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Insight, part of a Special Feature on The Energy-Water Nexus

Energy and Water Use Related to the Cultivation of Energy Crops: a Case Study in the Tuscany Region

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ABSTRACT. The contribution of agrobiomasses, as a source of energy, to the reduction of greenhouse gas emissions was confirmed by several studies. Biomass from agriculture represents one of the larger and more diverse sources to exploit and in particular ethanol and diesel have the potential to be a sustainable replacement for fossil fuels, mainly for transport purposes. However, the cultivation of energy crops dedicated to the production of biofuels presents some potential problems, e.g., competitiveness with food crops, water needs, use of fertilizers, etc., and the economic, energy, and environmental convenience of such activity depends on accurate evaluations about the global efficiency of the production system. In this study, the processes related to the cultivation of energy crops were analyzed from an energy and water cost perspective. The crops studied, maize (*Zea mais*) and sunflower (*Helianthus annuus*), were identified for their different water requirements and cultivation management, which in turns induces different energy costs. A 50-year climatic series of meteorological data from 19 weather stations scattered in the Tuscany region was used to feed the crop model CropSyst for the simulation of crop production, water requirement, and cultivation techniques. Obtained results were analyzed to define the real costs of energy crop cultivation, depending on energy and water balances. In the energy crop cultivation, the only positive energy balance was obtained with the more efficient system of irrigation whereas all the other cases provided negative balances. Concerning water, the results demonstrated that more than 1.000 liters of water are required for producing 1 liter of bioethanol. As a consequence, the cultivation of energy crops in the reserved areas of the region will almost double the actual water requirement of the agricultural sector in Tuscany.

Key Words: *agroenergy; bioethanol; energy balance; pure vegetable oil; water balance*

INTRODUCTION

A large number of studies demonstrate and describe the consequences of global change (IPCC 2001, Stern 2006). The main consequences of global change include higher temperatures, greater precipitation variability with floods and droughts, and increased intensity of tropical cyclones and frequency of extreme events. The increase in greenhouse gas (GHG) emissions due to the use of fossil fuel is considered the main cause of this problem (IPCC 2007).

In Europe, human activities in the energy sector cause approximately 78% of the total GHG emissions and fossil fuels represent the most exploited source of European energy consumption (EC 2006). The potential contribution of biomass as a source of energy, which would in turn contribute to the reduction of GHG emissions, has been investigated and confirmed by several studies (Berndes et al. 2003, EC 2005, Sims et al. 2006, Orlandini et al. 2007, 2008, de Vries et al. 2010). Biomass from agriculture represents one of the largest and most diversified sources to be exploited; in particular, ethanol and diesel deriving from crops are a potentially sustainable means for replacing fossil fuels for transport (Singh et al. 2008, Lechón et al. 2009, Duer and Christensen 2010).

At present, the use of biofuels for transport, which represent 50% of Europe’s energy demand, barely meets 2% of the total needs. Considering total energy needs in Italy, renewable sources provide about 9% of total energy consumption (ENEA 2009). Italy’s bioenergy is provided mainly by the hydroelectric sector (51%) and the utilization of biomass and waste (31%; ENEA 2005).

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More specifically, the economic and environmental advantages of the cultivation of energy crops dedicated to the production of biofuels depend on accurate assessments of the global efficiency of the production system. In fact, the large-scale substitution of biomass for fossil fuels presents several serious implications in terms of competitiveness with food crop cultivation, water requirements, use of fertilizers, and an increase in soil erosion (Fargione et al. 2008, Koh and Ghazoul 2008, de Gorter and Tsur 2010, Lapola et al. 2010). In particular, the quantity and quality of the inputs required represent crucial information for planning energy crop cultivations. Pimentel (2003) analyzed energy inputs and the real cost of ethanol production in every phase of the cycle, as well as environmental impacts. According to Berndes (2002), the expansion of energy crop production that represents specific strategies for climate change adaptation and mitigation influence, could compete with the demand for water resources. According to other studies (Chiu et al. 2009), bioethanol production increases water consumption in many regions of the U.S. and the continued expansion of corn ethanol development will have a significant impact on water sustainability. Recently, a few studies have analyzed the relationship between biofuel consumption and the pressure on water resources. In particular, Gerbens-Leenes et al. (2009) give an overview of the water footprint (WF) of 12 energy crops; the WF of bioethanol appears to be smaller than that of biodiesel. Although biodiesel production using sunflower (*Helianthus annuus*) requires less water input, oil extraction processes are highly energy intensive (Pimentel and Patzek 2005). In Spain, Galan del Castillo and Velazquez (2010) estimated the WF from the raw material production that will be needed to reach the Spanish target for biofuel consumption by 2010. However, an estimate of the energy balance in an entire production cycle, including cultivation, irrigation, feedstock, biofuel conversion, etc., that considers different methods of irrigation and different bioenergy crops, has not yet been investigated in the literature.

Several studies on the estimation of crop growth and development have been based on the application of crop models (Stockle et al. 2003). Different crop growth simulation models have been set up for simulating the production of various crops; in particular the CERES, CROPGRO, and OILCROP process-oriented crop specific models embedded in the Decision Support Systems for Agro-technology Transfer (DSSAT) have been widely used.

In Italy, the CropSyst model (Stokle et al. 2003) is used to estimate crop yield and many studies using this model are found in the literature (Sommer et al. 2008, Garofalo et al. 2009, Tingem et al. 2009). Sunflower seed yield has been analyzed in relation to different irrigation schedules and different sowing periods (Rinaldi et al. 2003), while spatial and temporal variability of yield in wheat (*Triticum* spp.), maize (*Zea mais*), and soybean (*Glycine max*) and the effects of climatic variability have been studied for identifying spatially and temporally stable management zones (Basso et al. 2007). In Tuscany, the CropSyst model has been applied for determining the biomass production in the hilly areas of the region (Moriondo et al. 2007, Orlandini et al. 2008).

In Tuscany, the agricultural lands make up about 700,000 ha, representing 30% of the total surface of the region; the more diffuse crops are cereals and sunflower (http://ius.regione.toscana.it/cif/stat/index-agric.shtml). Agriculture takes up about 20% of total water needs and maize, sunflowers, and vegetables are the crops responsible for the highest water demand (Natali et al. 2009). The energy requirement of the region is about 9000 Ktoe/year and according to Tuscany Regional Energy Plan (PIER 2008), the actual production of electricity from bioenergy is 530 Ktoe. By 2020, the Tuscany administration’s energy production will reach about 838 Ktoe of electricity and 432 Ktoe for thermic energy from renewable resources (Orlando 2008).

The aim of this study is to illustrate the potential production of energy from sunflower and maize cultivated with different water and fertilization supplies in reserved areas of Tuscany, central Italy. The relationship between energy and water in the production of bioethanol and pure vegetable oil were also analyzed to evaluate the sustainability of energy production, taking into consideration energy demand in the Tuscany region. The specific aim was to quantify the impact of the potential production of pure vegetable oil (sunflower) and bioethanol (maize) in terms of energy and water consumption.

METHODS

The study area in Tuscany covers a surface of about 23,000 km², with a varied and complex morphology. The climate is temperate with a mean annual rainfall of 950 mm and a mean temperature of approximately 14.5°C.

Table 1. Principal characteristics of weather stations used in the analysis.

STATION NAME	SOIL TEXTURE	ELEVATION (m)
St1	Sandy clay loam	249
St2	Sandy Loam	280
St3	Silty clay loam	596
St4	Clay sandy loam	380
St5	Sandy clay loam	454
St6	Silty clay	5
St7	Loam	9
St8	Clay Loam	25
St9	Sandy clay loam	38
St10	Loam	362
St11	Silty clay	575
St12	Sandy Loam	1
St13	Sandy clay loam	38
St14	Silt loam	3
St15	Sandy clay loam	88
St16	Clay loam	247
St17	Clay	346
St18	Sandy Loam	132
St19	Silty clay	465

The crop growth model CropSyst was fed into a historical series of meteorological data from 1955 to 2007 coming from 19 stations scattered throughout the region. More specifically, the daily minimum and maximum temperatures, together with precipitation and solar radiation data, were used after quality controls and homogenization via the Craddock test (Craddock 1979, Bartolini et al. 2008).

The CropSyst model, previously calibrated for the study area (Dalla Marta et al. 2010), was adopted to simulate crop yields because it is able to simulate the crop growth and development depending on cultivar, i.e., photosynthetic sensibility, maximum leaf area index, and phenology, etc.; management, i.e., irrigation and fertilization scheduling, sowing dates, etc.; and soil parameters, i.e., texture, depth, nitrogen, and organic matter content, etc.

Two different crops were analyzed in this study: maize and sunflower. A rain-fed system was applied for sunflower whereas irrigation was applied to maize when the available water content (AWC) fell below 35%.

The soil texture for each station was extracted from the Tuscany soil map (Table 1) while soil depth and organic matter content were considered at standard values of 1.10 m and 1.5%, respectively. This assumption was made to consider an "optimal" situation and prevent the quality of the soils from representing a limiting factor for crop productivity.

Crop management was different for the two crops studied. Nitrogen fertilization was applied by local farmers: 180 kg N/ha for maize and 90 kg N/ha for sunflower.

The production over the entire period was investigated by analyzing the averages of more (90th percentile) and less (10th percentile) productive years to have an idea of the possible variation range of crop production under the present climatic conditions for quantifying the interannual variability of productivity notwithstanding the impact of climate change on the yield levels. To this aim, before starting the analysis, all the yield values were processed to eliminate the trend deriving from climate change. This operation was performed by removing the difference between the value of the regression lines of the considered year and the last year of the historical series (2007) from the production of each year.

The results were then processed using Geographic Information Systems (GIS) to obtain a precise numerical estimation of yields for the two crops by considering the exact number of hectares of reserved areas of each regional district. The Inverse Distance Weighted method was used for interpolating crop productivities based on the assumption that the interpolating surfaces are influenced most by the nearby points and less by the more distant points. The interpolating surface is a weighted average of the scatter points, and the weight assigned to each scatter point diminishes as the distance increases from the interpolation point to the scatter point.

Cultivated arable lands were not considered in the study to avoid any competitiveness of energy crops with the regional high-quality food productions, such as durum wheat (*Triticum durum*), grapevine (*Vitis vinifera*), and olive trees (*Olea europaea*), thus giving a more realistic evaluation of the potential production. In fact, the competitiveness between food and energy crops represents one of the major critical points, together with concerns about water use and limiting the spread of energy cultivation. Consequently, all the analyses were carried out taking into account an available land extension equal to the acreages of the reserved lands of the region.

Biomass productions were then converted into biofuel amounts considering a yield coefficient of 0.39 for PVO from sunflower, and 0.30 for bioethanol from maize (Jodice and Pin 2007).

The entire production chain, from crop sowing to biofuel production, was analyzed in terms of water and energy used and/or produced by calculating their total balances. In particular, the processes were divided into different categories (Table 2). The first category considered the energy for transport necessary for field operations of ploughing, harrowing, sowing, weed control, hoeing, fertilization, pesticide treatments, and harvesting. The second category considered the cost of irrigation, both in terms of water applied for yield production and the energy used for its distribution; to analyze these costs, two different irrigation methods were selected based on their different efficiency and different energy consumption. The two systems, both usually adopted for maize irrigation in the study area, were the pivot (efficiency 72.5%, energy 0.64 kWh/m^3) and hose reel irrigators (efficiency 60.0%, energy 0.73 kWh/m^3). The third category took into account the energy stored in the feedstock used for the different processes, in particular in seeds, herbicide (glyphosate), N and P fertilizers (urea and perphosphate), and pesticides. Maize and sunflower have different requirements in terms of field operations, product applications, i.e., fertilizers, herbicides, and pesticides, and mean productivity (Table 3).

Table 2. Different categories considered for the calculation of energy balances of the biofuel production chain.

Cultivation	Ploughing Harrowing Sowing Weed Control Hoeing Fertilization Treatments Harvest
Irrigation	System 1 System 2
Feedstock	Seeds Herbicide N Fertilizer P Fertilizer Pesticide
Processing	Transformation/Transport

Finally, the energy and water used for transforming maize and sunflower biomass into biofuel was also calculated considering a final production of bioethanol and PVO, respectively. The final balances were then calculated as the difference between usable energy produced and energy used for the entire production chain. With regard to water, the balance was only represented by losses due to irrigation and transformation processes because it cannot be considered a product of the production chain. All the balances were calculated considering the productivity of the two crops for the total number of hectares in which they could be cultivated for energy production (ton/ha) to assess the potential contribution of both crops to the regional energy demand and to estimate its cost in terms of energy and water consumption.

Table 3. Agronomic needs and mean productivity of maize and sunflower.

		MAIZE	SUNFLOWER
Sowing Date		15 April	15 April
Fertilization (kg/ha)	N	180	100
	P	46	46
Herbicidal		1 treatment	1 treatment
Irrigation (m³/ha)	pivot	2580	none
	mobile	3118	
Mean Productivity (tons/ha)		8.00	1.20

RESULTS AND DISCUSSION

After removing the trend of climate change impact, an initial analysis was performed to assess the potential biomass obtainable, taking into account the acreages (about 50,000 hectares) of reserved areas of the region and analyzing the 10th (six years with lowest values) and the 90th (six years with highest values) percentile of production for the two crops. With maize, the mean productivity ranged from approximately 6.8 to more than 9.0 tons/ha, whereas for sunflower it varied between 0.8 to approximately 1.6 tons/ha in the lesser and more productive years, respectively (Table 4).

These productivity values, converted into biofuel, correspond to a yield in bioethanol ranging from 2.0 to 2.7 tons/ha, and in PVO ranging from 0.3 to 0.6 tons/ha (Table 4). The results were processed in a GIS for a territorial analysis of the potential availability of biofuels in Tuscany. In particular, productivity was spatially interpolated with the Inverse Distance Weighted technique and recorded on specific thematic maps.

The mean value of productivity obtained for each municipality using the map calculator tool was multiplied by the hectares of reserved lands and then converted into biofuel yields for the 10th and 90th percentile of bioethanol (Fig. 1), and for the 10th and 90th percentile of PVO (Fig. 2). The results demonstrated that the reserved lands of the region have the potential to produce from approximately 102,000 to over 136,000 tons of bioethanol or, alternatively, from approximately 4,700 to over 10,300 tons of PVO.

In Tuscany, the Regional Energy Plan (PIER) indicates that for 2020 the production of energy from biofuels for transportation should reach 108 ktoe to fulfill the targets imposed by the Kyoto Protocol for reducing GHG emissions. Considering the productivity of the two crops, the cultivation of maize in the reserved lands would supply from 50% to 62% of that amount of energy, whereas the cultivation of sunflower would supply an amount ranging from approximately 4% to 9%.

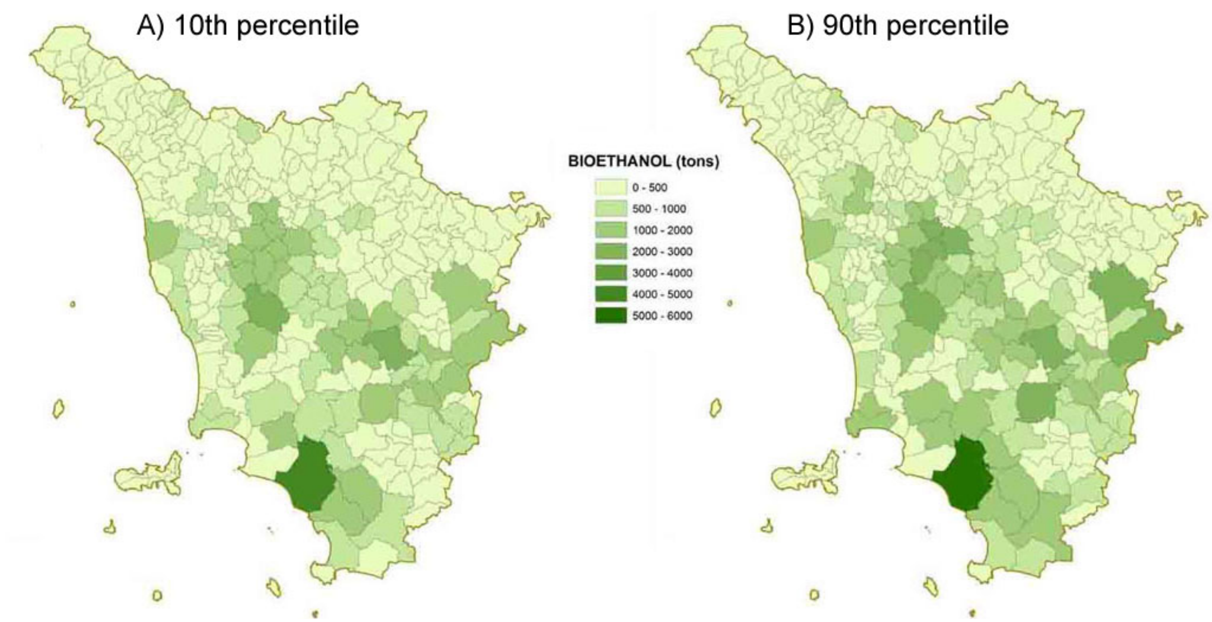
Based on the results obtained, a further analysis was carried out to evaluate the cost, in terms of energy (GJ/ha) and water (m³/ha) consumption, of the biofuel production in the two considered cases for both the 10th and 90th percentile of annual production.

With regard to maize and the two different irrigation systems considered, the only positive balance was obtained with the more efficient system for the 90th percentile of production while all the other cases gave rise to negative balances, indicating that the energy consumed for bioethanol production was greater than the energy obtainable from the biofuel produced (Table 5).

Table 4. Maize and sunflower productivity (ton/ha) simulated with meteorological data of the 19 weather stations in Tuscany, and potential bioethanol and pure vegetable oil obtainable (ton/ha), respectively. Legend: P10 = 10th percentile; P90 = 90th percentile.

LOCATION	MAIZE		BIOETHANOL		SUNFLOWER		PURE VEGETABLE OIL	
	P10	P90	P10	P90	P10	P90	P10	P90
St1	6.46	8.83	1.94	2.65	0.56	1.35	0.22	0.53
St2	5.61	9.15	1.68	2.74	1.05	1.86	0.41	0.73
St3	8.06	10.6	2.42	3.18	0.91	1.91	0.35	0.74
St4	5.60	7.52	1.68	2.26	1.20	1.39	0.47	0.54
St5	7.59	9.52	2.28	2.85	1.10	2.25	0.43	0.88
St6	7.08	8.89	2.13	2.67	0.29	0.43	0.11	0.17
St7	7.09	8.23	2.13	2.47	0.71	1.3	0.28	0.51
St8	6.24	8.41	1.87	2.52	1.06	1.9	0.41	0.74
St9	7.04	8.79	2.11	2.64	1.53	2.13	0.6	0.83
St10	6.82	9.32	2.05	2.79	0.49	1.36	0.19	0.53
St11	6.50	7.69	1.95	2.31	0.33	1.14	0.13	0.44
St12	5.14	7.19	1.54	2.16	0.83	0.95	0.32	0.37
St13	5.9	8.43	1.77	2.53	0.66	1.71	0.26	0.67
St14	7.34	8.44	2.20	2.53	0.34	1.61	0.13	0.63
St15	5.05	8.26	1.51	2.48	1.08	1.67	0.42	0.65
St16	6.40	9.47	1.92	2.84	1.36	2.2	0.53	0.86
St17	11.55	16.91	3.46	5.07	0.50	1.30	0.19	0.51
St18	6.14	7.86	1.84	2.36	0.68	1.39	0.27	0.54
St19	7.24	8.66	2.17	2.60	0.65	1.53	0.26	0.60
MEAN	6.78	9.06	2.03	2.72	0.81	1.55	0.31	0.60

Fig. 1. Maps of 10th and 90th percentile of potential production of bioethanol in the reserved lands of Tuscany.



In detail, the worst case is represented by the 10th percentile of production using the less efficient irrigation system that showed a negative balance of -5.84 GJ/ha. Conversely, when the crop production was at the 90th percentile and a more efficient irrigation system was used, the difference between the required energy and the usable energy was positive.

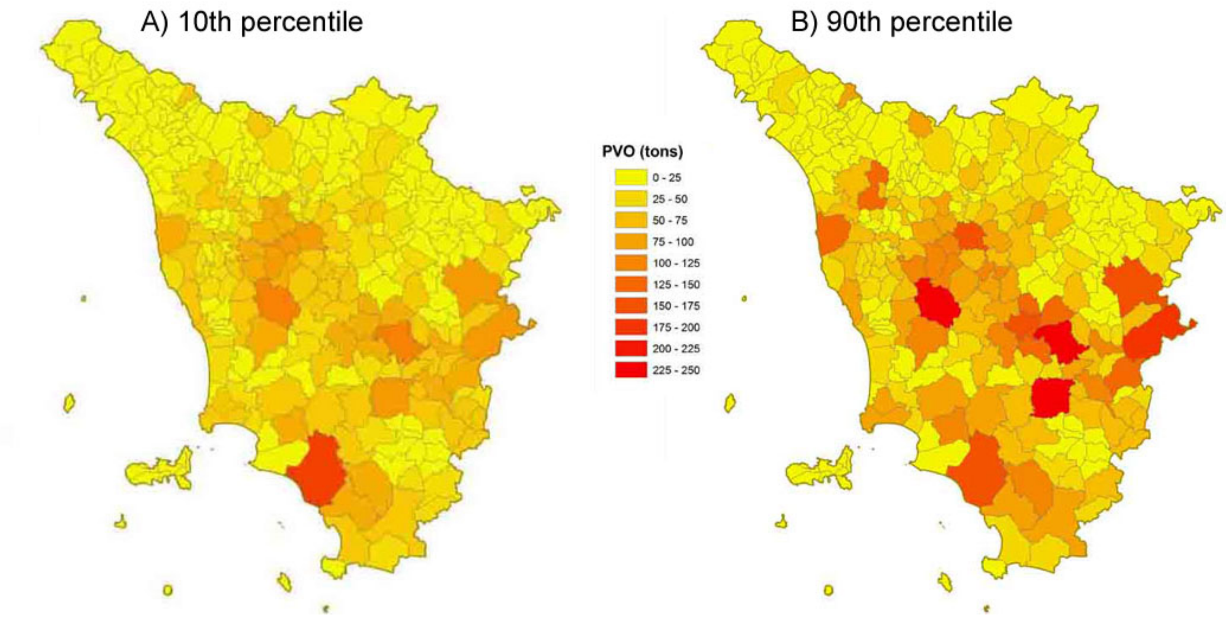
At the same time, the energy balances calculated for PVO production were also negative for both the 10th and 90th percentile (Table 5). In fact, even if sunflower cultivation and transformation into PVO requires less input energy, the final usable energy is also much less with respect to bioethanol. In particular, in comparing the average energy used for producing the two biofuels it can be noted that the production of PVO from sunflower requires about 70% less energy, mainly because of a less intensive use of nitrogen fertilization, the absence of irrigation, and the different processing of raw material into biofuel. Nevertheless, sunflower productivity is much lower compared with maize, also in view of the fact that it was managed as a rain-fed crop, and the quantity of PVO obtained is on average 80% less than the bioethanol obtained from maize.

It must be pointed out that nitrogen fertilization is the main energy input used for cultivating both crops and thus the net energy balance of biomass production can be enhanced by better crop and soil management and a greater understanding of the links between energy, water, climate, and soil. It follows that the application of organic agriculture should lead to smaller values of required energy but this would probably imply a decrease in productivity. Indeed, one of the main environmental concerns about cultivating energy crops is that cultivations should be input-intensive to reach a yield level capable of making the transformation into biofuels economically worthwhile.

With regard to the water used for biofuel production, the calculation was only made for maize because sunflower was considered a rain-fed crop and the water requirements for its biomass transformation into PVO is negligible. In fact, unlike the obtaining of biodiesel, the production of PVO does not require the esterification process.

The results demonstrated that the water requirement for bioethanol production ranged between about 2500 and 3200 m^3/ha considering the cases of the 10th percentile/more efficient irrigation and 90th

Fig. 2. Maps of 10th and 90th percentile of potential production of pure vegetable oil (PVO) in the reserved lands of Tuscany.



percentile/less efficient irrigation, respectively (Table 6). Therefore, by adding water for the processing of raw biomass into bioethanol, the water consumption is 3236.8 m³/ha that corresponds to a total of approximately 158 billion liters of water with regard to the acreage of reserved lands.

Taking into account a production of 2.375 ton/ha of bioethanol (average of the 10th and 90th percentiles) with a specific density of 0.789 g/cm³, the total yield of reserved lands is 147 million liters of biofuel, which means that according to Gerbens-Leenes et al. (2009), about 1.075 liters of water are required for producing 1 liter of bioethanol.

CONCLUSIONS

The challenges posed by climate change call for a profound transformation in the way we use energy and the way we produce energy. Governments around the world have turned to renewable energy technologies to reduce GHG emissions, and the potential of biofuels to curb carbon dioxide emissions, reduce dependence on imported fuels, maintain production, and generate new employment in the agricultural sector has been an important step toward that goal.

In this study we have analyzed the potential production of energy from sunflower and maize in the Tuscan region using different water and fertilization inputs. The results obtained show that the cultivation of energy crops may represent an interesting opportunity for the production of biofuels in Tuscany but great attention should be paid to the choice of crops and the agronomic practices adopted. In particular, the exploitation of abandoned farming areas offers the advantage of avoiding many problems such as competitiveness with food crop cultivation, however, the need for water to irrigate these lands and the energy used for crop production is critical.

The two crops, maize and sunflower, were analyzed to evaluate the alternatives offered by their different requirements in terms of energy and water in relation to the obtainable biofuel. The results demonstrate that the problems relating to water requirements and water availability are negative because of the scarcity of precipitation, the change in temporal distribution, and competitiveness with

Table 5. Energy balances (GJ/ha) calculated for the production of bioethanol from maize biomass and for the production of pure vegetable oil from sunflower biomass. Legend: PERC = percentile.

		MAIZE		SUNFLOWER	
		10th PERC (GJ/ha)	90th PERC (GJ/ha)	10th PERC (GJ/ha)	90th PERC (GJ/ha)
Cultivation	Ploughing	2.80	2.80	2.80	2.80
	Harrowing	0.75	0.75	0.75	0.75
	Sowing	0.43	0.43	0.43	0.43
	Weed Control	0.16	0.16	0.16	0.16
	Hoeing	0.38	0.38	0.38	0.38
	Fertilization	0.11	0.11	0.11	0.11
	Treatments	0.11	0.11	0.11	0.11
	Harvest	2.40	2.40	1.85	1.85
Irrigation				0.00	0.00
	System 1	6.23	6.49		
	System 2	7.53	7.84		
Feedstocks	Seeds	1.57	1.57	0.33	0.33
	Herbicide	0.63	0.63	0.63	0.63
	N Fertilizer	13.20	13.20	7.00	7.00
	P Feertilizer	0.31	0.31	0.16	0.16
	Pesticide	0.70	0.70	0.00	0.00
Processing	Transformation/Transport	31.00	44.00	4.25	8.16
Total Inputs	Required Energy			18.96	22.87
	Required Energy System 1	60.77	74.03		
	Required Energy System 2	57.97	71.23		
Total Outputs	Usable Energy	54.93	73.40	10.95	20.99
Input/Output	Balance			-8.01	-1.88
	Balance System 1	-5.84	-0.63		
	Balance System 2	-3.04	2.17		

other sectors of human activity. These considerations must be analyzed in planning the cultivation of dedicated energy crops for biofuel production and in the choice of cropping techniques.

This study showed that half the regional renewable energy demand in terms of biofuels for traction could be met by the cultivation of irrigated maize, whereas less than 10% could be met by the cultivation of rain-fed sunflower. Nevertheless, the energy balances demonstrated that depending on the crop selected and cropping techniques adopted, the production of biofuel is not currently sustainable in Tuscany, which has clear implications for policy makers in their decisions about renewable energy incentive schemes and related farm policy.

In conclusion, the obtained results showed that the cultivation of sunflower and maize for the production of PVO and bioethanol in reserved areas of Tuscany presents different critical aspects. First, the energy balance is positive only considering the more efficient system of irrigation whereas in the rest of the cases the energy invested is greater than the energy returned. Second, the water need for bioethanol production is too high considering the

Table 6. Water balance calculated for the production of bioethanol from maize biomass considering two different irrigation systems. Legend: System 1 = pivot; System 2 = mobile.

		10th PERC	90th PERC
		(m^3/ha)	(m^3/ha)
Irrigation	System 1	2528.13	2632.67
	System 2	3054.82	3181.14
Processing	Transformation	101.73	135.93
Total		3156.55	3317.06
Method Difference		160.51	

trend and the distribution of precipitation in the region in addition to water requirement of the other productivity sectors. On these bases and considering that the results are partly dependent on the cropping techniques adopted, the cultivation of maize and sunflower for energy production cannot be considered a sustainable choice in Tuscany.

Future research must investigate the economic, environmental, and energetic advantages of cultivating different types of energy crops by analyzing the impact that water storage and distribution for irrigation has on the final bioenergy production. Moreover, different cropping techniques should be investigated, considering first and foremost the energetic cost of nitrogen fertilization. For example, organic farming and the use of compost could represent sustainable strategies. Obviously, in the case of irrigated crops, particular attention must be paid not only to agronomic techniques for saving water, but also to varieties with higher water-use efficiency. At the same time, specific investigations should address alternative sources of biomass, such as forests and pruning residues from vineyards, olive groves, and urban forestry mainly within the territory.

Responses to this article can be read online at:
http://www.ecologyandsociety.org/vol16/iss2/art2/responses/

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