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Short communication

Site-adapted production of bioenergy feedstocks on poorly drained cropland through the cultivation of perennial crops. A feasibility study on biomass yield and biochemical methane potential

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ABSTRACT

Soil compaction depicts a major threat to soil fertility in extensive maize cultivation systems on soils that show conditions of waterlogging in autumn. Perennial energy crops may reduce the vulnerability for soil compaction by earlier harvest dates and improved soil stability. However, the performance of such crops to be grown on Stagnosols and Planosols is currently an open issue. Within the framework of a two-year experiment, we investigated the potential of five perennial energy crops and maize to be cultivated under periodically waterlogged soil conditions and effects on biomass and biomethane yield. Dry matter yields of perennial energy crops were 50% – 100% higher compared to maize. Contrarily, maize showed a weak yield performance under pronounced waterlogged conditions. Biochemical methane potentials were approx. 310 L_N CH_4 kg^{-1} VS for maize and on average 275 L_N CH_4 kg^{-1} VS for perennial energy crops, whereby different soil moisture regimes had no significant influence. Thus, our results reveal first indication for a sustainable biomass production on soils with periodically waterlogged conditions through the cultivation of perennial energy crops.

1. Introduction

The cultivation of bioenergy crops on arable land has increased during the last decades with maize as most economic crop for biomethanation under temperate conditions [1,2]. In the context of increasing maize cultivation, the apprehension of a creeping deterioration of soil fertility, resulting from a depletion of soil organic matter, soil compaction and erosion has initiated legislative regulations that are focussing on a diversification of cultivated crops (e.g. EU Regulation No. 1307/2013).

In Europe, soil compaction under maize cultivation potentially results from an unfavorable combination of pedogenic factors, prevailing weather conditions and crop-specific management efforts [3]. Stagnosols, Planosols, and related soil types that show periodic water stagnation during the winter half years are particularly sensitive for soil compaction by heavy machinery during harvesting of maize. From the perspective of soil protection, abundant autumn precipitation prior to the harvest period and the severely limited drainage of these soil types, resulting in high soil moisture contents and thus low carrying capacity, make them to least favorable sites for maize cultivation. This also means that these sites show great potential to establish a more sustainable biomass production. It is hypothesized that perennial energy crops (PECs) would have the capability to distinctly reduce vulnerability for soil compaction by combining earlier harvest dates in late summer with typically lower soil moisture contents and the stabilization of the soil by the permanent rooting system [4]. Indeed, the suitability of several PECs for anaerobic digestion were tested in a number of studies [5–11]. Although none of the tested crops could outperform maize with respect to methane yields per area, these studies revealed that some of the alternative crops do not lag far behind, do not require special preparations or technologies for digestion and that several plants provide specific ecosystem services [12,13]. To our knowledge, no study dealt with the general suitability and performance of PECs to be cultivated on soil that show periodically soil water stagnation, except for Reed Canary Grass [14,15]. In every respect, outliving of periods of waterlogging with associated altered soil chemical properties depicts a challenge for plants due to inadequate gas exchanges in the soil-atmosphere continuum [16–19]. Thus, plants' energy metabolism may be impaired by oxygen starvation resulting in an accumulation of plant-toxic substances in cytoplasm. Nonetheless, numerous plant species can tolerate these unfavorable environmental conditions due to morphological and biochemical adaptation mechanisms [17,20], such as the development of aerenchym tissue and modified energy (adenosine triphosphate) supply of the root cells. However, consequences of

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such conditions on biomass development and biochemical methane potential (BMP) need to be addressed.

In the framework of a two-year pot experiment, we examined the suitability of five promising PEC species and maize, to gain evidence about their performance if cultivated under periodically waterlogged conditions. We measured plant heights, quantified biomass yields and analyzed the BMP to evaluate the qualification of these crops to substitute maize on Planosols and Stagnosols.

2. Material and methods

In the framework of this feasibility study a pot experiment was conducted that allowed for a precise adjustment of soil water contents. The general drawbacks of pot experiments compared to field studies were accepted against the background of much better standardized conditions and working independently from natural precipitation. A total set of 72 Kick-Brauckmann pots were used whereby 60 pots were assigned to the main experiment aiming to determine growth parameters as well as the BMP and further 12 pots for monitoring of soil physical and hydraulic properties.

2.1. Experimental setup

72 Kick-Brauckmann pots had been stepwise filled and compacted with a sandy loam. FD-sensors were vertically installed at a medium depth in the pots for determination of volumetric water contents (Table 1).

Six different plants species were cultivated in the time from April 2015 to May 2017. Five PECs were selected resulting from (i) their promising BMPs and biomass yields determined in previous studies (c.f. section 1) and (ii) a literature research about the natural habitat of these species. Cup Plant (*Silphium perfoliatum*), Tall Wheatgrass (*Agropyron elongatum ‚Szarvasi-1'*), Giant Knotweed (*Fallopia japonicum x bohemica ‚IGNISCUM Candy'*), and Reed Canary Grass (*Phalaris arundinacea*) were obtained by vegetative propagation dividing the rootstocks of mature plants. Jerusalem Artichoke (*Helianthus tuberosus 'Gute Gelbe'*) was cultivated from tubers. After five weeks of precultivation, 10 similarly developed plants of each species, with respect to the number of shoots and habitus, were selected and repotted in each one Kick-Brauckmann pot. At the time of repotting, each two maize grains (*Zea mays 'Ronaldinio'*, KWS Saat AG, Einbeck, Germany) were seeded also in Kick-Brauckmann pots. For four weeks, the soil was kept moist in order to enable proliferation.

2.2. Determination of soil physical and hydraulic properties

The pore size distribution to relate volumetric soil water contents to soil water and air characteristics was determined by sampling (100 cm^3 sample rings) from 12 pots, also planted with PECs, using a pressure plate apparatus at 60, 300 and 15000 hPa (Table 1) according to Richards et al. [21]. Determination of particle size distribution was done by combining wet sieving and sedimentation after Köhn [22].

2.3. Soil moisture variants

Soil types that are characterized by waterlogging show stagnant soil water under mid European conditions particularly in autumn, winter, and spring until higher evaporation and transpiration rates lead to disappearance of stagnant soil moisture.

Our experimental setup aimed to constitute different duration and intensities of stagnant soil water in both years. Therefore, two different soil moisture variants with each 5 pots per plant species were established.

Table 1
Characterisation of the experimental setup.

Pots		
Type		Kick-Brauckmann
Volume	L	7.0
Target bulk density	$g\ cm^{-3}$	1.25
Soil[a]		
Origin		Stagnic cambisol developed from Devonian clay- and sandstones with small levels of loess; collected at 49.889°N, 6.712°E
Preparation		sieved to 6 mm
pH-value		5.87
Soil organic carbon	$g\ kg^{-1}$	13.0
Soil nitrogen	$g\ kg^{-1}$	0.95
C to N ratio		13.7
Grain size distribution		
Sand fraction	%	57.8
Silt fraction	%	22.7
Clay fraction	%	19.4
Texture class		Ls4 (acc. to [23]) SL (acc. to [24])
Bulk density[b]	$g\ cm^{-3}$	1.32 (± 0.08)
Pore size distribution[b]		
Total pore volume	%	49.9 (± 2.9)
Field capacity	%	30.4 (± 2.8)
Plant avail. water content	%	20.4 (± 3.1)
Not plant avail. water content	%	10.3 (± 0.2)
Instrumentation for soil moisture monitoring		FD-sensors (ECH$_2$O EC-5, Decagon Devices, Pullman, United States) connected to a Delta-T Data-Logger (Delta-T Devices Ltd., Cambridge, Great Britain)
Fertilization		
Type		‚Vollkorndünger Perfekt' (Raiffeisen GmbH, Frankfurt, Germany)
Dates		02.06.15; 11.04.16; 07.03.2017
Amounts[c]		
• N (47% as NO_3-N, 53% as NH_4-N)		2.10 g pot equals approx. 122 kg ha^{-1}
• P (as P_2O_5)		0.30 g pot equals approx. 17 kg ha^{-1}
• K (as K_2O)		2.32 g pot equals approx. 134 kg ha^{-1}
• Mg (as MgO)		0.17 g pot equals approx. 10 kg ha^{-1}
• S		1.12 g pot equals approx. 65 kg ha^{-1}
Harvesting		
Cutting height		5 cm above the soil surface
Single cut regime		Maize, Cup Plant, Jerusalem Artichoke
Double cut regime		Tall Wheatgrass, Giant Knotweed, Reed Canary Grass

[a] Parameters determined at the beginning of the experiment.
[b] Shown values represent mean values (± S.D.) of 4 sampling dates (13.06.15; 07.11.15; 22.04.16; 29.01.17) with each 18 sampling rings (3 pots with each 6 rings).
[c] Recalculated to kg ha^{-1} taking into consideration the higher plant densities in the pots compared to field conditions.

- The "Excess soil moisture" variant (in the following referred to as "EM") aimed to represent periodically waterlogged soil conditions. In the context of this study, the term 'excess soil moisture' defines soil water contents above field capacity (pF 1.8) leading to a