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Evaluation of carbon sequestration in energetic crops (*Miscanthus* and coppice willow)**

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A b s t r a c t. The aim of the project was analytical evaluation of carbon content and soil carbon sequestration in *Miscanthus* and coppice willow crops biomass. In this paper, we present the results from a field experiment carried out in 2004-2006 at two Experimental Stations of the Institute of Soil Science and Plant Cultivation, Puławy, and net C sequestration under this cultivation. The C-sequestration model adapted by Matthews and Grogan (2001) was used for the simulations. The abovementioned crops are cultivated for the production of solid fuels. The three-year average yield for *Miscanthus* was between 15 and 17 t ha^{-1} y^{-1}, dependent on location, whereas for willow it was 12 and 13 t ha^{-1}y^{-1}. The net soil carbon sequestration for *Miscanthus* cultivation was 0.64 t C ha^{-1} y^{-1} while for coppice willow it was 0.30 t C ha^{-1} y^{-1}.

K e y w o r d s: carbon sequestration, *Miscanthus,* coppice willow, greenhouse gas emissions

INTRODUCTION

Agriculture, besides contributing to greenhouse gas emissions, also contributes to carbon dioxide absorption and soil sequestration of carbon into a solid organic form (Faber, 2001; Freibauer *et al.,* 2004; Smith, 2004). It is estimated that global potential scale of carbon sequestration in soils used for agricultural purposes is around 0.3 t C ha^{-1} y^{-1} on arable lands and around 0.5-0.7 t C ha^{-1} y^{-1} on grasslands (IPCC, 2000). Hopes for increased soil carbon sequestration are associated with increase in large-scale energetic crops cultivation. However, different authors found that the carbon sequestration rates for these cultivars are different. Bradley and King (2004) determined carbon sequestration in forests and willow cultivations at 0.15-0.22 t C ha^{-1}y^{-1}, whereas in *Miscanthus* cultivation at 0.13-0.20 t C ha^{-1}y^{-1}. According to Matthews and Grogan (2001), carbon sequestration in the surface layer of soil (0-23 cm) was at 0.31 for forests, and 0.41 for the cultivation of willow, whereas for *Miscanthus* it was measured at 0.93 t C ha^{-1}y^{-1}. Freibauer *et al.* (2004) and Smith (2004) determined carbon sequestration in cultivations of energy crops at 0.6 and 0.62 t C ha^{-1}y^{-1}, respectively. The carbon sequestration showed by Smith (2004) was higher than in no-tillage cultivation (0.38 t C ha^{-1}y^{-1}) or organic farming (0-0.54 t C ha^{-1}y^{-1}), but at much lower levels than by converting arable land into grasslands (1.2-1.69 t C ha^{-1} y^{-1}). The cultivation of energy crops is associated with greenhouse gas emission (burning fuel, production of fertilizers, crop protection). The assumption is that carbon sequestration of around 0.25 t C ha^{-1} y^{-1}, resulting from energetic crops cultivation, makes biomass combustion neutral in terms of greenhouse gas emissions (Volk *et al.,* 2004).

MATERIALS AND METHODS

The plant material used for this research came from field experiments conducted in 2004-2006 with several genotypes of *Miscanthus* and coppice willow clones. The abovementioned crops are cultivated for the production of solid fuels. The field experiment was established in 2003 at two Experimental Stations of the Institute of Soil Science and Plant Cultivation, Puławy. The experimental fields are located in the Experimental Station Puławy-Osiny on heavy black earth (complex 8 – cereal-fodder strong), and at the Experimental Station in Grabów on medium-heavy soil (complex 4 – very good rye), where five genotypes of *Miscanthus* and four clones of willow were planted. The sizes of the individual experimental plots ranged from 200 to 700 m^2.

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Bio-energy crops have a very high dependence on water. *Miscanthus* needs 450 mm of rainfall (Beale and Long, 1997) and willow needs 500 mm of rainfall (Szczukowski *et al*., 2004). Water available for crops comes from autumn-winter retention and from rainfalls. The rainfalls in the researched time were lower than the long-term average rainfalls (Table 1).

Basic information concerning the agrotechnique of experimental plots is shown in Table 2. In late autumn, the harvest was carried out and the yield of dry matter was determined.

Based on the experimental yield of aboveground biomass the total yield of plant and underground biomass were estimated, accepting that the roots of *Miscanthus* constitute 35% of the whole mass, whereas the roots of coppice willow constitute 25% of the produced dry matter (Matthews and Grogan, 2001). In addition, soil carbon sequestration was evaluated by using the Matthews and Grogan model.

The annual amount of C input into the fresh C pool from *Miscanthus* was accepted at the level of 30% (Matthews and Grogan, 2001), because of the senescent leaves and post harvest remnants entering the soil during wintertime. In the case of willow leaves, the mass that enters the soil was predicted from the equation showed by Matthews and Grogan (2001):

$$W_{C\ in} = (L\ f_c)/SLA\ 10^5 + W_{AG}\ f_W \qquad (1)$$

where: $W_{C\ in}$ – annual amount of C input into the fresh C pool (kg C $ha^{-1}y^{-1}$), L – LAI (leaf area index) ($m^2\ m^{-2}$), f_c – fraction of C in biomass = 0.4 g C g d.m.$^{-1}$, SLA – specific leaf area = 250 cm^2g^{-1}, W_{AG} – weight of C aboveground biomass = (0.75 dW/dt) (kg C $ha^{-1}y^{-1}$), f_W – fraction aboveground C input = 0.0004.

The LAI measurements for willow were taken four times with a Lai Canopy Analyzer-2000, from June until August at five replications.

The total contribution of C input into the fresh C pool from the root system of willow and *Miscanthus* (*WRin*, kg C ha^{-1}) was calculated as:

$$W_{R\ i} = dW/dt\ f_R\ f_{FRTO} + W_{BG}\ f_W \qquad (2)$$

where: f_R – fraction of C input from roots to soil = 0.25, f_{FRTO} – fraction C input from fine roots to soil = 0.85, W_{BG} – weight of C belowground in the root system = (f_R dW/dt) (kg C $ha^{-1}y^{-1}$).

The total inflow of organic substance to the soil is the amount of leaves and dead underground biomass ($W_{C\ in}$ + $W_{R\ i}$). It was adopted, according to the Matthews and Grogan model, that 18% of carbon is processed into solid humus. The quantity of carbon in solid humus calculated in this way was reduced by the amount of carbon that was emitted during the cultivation of the examined crops (RcoEP, 2003).

T a b l e 1. Sums of rainfalls (mm)

Year	Months							Sum
	IV	V	VI	VII	VIII	IX	X	IV-X
Experimental Station Puławy-Osiny								
2004	39	19	52	93	62	33	31	329
2005	16	67	32	106	56	24	4	305
2006	27	58	19	21	240	8	30	403
1951-2006	41	54	75	82	68	54	42	416
Experimental Station Grabów								
2004	67	41	84	112	59	18	35	416
2005	10	84	46	133	37	44	6	359
2006	30	53	38	10	220	14	34	399
1962-2006	48	62	81	85	71	58	43	408

T a b l e 2. Technique of energy crops production

Crop	Plant density (1000 ha^{-1})	Fertilization (kg ha^{-1})			Weed control	Disease control
		N	P_2O_5	K_2O		
Willow coppice	40	75	50	75	Azotop, Symazine	Cooper oxychloride
Miscanthus	15	75	50	75	mechanical	-

RESULTS AND DISCUSSION

The yields of willow clones dry matter did not demonstrate any significant differences and was in the range of 11.6-13.7 t ha^{-1} at a three year average for the first location (Table 3), and 11.1-12.9 t ha^{-1} at the second location. They were lower from simulated yields for willow cultivations (13.8-18.1 t ha^{-1}) located on very good soils of Eastern Europe (Fischer *et al*., 2005). It can be assumed that the limited water influenced the experimental yield of willow. The average yearly yield of all clones was falling as the crops were getting older.

T a b l e 3. Yield of dry matter (t ha^{-1} y^{-1}) of coppice willow *(Salix viminalis)*

Clone (No. in collection)	Cutting cycle annual			3 year average
	2004	2005	2006	
		Heavy black earth – Osiny		
1023	16.6	12.6	10.0	13.1
1047	14.1	12.7	12.8	13.2
1052	17.2	13.7	10.1	13.7
1054	10.8	12.4	11.5	11.6
average	14.7	12.8	11.1	12.9
LSD $\alpha_{0.05}$ Tukey	3.5	n.s.	n.s.	n.s.
		Medium-heavy soil – Grabów		
1023	13.4	11.0	11.2	11.9
1047	12.7	9.4	11.2	11.1
1052	13.1	10.8	10.8	11.6
1054	14.0	12.1	12.7	12.9
average	13.3	10.8	11.5	11.9
LSD $\alpha_{0.05}$ Tukey	r.n.	r.n.	r.n.	r.n.

The dry matter yield of *Miscanthus* genotypes was significantly different within average of 10.2-20.7 t ha^{-1} (Table 4) at both locations. The yield for the first year of the experiment was low; this could be because it was the second year of cultivation when the plant was still not mature enough to obtain an economic yield (Clifton-Brown and Lewandowski, 2000). In the second year of the experiment, the yield witnessed a high increase. The third year of the experiment was characterized with very bad weather conditions, including a late spring ground-frost and long summer draught. The yields were approaching the presupposed simulated yields for *Miscanthus* cultivations (17.7-21.8 t ha^{-1}) located on the very good soils of Eastern Europe (Fischer *et al.,* 2005). It can be assumed with a high probability that limited water in 2005 did not influence the experimental *Miscanthus* yield, but there was an influence from weather conditions in 2006. The average three-year moisture content was, at the harvest in autumn, between 33.5 and 52.2%. The moisture content for biomass should be under 25%, that is why it is advisable to harvest in late winter or early spring (Jorgensen *et al*., 2003).

The model applied in the research allows the evaluation of the input of biomass into soil, gross soil carbon sequestration, net soil humus sequestration, and greenhouse gas emissions resulting from willow and *Miscanthus* cultivations. According to the simulation for the Experimental Station Puławy-Osiny, the total input of biomass entering the soil from willow biomass was 1.75 to 3.03 t C ha^{-1} y^{-1} (Table 5). This value was lower compared to 5.2 t d.m. ha^{-1} y^{-1} obtained for the UK (Matthews and Grogan, 2001). The gross soil carbon sequestration was 0.32 up to 0.55 t C ha^{-1} y^{-1} (Table 5), and it was within the evaluation range for the UK (Matthews and Grogan, 2001). After deducting the emissions from the greenhouse gas, resulting from willow cultivation, it was established that net soil carbon sequestration was around 0.22-0.39 t C ha^{-1} y^{-1}. As a result, the net soil carbon sequestration was just a little higher than on arable lands (0.3 t C ha^{-1} y^{-1}) (IPCC, 2000). However, even with such a level of sequestration, willow coppice combustion may be considered as neutral greenhouse gas emission.

The aboveground biomass has a high influence on the amount of carbon sequestration which enters the soil usually in the form of senescent leaves and postharvest remnants. Kahle (2001) measured, in Germany, that about

T a b l e 4. Yields (t ha^{-1} d.m.) and moisture content (%) of *Miscanthus*

Genotype	2004	2005	2006	3 year average	
				(t ha^{-1})	moisture (%)
		Heavy black earth - Osiny			
Giganteus*	9.0 a	21.7 a	18.0 a	16.2	52.2
M7	12.8 a	20.7 ab	17.1 a	16.9	44.5
M40	10.8 a	18.8 ab	15.0 a	14.9	33.5
M105	8.4 a	16.1 b	14.3 a	12.9	49.9
M115	10.1 a	18.6 ab	13.8 a	14.2	47.1
Average	10.2	19.2	15.6	15.0	45.4
		Medium-heavy soil - Grabów			
Giganteus*	10.4 b	19.2 bc	14.9ab	14.8	46.2
M7	16.2 a	23.7 ab	20.5a	20.1	40.2
M40	11.4 b	16.2 c	16.7ab	14.8	47.2
M105	13.5 b	17.7 bc	13.8b	15.0	42.4
M115	18.1 a	26.8 a	17.6a	20.8	37.8
Average	13.9	20.7	16.7	17.1	42.8

**Miscanthus* x giganteus - *M. sacchariflorus* x *M. sinensis*. Yields with the same letters are not significantly different. M 7 – *M. sinensis* Gofal, M40 – *M. sinensis* Silver Feather, M105 – *M. sacchariflorus Robustus* x *M. sinensis*, M115 – *M. sacchariflorus Robustus* x *M. sinensis*.

T a b l e 5. Evaluated input of biomass into soil, gross soil carbon sequestration, and greenhouse gas emissions resulting from willow cultivation, net soil humus sequestration (cereal-fodder strong soil complex)

Year	Clone	Total input of biomass into soil	Gross soil carbon sequstration	Greenhouse gas emissions (GHG)	Net soil carbon sequestration
		(t C ha^{-1} y^{-1})			
2004	1023	3.03	0.55	0.16	0.39
	1047	2.58	0.46	0.13	0.33
	1052	3.03	0.55	0.16	0.38
	1054	2.28	0.41	0.10	0.31
2005	1023	2.56	0.46	0.12	0.34
	1047	2.45	0.44	0.12	0.32
	1052	2.65	0.48	0.13	0.35
	1054	2.49	0.45	0.12	0.33
2006	1023	1.75	0.32	0.10	0.22
	1047	2.11	0.38	0.12	0.26
	1052	1.94	0.35	0.10	0.24
	1054	1.97	0.35	0.11	0.24

T a b l e 6. Evaluated input of biomass into soil, gross soil carbon sequestration, greenhouse gas emissions resulting from *Miscanthus* cultivation, net soil humus sequestration (cereal-fodder strong soil complex)

Year	Genotype	Total input of biomass into soil	Gross soil carbon sequstration	Greenhouse gas emissions (GHG)	Net soil carbon sequestration
		(t C ha^{-1} y^{-1})			
2004	Giganteus	2.77	0.50	0.10	0.40
	M 7	3.27	0.59	0.12	0.47
	M 40	3.19	0.57	0.11	0.46
	M 105	2.84	0.51	0.10	0.41
	M 115	2.63	0.47	0.09	0.38
2005	Giganteus	6.58	1.18	0.24	0.95
	M 7	6.27	1.13	0.23	0.90
	M 40	5.70	1.03	0.21	0.82
	M 105	4.88	0.88	0.18	0.70
	M 115	5.64	1.01	0.20	0.81
2006	Giganteus	5.39	0.97	0.20	0.77
	M 7	5.23	0.94	0.19	0.75
	M 40	4.58	0.83	0.16	0.66
	M 105	4.37	0.79	0.16	0.63
	M 115	4.22	0.76	0.15	0.61

3-7.5 t d.m. ha^{-1} y^{-1} aboveground biomass full to soil. Matthews and Grogan (2001), in Great Britain, estimated the inflow of organic matter at a level of 7.5 t d.m. ha^{-1} y^{-1}. Correspondingly, in this research, the input of biomass entering the soil was evaluated as from 2.63 to 6.58 t d.m. ha^{-1} y^{-1}.

The sequestration model calculated the gross soil carbon sequestration at 0.47- 1.18 t d.m. ha^{-1} y^{-1} (Table 6) for *Miscanthus* cultivations in the Experimental Station Puławy-Osiny. An assumption according to literature on the subject was made that 18% of that carbon is processed into solid humus. After deducting the greenhouse gas emissions, resulting from the *Miscanthus* cultivations, it was calculated that the net soil carbon sequestration was around 0.38-0.95 t C ha^{-1} y^{-1}. Such a high result was obtained due to the fact that during the winter *Miscanthus* crops lose 30% of their biomass, which is absorbed into the soil. Matthews and Grogan (2001) estimated the sequestration level at 0.93 t C ha^{-1} y^{-1}. Bradley and King (2004) estimated the carbon sequestrations at a level of 0.13 to 0.20 t C ha^{-1} y^{-1}; whereas Clifton-Brown *et al.* (2004) in Great Britain obtained sequestrations at levels up to 0.93 t C ha^{-1} y^{-1}.

The agriculture net retention at the scale of Poland was 0.07 t C ha^{-1} y^{-1}, and the greatest net retainer assures the usage of farm manure and cover crops (0.14 t C ha^{-1} y^{-1}) and grassland (0.10 t C ha^{-1} y^{-1}) (Faber, 2001).

The obtained results distinguish a conflict between the profitability of energy crops production. The cultivation of crops demands substantial input in the form of additional factors, including farming practices, logistics, and management. These alternative crops take several years to establish a plantation, though it requires very little work once it has been successfully established. The profitability of this investment depends on the achievable yield and biomass prices. The main aim of the energy plantation cannot only be ecological issues, but also it needs to be economically viable.

CONCLUSIONS

The results obtained from the presented research allow the formulation of the following conclusions:

1. The net soil carbon sequestration in *Miscanthus* crops was around 0.38-0.95 t C ha^{-1} y^{-1} and 0.22-0.39 t C ha^{-1} y^{-1} for coppice willow.

2. The obtained sequestration results confirm the neutrality of biomass combustion in terms of greenhouse gas emissions.

3. An increase of soil carbon sequestration in energy crops leads to a decrease in the efficiency of the economic plantation.

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