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OPINION

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Different life-form strategies of perennial energy crops and related nutrient exports require a differentiating view specifically concerning a sustainable cultivation on marginal land

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Abstract

Perennial energy crops (PECs) are increasingly used as feedstock to produce energy in an environmental friendly way. Compared to traditional conversion strategies like thermal use, sophisticated technologies such as biomethanation defined different requirements of the feedstock. Whereas the first concept relies on dry, woody material, biomethanation requires a moist feedstock. Thus, over time, the spectrum of species used as PECs has widened. Moreover, harvest dates were adjusted to provide the feedstock at suitable moisture contents. It is well known that perennial, lignocellulose-based energy crops, compared to annual, sugar- and starch-based ones, offer ecological advantages such as, inter alia, improving biodiversity in landscape, protecting soil against erosion, and protecting groundwater from nutrient inputs. However, one of the main arguments for PEC cultivation was their undemanding nature concerning external inputs. With respect to the broader spectrum of PEC species and changed harvest dates, the question arises whether the concept of PECs being low-input energy crops is still valid. This also implies the question of suitable growing conditions and sustainable management. The aims of this opinion paper were to classify different PECs according to their life-form strategy, compare nutrient exports when harvested in different maturation stages, and to discuss the results in the context of sustainable PEC cultivation on marginal land. This study revealed that nutrient exports with yield biomass of PECs harvested in green state are in the same range than those of annual energy crops and therewith several times higher than those of PECs harvested in brown state or of woody short rotation coppices. Thus, PECs cannot universally be claimed as low-input energy crops. These results also imply the consequences of cultivation of PECs on marginal land. Finally, the question has to be raised whether the term PECs should prospectively be better specified in written and spoken words.

KEYWORDS

harvest dates, low-input management, mature harvest, nutrient demands, nutrient exports, premature harvest, utilization pathways

1 | INTRODUCTION

In the past decades, lots of research have been done in the field of dedicated energy crops. In the course of time, perennial energy crops (PECs) have received growing interest as they seem to be "ideal energy crop species" that "require low inputs and, by virtue of deep roots, are suitable to land of low agricultural or biodiversity value or abandoned land no longer suitable for quality food production" (Valentine et al., 2012). Moreover, research has shown that PECs may provide several beneficial effects on the environment when compared to annual energy crops (AECs). The beneficial effects include an enhanced biodiversity in agricultural landscape (Rowe et al., 2009; Schorpp et al., 2016; Semere et al., 2007a, 2007b), soil protection against erosion (Blanco-Canqui, 2010; Hartman et al., 2011), and protection of groundwater by their potential to reduce nitrate leaching (Grunwald et al., 2020; Pugesgaard et al., 2015). Additionally, PECs seem to be superior to AECs due to their better overall greenhouse gas balance particularly due to the absence of soil tillage with a concurrent accumulation of soil organic matter (Adler et al., 2007; Cadoux et al., 2014; Don et al., 2012; Felten et al., 2013). Thus, Whitmore et al. (2015) classified them as a "technology" to mitigate climate change. Besides the absence of tillage, the prevalent opinion suggests that PECs typically have very low demands for fertilization and do not require the application of plant protection agents after the phase of crop establishment (Agostini et al., 2015; Gansberger et al., 2015; Karp & Shield, 2008). These management-related aspects led to the fundamental statement that PECs are, compared to AECs, identified by a distinct low-input character (Adler et al., 2007; Lewandowski et al., 2003; McLaughlin & Walsh, 1998).

At all times, those species were in focus for which economically viable utilization pathways existed. Chronically, systematic research started in the 1980s with high yielding, perennial C4 grasses of the genus *Miscanthus* (*Miscanthus* × *giganteus*, *Miscanthus sinensis*) and woody short rotation coppices (WSRC) comprising species such as poplar (*Populus* spp.) and willow (*Salix* spp.; Heaton et al., 2010; Karp & Shield, 2008; Long, 1999). At that time, the biomass was subjected to a direct thermal use aiming to substitute fossil energy carriers. Also industrial applications were developed targeting on fibers as value-bringing constituents (Mohanty et al., 2011; Visser & Pignatelli, 2001). Requirements for both applications were quite similar: high dry matter and low ash contents, suitable for storage, and low impurities (Lewandowski et al., 2003; Visser & Pignatelli, 2001). Therefore, the biomass was harvested in winter or early spring in brown state, after maturation and drying off in winter.

In the past decade, numerous species have been added to the portfolio of dedicated, lignocellulosic energy crops. Additionally, in order to increase the overall energy efficiency of conversion techniques, more sophisticated energetic utilization pathways such as biomethanation coupled with combined heat and power plants were established in recent years (Ptasinski, 2016). Based on this, the requirements of the feedstocks have significantly changed compared to thermal use. Due to the basic mechanism of anaerobic digestion as a biochemical degradation process of organic matter by the activity of micro-organisms, the feedstock should possess properties suitable for microbial decomposition. This primarily includes a moisture content of the biomass that meets the optimum living and activity range of the micro-organisms and enzymes involved (Dufour et al., 2011). Moreover, PECs tend to accumulate lignocellulosic components with progressing maturation (Kramer & Belanger, 2011; Langeveld & Peterson, 2018). Although pretreatment techniques can improve the accessibility of the lignocellulosic structures for microbial digestion, these procedures failed to establish themselves in practice due to (i) disproportionate high investment costs, (ii) heavy consumption of energy, or (iii) duration of the process (Čater et al., 2014; da Costa Sousa et al., 2009; Zheng et al., 2014). Thus, the selection of suitable harvest dates for the feedstock in combination with longer retention times is inevitable for an effective ensiling of the feedstock and productive methanation (Klimiuk et al., 2010; Lehtomäki et al., 2008; Schmidt et al., 2018).

Generally speaking, for an effective methanation of lignocellulose-rich feedstocks like Miscanthus without a pretreatment, the harvest dates have to be preponed compared to the traditional harvest (Kiesel et al., 2017; Mangold et al., 2019; Schmidt et al., 2018). Harvesting in a green state also presents the common procedure for a couple of more recently established forbs as feedstock for methanation such as cup plant (*Silphium perfoliatum*), Virginia mallow (*Sida hermaphrodita*), and giant knotweed (*Fallopia sachalinensis*).

As a result, it has to be expected that harvesting PECs in a green, hence premature, state significantly alters the typical characteristics of PEC cultivation by impacting plant physiological processes. Furthermore, there is the (currently unanswered) landmark question, whether forbs that were introduced as PECs more recently can universally be handled as low-input crops. In this context, also the suitability of PECs to be cultivated on marginal land needs to be discussed more specifically.

The aims of this opinion paper are therefore, (i) to point out the botanical differences of various PECs focusing on their life-form strategies and (ii) resulting implications for nutrient exports and efficiencies. Based on this, (iii) the suitability of different PECs to be cultivated on marginal lands is discussed. Furthermore, the paper likes to stimulate the scientific debate about introducing subcategories of PECs, which are oriented on the maturity status when harvested. The overarching goal of this opinion is to treat and debate PECs more specifically and in a way that they can further contribute to a sustainable and viable way of energy production.

2 | LIFE-FORM CATEGORIES OF PERENNIAL, LIGNOCELLULOSIC ENERGY CROPS

The term perennial energy crops has widened in the course of years by deeming additional crop species to be suitable to serve as feedstock for a certain use. Today, the group of PECs includes WSRC, perennial rhizomatous grasses (PRGs), and forb species that are harvested in different vegetative states, depending on the further utilization pathway. What all PECs have in common, as already expressed in the name, is the multiannuality of their vegetative life cycles. However, the different species show distinct differences in the strategies for reproduction and overwintering with significant effects on plant physiological processes.

In contrast to AECs, that generally aim for a generative reproduction by seeds (Therophytes; Allaby, 2015), all perennial plants perusing the strategy to "survive the unfavorable period of the year" (in temperate climates usually the winter) by a considerable reduction of the aboveground biomass (Raunkiær, 1934). The characteristic of species, belonging to the life-form groups of Crypto- and Hemicryptophyts (Table 1), is that at least large parts of the total aboveground biomass die off following a process of maturation (Allaby, 2015; Raunkiær, 1934). In this phase, downwards-directed translocation processes of assimilates and plant nutrients take place targeting to fill up reserves facilitating sprouting in the next vegetation season (Chapin et al., 1990). In this context, plants with dedicated storage organs such as rhizomes, bulbs, tubers, or nodules are particularly efficient in nutrient and assimilate recycling, thus showing a very high nutrient efficiency. Compared to that, the aboveground biomass of Phanerophytes (shrubby and woody plants) survives wintertimes in a dormant stage, and assimilates and nutrient of the annual parts of the plant (leaves) were maintained in the system by internal relocation or external (leave shedding) pathways (Raunkiær, 1934).

Consequently, removing the aboveground biomass (harvesting) of perennial crops prior to maturation presents a significant cut in plant physiological processes with species-specific reactions, particularly an inhibition of the nutrient recirculation via internal and external pathways (Robson et al., 2012; Xiong et al., 2009). Therefore, it is presumable that nutrient concentrations and exports with biomass yields are highly associated with a green, premature harvest of all perennial crops or in a foliated stage of WSRC.

3 | NUTRIENT EXPORTS AND EFFICIENCIES ARE AFFECTED BY SPECIES AND HARVEST REGIME

The different life-form groups of PECs provide reason to suspect that harvest dates in autumn (green, premature state) compared to early spring (brown, mature state) will affect nutrient exports, sprouting, yields in the following vegetation period as well as soil parameters, as, for example, investigated for Miscanthus by Clifton-Brown et al. (2001), Purdy et al. (2015) and Ruf et al. (2017). Although this reason can likely be observed for all PRGs, there is a significant lag in understanding of the nature and scale of retranslocation processes in forb species that are used as feedstock for anaerobic digestion. However, the analysis of published data may provide insights and allows comparisons.

TABLE 1 Assignment of groups of energy crops to the scheme of life-form categories acc. to the system initially developed by Raunkiær (1905) and specified, among others, by Ellenberg and Mueller-Dombois (1967)

Group of energy crop	Woody short rotation coppice (WSRC)	Perennial rhizomatous grasses (PRG)	Forbs	Annual energy crops (AEC)
Class	Dicotyledons	Monocotyledons	Dicotyledons	Monocotyledons and dicotyledons
Life-form Group	Phanerophytes	Cryptophytes	Hemicryptophytes	Therophytes
Example of species (temperate regions)	• Poplar (*Populus* spp.) • willow (*Salix* spp.) • elder (*Alnus glutinosa*)	• Miscanthus (*Miscanthus* spp.) • switchgrass (*Panicum virgatum*) • reed canarygrass (*Phalaris arundinacea*)	• Cup plant (*Silphium perfoliatum*), • Virginia mallow (*Sida hermaphrodita*) • giant knotweed (*Fallopia sachalinensis*)	• Maize (*Zea mays*) • rye (*Secale cereale*) • wheat (*Triticum* spp.) • rapeseed (*Brassica napus*) • sugarbeet (*Beta vulgaris*)

3.1 | Methodology

A non-systematic search for published study results dealing with nutrient exports with yield biomass was conducted based on keywords such as "annual energy crop," "perennial energy crop," "woody short rotation coppice" including single species of this groups and both, trivial (English and German language) and botanic names (such as silage maize, *Miscanthus*, willow) as well as their acronyms (such as PEC, WSRC). Some studies presented several nutritional elements, whereas others focused on a single element only. Results were presented in nutrient concentrations (e.g., in g kg^{-1}), partially stating the yield level but also nutrient exports based on a reference surface area (e.g., in kg ha^{-1}). Moreover, usually the reference level was expressed as "per dry matter"; however, sometimes it was also stated as "per fresh matter." For some studies, the nitrogen contents were recalculated if only C-to-N ratios were mentioned, given protein contents were recalculated under the assumption of a nitrogen content of 16% in proteins (Jeroch et al., 2008).

A total of 26 studies were found reliable and considered suitable in the context of this opinion article. This particularly concerned the availability of data to allow for a recalculation to nutrient contents per dry matter biomass and exports on the reference level of one hectare per year. Thereby, for studies that presented multiple fertilization or management variants, mean values for the studies were calculated. In contrast to that, for papers that presented the results of different study locations or crops, these values were used as single data points. Finally, 276 single values were considered appropriate. In order to account for the different species and harvest dates, the following crop categories were assigned for the data analysis: AECs, WSRC, PECs harvested in brown state, and PECs harvested in green state.

However, different species cannot be compared based on nutrient exports (kg ha^{-1}) in a judicious way as the biomass yield levels of a certain species vary in wide ranges depending on the conditions of the study site. Thus, in order to diminish this potential bias, nutrient export ratios were calculated by standardizing the nutrient export to the biomass yields. The more efficient a species, the higher is the ratio for a certain nutritional element.

$$E_i = \frac{\text{biomass yield}}{\text{export of element}_i},$$

where E_i is efficiency (subscript represents specific element: N, nitrogen; P, phosphorous; K, potassium; Ca, calcium; Mg, magnesium); biomass yield in kg dry matter ha^{-1}; export of element "*i*" in kg ha^{-1}.

The macronutrient exports of the crop categories were compared using a Kruskal–Wallis *H*-test followed by a Tukey-HSD post-hoc test. Furthermore, it was tested which categories of energy crops are similar or dissimilar concerning nutrient efficiency (E_i values). Therefore, a principal component analysis (PCA) was calculated incorporating E_N, E_P, E_K, E_{Ca}, and E_{Mg} in order to reduce the dimensions. The PCA was then overlapped with arrows showing the loadings of the efficiencies of single element on the PCA result.

The statistical analysis and data representation were done using R programming language version 3.3.2 (R Core Team, 2016).

3.2 | Results and discussion

The analysis of data from published studies concerning exports of macronutrients with yield biomass is presented in Figure 1a–e. The nutrient exports of PECs harvested in green state, with mean values of 133 kg ha^{-1} for N, 26 kg ha^{-1} for P, and 231 kg ha^{-1} for K, were close to the values of AECs (181, 32, and 174 kg ha^{-1} for N, P, and K, respectively) but were several times larger than that of PECs harvested in brown state (38, 11, and 81 kg ha^{-1} for N, P, and K, respectively) and WSRC (30, 5, and 18 kg ha^{-1} for N, P, and K, respectively). However, specific species of PECs harvested in green state, as, for example, the cup plant, even showed significantly higher exports than AECs for certain nutritional elements like K. For Ca and Mg, the same behaviour could be shown with very low exports for WSRC and PECs harvested in brown state, and significantly higher exports for PECs harvested in green state as well as for AECs. However, a closer look at the site conditions of the considered studies revealed that the Ca and Mg exports strongly correlated with soil pH values and were thus covering a wide range.

One reason for the low nutrient exports of WSRC and PECs harvested in brown state is presented by the reduced yield of these categories compared to PECs harvest in green state and AECs resulting from leave shedding (Kiesel et al., 2017; Mangold et al., 2019; Ruf et al., 2017). Moreover, processes of maturation lead to an internal and external recycling of nutritional elements; significantly reduced element concentrations in yield biomass after senescence of Miscanthus were, for example, described by Schwarz et al. (1994) and Ruf et al. (2017).

In order to cope with differences in yield, the nutrient efficiencies (E_i) of the crop categories were calculated. The result presented in Figure 2 shows that there is a clear grouping of nutrient efficiencies according to the crop categories. The size of the clusters also shows that the nutrient efficiencies of AECs are quite similar among different AEC species and studies, whereas the much larger clusters for PECs (harvested in brown and green state) and WSRC express a large magnitude of overall nutrient (N, P, K, Ca, and Mg) efficiencies. Nonetheless, a clear delimitation expresses distinct differences in overall nutrient efficiency based on the selected crop

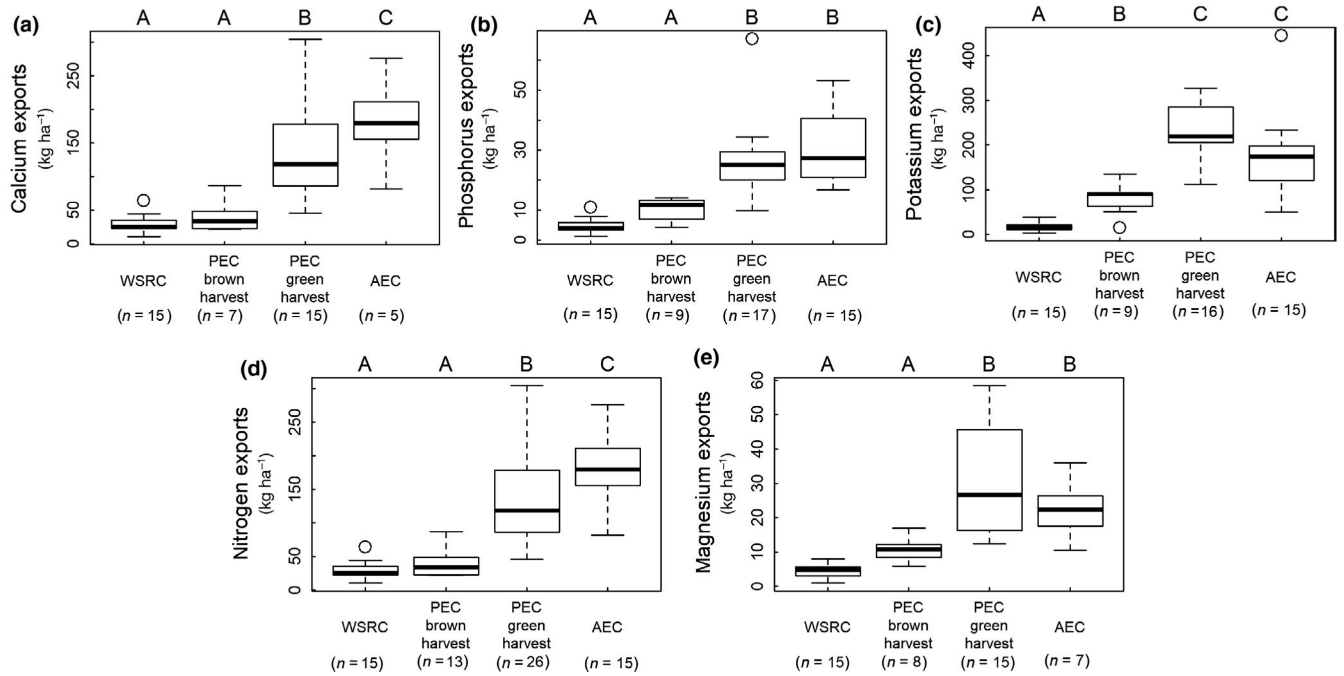

FIGURE 1 Exports (kg ha^{-1}) of nitrogen (a), phosphorous (b), potassium (c), calcium (d), and magnesium (e) for woody short rotation coppice (WSRC), perennial energy crops harvested in brown, mature state (PEC brown harvest), perennial energy crops harvested in green, premature state (PEC green harvest), and annual energy crops (AEC). The number of data points for the single elements and crop categories is indicated below the group name. Significant differences ($p < 0.05$) among crop categories are indicated by different letters, values defined as outliers are displayed as circles

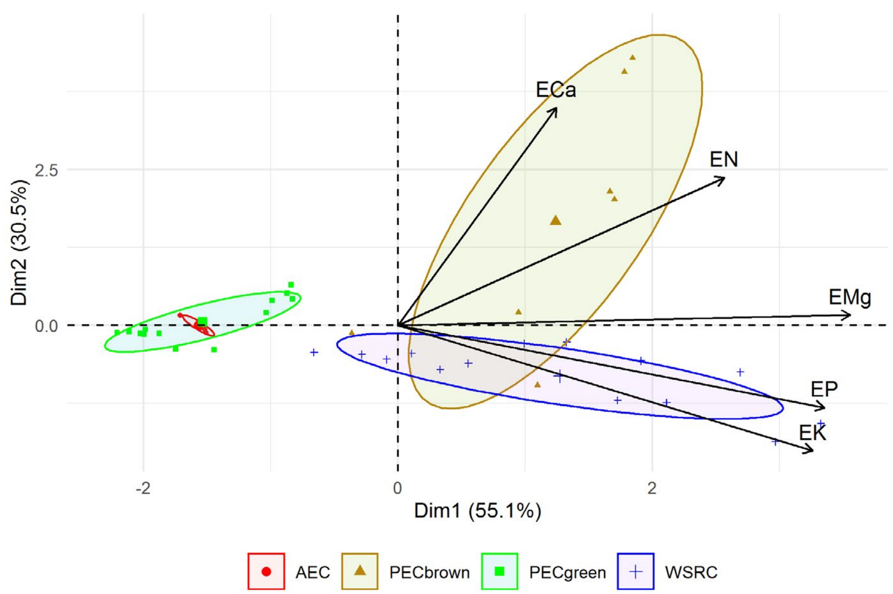

FIGURE 2 Principal component analysis using the nutrient efficiencies (nitrogen [E_N], phosphorous [E_P], potassium [E_K], calcium [E_{Ca}], and magnesium [E_{Mg}]) of the different categories of crops as input variables. Strength of loadings of the variables is presented by the length of the arrows

categories. Thereby, the arrows indicate a much better overall nutrient efficiency for WSRC and PECs harvested in a brown state compared to AECs and PECs harvested in a green state. The enclosure of AECs in the cluster of PECs harvested in green state further indicates (i) no significant difference between both crop categories and (ii) that some studies even state lower nutrient efficiency for PECs harvested in a green state. Although the data used do not present a comprehensive meta-analysis of nutrient efficiency and exports, the clear separation of the clusters according to different categories of energy crops and harvest dates impressively shows the significant differences among different crop categories.

By comparing the nitrogen export values presented in Figure 1a with diffuse atmospheric deposition, it can be assumed that the nitrogen exports of PECs harvested in a brown state and WSRC are largely compensated by this process. Stevens et al. (2004) stated a typical range of 5–35 kg N ha^{-1} $year^{-1}$, with a mean value of 17 kg N ha^{-1} $year^{-1}$, for atmospheric

N-deposition in populated regions. In clear contrast to that, the nitrogen exports of PECs harvested in green state (Figure 1a) are three to five times higher than the diffuse atmospheric N-deposition rates given by Stevens et al. (2004) and Stevens et al. (2015). These data provide an argument that PECs, when harvested in a green state, are not that undemanding concerning fertilization and related management efforts, and should no longer be classified as low-input energy crops. Quite the contrary, a compensation fertilization based on the site-specific nutrient export rates is urgent in order to (i) stabilize yield levels (ii) avoid a degradation of the soil fertility on the long term, and (iii) to facilitate the realization of one of the main projected benefits of PECs: carbon sequestration in soil. As stated by Ye and Hall (2020), unfertilized PECs bear the risk of depleting soil organic matter caused by microbial nitrogen mining from soil organic matter due to the limitation of mineral nitrogen in soil. In conclusion, the definition of the requirements of PECs needs to be strongly linked to utilization pathways and harvest dates.

4 | PERENNIAL ENERGY CROPS ON MARGINAL LAND: A SUSTAINABLE SOLUTION?

Several scientific articles of the last two decades proposed using marginal lands for cultivation of bioenergy crops (e.g., Fahd, Fiorentino, et al., 2012; Fahd, Mellino, et al., 2012; Feng et al., 2017; Gelfand et al., 2013; Liu et al., 2017; Valentine et al., 2012; Wagner et al., 2019). For this reason, the authors commonly state a reduced competition for high value arable land, thereby diminishing the rivalry between food, feed, and fuel. Currently unused, set-aside land may also provide additional land potentials for arable use (Baxter & Calvert, 2017). However, Richards et al. (2014) pointed out that the term marginal land is "often used in a subjective sense for less-than-ideal lands." Moreover, they highlighted that land attributed to be marginal varies in a spatiotemporal manner depending on the value of the soils in the surrounding landscape in combination with the concurrent agro-economic situation.

4.1 | Marginality of land depends upon definition

Traditionally, land is defined to be marginal if it has a low value for agriculture due to various reasons, such as low soil quality caused by unfavorable soil pH values, shallowness, pollution, poor or excessive water supply, challenging terrain profile, or disadvantageous climatic conditions (Boe et al., 2009; Fahd, Fiorentino, et al., 2012; Fahd, Mellino, et al., 2012; Gutierrez & Ponti, 2009; Jesus et al., 2010; Kang et al., 2013; McKenzie et al., 2011; Shortall, 2013). Shortall (2013) also deemed land that is "unsuitable for food production" as marginal land. Usually, yields from crop cultivation on marginal land are "meagre or precarious," and remuneration do not cover production costs on the long term (Peterson & Galbraith, 1932). Moreover, against the ongoing situation with significant losses of biodiversity in landscape due to agricultural intensification (Matson et al., 1997), it appears indicated to add an ecologically reasoned definition of marginal land. A number of lands may be classified to be marginal in providing ecosystem services due to the enlargement of farm sizes, specialization in agricultural production, as well as pervasive and extensive use of agrochemicals. As a consequence, these lands are poor in habitats and biodiversity, suffer regulative ecosystem services, and show low resistance and resilience against disturbances, for example, induced by signs of climate change.

4.2 | Limitations of perennial energy crop cultivation on marginal land

The basic underlying assumption for recommending PECs to be cultivated on marginal land has been their undemanding nature concerning management efforts (McLaughlin & Walsh, 1998; Shepherd et al., 2020; Tilman et al., 2006). However, as described in Section 3.2 and shown in Figures 1 and 2, this fundamental assumption is only true for WSRC and those PECs that are harvested in brown state. In contrast to that, PECs harvested in green state show similar nutrient exports than AECs, however still associated with lower efforts for stand management. Nonetheless, as presented by recent research, established stands of PECs show intense and deep-reaching rooting system and have a high ability to mine nutrients and prevent them from leaching (Grunwald et al., 2020), coincidently reducing amounts of nutrients to be replaced. Notwithstanding, based on this data analysis, PECs harvested in green state should not unconditionally be recommended for cultivation on marginal land in regard to combine both, economically viable feedstock production and sustaining or even increasing soil fertility. In fact, the reasons for marginality have to be taken into account.

Land that is defined to be marginal due to soil pollution like brownfields was also mentioned to be suitable for bioenergy cultivation (Lord, 2015; Rodrigues et al., 2019; Smith et al., 2013). In this case, the cultivation of PECs harvested in green state is impeded by the further utilization pathway. In contrast to PECs harvested in brown state, PECs harvested in green state are usually used as feedstock for biomethanation purposes. Unfortunately, due to the described high biotransfer and accumulation factors, for example, of heavy metals from soil to plant (Chojnacka et al., 2005; Jiang et al., 2015; Wang et al., 2020), the enzymatic-mediated process of anaerobic digestion may be impeded due to the cytotoxic effects of elevated heavy metal concentrations (Mudhoo & Kumar, 2013). Moreover, these elements would highly accumulate in the digestates excluding their application in agriculture as fertilizers in order to close nutrient cycles. In contrast to that, PECs harvested in brown state usually serve as commodity for combustion or, in future, in the commercial production of fuels following biomass-to-liquid processes. Hereby, an enrichment of the pollutants in the ash comes along with a distinct mass reduction. Several recovery processes have been developed to (i) disarm the ashes and (ii) use them as a secondary resource to mine elements from (Mondal et al., 2019; Quina et al., 2018; Sahoo et al., 2016).

With a focus on land that is marginal due to its topography, its size, shape, slope, the spatial location relative to the site of feedstock use, or, as introduced above the diversity in agricultural landscape, all PECs, regardless the specific species or harvest regime, may provide a couple of species-specific benefits compared to AECs. On sites, for example, prone for soil erosion or soil compaction all PECs have potentials to strengthen soil resilience, thus making bioenergy cropping more environmental friendly due to achievable reduction in erosion rates, risk for soil compaction, and nutrient losses, as summarized by Blanco-Canqui (2010). Moreover, particularly perennial forbs such as cup plant, giant knotweed, or Jerusalem artichoke may contribute to more ecologically viable bioenergy cultivation. Several studies have proven their value for biodiversity in agricultural landscapes (Dauber et al., 2010; Haughton et al., 2016; Immerzeel et al., 2014). Although all PECs provide habitats for birds and mammals, the flowering aspect of the forbs presents a valuable food source for insects, in otherwise inferior, extensively managed agricultural landscapes (Schorpp et al., 2016; Stanley & Stout, 2013). Indeed, the fields and PECs mentioned in this section appear to be predestined for fulfillment of the regulations of European Unions' strategy for (i) diversification of cultivated crops and (ii) dictated 5% share of ecological focus areas (EFA) per agricultural farm (European Union, 2017; amendment PE-CONS 56/17 to EU Regulation No. 1307/2013).

5 | CONCLUSION

Although PECs are cultivated since three decades for exploitation, a significant separation of utilization pathways could only be observed in recent years. Accompanying, premature harvest dates of "traditional" PECs like Miscanthus as well as "new" crops (forbs) to be harvested in green state were introduced. It has to be concluded that both have made the spectrum of uses more flexible. Particularly, the anaerobic digestion of feedstocks is an important interim technology in energy transition strategy. It allows the beneficial production of biomethane as a versatile, high caloric energy carrier that can easily be stored and flexibly be used, thus timely meeting energy demands of the public grids.

However, harvesting perennial crops in green, immature state involved higher management efforts regarding external inputs, particularly concerning the issues of fertilization and weed control. Significantly lower leaf shedding of forbs, including prematurely harvested Miscanthus (Ruf et al., 2017), reduces the potential for intrinsic weed suppression leading to higher demands for mechanical or chemical weed control. Moreover, considering the presented nutrient exports for the yield biomass of PECs harvested in green state, the term "low-input energy crop" appears no longer appropriate as they take an intermediate position between AECs and "traditional PECs" like Miscanthus (harvest in brown, mature state) or WSRC. The characteristic of PECs harvested in green state as "medium-input energy crops" appears more suitable.

Hence, it seems only reasonable that an appropriate specification and modernization of the term "perennial energy crop," its definition and their characteristics are required. Based on the data shown and arguments stated, the specification should be oriented toward the vegetative state of the crops when harvested. Thus, it is proposed to add "green harvest" or "brown harvest" when using the term PEC, maybe abbreviated as "PEC_{GH}" or "PEC_{BH}." The reader would then be able to immediately apprehend the cropping system, general feedstock parameters and implications for soil and the environment.

The highlighted differences between PEC_{GH} and PEC_{BH} are also not considered in the national application of the CAP regulations for ecological focus areas. For example in Germany, a herbicide application is only allowed in the year of establishment and mineral fertilization is generally prohibited for Miscanthus and cup plant, regardless the conducted harvest regime (European Union, 2017; amendment PE-CONS 56/17 to EU Regulation No. 1307/2013; DirektZahlDurchfV, 2019: §§32b and 32c). Thus, for a sustainable management of PEC_{GH}, the need for rectifications should be analyzed.

Moreover, the context of this study also revealed, in agreement with the statements of Richards et al. (2014) that the term "marginal land" has to be handled more precise by explicitly stating the factor(s) for marginality. Recapitulating, with respect to elevated requirements for stand management and nutrient export compensation, PEC_{GH} may not serve as a viable alternative for replacing Miscanthus harvested in brown state or WSRC on marginal land characterized by low soil fertility, as they are not remarkably undemanding.

Nonetheless, all PECs, regardless the specific species or harvest regime, imply beneficial aspects compared to AECs. Particularly on sites that are not suitable for AEC cultivation in a sustainable manner, PECs may offer large potentials for combining environmental conservation issues and enhancement of ecosystem services in agricultural landscape while providing viable feedstocks.

In evaluating cropping systems, the overall effect should dominate over single aspects like input requirements. Higher nutrient exports associated with PEC_{GH} cropping for anaerobic digestion purposes do not present a serious problem and can be compensated by the application of digestates keeping the concept of a closed-loop management. However, the issue of adjusting management strategies needs to be considered for a sustainable PEC_{GH} cropping over the long term. Otherwise, soils may be degraded and PECs may not meet the expectations concerning yield quantity and quality as well as regarding their expected life-span. Holistic region and site-specific assessments are necessary to evaluate whether cropping of PEC_{GH} may presents an advisable solution in supporting energy transition strategies. In this context, the field of PEC_{GH} cropping bears a particular deficit in knowledge.

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DATA AVAILABILITY STATEMENT

Data derived from public domain resources.

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