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Crop Rotations and Soil Tillage Interactions for Biomass Production

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Abstract: The introduction of energy crops for biofuel production is expected to cause severe soil degradation as all crop material will be removed from the fields leaving the soil bare and susceptible to soil erosion. The adoption of crop rotations to keep the soil covered by vegetation all year round along with the application of reduced tillage or no-tillage methods can offer considerable soil protection. Basic criterion for an energy crop is the positive energy balance. Energy budgets for two energy crop rotations (in the first one all the plant material is removed from the field while in the second one the residues are left on the soil) and five tillage methods were estimated. Crop rotations were combined with: 1. Conventional Tillage (CT), 2. Reduced tillage with heavy cultivator (HC), 3. Reduced tillage with rotary cultivator (RC), 4. Strip tillage or disk harrow (ST/DH) and no-tillage (NT). The energy budget proved to be positive when the whole plant material of a crop was used as an energy feedstock but turned to negative if part of it was left on the field and crop yield was not high enough. The first rotation presented higher net energy gain as the whole plant material was utilized. Energy efficiency was higher in the ST/DH for both rotations and all the crops. Soybean proved to be most efficient as a second crop in the year than sunflower. In sweet sorghum net energy was high due to the high biomass production but energy efficiency was low due to high energy requirements of irrigation. The most efficient crops were the low-input, non-irrigated winter mixtures of vetch / oats and triticale / peas.
Key words: Crop rotations, soil tillage, energy budgets

INTRODUCTION

Biomass production for second generation biofuels will remove all crop material from the fields leaving bare soil for long periods of the year. It is well established that this practice would enhance soil erosion, reduce soil organic matter and biodiversity and the heavy equipment for biomass harvesting would cause soil compaction. These are factors adversely affecting soil fertility according to SOCO research team (SoCo, 2009). Crop cultivation practices like double cropping per year and rotations that keep the soil covered all year round as well as reduced or no-tillage can offer possible solutions to the problem.

Reduced and no-tillage systems leaving soil surface covered by crop residues increase soil profile carbon and nitrogen and enhance soil fauna activity resulting in improved soil structure and fertility (Roger-Estrade et al., 2010, Varvel and Wilhelm, 2011), reduce soil erosion and runoff (Leys et al., 2010) and increase soil water retention and capacity (Soane et al., 2012). On the other hand, crop rotations benefit the development of the soil microorganisms, give opportunities to roots of different plants to exploit different soil depths and recycle nutrients that have been leached to deeper layers, lead to a diverse soil flora and fauna, enhance an important phytosanitary function and reduce weed infestations (Tomasoni et al., 2003, Munkholm et al., 2013, Navarro-Noya et al., 2013).

Energy analysis is a fundamental validation tool for every bioenergy production system. A system, to be usable should produce more energy than the energy spent for the production. For example sunflower, rapeseed and soybean present positive energy balances as individual crops (Venturi and Venturi, 2003). According to Rȯdiger GraB et al. (2013) double-cropping systems present mostly higher yield stability than sole cropping systems as the two crops within one year spread the risk of weather extremes among the crops. Moreno et al

(2011) suggest crop rotations, including a leguminous plant, for increasing energy efficiency. The researchers also recommend for the semi-arid Mediterranean conditions for the adoption of low-input practices instead of farming systems requiring increased amount of agrochemicals and other inputs. It is true that high value spring crops often require substantial amounts of energy inputs that negatively affect the energy balance of the crop. The introduction of low-input / sustainable cropping techniques offers an outstanding challenge to reduce energy use. A research by Rathke et al. (2007) showed that the output/input ratio tends to increase when soil tillage operations are reduced.

A research project was initiated at the University of Thessaly Farm in Central Greece to study the effect of tillage and crop rotation to the soil and the crops. The experiment was established in 1996 and several crop rotations were tested. In 2012 crop rotations including energy crops were introduced. Winter and spring crops were used to keep the soil covered all year round. In the present work, results from the last two years (2012 & 2013) are presented.

MATERIALS and METHODS

Two different crop rotations were tested (Table 1). In the first, all the crop material was removed from the field while in the second, the crop residue was left on the soil. The rotations were combined with the following five tillage treatments:

1. Conventional tillage (CT) with ploughing at 25-30 cm and 2-3 passes of a disk harrow at 7-9 cm or a light cultivator at 6-8 cm for seedbed preparation.
2. Reduced tillage (HC) using a heavy cultivator at a depth of 20-25 cm and 2 passes of a disk harrow or a light cultivator for seedbed preparation.
3. Reduced tillage (RC) with a single pass of a rotary cultivator at 10-15 cm.
4. Reduced tillage (ST/DH). Two tillage treatments were used. For winter crops primary and secondary tillage were carried out by disk harrow (DH) at 6-8 cm. For summer crops a strip tillage machine (ST) was used. The tillage depth of the strips was 25-30 cm.
5. No-tillage (NT). Direct planting with the use of two no-till planting machines. Weeds were destroyed with glyphosate or diquat application.

A split plot experimental design was used, with rotations as the main plots and tillage as sub-plots. Sub-plot dimensions were 6 by 21 m long.

Every field operation and inputs were recorded during the experiments (Table 2). An 82kW four wheel tractor was used for all the operations. Harvesting was done with a plot combine harvester (HEGE 125) modified with a basket and a balance at the back to directly measure crop residue mass. Based on the records kept during the experiments an energy analysis of the system was undertaken. Data for indirect energy inputs (machinery, fertilizers, pesticides etc.) was taken from the literature and adapted to the machinery used (Fluck 1992, Pimentel 1980 Cavalaris et al., 2008). Direct energy was estimated based on direct measurements during the experiments. An instrumented tractor was used to measure the power of the tractor and the energy requirements of the implements (Papathanasiou *et al.,* 2002). The procedure is described by Cavalaris et al (2008).

RESULTS and DISCUSSION

The energy budgets of the crops were positive or negative depending on the harvested portion of the crop, utilized as biomass feedstock, and the obtained yields. Partial plant material use in combination with poor yields led to negative energy budgets.

In sunflower, when both seed and stalks were utilized (rotation 1), the energy budget was always positive and energy efficiencies for the five tillage methods ranged from 2.66 for NT to 3.58 for ST (Table 3). In rotation 2 however, the sunflower presented negative budget for four of the five tillage methods (Table 8).

Table 1. The two crop rotations

Year	2012								2013										
Month	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7	8	9	10	11
Rotation 1	Su	Su	Su	Su	Su		VO	VO	VO	VO	VO	VO	VO	SS	SS	SS	SS	SS	SS
Rotation 2		So	So	So	So	So	TP	TP	TP	TP	TP	TP	TP	Su	Su	Su	Su	Su	Su

Su = Sunflower, VO = Vetch / Oats mixture, SS= Sweet Sorghum

So = Soybean, TP = Triticale / Peas mixture

Table 2. Inputs for the six crops

	Rotation 1			Rotation 2		
	Sunflower	Vicia/oats	Sweet Sorghum	Soybean	Triticale/ Peas	Sunflower
Sowing (kg/ha)	7.8	230.0	1.5	69.0	230.0	7.8
Fertilisation (kg/ha)						
Nitrogen	120	31	202	27.5	31	120
Phosphorus	37.5	42	34		42	37.5
Potasium	37.5	42	54		42	37.5
Herbicides (kg/ha)						
Tribenuron methy1	0.037					0.037
Haloxyfop-P						1
Bentazon			2.5			
Dicamba			0.6			
Glyphosate (only in NT)	8			8		8
Diquat (only in NT)		2.5			2.5	
Irrigation (m^3/ha)	2300		6540	4400		3350

The negative effect resulted from the poor yields obtained with the late establishment of sunflower as second crop of the year due to bad weather conditions that delayed planting (mid June). When only the seed was used, the energy outputs were not enough to exceed the energy inputs. In a similar way, soybean in rotation 2 showed negative balance in the case of NT because of the reduced yield (Table 4). The other methods however performed well as the soybean yields were high. The energy efficiency was higher in the HC and ST methods. Soybean proved to be more suitable as a second crop than sunflower.

The non-irrigated winter crop mixtures, vetch – oats and triticale – peas presented the higher energy efficiencies (Tables 5 & 6). This was results of the whole plant material harvested and removed and the low energy inputs due to the lack of irrigation and the reduced nitrogen fertilization because of the legumes. It is estimated that irrigation accounted almost for the 62-71% of the total energy inputs in the irrigated crops. This high rate is attributed to the great water pumping depth (70m). The higher energy efficiencies (17.34 – 19.24) were obtained with the DH method and the lower with CT (9.87 – 11.92).

Table 3. Energy budgets for the five tillage methods in the sunflower crop (rotation 1)

Sunflower 2012 (Rotation 1)					
Energy Budget	**CO**	**HC**	**RC**	**ST**	**NT**
Energy Inputs (MJ/ha)					
Tillage	3853	2259	1765	1400	0
Sowing	494	494	494	494	494
Fertilization	6672	6672	6672	6672	6672
Pesticide application	1737	1737	1737	1737	3149
Irrigation	23475	23475	23475	23475	23475
Harvest	1117	1117	1117	1117	1117
Bailing	732	732	732	732	732
Transportation	73	64	80	80	60
Total	38153	36550	36072	35708	35698
Yield (kg/ha)					
seed	2501	2180	2726	2745	2035
Stalks	3513	3062	3828	3855	2858
Energy Outputs (MJ/ha)					
seed	66361	57842	72310	72822	53995
Stalks	50237	43787	54740	55128	40875
Total	116598	101629	127049	127950	94870
Net Energy (MJ/ha)	78444	65079	90978	92242	59171
Energy Efficiency	3.06	2.78	3.52	3.58	2.66
Energy Productivity (kg/MJ)	0.16	0.14	0.18	0.18	0.14

Table 4. Energy budgets for the five tillage methods in the soybean crop (rotation 2)

Soybean 2012 (Rotation 2)					
Energy Budget	**CO**	**HC**	**RC**	**ST**	**NT**
Energy Inputs (MJ/ha)					
Tillage	5187	2590	2161	1400	0
Sowing	1764	1764	1764	1764	1764
Fertilization	6672	6672	6672	6672	6672
Pesticide application	569	569	569	569	1980
Irrigation	38045	38045	38045	38045	38045
Harvest	1091	1091	1091	1091	1091
Transportation	90	90	79	88	60
Total	53418	50820	50380	49629	49612
Yield (kg/ha)					
seed	3558	3576	3106	3497	2366
Stalks					
Energy Outputs (MJ/ha)					
seed	59779	60072	52179	58756	39756
Stalks					
Total	59779	60072	52179	58756	39756
Net Energy (MJ/ha)	6362	9251	1799	9127	-9856
Energy Efficiency	1.12	1.18	1.04	1.18	0.80
Energy Productivity (kg/MJ)	0.07	0.07	0.06	0.07	0.05

Table 5. Energy budgets for the five tillage methods in the vetch - oats crop mixture (rotation 1)

Vetch - Oats 2012-13 (Rotation 1)					
Energy Budget	**CO**	**HC**	**RC**	**DH**	**NT**
Energy Inputs (MJ/ha)					
Tillage	5261	1797	1765	1189	0
Sowing	951	951	951	951	951
Fertilization	3715	3715	3715	3715	3715
Pesticide application	0	0	0	0	765
Irrigation	0	0	0	0	0
Harvest	948	948	948	948	948
Transportation	125	115	100	138	112
Total	11000	7526	7478	6941	6491
Yield (kg/ha)					
seed	2744	2530	2167	3061	2463
Stalks	4150	3850	3344	4592	3758
Energy Outputs (MJ/ha)					
seed	37565	34657	29737	41860	33757
Stalks	70965	65843	57177	78528	64258
Total	108530	100501	86914	120388	98016
Net Energy (MJ/ha)	97530	92975	79435	113447	91524
Energy Efficiency	9.87	13.35	11.62	17.34	15.10
Energy Productivity (kg/MJ)	0.63	0.85	0.74	1.10	0.96

Table 6. Energy budgets for the five tillage methods in the triticale - peas crop mixture (rotation 2)

Triticale - Peas 2012-13 (Rotation 2)					
Energy Budget	**CO**	**HC**	**RC**	**DH**	**NT**
Energy Inputs (MJ/ha)					
Tillage	5261	1797	1765	1189	0
Sowing	951	951	951	951	951
Fertilization	3715	3715	3715	3715	3715
Pesticide application	0	0	0	0	765
Irrigation	0	0	0	0	0
Harvest	948	948	948	948	948
Transportation	137	131	137	139	128
Total	11012	7542	7516	6943	6507
Yield (kg/ha)					
seed	3054	2911	3056	3110	2840
Stalks	4535	4337	4538	4612	4239
Energy Outputs (MJ/ha)					
seed	53757	51229	53787	54737	49976
Stalks	77553	74166	77592	78865	72487
Total	131310	125395	131379	133602	122463
Net Energy (MJ/ha)	120297	117853	123863	126659	115956
Energy Efficiency	11.92	16.63	17.48	19.24	18.82
Energy Productivity (kg/MJ)	0.69	0.96	1.01	1.11	1.09

Sweet sorghum presented significantly higher energy outputs due to the high yields (Table 7). Energy efficiency however was low because of the excessive energy use for irrigation. The highest efficiency was obtained again with the ST (2.93) and the lowest with HC (2.44).

Table 7. Energy budgets for the five tillage methods in the sweet sorghum crop (rotation 1)

Sweet Sorghum 2013 (Rotation 1)					
Energy Budget	**CO**	**HC**	**RC**	**ST**	**NT**
Energy Inputs (MJ/ha)					
Tillage	6233	3165	1765	1400	0
Sowing	269	269	269	269	269
Fertilization	16839	16839	16839	16839	16839
Pesticide application	915	915	915	915	915
Irrigation	55119	55119	55119	55119	55119
Harvest	2388	2388	2388	2388	2388
Transportation	1747	1475	1533	1735	1640
Total	83510	80170	78828	78666	77171
Yield (kg/ha)					
seed					
Stalks	49999	42222	43881	49667	46960
Energy Outputs (MJ/ha)					
seed					
Stalks	231802	195746	203436	230260	217713
Total	231802	195746	203436	230260	217713
Net Energy (MJ/ha)	148292	115576	124609	151594	140542
Energy Efficiency	2.78	2.44	2.58	2.93	2.82
Energy Productivity (kg/MJ)	0.60	0.53	0.56	0.63	0.61

Table 8. Energy budgets for the five tillage methods in the sunflower crop (rotation 2)

Sunflower 2013 (Rotation 2)					
Energy Budget	**CO**	**HC**	**RC**	**ST**	**NT**
Energy Inputs (MJ/ha)					
Tillage	3853	2259	1765	1400	0
Sowing	494	494	494	494	494
Fertilization	6672	6672	6672	6672	6672
Pesticide application	1737	1737	1737	1737	3149
Irrigation	29354	29354	29354	29354	29354
Harvest	1117	1117	1117	1117	1117
Transportation	43	44	37	44	39
Total	43271	41677	41176	40818	40825
Yield (kg/ha)					
seed	1580	1555	1315	1543	1408
Stalks					
Energy Outputs (MJ/ha)					
seed	41913	41256	34880	40942	37349
Stalks					
Total	41913	41256	34880	40942	37349
Net Energy (MJ/ha)	-1358	-422	-6297	124	-3476
Energy Efficiency	0.97	0.99	0.85	1.00	0.91
Energy Productivity (kg/MJ)	0.04	0.04	0.03	0.04	0.03

Considering crop rotations as a whole, the best results were obtained with rotation 1 in which the whole crop biomass was utilised as energy feedstock (Table 9). Net energy gain was higher in ST/DH (358,014 MJ/ha) and lower in NT (291,970 MJ/ha). Energy efficiencies were 3.97 and 3.46, respectively. In the HC, efficiency was even less (3.22).

Table 9. Energy budgets for the five tillage methods in rotation 1 (sum of crops)

Rotation 1 (crop summary)					
Energy Budget	**CO**	**HC**	**RC**	**ST**	**NT**
Energy Inputs (MJ/ha)					
Tillage	15347	7221	5294	3990	0
Sowing	1715	1715	1715	1715	1715
Fertilization	27226	27226	27226	27226	27226
Pesticide application	2652	2652	2652	2652	4828
Irrigation	78594	78594	78594	78594	78594
Harvest	4453	4453	4453	4453	4453
Transportation	1944	1654	1712	1954	1812
Total	131931	123514	121646	120583	118628
Energy Outputs (MJ/ha)					
seed	103926	92499	102046	114682	87752
Stalks	353004	305377	315353	363916	322846
Total	456930	397877	417399	478598	410598
Net Energy (MJ/ha)	324998	274362	295754	358014	291970
Energy Efficiency	3.46	3.22	3.43	3.97	3.46

Table 10. Energy budgets for the five tillage methods in rotation 2 (sum of crops)

Rotation 2 (crop summary)					
Energy Budget	**CO**	**HC**	**RC**	**ST**	**NT**
Energy Inputs (MJ/ha)					
Tillage	14301	6645	5690	3990	0
Sowing	3210	3210	3210	3210	3210
Fertilization	17059	17059	17059	17059	17059
Pesticide application	2306	2306	2306	2306	5894
Irrigation	67399	67399	67399	67399	67399
Harvest	3156	3156	3156	3156	3156
Transportation	271	265	253	272	227
Total	107701	100039	99072	97390	96943
Energy Outputs (MJ/ha)					
seed	155450	152557	140845	154435	127081
Stalks	77553	74166	77592	78865	72487
Total	233002	226723	218438	233300	199567
Net Energy (MJ/ha)	125302	126683	119366	135910	102624
Energy Efficiency	2.16	2.27	2.20	2.40	2.06

The net energy gain in rotation 2 (Table 10) was remarkably lower because soybean and sunflower stalks were left to the field and sunflower crop gave low yields as a second crop. Net energy ranged from 102,624 to 135,910 MJ/ha for NT and ST/DH, respectively. Corresponding energy efficiencies ranged from 2.06 to 2.40. It is remarkable that if the sunflower crop was taken away from the rotation, keeping the land fallow, the energy efficiency range could be improved to 2.89 and 3.40. Despite the lower productivity, the second rotation has the potential to provide the benefit of improved soil organic matter as the biomass returned to the field enriches the soil. The suggestion remains to be proved from the results of soil analysis that will be carried at the end of the experiment.

CONCLUSIONS

The following were concluded from the study:

- The energy budget of a crop proved to be positive when the whole plant material was used as energy feedstock but turned to negative if the residues were left to the field and crop yield was low.
- Rotation 1 had higher energy productivity because it utilized the whole plant material.
- Energy efficiency was higher in the ST/DH for both rotations and all the crops.
- Soybean proved to be more suitable as a second crop than sunflower. Sunflower as second crop may have a negative effect on energy balance.
- In sweet sorghum net energy was high due to high biomass yield but energy efficiency was low due to high energy consumption by irrigation
- The most efficient crops for biomass production were the non-irrigated, low-input winter mixtures of vetch / oats and triticale / peas.

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