilizer screw conveyor				0.01	0.00	0.02	0.00	0.01	0.01	0.01	0.00	0.00	0.09	0.09
Mounted centrifugal spreader, 0.8 m³; 45 kW				0.14	0.62	0.63	0.16	0.09	0.82	0.47	0.00	30.00	6.15	36.15
Digestate application, from the farm with pump tanker, drag hose	1	20	m³ ha-1											
5 m³, 7.5 m; 45 kW				2.16	7.20	19.36	4.69	2.60	19.31	5.40	0.00	354.00	154.07	508.07
Chopping, transporting and compacting	1	40	Mg ha^{-1}											
Service				0.00	0.00	0.00	0.00	0.00	0.00	0.00	170.00	0.00	692.06	692.06
Limestone application off the field	0.33	3	Mg ha^{-1}											
Front loader, 1500 daN; mineral fertilizer shovel, 0.55 m³; 45 kW				0.03	0.17	0.19	0.05	0.04	0.23	0.13	0.00	8.58	2.11	10.69
Trailed spreader, 4 m³; 67 kW				0.07	0.75	1.64	0.39	0.30	0.91	0.56	0.00	36.63	17.66	54.29
Stubble working, flat, oblique (30°)	1													
2.5 m; 67 kW				0.68	7.12	6.08	1.76	1.18	9.57	5.34	0.00	350.00	59.48	409.48
Interest costs (3%, 3 months)									0.64	0.34	1.28			
Total				8.04	60.94	71.95	18.88	10.15	85.68	46.08	171.28	2994.81	1293.81	4288.62

Table A5. Data basis for the calculation of diesel demand, labor and energy consumption in winter rye cultivation for whole crop cereal silage (adapted from KTBL (https://www.ktbl.de/webanwendungen/pflanzenbauverfahren/)).

Work process	Frequency	Amount		Working time requirement [h ha^{-1}]	Diesel requirements [L ha^{-1}]	Machine costs [€ ha^{-1}]						Accumulated energy demand [MJ ha^{-1}]		
		Value	Unit			Amortization	Interest cots	Others	Repairs	Operating materials	Services	Operating materials	Machinery, plant and building	Total
Soil sample	0.2													
Removal by hand; driving with pick-up truck				0.03	0.01	0.05	0.01	0.02	0.01	0.01	0.00	0.60	0.25	0.85
Ploughing with reversible plough	1													
4 shares, 1.4 m, mounted; 67 kW				1.67	22.79	14.04	4.04	1.79	22.13	17.09	0.00	1120.00	130.04	1250.04
Harrowing with seedbed combination	1													
4 m; 67 kW				0.45	5.34	6.66	2.00	1.21	6.98	4.01	0.00	262.00	66.22	328.22
Seeding with seed drill	1	140	kg ha^{-1}											
3 m; 45 kW				0.72	4.56	6.52	1.94	0.74	6.57	3.42	0.00	224.00	45.83	269.83
Weed bonitur	1													
Visual bonitur; rides with pick-up				0.12	0.12	0.36	0.05	0.15	0.08	0.09	0.00	6.00	1.91	7.91
Plant protection measure	1	300	L ha^{-1}											
crop protection sprayer, 15 m, 1000 L; 45 kW				0.25	0.94	3.76	0.88	0.29	1.98	0.71	0.00	46.00	18.02	64.02
N_{min} sampling	1													
Removal by hand; drive with pick-up truck				0.47	0.12	0.40	0.06	0.16	0.12	0.09	0.00	6.00	2.09	8.09
Digestate application, from the farm with pump tanker, drag hose	1	7	m^3 ha^{-1}											
5 m^3, 7.5 m; 45 kW				0.93	3.93	7.36	1.80	0.99	7.74	2.95	0.00	193.00	60.51	253.51
Stock bonitur	1													
Visual bonitur; rides with pick-up				0.11	0.06	0.23	0.03	0.09	0.05	0.05	0.00	3.00	1.21	4.21
Digestate application, from the farm with pump tanker, drag hose	1	20	m^3 ha^{-1}											
5 m^3, 7.5 m; 45 kW				2.16	7.20	19.36	4.69	2.60	19.31	5.40	0.00	354.00	154.07	508.07
Chopping, transporting and compacting	1	40	Mg ha^{-1}											
Service				0.00	0.00	0.00	0.00	0.00	0.00	0.00	170.00	0.00	692.06	692.06
Limestone application off the field	0.33	3	Mg ha^{-1}											
Front loader, 1500 daN; mineral fertilizer shovel, 0.55 m^3; 45 kW				0.03	0.17	0.19	0.05	0.04	0.23	0.13	0.00	8.58	2.11	10.69
Trailed spreader, 4 m^3; 67 kW				0.07	0.75	1.64	0.39	0.30	0.91	0.56	0.00	36.63	17.66	54.29
Stubble tillage, flat, oblique (30°)	1													
2.5 m; 67 kW				0.68	7.12	6.08	1.76	1.18	9.57	5.34	0.00	350.00	59.48	409.48
Interest costs (3%, 3 months)									0.57	0.30	1.28			
Total				7.69	53.11	66.65	17.70	9.56	76.25	40.15	171.28	2609.81	1251.46	3861.27

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Conflict of Interest

The author declares no conflict of interest.

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