OPINION

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 (Cater 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 hermaphrodit), 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 stimu-
late the scientific debate about introducing subcat-
gegories 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 re-
production 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 con-
siderable 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 fol-
lowing 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 assimil-
lates 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 (har-
vesting) 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, investi-
gated 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 pro-
cesses in forb species that are used as feedstock for anaerobic
digestion. However, the analysis of published data may pro-
vide insights and allows comparisons.

| 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.) | Miscanthus (Miscanthus spp.) | Cup plant (Silphium perfoliatum), | Maize (Zea mays) |
|                     | willow (Salix spp.)             | switchgrass (Panicum virgatum)   | Virginia mallow (Sida hermaphrodita), | rye (Secale cereale) |
|                     | elder (Alnus glutinosa)         | reed canarygrass (Phalaris arundinacea) | giant knotweed (Fallopia sachalinensis), | wheat (Triticum spp.) |
|                     |                                |                                  |                                  | rapseseed (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.
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 deposition.
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 a 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 PECGH 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 PECGH 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 PECGH may present an advisable solution in supporting energy transition strategies. In this context, the field of PECGH cropping bears a particular deficit in knowledge.

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DATA AVAILABILITY STATEMENT
Data derived from public domain resources.

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REFERENCES
Adler, P. R., Del Grosso, S. J., & Parton, W. J. (2007). Life-cycle assessment of the net greenhouse-gas flux for bioenergy cropping systems. Ecological Applications, 17, 675–691. https://doi.org/10.1890/05-2018
Agostini, F., Gregory, A. S., & Richter, G. M. (2015). Carbon sequestration by perennial energy crops: Is the jury still out? Bioenergy Research, 8(3), 1057–1080. https://doi.org/10.1007/s12155-014-9571-0
Allaby, M. (2015). A dictionary of ecology (5th ed.). Oxford University Press, 432 pp.
Baxter, R. E., & Calvert, K. E. (2017). Estimating available abandoned cropland in the United States: Possibilities for energy crop production. Annals of the American Association of Geographers, 107, 1162–1178. https://doi.org/10.1080/24694452.2017.1298985
Blanco-Canqui, H. (2010). Energy crops and their implications on soil and environment. Agronomy Journal, 102, 403–419. https://doi.org/10.2134/agronj2009.0333
Boe, A., Owens, V., Gonzalez-Hernandez, J., Stein, J., Lee, D. K., & Koo, B. C. (2009). Morphology and biomass production of prairie cordgrass on marginal lands. Global Change Biology Bioenergy, 1, 240–250. https://doi.org/10.1111/j.1757-1707.2009.00108.x
Cadoux, S., Ferchaud, F., Demay, C., Boizard, H., Machet, J.-M., Fourdinier, E., Preudhomme, M., Chabbert, B., Gosse, G., & Mary, B. (2014). Implications of productivity and nutrient requirements on greenhouse gas balance of annual and perennial bioenergy crops. Global Change Biology Bioenergy, 6, 425–438. https://doi.org/10.1111/gcbb.12065
Cater, M., Zorec, M., & Logar, R. M. (2014). Methods for improving anaerobic lignocellulosic substrates degradation for enhanced biogas production. Springer Science Reviews, 2, 51–61. https://doi.org/10.1007/s40362-014-0019-x
Chapin, F. S., Schulze, E.-D., & Mooney, H. A. (1990). The ecology and economics of storage in plants. Annual Review of Ecology and Systematics, 21, 423–447. https://doi.org/10.1146/annurev.es.21.110190.002231
Chojnacka, K., Chojnacka, A., Görecka, H., & Görecki, H. (2005). Bioavailability of heavy metals from polluted soils to plants. Science of the Total Environment, 337, 175–182. https://doi.org/10.1016/j.scitotenv.2004.06.009
Clifton-Brown, J. C., Lewandowski, I., Andersson, B., Basch, G., Christian, D. G., Bondrup Kjeldsen, J., Jorgensen, U., Mortensen, J. V., Riche, A. B., Schwarz, K.-U., Tayebi, K., & Teixera, F. (2001). Performance of 15 Miscanthus genotypes at five sites in Europe. Agronomy Journal, 93, 1013–1019. https://doi.org/10.2134/agronj2001.9351013x
da Costa Sousa, L., Chundawat, S. P. S., Balan, V., & Dale, B. E. (2009). ‘Cradle-to-grave’ assessment of existing lignocellulose pretreatment technologies. Current Opinion in Biotechnology, 20, 339–347. https://doi.org/10.1016/j.copbio.2009.05.003
Dauber, J., Jones, M. B., & Stout, J. C. (2010). The impact of biomass crop cultivation on temperate biodiversity. Global Change Biology Bioenergy, 2, 289–309. https://doi.org/10.1111/j.1757-1707.2010.01058.x
DirektZahlDurchfV. (2019). Verordnung zur Durchführung der Direktzahlungen an Inhaber landwirtschaftlicher Betriebe im Rahmen von Stützungsregelungen der Gemeinsamen Agrarpolitik (National Regulation for direct payments on agricultural holdings in the framework of the common agricultural policy). Direktzahlungen-Durchführungsverordnung vom 3. November 2014 (BGBl. I S. 1690), die zuletzt durch Artikel 1 der Verordnung vom 24. September 2019 (BAnz AT 27.09.2019 V1) geändert worden ist.
Don, A., Osborne, B., Hastings, A., Skiba, U., Carter, M. S., Drewer, J., Flessa, H., Freibauer, A., Hyvönen, N., Jones, M. B., Manigan, G. J., Mander, Ü., Monti, A., Djomo, S. N., Valentine, J., Walter, K., Zegada-Lizarazu, W., & Zonone, T. (2012). Land-use change to bioenergy production in Europe: implications for the greenhouse gas balance and soil carbon. Global Change Biology Bioenergy, 4, 372–391. https://doi.org/10.1111/j.1757-1707.2011.01116.x
Dufour, N., Swana, J., & Rao, R. P. (2011). Fermentation organisms for 5- and 6-carbon sugars. In E. E. Hood, P. Nelson, & R. Rowell (Eds.), Plant biomass conversion (pp. 157–198). Wiley-Blackwell.
Ellenberg, H., & Mueller-Dombois, D. (1967). A dictionary of ecology. Berichte des Geobotanischen Institutes der ETH, 37, 56–73.
European Union. (2017). PE-CONS 56/17 amending EU Regulation No. 1307/2013: Establishing rules for direct payments to farmers under support schemes within the framework of the common agricultural policy. http://data.consilium.europa.eu/doc/document/PE-56-2017-INIT/en/pdf
Fahd, S., Fiorentino, G., Mellino, S., & Ugliati, S. (2012). Cropping bioenergy and biomaterials in marginal land: The added value of the
land. Proceedings of the 41st Agronomy Society of New Zealand Conference, Gisborne, New Zealand, 8–10 November 2011. Agronomy New Zealand 41, 97–107.

McLaughlin, S. B., & Walsh, M. E. (1998). Evaluating environmental consequences of producing herbaceous crops for bioenergy. *Biomass and Bioenergy*, 14, 317–324. https://doi.org/10.1016/s0961-9534(97)0066-6

Mohanty, A. K., Seydibezuglu, M. O., Sahoo, S., & Misra, M. (2011). Matching crops for selected bioproducts. *Comprehensive Biotechnology, 4*, 101–109. https://doi.org/10.1016/B978-0-08-088504-9.00259-2

Mondal, S., Ghar, A., Satpati, A. K., Sinharoy, P., Singh, D. K., Sharma, J. N., Sreenivas, T., & Kain, V. (2019). Recovery of rare earth elements from coal fly ash using TEHDGA impregnated resin. *Hydrometallurgy, 185*, 93–101. https://doi.org/10.1016/j.hydromet.2019.02.005

Mudhoo, A., & Kumar, S. (2013). Effects of heavy metals as stress factors on anaerobic digestion processes and biogas production from biomass. *International Journal of Environmental Science and Technology, 10*, 1383–1398. https://doi.org/10.1007/s13762-012-0167-y

Peterson, G. M., & Galbraith, J. (1932). The concept of marginal lands. *Journal of Farm Economics, 14*, 295–310. https://doi.org/10.2307/1230112

Ptasinski, K. J. (2016). Efficiency of biomass energy: an exergy approach to biofuels, power, and biorefineries. *Wiley, 756 pp.*

Pugesgaard, S., Schelde, K., Larsen, S. U., Laerke, P. E., & Jorgensen, U. (2015). Comparing annual and perennial crops for bioenergy production – Influence on nitrate leaching and energy balance. *Global Change Biology Bioenergy, 7*, 1136–1149. https://doi.org/10.1111/gcbb.12215

Purdy, S. J., Cunniff, J., Maddison, A. L., Jones, L. E., Barracough, T., Castle, M., Davey, C. L., Jones, C. M., Shield, I., Gallagher, J., Donnison, I., & Clifton-Brown, J. (2015). Seasonal carbohydrate dynamics and climatic regulation of senescence in the perennial grass, *Miscanthus*. *Bioenergy Research, 8*, 28–41. https://doi.org/10.1007/s12155-014-9500-2

Quina, M. J., Bontempi, E., Bogush, A., Schlumberger, S., Weibel, G., Braga, R., Funari, V., Hyks, J., Rasmussen, E., & Lederer, J. (2018). Technologies for the management of MSW incineration ashes from gas cleaning: New perspectives on recovery of secondary raw materials and circular economy. *Science of the Total Environment, 635*, 526–542. https://doi.org/10.1016/j.scitotenv.2018.04.150

R Core Team. (2016). *R: A language and environment for statistical computing*. R Foundation for Statistical Computing. https://www.R-project.org/

Raunkier, C. (1905). Types biologiques pour la géographie botanique. *Oversigt over Det Kongelige Danske Videnskabernes Selskabs Forhandlinger*, 347–438.

Raunkier, C. (1934). The life-forms of plants and their bearing on geography. In K. Gram, H. Molholm Hansen, O. Paulsen, J. Gronvad, & C. H. Ostenfeld (Eds.), *The life forms of plants and statistical plant geography* (pp. 2–104). Collected papers of C. Raunkier. Oxford at the Clarendon Press.

Richards, B. K., Stoof, C. R., Cary, I. J., & Woodbury, P. B. (2014). Reporting on marginal lands for bioenergy feedstock production: A modest proposal. *Bioenergy Research, 7*, 1060–1062. https://doi.org/10.1007/s12155-014-9408-x

Robson, P., Moss, M., Clifton-Brown, J., & Donnison, I. (2012). Phenotypic variation in senescence in *Miscanthus*: Towards optimising biomass quality and quantity. *Bioenergy Research, 5*, 95–105. https://doi.org/10.1007/s12155-011-9118-6

Rodrigues, J., Gérard, A., Séré, G., Morel, J.-L., Guimont, S., Simonnot, M.-O., & Pons, M.-N. (2019). Life cycle impacts of soil construction, an innovative approach to reclaim brownfields and produce nonedible biomass. *Journal of Cleaner Production, 211*, 36–43. https://doi.org/10.1016/j.jclepro.2018.11.152

Rowe, R. L., Street, N. R., & Taylor, G. (2009). Identifying potential environmental impacts of large-scale deployment of dedicated energy crops in the UK. *Renewable and Sustainable Energy Reviews, 13*, 271–290. https://doi.org/10.1016/j.rser.2007.07.008

Ruf, T. H., Schmidt, A., Delfosse, P., & Emmerling, C. (2017). Harvest date of *Miscanthus x giganteus* affects nutrient cycling, biomass development and soil quality. *Biomass and Bioenergy, 100*, 62–73. https://doi.org/10.1016/j.biombioe.2017.03.010

Sahoo, P. K., Kim, K., Powell, M. A., & Esqueenuddin, S. M. (2016). Recovery of metals and other beneficial products from coal fly ash: A sustainable approach for fly ash management. *International Journal of Coal Science and Technology, 3*, 267–283. https://doi.org/10.1007/s40789-016-0141-2

Schmidt, A., Lemaigre, S., Ruf, T., Delfosse, P., & Emmerling, C. (2018). *Miscanthus* as biogas feedstock: influence of harvest time and stand age on the biochemical methane potential (BMP) of two different growing seasons. *Biomass Conversion and Biorefinery, 8*, 245–254. https://doi.org/10.1007/s13399-017-0274-6

Schorpp, Q., Müller, A. L., Schrader, S., & Dauber, J. (2016). Agrarökologisches Potential der Durchwachsenen Silphie (*Silphium perfoliatum*) aus Sicht biologischer Vielfalt. *Journal für Kulturpflanzen*, 68, 412–422. https://doi.org/10.5073/jfk.2016.12.12

Schwarz, H., Liebhard, P., Ehrendorfer, K., & Rubenbauer, P. (1994). The effects of fertilization on yield and quality of *Miscanthus sinensis* ‘Giganteus’. *Industrial Crops and Products, 2*, 153–159. https://doi.org/10.1016/0926-6690(94)00031-0

Semere, T., & Slater, F. M. (2007a). Ground flora, small mammal and bird species diversity in miscanthus (*Miscanthus x giganteus*) and reed canary-grass (*Phalaris arundinacea*) fields. *Biomass and Bioenergy, 31*, 20–29. https://doi.org/10.1016/j.biombioe.2006.07.001

Semere, T., & Slater, F. M. (2007b). Invertebrate populations in miscanthus (*Miscanthus x giganteus*) and reed canary-grass (*Phalaris arundinacea*) fields. *Biomass and Bioenergy, 31*, 30–39. https://doi.org/10.1016/j.biombioe.2006.07.002

Shepherd, A., Littleton, E., Clifton-Brown, J., Martin, M., & Hastings, A. (2020). Projections of global and UK bioenergy potential from *Miscanthus x giganteus* – Feedstock yield, carbon cycling and electricity generation in the 21st century. *Global Change Biology Bioenergy, 12*, 287–305. https://doi.org/10.1111/gcbb.12671

Shortall, O. K. (2013). “Marginal land” for energy crops: Exploring definitions and embedded assumptions. *Energy Policy, 62*, 19–27. https://doi.org/10.1016/j.enpol.2013.07.048

Smith, S. L., Thelen, K. D., & MacDonald, S. J. (2013). Yield and quality analyses of bioenergy crops grown on a regulatory brownfield. *Biomass and Bioenergy, 49*, 123–130. https://doi.org/10.1016/j.biombioe.2012.12.017

Stanley, D. A., & Stout, J. C. (2013). Quantifying the impacts of bioenergy crops on pollinating insect abundance and diversity: A field-scale evaluation reveals taxon-specific responses. *Journal of Applied Ecology, 50*, 335–344. https://doi.org/10.1111/1365-2664.12060

Stevens, C. J., Dise, N. B., Mountford, J. O., & Gowing, D. J. (2004). Impact of nitrogen deposition on the species richness of grassland. *Science, 303*, 1876–1879. https://doi.org/10.1126/science.1094678
DATA SOURCES

Amougou, N., Bertrand, I., Cadoux, S., & Recous, S. (2012). *Miscanthus x giganteus* leaf senescence, decomposition and C and N inputs to soil. *Global Change Biology Bioenergy*, 4, 698–707. https://doi.org/10.1111/j.1757-1707.2012.01992.x

Berthelot, A., Ranger, J., & Gelhaye, D. (2000). Nutrient uptake and immobilization in a short-rotation coppice stand of hybrid poplars in north-west France. *Forest Ecology and Management*, 128, 167–179. https://doi.org/10.1016/S0378-1173(99)00145-0

Beuch, S., Boelcke, B., & Belau, L. (2000). Effect of organic residues of *Miscanthus x giganteus* on the soil organic matter level of arable soils. *Journal of Agronomy and Crop Science*, 183, 111–119. https://doi.org/10.1046/j.1439-037x.2000.00367.x

Eder, J. (1998). *Mais*. In J. Frahm & M. Munzert (Eds.), *Pflanzliche Erzeugung. Band I: Grundlagen der Acker- und Pflanzenbau-Grundlagen des integrierten Landbaus. Produktionstechnik der Kulturpflanzen* (pp. 322–348).

Himken, M., Lammel, J., Neukirchen, D., Czyponika-Krause, U., & Ols, H. W. (1997). Cultivation of Miscanthus under West European conditions: Seasonal changes in dry matter production, nutrient uptake and remobilization. *Plant and Soil*, 189, 117–126.

Hytnén, J. (2018). Biomass, nutrient content and energy yield of short-rotation hybrid aspen (P. tremula x P. tremuloides) coppice. *Forest Ecology and Management*, 413, 21–31. https://doi.org/10.1016/j.foreco.2018.01.056

Jones, P., & Salter, A. (2013). Modelling the economics of farm-based anaerobic digestion in a UK whole-farm context. *Energy Policy*, 62, 215–225. https://doi.org/10.1016/j.enpol.2013.06.010

Kiesel, A., & Lewandowski, I. (2017). *Miscanthus* as biogas substrate – Cutting tolerance and potential for anaerobic digestion. *Global Change Biology Bioenergy*, 9, 153–167. https://doi.org/10.1111/gcbb.12330

Kryszwy-Gawrońska, E. (2012). The effect of industrial wastes and municipal sewage sludge compost on the quality of Virginia fanpetals (SIDA HERMAPHRODITA RUSBY) biomass Part 1. Macromolecules content and their uptake dynamics. *Polish Journal of Chemical Technology*, 14, 9–15. https://doi.org/10.2478/v10026-012-0078-1

KTBL. (2012). *Energiepflanzen. Daten für die Planung des Energiepflanzenanbaus. Kuratorium für Technik und Bauwesen in der Landwirtschaft* (p. 2). Auflage.

Lunenberg, T., & Hartmann, A. (2016). Nährstoffentzüge von Durchwachsener Silphie in Bayern (Nutrient uptake by cup plant in Bavaria). *Journal Für Kulturpflanzen*, 68, 389–391. https://doi.org/10.5073/JfK.2016.12.08

Möller, K., Schulz, R., & Müller, T. (2010). Substrate inputs, nutrient flows and nitrogen loss of two centralized biogas plants in southern Germany. *Nutrient Cycling in Agroecosystems*, 87, 307–325. https://doi.org/10.1007/s10705-009-9340-1

Pichard, G. (2012). Management, production, and nutritional characteristics of cup-plant (*Silphium perfoliatum*) in temperate climates of southern Chile. *Ciencia e Investigación Agraria*, 39, 61–77.

Rincón, B., Banks, C. J., & Heaven, S. (2010). Biochemical methane potential of winter wheat (*Triticum aestivum* L.): Influence of growth stage and storage practice. *Bioresource Technology*, 101, 8179–8184. https://doi.org/10.1016/j.biortech.2010.06.039

Ruf, T. H., & Emmerling, C. (in preparation). Contrasting biomass partitioning and nutrient recycling in silage maize (*Zea mays*) and cup plant (*Silphium perfoliatum*).

Ruf, T. H., Schmidt, A., Delfosse, P., & Emmerling, C. (2017). Harvest date of *Miscanthus x giganteus* affects nutrient cycling, biomass development and soil quality. *Biomass and Bioenergy*, 100, 62–73. https://doi.org/10.1016/j.biombioe.2017.03.010

Schwarz, H., Liebhard, P., Ehrendorfer, K., & Ruckenbauer, P. (1994). The effects of fertilization on yield and quality of *Miscanthus sinensis* ‘Giganteus’. *Industrial Crops and Products*, 2, 153–159. https://doi.org/10.1016/0926-6690(94)90031-0
Šiaudinis, G., Jasinskas, A., Šarauskis, E., Steponavičius, D., Karčiauskienė, D., & Liaudanskienė, I. (2015). The assessment of Virginia mallow (Sida hermaphrodita Rusby) and cup plant (Silphium perfoliatum L.) productivity, physico-mechanical properties and energy expenses. *Energy, 92*, 606–612. https://doi.org/10.1016/j.energy.2015.09.065

Sokolov, V., & Gritsak, Z. (1972). *Silphium*: A valuable fodder and nectariferous crop. *World Crops, 24*, 299–301.

Stolzenburg, K., Bruns, H., Monkos, A., Ott, J., & Schickler, J. (2016). Produktion von Kosubstraten für die Biogasanlage. Ergebnisse und Versuche mit Durchwachsener Silphie (Silphium perfoliatum L.) in Baden Württemberg. Informationen für die Pflanzenproduktion 04-2016. Landwirtschaftliches Technologiezentrum Augustenberg (Hrsg.).

Ust’ak, S. (2008). Anbau und Verwertungsmöglichkeiten von Sida hermaphrodita in der Tschechischen Republik (Cultivation and use of Virginia fanpetals in conditions of the Czech Republic). Praxisempfehlungen. Forschungsinstitut für Ackerbau, Prag ISBN 978-80-87011-74-4.

von Gehren, P., Gansberger, M., Pichler, W., Weigl, M., Feldmeier, S., Wopienka, E., & Bochmann, G. (2019). A practical field trial to assess the potential of *Sida hermaphrodita* as a versatile, perennial bioenergy crop for Central Europe. *Biomass and Bioenergy, 122*, 99–108. https://doi.org/10.1016/j.biombioe.2019.01.004

Walter, D. (2016). Nutrient Dynamics within a Short Rotation Woody Coppice Biofuel Production System in Southern Ontario, Canada. Master Thesis, University of Guelph, Ontario, Canada. 123 pp. https://atrium.lib.uoguelph.ca/xmlui/bitstream/handle/10214/10149/walter_deanna_201612_msc.pdf?sequence=3&isAllowed=y

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