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Soil quality indicator response to land-use change from annual to perennial bioenergy cropping systems in Germany

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Abstract

Production of biomass feedstock for methanation in Europe has focused on silages of maize and cereals. As ecological awareness has increased in the last several years, more attention is being focused on perennial energy crops (PECs). Studies of specific PECs have shown that their cultivation may enhance agrobiodiversity and increase soil organic carbon stocks while simultaneously providing valuable feedstock for methanation. This study was designed to compare soil quality indicators under annual energy crops (AECs), PECs and permanent grassland (PGL) on the landscape level in south-western Germany. At a total 25 study sites, covering a wide range of parent materials, the cropping systems were found adjacent to each other. Stands were commercially managed, and PECs included different species such as the Cup Plant, Tall Wheatgrass, Giant Knotweed, *Miscanthus*, Virginia Mallow and Reed Canary Grass. Soil sampling was carried out for the upper 20 cm of soil. Several soil quality indicators, including soil organic carbon (C_{org}), soil microbial biomass (C_{mic}), and aggregate stability, showed that PECs were intermediate between AEC and PGL systems. At landscape level, mean C_{org} content for (on average) 6.1-year-old stands of PEC was 22.37 ($\pm$7.53) g kg^{-1}, compared to 19.23 ($\pm$8.08) and 32.08 ($\pm$10.11) for AEC and PGL. C_{mic} contents were higher in PECs (356 $\pm$ 241 μg C g^{-1}) compared to AECs (291 $\pm$ 145) but significantly lower than under PGL (753 $\pm$ 417). The aggregate stability increased by almost 65% in PECs compared to AEC but was still 57% lower than in PGL. Indicator differences among cropping systems were more pronounced when inherent differences in the parent material were accounted for in the comparisons. Overall, these results suggest that the cultivation of PECs has positive effects on soil quality indicators. Thus, PECs may offer potential to make the production of biomass feedstock more sustainable.

Keywords: aggregate stability, annual energy crops, land-use change, land-use intensity, microbial biomass, perennial energy crops, permanent grassland, soil organic carbon, soil quality indicators

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Introduction

The cropping of biomass for methanation has shown enormous growth as a substitute for fossil energy sources and as a source of renewable energy with less of an environmental impact (Bowyer & Kretschmer, 2011; Alexander *et al*., 2015; FNR, 2016). Although silage maize (*Zea mays*) and whole plant silage of cereals have been the dominant feedstocks in agricultural biogas plants in Germany (Weiland, 2003), a growing interest in alternative, perennial energy crops, such as the Cup Plant (*Silphium perfoliatum*), Tall Wheatgrass (*Agropyron elongatum*) or Giant Knotweed (*Fallopia japonicum x bohemica*), can currently be observed in several countries, such as the United States and Germany (Jessup, 2009; FNR, 2016). This results from serious concerns about the susceptibility of conventionally managed silage maize stands in the depletion of soil organic matter and soil erosion, further reduction of agrobiodiversity and the loss of associated ecosystem services by exhaustive maize monocultures (Scopel *et al*., 2005; Moebius-Clune *et al*., 2008; Anderson-Teixeira *et al*., 2009; Blanco-Canqui, 2010; Don *et al*., 2012; Pedroli *et al*., 2013; Vogel *et al*., 2015). This issue is particularly striking in areas with high densities of biogas plants that often show close crop rotations (Wiehe *et al*., 2009). Greening measures of the Common Agricultural Policy (CAP) of the European Union have recently focused on the diversification of cultivated crops (EU Regulation No. 1307/2013). Moreover, national regulations for substrate use in biogas plants, particularly the

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limitation of the amount of maize as feedstock, were introduced into Germany's renewable energy legislation (EEG) in 2014 (Bundesgesetzblatt, 2016). These regulations have also induced a search for alternative feedstocks for methanation, particularly by 'energy farmers' with a low number of cultivated crops.

On the other hand, remuneration payments for electricity from methanation are decreasing significantly within the new legal regulations of Germanys' EEG, which came into force in 2017 (Bundesgesetzblatt, 2016). Thus, pressure on farmers to reduce the costs of feedstock provisioning will further increase. Lignocellulosic perennial energy crops (PECs) offer the potential for cost-effective cultivation in the long term due to intensely reduced management efforts. Compared to annual energy crops (AEC), such as maize or whole-crop silage of cereals, cultivation of PECs also requires lower external inputs such as fertilizers and pesticides (Boehmel *et al*., 2008; Felten *et al*., 2013; Gissén *et al*., 2014). (Boehmel *et al*., 2008; Felten *et al*., 2013; Gissén *et al*., 2014). From an energy point of view, several studies have shown that PECs provide methane yields per area that are approximately equal to those of maize (Mast *et al*., 2014; Mayer *et al*., 2014; Kiesel & Lewandowski, 2016). Moreover, the beneficial side effects on agrobiodiversity (Dauber *et al*., 2010; Rowe *et al*., 2011; Bourke *et al*., 2014; Schorpp & Schrader, 2016), potential for carbon sequestration (Felten & Emmerling, 2012; Chimento *et al*., 2016), reduction of risk for erosion and soil compaction (Lal, 2005), as well as nutrient leaching (Pugesgaard *et al*., 2015), have been demonstrated. Thus, cropping PECs seem to achieve multiple objectives: (i) production of cost-effective, viable feedstock for anaerobic digestion, (ii) fulfilment of agricultural policy regulations and (iii) selection of the most suitable crop for specific site conditions, thus (iv) clearly reducing the environmental footprint of agricultural biomass production and improving soil quality.

However, despite the apparent advantages of PECs, they represented only approximately 1% of all feedstock in agricultural biogas plants in Germany in 2015 (FNR, 2016). Nonetheless, it can be hypothesized that the beneficial economic and ecological aspects will lead to a continuing expansion of the cultivation area of PECs in the future.

To date, little is known about the implications of PEC cultivation on soil health. The findings are predominantly based on experimental stands and modelling approaches (Emmerling, 2014; Heděnec *et al*., 2014; Tiemann & Grandy, 2015; Carvalho *et al*., 2017). Thus, the outcomes of these experiments are discrete and transferability to locations with different environmental conditions or even their generalization seems to be critical. In addition to cultivated crops, the influences of edaphic and climatic variation as well as the individual 'human factor' in agricultural practise are likely to modify the effects of PEC cultivation on soil quality indicators. Commercially managed and used stands of several different but less well-known PECs that were established several years ago now permit the inclusion of such external variables that likely modify the overall evaluation of the PECs.

With this study, we investigated the effects of PEC cultivation on soil quality indicators at the landscape level and compared the results with AEC and permanent grassland (PGL), which were cultivated close to the study locations. The annual and perennial cropping systems were further subdivided into specific crops to figure out whether the factor 'cropping system' or 'crop' dominates the effects on soil quality indicators. The study sites were located at numerous locations in a low mountain area in south-western Germany covering a broad range of pedological and climatic conditions. For a final valuation of effects, we characterized and grouped the study locations based on geopedological criteria that also depict areas of different natural yield potential.

Materials and methods

Study area

The study was conducted at 25 locations in south-western Germany, in the Federal States of Rhineland-Palatinate and Saarland (Fig. 1). The study locations covered six distinct natural areas, primarily based on the geopedological situation and its geomorphology in the valleys of the Saar and Mosel rivers as well as on plateaus and elevated areas of the Eifel and Hunsrück low mountain ranges (Schneider, 1972; State Office for Environment, Water Management, and Trade Control Rhineland-Palatinate, 2010). Soil properties and related conditions for plant growth based on the parent material, plant available water capacity (PAWC) and score of land appraisal were comparable for some of the natural areas (Table 2). For reasons of interpretation of the results, a further assignment of natural areas with comparable pedo-climatic conditions was conducted:

- Sites of high natural yield potential:
  Study sites located in the valleys of the Moselle and Saar rivers.
- Sites of medium natural yield potential:
  Study sites located on the plateaus of limestone areas.
- Sites of low natural yield potential:
  Study sites located in the low mountain ranges.

Sampling design

Soil quality indicators were determined at 25 study sites. At these sites, samples were taken in stands of annual crops (AEC; $n = 44$), perennial crops (PEC; $n = 38$) and permanent

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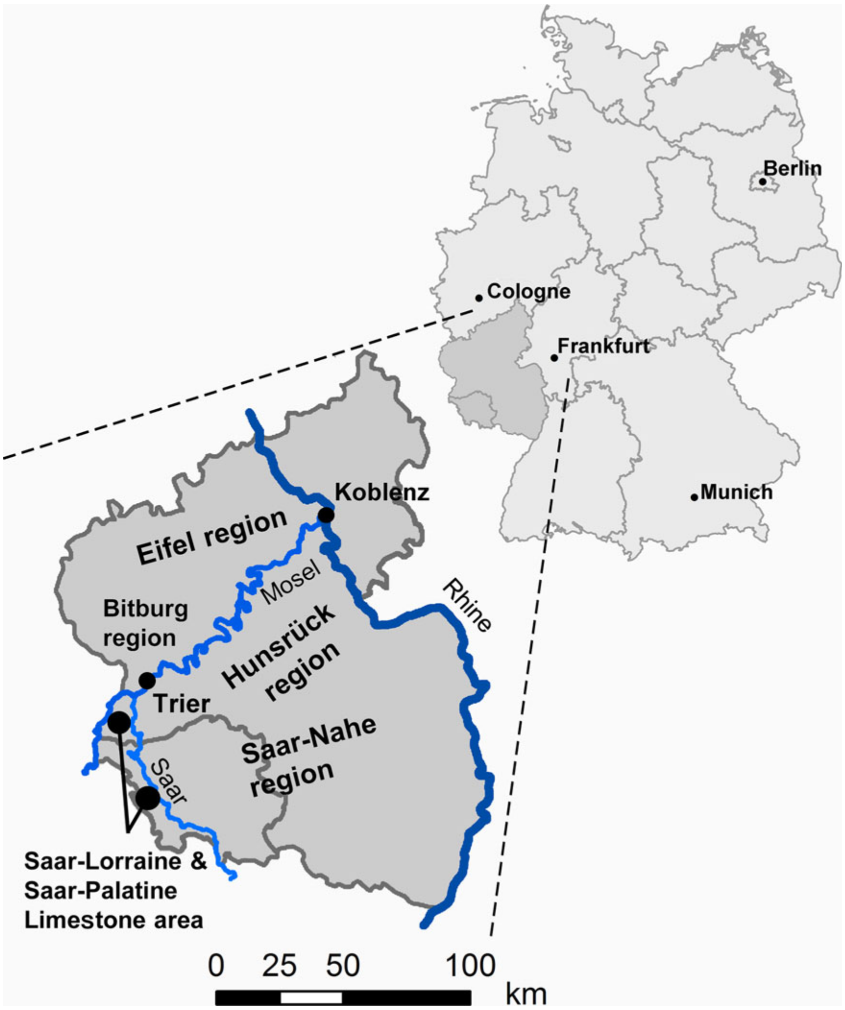

Fig. 1 Geographical survey map illustrating the study regions in Rhineland-Palatinate (light grey) and Saarland (darker grey) in the larger context of Germany. The spatial locations of the natural areas covered by the study are outlined. Author's own illustration based on a geographical map from OpenStreetMap (©OpenStreetMap Contributors) distributed under the Open Database License (ODbL) 1.0 (http://download.geofabrik.de/europe/germany.html; last accessed: 18.09.2017).

grassland (PGL; n = 25). At all study sites, the three cropping systems (AEC, PEC and PGL) were found in close proximity to each other, which allowed for a paired-site approach. At the study sites, the soil conditions were tested by field investigation and were comparable for the cropping systems.

- The group of AEC comprised cereals ('C'; n = 23) and maize ('M'; n = 21). The specific management of AEC varies slightly between farms. However, AEC stands were typically managed by more or less intense conventional tillage whereas cultivation of cover crops is still rather rare in the study region.
- The PECs consisted of Giant Knotweed ('GK'; *Fallopia japonicum x bohemica ‚Igniscum'*; n = 13), *Miscanthus* ('Mxg'; *Miscanthus x giganteus*; n = 8), Cup Plant ('CP'; *Silphium perfoliatum*; n = 5), Virginia Mallow ('VM'; *Sida hermaphrodita (L.) Rusby*; n = 2), Tall Wheatgrass ('TW'; *Agropyron elongatum ‚Szarvasi'*; n = 7), Reed Canary Grass ('RC'; *Phalaris arundinacea*; n = 2) and a wild flower mixture ('WFM'; composition of annual, biannual and perennial herbaceous plants; n = 1). All PEC stands included in this study were established on sites that were formerly used for the rotational cultivation of annual crops such as cereals, rapeseed and maize. At the time of the sampling, the stands of the PECs were between 1 and 35 years old ('time since transition') with a mean age of approximately 6 years (Table 1). Therefore, our data set also exhibits a gradient of stand ages of PECs.
- The PGLs have been managed at different intensities regarding fertilization and cutting regimes. Thus, site- and management-specific species composition of the PGLs has developed over the past several decades. Meadows used for cattle grazing were excluded.

Characterization of the study sites

Information about the geological situation at the study sites and the parent materials of soil formation was gathered from

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Table 1 Time since the transition from AEC to PEC cultivation, for all PEC stands covered by the study and subdivided into areas of similar yield potential

	n	Range Years	Mean
Total	38	1–35	6.1
High yield potential	8	1–24	8.8
Medium yield potential	9	1–23	4.1
Low yield potential	21	1–35	6.0

geological maps from the State Office for Geology Saarland (1975), Wagner *et al.* (1983) and the WMS-service of the State Office for Geology and Mining Rhineland-Palatinate (2016a). The obtained information was transferred to the current version of the international chronostratigraphic system (Cohen *et al.*, 2013).

The soil characteristics at the different study sites were determined by own Pürckhauer soundings. Soil descriptions were created with special respect to the soil type and texture as well as rootability. For the purposes of classification, the system of the WRB 2015 (FAO, 2015) was used. Supporting information about the soil conditions such as the score of land appraisal – which characterizes the natural yield potential of sites with relative numbers in a range from 7 (quite infertile) to 100 (highest feasible fertility in Germany) – field capacity, and PAWC of rootable layers was obtained from thematic soil maps. These maps, representing a derivation of thematic spatial information based on Germanys' land appraisal, were freely provided as WMS-features at a scale of 1 : 5000 in geological surveys (State Office for Environment and Occupational Safety Saarland, 2016; State Office for Geology and Mining Rhineland-Palatinate, 2016b).

Data of the climatic situation were based on annual grid data (grid size of 1 km²) provided by the German Meteorological Service (2016). Long-term mean values from 2000 to 2015 were calculated from annual data of the single years and grid cells using ESRI's ArcMap 10.2. The mean values were finally read from respective cells of the study site location.

Geology, soils and conditions for plant growth and natural yield potential

The study sites were characterized by distinctly different geological parent materials, soil characteristics and climatic situation. These environmental factors directly result in considerably different conditions for plant growth and natural yield potential. Consequently, this study covers a wide range of parent materials, resulting in different physical (texture, soil type, bulk density, rootability…) and chemical characteristics (pH values, CEC, buffer ranges …) of the soil. Moreover, our investigation covered a gradient of climatic conditions typical for low mountain ranges in Germany which lead to further modifications of the site conditions.

A summarizing and comparative presentation of parent materials, soil types, textures and natural yield potentials of the study sites is given in Table 2.

Climatic situation

Based on the geographic location in the landscape, climatic conditions at the study sites differed significantly. The mean annual temperatures at the study sites ranged from 8.6 °C on elevated levels of the Eastern Eifel region and the Hunsrück to above 10.5 °C in the Moselle and Saar valleys with their viticultural climates. Moreover, the vegetation periods were comparably shorter at the study sites located at higher altitudes. Governed by topographical locations, the amounts of precipitation also showed considerable variation. In the Mosel valley, leeward of the low mountain ranges of the Eifel region slightly <685 mm a^{-1} was observed, whereas on the plateaus of the Hunsrück and the Saar-Nahe region, the long-term mean precipitation approached 1000 mm a^{-1}.

Soil sampling

The soil sampling occurred during the spring of 2015. Soil samples for laboratory analysis were only taken from the topsoil at a depth of 0–20 cm. The sampling points were located at a transect intersecting the stands diagonally. On this virtual line, soil sampling was conducted every 10 to 20 m for a total of approximately 15 samples, depending on the size of the stand. From the sampled soil, one composite sample of each stand was prepared. Sampling was generally carried out using an auger (diameter: 35 mm) or, in cases where the stone content was high and auger drilling was not successful, with a spate.

The soil samples were divided up into two subsamples; the first subsample was sieved (2 mm mesh) for further chemical and biological analysis whereas the second subsample was kept untreated for a determination of aggregate stability.

Determination of soil chemical and physical parameters

The soil pH measurement was taken in a 10 mmol L^{-1} $CaCl_2$ solution using air-dried, sieved soil and a pH/Cond 340i glass electrode (WTW GmbH, Weilheim).

A subsample of the sieved soil was dried at 105 °C until a constant weight was reached. After pulverization using an agate mortar, the total carbon and nitrogen concentrations were simultaneously determined using an Elemental Analyzer EA3000 Series (HEKAtech GmbH, Wegberg). Soils exceeding pH values of 6.6 (in 10 mmol L^{-1} $CaCl_2$) were suspected of containing inorganic carbon. Thus, the inorganic carbon concentration was determined by carbonate destruction using phosphoric acid at elevated temperatures of 100 °C (IC Kit combined with Elemental Analyzer EA3000 Series, HEKAtech GmbH, Wegberg). The soil organic carbon content (C_{org}) was finally calculated as the difference between the total carbon (C_t) and the inorganic carbon (C_{inorg}).

Aggregate stability was measured using a modified method according to Kemper & Koch (1966) on a representative subset of samples (n = 30; 8 study sites). An unsieved, air-dried soil sample was first carefully sieved in 8-mm and 2-mm sieves, whereby all aggregates larger than 8 mm and smaller than 2 mm were discarded. Subsequently, the remaining aggregates were separated by dry sieving into 3 size fractions (2 to <3 mm, 3 to <5 mm and 5 to <8 mm), and the weights of the

Table 2 Characterization of study sites with respect to the parent materials, developed soils and conditions for plant growth with resulting yield potential

Natural area	No. of study sites	Yield potential	Parent material	Soils	Conditions for plant growth and yield potential
Valleys of the Mosel and Saar rivers	5	High	Quaternary sediments of the Moselle and Saar river	Well-grounded, fertile fluvic Cambisols, exceptionally showing stagnant properties. Sandy–silty loams with slightly acidic to neutral soil reaction in carbonate buffer range.	Excellent conditions for plant growth resulting from high PAWC, and favourable climatic conditions with long vegetation periods which express in land appraisal scores typically between 65 and 80.
Plateau of the Bitburg region	2	Medium	Calcareous sedimentary rocks and marls of Middle and Upper Trias, partly with small levels of loess	Silty-loamy medium-grounded stagnic Cambisols or Planosols in the carbonate buffer range. Medium soil skeleton content.	Fertile soils with high base saturation, neutral pH values and loamy texture. The yield potential is limited by the partially high stone content and shallowness of the soils which express in land appraisal scores in a range of 35–60.
Plateaus of the Saar-Lorraine resp. Saar-Palatinate Limestone area	5		Calcareous sedimentary rocks of Middle Trias partly with low levels of loess	Clay-dominated Rendzinas and Cambisols, partly stagnic Cambisols and Planosols in the carbonate buffer range. Dominantly shallow soils frequently found with a high level of coarse skeleton.	
Low mountain area of the Eastern Eifel region	5	Low	Devonian (schistose) clay and siltstones, partly with low levels of loess	Regosols and shallow Cambisols partially with stagnant properties. Typically sandy–silty loams in silicate buffer range with high contents of skeleton.	Conditions for plant growth and yield potential are rather unfavourable due to low PAWC, naturally low pH values resulting from base-poor parent materials, partially high stone content, and shallowness as well as the comparably short vegetation periods resulting from the location in the low mountain range. Land appraisal scores of 30–40.
Low mountain area of the Saar-Nahe region	3		Sand and claystones from the Permian and Lower Trias	Middle-grounded Cambisols of a loamy texture with partially high sand and clay content; generally poor in silt with a slightly to strongly acidic soil reaction in the silicate and exchanger buffer range.	
Low mountain area of the Hunsrück region	5		Schistose Devonian clay and siltstones, in parts with small levels of loess	Typically medium-grounded Cambisols, occasionally with slight stagnant properties. Textures are silty to clayey loams. Ordinarily in silicate buffer range.	

fractions were noted. After careful prewetting for 24 h with a water volume accounting for 20% of the aggregate weight, the aggregates were placed on the upper sieve of a sieve tower that consisted of one sieve each with 5-mm, 3-mm, 2-mm and 1-mm mesh. Wet sieving was taken by submerging the sample for 5 min at 35 stokes min^{-1} with stokes of 3 cm length, using an automatized apparatus. After that, the size fractions were again air-dried. The parameter calculated from the fractions before and after wet sieving was the change of the mean weight diameter of the fractions (ΔMWD). For these methodological reasons, lower values indicate higher aggregate stability.

The measurements of soil biological parameters were taken with sieved samples that have been adjusted to 40–60% of the maximum water holding capacity (WHC). WHC was determined for each sample as stored water using percolation tests in accordance with the procedure described by Alef & Nannipieri (1995). The current water content was determined by water loss during drying at 105 °C for 24 h. The samples for analysis were subsequently conditioned for

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10 days at 21 °C, allowing a gas exchange while preventing drying.

Microbial biomass carbon (C_{mic}) was determined by the chloroform fumigation extraction method as described by Vance *et al.* (1987). Measurement of the total organic C in the extracts was taken with a TOC-TN Analyzer (Shimadzu TOC-V+TNN). For the extraction, a 10 mmol L^{-1} $CaCl_2$ solution was used; for calculation of C_{mic}, a k_{EC} – coefficient of 0.45 was used (Joergensen, 1996).

Soil respiration measurements were conducted according to Heinemeyer *et al.* (1989). Therefore, 30 g dry equivalent moist soil adjusted to 40–60% of WHC was conditioned for 8 days, preventing water loss. Soil samples were weighted in a tube that was flushed with 200 mL min^{-1} of CO_2-free, humid air for two days. The formed CO_2 was measured after the soil passage using an infrared gas analyser (ADC 225 MK3, The Analytical Development, Hoddesdon, England).

Statistical analysis

A statistical analysis of the data was performed using the R language version 3.3.2 (R Core Team, 2016). Prior to testing for significant differences between cropping systems and crops, two-tailed Grubbs test in cases where $n > 10$ (Grubbs, 1950) or single-tailed Dixon test in cases where $n < 10$ (Dixon, 1950) were used to detect extreme values at a *P*-value of 0.01. Extreme values were further assessed for their plausibility to decide whether these values are outliers or part of the continuum.

The preconditions for further parametric testing, that is data distribution and variability using Shapiro–Wilk and Levene tests, were not adequately fulfilled in some cases; thus, testing for group differences was generally carried out using nonparametric Mann–Whitney U-tests and Kruskal–Wallis H-tests. Significant H-tests were followed by Nemenyi tests for group classification. The differences were described as significant in cases where $P < 0.05$; trends were reported for differences with *P*-values between 0.05 and 0.10. For an analysis of explaining variables for C_{org}, C_{mic} and aggregate stability, multiple linear regression models with numeric and categorical variables were generated. The cultivation system (AEC, PEC, PGL), pH value, C_{org}, C_{mic}, inorganic carbon, classified clay content (low: <20%, medium: 20–40%, high: >40%), yield potential, classified rooting depth (low: <0.50 m, medium: 0.50–1.00 m, high: >1.00 m), classified field capacity of rooting depth (low: <200 L m^{-2}, medium: 200–300 L m^{-2}, high: >300 L m^{-2}), mean annual precipitation (MAP) and mean annual temperature (MAT) were provided as possible independent variables. Thereby, the middle class of the categorical variables and permanent grassland (PGL) for cultivation system were always set as the base level in the regression models. For an objective selection of the most appropriate model fitting, a stepwise algorithm that evaluates model performance using the Akaike information criterion ('AIC', 'step' function in R) was used. Interaction terms between explaining variables were preliminarily checked but showed only minor influence for overall model performance; thus, they were not included in final regression models. Furthermore, the quality of regression models was visually evaluated by an analysis of the residuals concerning linearity, normality and symmetrical distribution around zero.

Local changes of C_{org} in PEC stands compared to those of AEC were correlated with duration of PEC cultivation. Therefore, the relative difference between C_{org} contents in PEC and adjacent AEC as a reference were calculated separately for all study sites; in cases where more than one AEC was sampled at a certain site (maize and cereals), the mean value of both was used as a reference.

Results

The chemical analysis revealed that the pH values were in a typical range for agricultural soils and varied between pH 4.1 and pH 7.4 with a mean value of 6.0 (Fig. 2a). The pH values showed distinct variations among agricultural landscapes as well as among different cultivation systems (Table 3). The pH values of stands under AEC cultivation appeared to be adjusted by management, whereas the soil pH values of PGL primarily reflected the characteristics of the parent materials of pedogenesis. Natural areas exhibiting high and medium yield potential had a typically neutral to slightly acid pH, whereas locations with low yield potential are characterized by pH values in the silicate buffer range of pH 5.5 (Table 3). Mean amounts of C_{org} showed distinct differences between cropping systems. Mean values (± standard deviation) on the landscape level were 19.23 (±8.08), 22.37 (±7.53) and 32.08 (±10.11) g kg^{-1} for AEC, PEC and PGL, respectively (Fig. 2b). Notwithstanding the large variability in the data, the soils of PGL showed significantly higher ($P < 0.001$) amounts of C_{org} in the whole study area. Soils under PEC cultivation showed only slightly higher C_{org} content than AECs ($P = 0.35$). This gradient could similarly be observed after subdividing the data set according to the yield potential of the study sites (Table 3). Remarkably, lowest C_{org} values of certain cropping systems were observed in soils of high yield potential. The amounts of C_{org} below PECs were fairly constant with approximately 22 g kg^{-1} in the whole study area. In contrast to that, for AEC and PGL, significant differences among areas of different yield potential could be observed. The amounts of total nitrogen (TN) strongly correlated with the amounts of C_{org} and ranged between 1.86 g kg^{-1} and nearly 3.20 g kg^{-1} with lowest values in stands of AEC and highest values in PGL. AEC and PEC significantly differed ($P < 0.001$) from PGL.

Resulting from that, the C to N ratio was typically approximately 10 and showed no clear trend, neither concerning the cultivation system nor the natural area. However, the C to N ratio was in trend highest at study sites with high yield potential. C to N ratios of soils cultivated with Giant Knotweed were approximately 9.5; *Miscanthus* and Tall Wheatgrass showed mean values of approximately 11.5 whereas C to N ratios exceeded 12 in soils cultivated with Cup Plant.

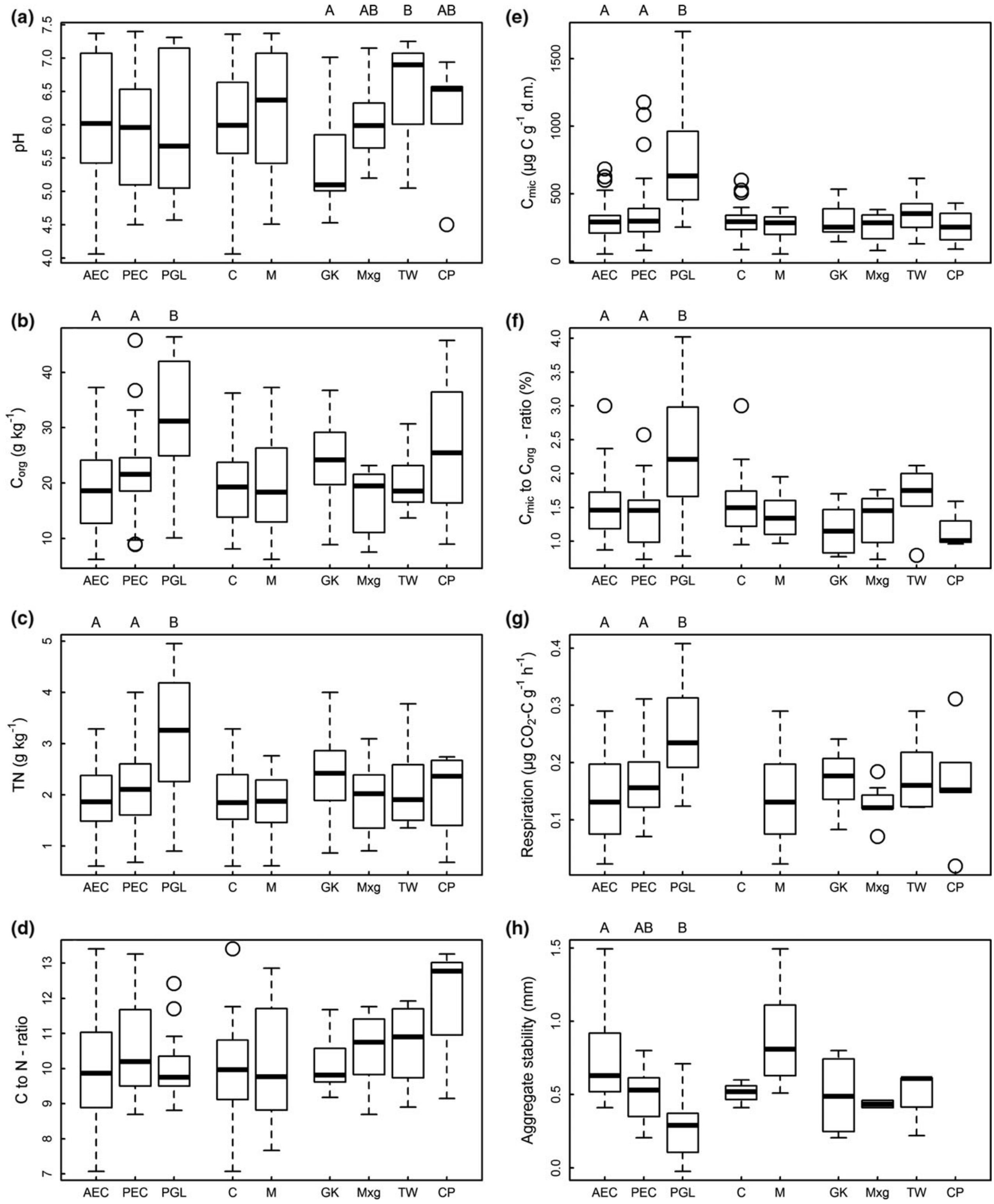

Fig. 2 Depiction of soil quality indicators on the landscape level. On the left hand, the crops grouped according to cultivation strategies (AEC, PEC, PGL) are shown. The results of crops forming the AEC (C and M) and PEC (GK, Mxg, TW, CP) groups are furthermore separately shown and statistically tested. Significant differences at the 5% level are indicated by different letters.

Table 3 Indicators of soil quality associated with different cultivation strategies (AEC, PEC, PGL) subdivided by areas of similar yield potential of the study sites. Significant differences ($P < 0.05$) between AEC, PEC and PGL according to the Nemenyi post hoc tests at study sites with a similar yield potential are indicated by different letters. The calculated *P*-values and the results of the Nemenyi post hoc tests for soil parameters depending on the yield potential of the study sites grouped by cultivation strategies are shown in the three right-hand columns

		High yield potential ('H')			Medium yield potential ('M')			Low yield potential ('L')					
		AEC	PEC	PGL	AEC	PEC	PGL	AEC	PEC	PGL	AEC	PEC	PGL
	n	8	8	4	12	9	8	24	21	13	44	38	25
pH	()	6.1 (±0.8)	6.2 (±0.7)	6.1 (±1.0)	6.8 (±0.8)	6.9 (±0.5)	7.2 (±0.1)	5.62 (±0.7)	5.5 (±0.7)	5.3 (±0.6)	*P* = 0.001 L, (H)<M,(H)	*P* < 0.001 L,(H)<M, (H)	*P* < 0.001 L,(H)<M, (H)
C_{org}	(g kg^{-1})	14.18 (±10.0)	22.78 (±15.48)	25.64 (±6.67)	21.84 (±8.36) A	22.13 (±13.89) A	40.71 (±5.40) B	18.89 (±5.84) A	22.41 (±3.71) A	32.07 (±7.35) B	*P* = 0.07 H, (L)<M,(L)	*P* = 0.55	*P* = 0.01 H,(L)<M, (L)
TN	(g kg^{-1})	0.99 (±0.23) A	2.03 (±0.99) B	2.23 (±0.24) B	2.18 (±0.40) A	2.07 (±0.59) A	3.88 (±0.87) B	1.96 (±0.64) A	2.28 (±0.49) A	3.09 (±1.09) B	*P* = 0.001 H<L,M	*P* = 0.53	*P* = 0.02 H, (L)<M,(L)
C to N ratio	()	11.0 (±3.7)	12.3 (±3.8)	12.1 (±2.8)	9.3 (±2.6)	11.3 (±1.3)	9.9 (±0.3)	9.9 (±1.4)	10.1 (±1.1)	10.0 (±1.1)	*P* = 0.98	*P* = 0.07 L<H,M	*P* = 0.17
C_{mic}	(μg C g^{-1} d.m.)	156.9 (±88.6) A	243.2 (±99.1) AB	477.9 (±133.1) B	468.1 (±160.8) A	586.8 (±376.5) A	1201.6 (±570.8) B	265.1 (±75.2) A	308.5 (±102.0) A	547.0 (±157.4) B	*P* < 0.001 L,H<M	*P* = 0.04 H, (L)<M,(L)	*P* = 0.02 L, H<M
C_{mic} to C_{org} ratio	(%)	1.21 (±0.36)	1.15 (±0.44)	2.02 (±1.02)	2.16 (±0.87) A	1.73 (±0.59) A	3.33 (±0.90) B	1.43 (±0.28) A	1.29 (±0.39) A	1.97 (±0.42) B	*P* = 0.004 L,H<M	*P* = 0.16	*P* = 0.03 L, H<M
Respiration	(μg CO_2-C g^{-1} d.m. h^{-1})	0.10 (±0.06) A	0.15 (±0.06) AB	0.21 (±0.03) B	0.16 (±0.05) A	0.22 (±0.08) AB	0.38 (±0.16) B	0.14 (±0.10) A	0.16 (±0.04) A	0.25 (±0.09) B	*P* = 0.45	*P* = 0.07 L,H<M	*P* = 0.05 L, H<M
Aggregate stability	(mm)	1.46 (±0.99) B	0.60 (±0.15) AB	0.27 (±0.05) A	0.65 (±0.26) B	0.41 (±0.29) AB	0.01 (±0.02) A	0.87 (±0.54)	0.44 (±0.20)	0.58 (±0.18)	*P* = 0.33	*P* = 0.52	*P* = 0.07 M, (H)<L,(H)

In contrast to that, C_{mic} of PGL was significantly higher than in PECs ($P < 0.001$) (Fig. 2e). In PGL, the mean C_{mic} content was slightly higher than 750 (± 417) μg C g^{-1} d.m. and thus more than twice as high as in AEC (291 ± 145 μg C g^{-1} d.m.) and PEC (356 ± 241 μg C g^{-1} d.m.). A gradient from AEC and PEC to a significantly higher PGL was observed on the landscape level as well as at sites of a similar yield potential. In general, C_{mic} showed distinct variations depending on site characteristics, particularly within the group of PECs. Some extreme values in the group of PECs were identified for C_{org} and C_{mic}. Similar to C_{mic}, the C_{mic} to C_{org} ratio showed large variation but was highest in PGL (2.31 ± 0.95%) and differed significantly ($P < 0.001$) from AEC (1.49 ± 0.45%) and PEC (1.36 ± 0.44%). Differences in the C_{mic} to C_{org} ratios between AECs and PECs within areas of comparable yield potential (Table 3) could not be statistically confirmed. The differences among the crops forming the groups of AEC and PEC could not be observed (Fig. 2f).

In PGL, soil respiration was generally highest with an average of 0.25 (± 0.08) μg CO_2-C g^{-1} d.m. h^{-1} (Fig. 2g). In all study regions, the respiration rates of PGL soils were significantly higher than under AEC and PEC, which themselves did not differ from each other (Table 3). Respiration rates in stands of AEC and PEC were quite similar for all study regions lying between 0.10 (± 0.06) and 0.16 (± 0.05) as well as 0.15 (±0.06) and 0.22 (±0.08) μg CO_2-C g^{-1} d.m. h^{-1}, respectively. In contrast, PGL soils showed distinct variations among study regions; respiration rates were nearly twice as high at sites with medium (0.38 ± 0.16) compared to sites with high and low yield potential.

Aggregate stability was significantly highest in PGL (0.28 ± 0.26 mm) and lowest in AEC (0.77 ± 0.35 mm). In stands of AEC, large variability and skewness towards low aggregate stability were observed (Fig. 2h). The aggregate stability of soils cultivated with PECs (0.49 ± 0.20 mm) took an intermediate position between AECs and PGL. Therefore, aggregate stability also exhibited a significant gradient from PGL via PEC to AEC. The aggregate stability under PGL was affected by areas of different yield potentials exhibiting a trend of higher stability in areas with medium rather than low yield potential.

Using a multiple linear regression analysis, the impact of the environmental factors and management practices on selected soil quality indicators could be assessed. In particular, AEC cultivation led to a trend ($P = 0.08$) of lower amounts of C_{org} compared to PGL as reference level whereas PEC cultivation had no significant influence (Table 4). Additionally, larger amounts of C_{org} were associated with higher clay content and both lower and higher potential rooting depth compared to the respective medium reference levels. A higher mean annual temperature (MAT) and amounts of inorganic carbon also showed a negative correlation with C_{org}. In total, 66% of the variability in C_{org} content was represented by the explaining variables (Table 4). C_{org} and C_{mic} were clearly intercorrelated. Thus, C_{org} positively influences C_{mic} and vice versa. C_{mic} was further positively correlated with inorganic carbon, whereas the pH value had only a slight positive effect (Table 5). AEC cultivation significantly reduced C_{mic} amounts to roughly the same degree as PEC compared to the reference PGL. The fitted model explained 71% of the variability in C_{mic}. Nearly 50% of the variability in aggregate stability could be explained by content of C_{org}, the cultivation strategies and the classified clay content (Table 6). Therefore, aggregate stability was significantly reduced ($P = 0.01$) in AEC soils, whereas aggregate stability was not significantly influenced ($P = 0.30$) by PEC cultivation compared to PGL as a reference. Compared to AEC cultivation, the effect of lower clay content on aggregate stability was of minor importance, despite the fact that they contributed to the model performance ($P = 0.06$).

The duration of PEC cultivation distinctly affected the local increase in C_{org} content compared to AECs (Fig. 2). Whereas the C_{org} content of the newly established stands of PEC showed large variation, soil cultivated with PECs for 3 to 10 years showed distinctly higher values compared to adjacent AEC stands. The older stands of PEC did not show a further increase in C_{org}. Despite the large variability and small number of samples, particularly of old stands, a continuous increase in amounts of C_{org} with stand age and a steady state level can carefully be concluded. The fitting of a logarithmic zgrowth function revealed a highly significant

Table 4 Multiple linear regression analysis for the determination of factors influencing the content of C_{org}. The overall model performance was $R^2_{(adj.)} = 0.66$ with a P-value of 2.2×10^{-16} (df = 86)

Explaining variables	Coefficients	*P*-values
Intercept	41.07	2.8×10^{-4}
C_{mic}	0.02	3.3×10^{-11}
MAT	−2.97	9.3×10^{-3}
Inorganic carbon	−2.37	1.4×10^{-3}
Cultivation system: AEC	−3.38	0.08°
Cultivation system: PEC	0.02	0.99
Classified clay content: high	3.25	0.05
Classified clay content: low	−1.96	0.33
Classified rooting depth: high	11.90	8.3×10^{-4}
Classified rooting depth: low	4.32	5.5×10^{-3}
Classified PAWC: high	4.29	0.01
Classified PAWC: low	0.00	1.00

Table 5 Multiple linear regression analysis for the determination of factors influencing the content of C_{mic}. The overall model performance was $R^2_{(adj.)}$ = 0.71 with a P-value of 2.2e-16 (df = 90)

Explaining Variables	Coefficients	P-values
Intercept	−45.32	0.77
pH	36.23	0.17
C_{org}	18.16	3.7×10^{-12}
Inorganic carbon	82.77	5.3×10^{-4}
Cultivation system: AEC	−228.78	7.5×10^{-5}
Cultivation system: PEC	−248.35	8.7×10^{-6}
Classified rooting depth: high	−259.05	8.4×10^{-3}
Classified rooting depth: low	−26.40	0.50

Table 6 Multiple linear regression analysis for the determination of factors influencing the content of aggregate stability. The overall model performance was $R^2_{(adj.)}$ = 0.47 with a P-value of 0.003 (df = 18)

Explaining Variables	Coefficients	P-values
Intercept	0.63	0.013
C_{org}	−0.01	0.05°
Cultivation system: AEC	0.34	0.03
Cultivation system: PEC	0.18	0.22
Classified clay content: Low	0.27	0.06°

(P = 0.005) influence of time since the transition to PEC with the content of C_{org}.

Discussion

Modification of soil quality by edaphic and cropping system-related factors

The findings of this study aiming to determine the effects of PEC cultivation on the landscape level depict a wide range in measured values of soil quality indicators that may be governed by covering several natural areas with considerably different geologic, pedologic and climatic conditions. Thus, the values are likely influenced by a combination of edaphic and cropping system-related factors. Indeed, with respect to the reduced variability (i) when grouping the data according to comparably homogeneous study regions (Table 3) and (ii) the significant loadings of edaphic factors (Tables 4–6), variation of soil quality indicators within specific cropping systems can be certainly traced back to the spatial distribution of sampling sites in the landscape. Earlier, Emmerling & Udelhoven (2002)also detected strong correlations of soil quality parameters with edaphic factors. Accounting for the variability by edaphic factors allowed for improved interpretability with respect to consequences of different energy crop cultivation systems on soil quality indicators (Table 3).

Our results showed, for example, that the mean C_{mic} content under AEC in areas exhibiting medium yield potential (468 ± 161 μg C g^{-1} d.m.) was quite similar to them under PGL in areas of high yield potential (478 ± 133 μg C g^{-1} d.m.). Additionally, the aggregate stability of soil under AEC at study sites with a medium yield potential (0.65 ± 0.26 mm) was quite similar to that of PGL in areas with low yield potential (0.58 ± 0.18 mm). Comparably low values of C_{mic} and aggregate stability under PGL in areas with low yield potential could reasonably be explained by their typically coarse texture, low base saturation and low WHC, which are genetically derived from siliceous, parent materials (Tables 2 and 3). Whalen & Sampedro (2010) stated that such soil conditions restrict the activity of soil organisms and stabilization of aggregates, particularly compared to soils that have developed from calcareous parent materials. Moreover, Tisdall & Oades (1982) noted that C_{org} strongly influences aggregate stability, which was also confirmed by the high loading of this factor in the regression model (Table 4). Some remarkably high values for C_{org} and C_{mic} in the group of PECs appeared plausible because they were associated with sites exhibiting high clay content and a long-established cultivation of PECs (Fig. 2b, e).

Effects of PEC cultivation on soil quality indicators at different spatial scales

For most of the soil quality indicators investigated, the lowest values were commonly found in soils under AEC and were highest in PGL, whereby PECs typically took an intermediate position between them (Fig. 2). It is worth highlighting that the ascending soil quality from AEC via PEC to PGL was observed on several spatial dimensions from the plot to landscape scale. However, the difference between AEC and PEC could not be statistically secured in most cases due to large variability in the groups. First, the mentioned gradient in soil quality was found at 22 of 25 study locations with adjacent stands of AEC, PEC and PGL. Second, based on areas with high, medium and low yield potential, we observed, for example, 60.6%, 1.3% and 18.6% higher C_{org} content in soils under PEC compared to AEC (Table 3). Third, at the landscape level, despite the interactions of edaphic and cropping system-related factors, C_{org} and C_{mic} values were 16.3% and 22.3% higher in PEC stands compared to AECs (Fig. 2b, e).

Notably, with respect to C_{org} development in soils under PEC cultivation, the results of this study resemble a recent meta-analysis. Harris *et al.* (2015) summarized 63 plot-size studies concerning land-use change to biomass cropping and the effects on C_{org} conducted. They revealed a significant increase in C_{org} by 25.7% due to a transition from arable land to perennial grasses, mainly *Miscanthus* and Switchgrass, with a mean time since transition of 5.4 years. In the framework of this study, we measured 16.3% higher C_{org} values at the landscape level in PEC stands with a mean age of 6.1 years.

Effects of cropping systems and crops on soil quality

From the intermediate position of PECs between AEC and PGL, it can be deduced that different cultivation systems significantly modify soil conditions (Table 3). In contrast to that, differences could not be observed in either the crops that compose the AEC or the PEC cultivation systems (Fig. 2). Differences between the cultivation systems within a certain region of comparable yield potential (Table 3) can thus reasonably be traced back to factors related to soil management, which are, aside from inherent soil properties, meaningful for soil quality (Burke *et al*., 1989; Karlen *et al*., 1997). However, within the framework of this study, we were not able to address the influences governed by the specific management intensity of AEC or PGL (e.g. fertilization, plant protection, tillage) cultivation. Although all PEC stands had been established on sites with former rotational cropping of annual crops, the history of the stands remains partly unknown. In particular, previously cultivated crops, tillage practices, soil preparation and amendments prior to planting PECs as well as weed control measured during the establishment phase could not be traced in most cases.

Management intensity

In general, the cultivation of PECs, compared to that of AEC, is characterized by distinctly reduced management efforts. Soil tillage is abandoned in PECs, similar to plant protection measures, which are typically only conducted to reduce weed pressure during the phase of crop establishment (Agostini *et al*., 2015; Gansberger *et al*., 2015). Generally, the intensity of the PEC cultivation systems is typically intermediate between AEC and PGL. Reduced soil tillage was found to distinctly enhance the general soil quality (Burke *et al*., 1989; Havlin *et al*., 1990). Amézketa (1999) stated that the stability of soil aggregate is sensitive to internal soil properties, such as texture and organic and inorganic stabilization agents, but particularly towards external factors such as tillage. Thus, significantly higher aggregate stability at certain study sites in PECs compared to adjacent AECs appeared appropriate to reflect the effects of the cultivation systems on the overall soil quality. At more than 80% of the study sites, aggregate stability was higher under PECs than under AECs but was still distinctly lower than under PGLs; on the landscape level, aggregate stability was 55.7% higher, particularly in areas with high yield potential. At these sampling sites, quite low aggregate stability under AEC accompanied low C_{org} content (Table 3), which may reflect the more intense soil tillage in these extensively cultivated regions.

Sources of organic C-input and degradability

Currently, investigations on the sources of organic substances in PEC stands that generate the potential for accumulation of C_{org} and enhanced soil quality indicators are pending for most PECs covered by this study. To our knowledge, the processes of C-input by PECs to soil as well as quantitative and qualitative contributions of plant fractions were extensively estimated for *Miscanthus* only (Neukirchen *et al*., 1999; Amougou *et al*., 2012; Ruf *et al*., 2017). However, it appears likely that important sources for C-inputs to soil in PECs are aboveground crop residues, the regular turnover of root biomass and root exudates (Tiemann & Grandy, 2015; Carvalho *et al*., 2017).

Accrual and recycling of aboveground plant residues

Usually, PECs show slow aboveground biomass development and, consequently, residue accrual during the phase of establishment (Anderson-Teixeira *et al*., 2013; Gansberger *et al*., 2015). After establishment, PECs may generate large amounts of aboveground C-inputs. Investigations in established *Miscanthus* stands revealed that 5 to 6 Mg d.m. ha^{-1} yr^{-1} of abscised leaves and approximately 2 Mg d.m. ha^{-1} yr^{-1} of stubbles remain in the stands serving as a huge resource of organic residue (Kahle *et al*., 2001; Lewandowski & Heinz, 2003; Ruf *et al*., 2017). However, the amounts of aboveground organic inputs in *Miscanthus* stands should be considered to represent an upper limit. Although comprehensive data are missing, it seems realistic that herbaceous PECs show significantly lower aboveground C-inputs than grasses. Hedĕnec *et al*. (2014, p. 143) observed that *Helianthus tuberosus*, *Reynoutria sachalinensis* and *Silphium perfoliatum* 'did not produce much litter, so there was mostly bare soil between plants', which coincides with our field observations. We observed an occurrence of preharvest losses by herbaceous PECs towards the end of the vegetation period. The leaf shedding probably resulted from drought stress, low light intensities after canopy closure and redistribution processes during senescence (Neukirchen *et al*., 1999; Amougou *et al*., 2012; Ruf *et al*., 2017). Thus, the influence of harvest dates on amounts of preharvest losses becomes obvious. In agricultural practice, the harvest dates of PECs were selected to obtain optimal methane yields per area. In general, the reduced digestibility of PECs and the biomass yield decline during senescence are caused by progressive lignification and preharvest losses (Le Ngoc Huyen *et al*., 2010; Amougou *et al*., 2012; Ragaglini *et al*., 2014; Gansberger *et al*., 2015). Mast *et al*. (2014), for example, have shown that specific methane yields were best for the Cup Plant before peak biomass was reached. The situation is even more pronounced for *Miscanthus*, where harvest dates in autumn led to reduced C-inputs by almost 60% compared to harvesting in the spring (Ruf *et al*., 2017). Consequently, management strategies targeting maximum yields will certainly reduce amounts of organic residues. The C to N ratios of aboveground residues ranged between 25 and 57 with lower values for Virginia Mallow, Switchgrass and Giant Knotweed and were higher for the wild flower mixture, Cup Plant and maize (Emmerling, 2014; Heděnec *et al*., 2014). *Miscanthus* residues show two or three times higher C to N ratios than the other mentioned crops and distinct differences among plant fractions (Kahle *et al*., 2001; Felten & Emmerling, 2011; Ruf *et al*., 2017).

Despite the lack of comprehensive studies for most PECs, we can carefully conclude that herbaceous PECs cannot generally be classified as high aboveground residue-producing crops and that harvest regimes, among other factors, control the aboveground C-input.

Accrual and recycling of belowground plant residues

Anderson-Teixeira *et al*. (2013) demonstrated that PECs generally allocate larger amounts of C belowground compared to annual crops. For example, Carvalho *et al*. (2017) reviewed an aboveground to belowground C-input of 81 : 19 for corn and an almost inverse ratio of 29 : 71 for *Miscanthus*. Aside from plant species, the amount of root biomass distinctly depends on soil texture, available nutrients, water supply and aboveground biomass growth (Gill & Jackson, 2000; Carvalho *et al*., 2017). There is a strong indication that PECs show, with respect to plant physiology and root architecture, different species-specific patterns of carbon input to soil. Presumably not least because of this, absolute values of belowground accrual of organic residuals vary widely and have, in a practical sense, not been investigated for most energy crops up to now. Using data from Shoji *et al*. (1990), Greef (1996) and Himken *et al*. (1997), it can be calculated that approximately 3 Mg d.m. ha^{-1} of *Miscanthus* rhizomes decays annually. For Reed Canary Grass, Bolinder *et al*. (2002) calculated a shoot-to-root ratio of 1.35 and 0.63 in the first and second year after seeding, respectively. Shoot-to-root ratios smaller than 1.0 also depict the mean value of 8 grasses investigated in their study. According to a global review of Gill & Jackson (2000), the fine root turnover of temperate grasslands was with 0.53 distinctly higher than for herbaceous species. Generally, the C to N ratio of roots and rhizomes is much smaller than that of aboveground litter, coincidently with higher amounts of phenolic and lignaceous compounds (Amougou *et al*., 2011; Carvalho *et al*., 2017). Thus, it is likely that, similar to PGL, large amounts of easily degradable organic residues accrue below stands of energy grass species that may account for C-sequestration potential, growth of microbial community and soil respiration. The quite similar C_{org} content for PEC stands (Table 3), regardless of the location in the landscape, may show that lower shoot-to-root ratios were typically observed at sites with coarser soil texture, each with lower PAWC and available nutrient content.

Accrual and recycling of root exudates

The quantitative contribution of root exudates in PEC cultivation systems to C_{org}, and microbial activity, and the stabilizing effects on soil aggregates represent rarely researched territory. However, it is well known that root exudates promote both the growth of microbial communities and the formation of organo-mineral complexes (Morel *et al*., 1991; Amézketa, 1999; Tiemann & Grandy, 2015). Brimecombe *et al*. (2007) stated that the amounts of root exudates depend on several pedologic factors but particularly on plant species, and Newman (1985) outlined the relationship between living root mass and the amount of root exudates. Thus, larger root masses of PECs and higher amounts of exudates released compared to annual crops (Brimecombe *et al*., 2007) suggest beneficial effects. Nevertheless, the net effects of increased root exudation under PECs appear to be difficult to estimate due to two opposing effects. Root exudates likely contribute significantly to belowground C-accrual and stabilization by formation of organo-mineral complexes, particularly in deeper soil layers (Kuzyakov & Schneckenberger, 2004; Tiemann & Grandy, 2015). On the other hand, as stated by Tiemann & Grandy (2015), root exudation stimulates microbial activity, which may result in increased decomposition rates of older C_{org}.

Time-dependent accumulation of SOM under PECs

In the framework of this study, the time-dependent C_{org} dynamics under PEC cultivation can be shown with a regression analysis (Fig. 3). The observed development of the C_{org} pool appears plausible and coincides with the

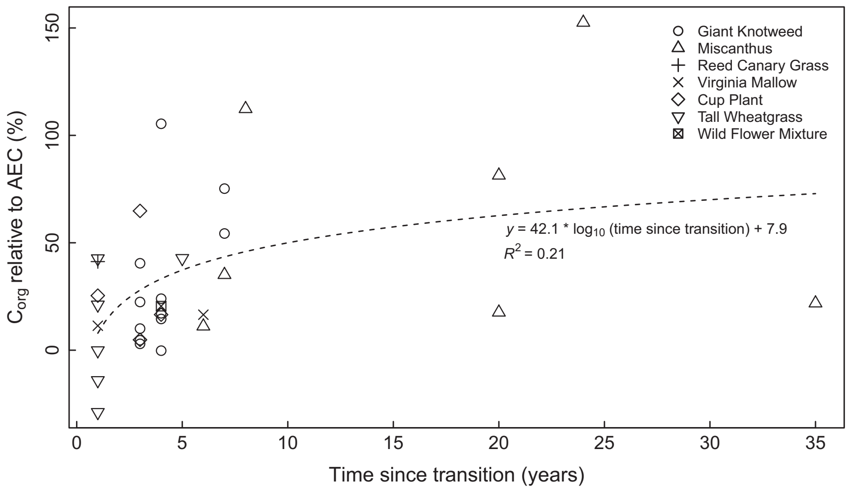

Fig. 3 Development of C_{org} content in soils cultivated with PECs compared to adjacent AEC stands as a function of time since transition.

results of Agostini *et al.* (2015), who traced slow initial C_{org} enrichment back to low amounts of C-input during the phase of establishment. Additionally, after the conversion from AEC to PECs, the initial losses of C_{org} appear conceivable, for instance, when formerly non-tilled soils were again tilled to (re-)plant PECs (Dufossé *et al.*, 2014). Similar to tillage, intense rooting may also physically disturb soil aggregates resulting in a mechanical destabilization and altered aggregate structure. Thus, 'older, previously protected SOC could be newly exposed to decomposition' (Tiemann & Grandy, 2015, p. 162). However, although our results showed slow increases of C_{org} content under PECs, there were no signs of an initial destabilization of aggregates.

Potential of SOM formation as a driver for improved soil quality in PECs

The quality and quantity of C_{org} were identified as controlling parameters and therefore key indicators of soil quality (Bezdicek *et al.*, 1996; Lal, 2015). Reduced soil tillage (Burke *et al.*, 1989; Havlin *et al.*, 1990), the application of manure, fertilizers and lime (Haynes & Naidu, 1998), rotational crop cultivation and crop residues (Rasmussen *et al.*, 1980) led to higher amounts of C_{org}, C_{mic} and general soil quality (Wardle, 1992).

Mean annual C-sequestration rates of *Miscanthus* for the upper 30 cm were determined with 0.11 g kg^{-1} yr^{-1} and 0.23 g kg^{-1} yr^{-1} for a 9-year-old stand in sandy soil and a 12-year-old stand in loamy soil conditions, respectively (Schneckenberger & Kuzyakov, 2007). The belowground accrual of organic substances and intense bioturbation (Felten & Emmerling, 2011; Emmerling, 2014; Schorpp & Schrader, 2016), in combination with decreasing microbial activity with soil depth, may significantly contribute to the C-sequestration potential of PECs in deeper soil layers. For the whole rooting depth of 150 cm, Felten & Emmerling (2012) calculated average increases of 1.1 Mg C ha^{-1} yr^{-1} after 16 years of *Miscanthus* cultivation. Conant *et al.* (2001) calculated that C_{org} stocks of PGLs increased over the first 40 years by a mean of 0.54 Mg C ha^{-1} a^{-1} for a wide range of climates. Thus, C-sequestration rates of *Miscanthus* were in the same range as under PGL.

In comparison, Herrmann (2013) calculated, based on the C balance approach according to VDLUFA (2004), that in silage maize cultivations (AEC) with a slurry application of 30 m^3 ha^{-1}, a negative humus balance of 290 to 530 kg C is to be expected. For cereals, the humus balance distinctly depends on the amount of straw removal and can thus be both negative in a range similar to maize or considerably positive when the total amount of straw is left in the field. Thus, the long-term humus balance distinctly depends on specific management. Indeed, in the framework of this study, we could not determine any differences between maize and cereals. These findings may be attributable to similar crop management practices of AECs with respect to tillage as well as rotational cropping systems with alternating silage maize and cereals for grains, which are typical in the study region.

Implications of PEC cultivation for soil protection in agriculture

The results of this study have shown that cultivation of PECs improved soil quality indicators compared to stands of AEC on several spatial scales. However, probably influenced by interactions of edaphic factors, AEC and PEC formed a statistical group for several indicators that was significantly different from PGL.

Remarkably, specific crops forming the cropping systems did not differ from each other in any case, which implies that cropping-related factors, such as the frequency of tillage and amounts of C-input, were dominating factors that have modified the local soil quality.

Based on the enhanced aggregate stability in PECs observed in this study and reports about higher abundance and the burrowing activity of earthworms (Emmerling, 2014; Schorpp & Schrader, 2016), we reasonably assume that soils cultivated with PECs develop a stable and firm soil structure with improved preferential flow paths and high infiltration capacities. Additionally, the permanent, intense rooting as well as dense soil coverage by leaf canopies and plant residues over distinctly longer periods of the year compared to AECs will certainly allow mitigation of soil erosion. Together with lower fertilizer requirements and pesticide use, the beneficial effects of PEC cultivation extend far beyond the field borders, for example with respect to reduced groundwater pollution and the eutrophication of receiving waters (Johnson & Novak, 2012), thus enabling the protection of public goods. The investigation of rhizosphere processes under PECs seems to be extremely important to understanding the potential of PECs in carbon sequestration but also for microbial biomass and stabilization of soil structure (c.f. McNear, 2013). Considering the clear signs of improvements of soil quality PEC stands over time, replacing AECs with PECs may offer great potential to combine ecological and economic advantages. Thus, PEC cultivation may result in more sustainable agricultural biomass production. Therefore, we recommend a strategic substitution of AECs by PECs, particularly at sites vulnerable to soil erosion and compaction and to loosen up cleared, monotonous agrarian landscapes.

However, further research and monitoring of PECs on the landscape level will be necessary to address specific issues discussed in the present study.

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