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Environmental effects of energy crop cultivation – results of a long-term field trial

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Abstract. In order to identify crop species for sustainable energy farming it is necessary to determine the significance of genetic, environmental and growing-technical factors. Therefore, in 1994 a long-term practically oriented field experiment on a sandy soil was established to investigate ten annual and perennial plant species and the effects of different N-fertilisation. The measuring programme includes yields, energy gain, N_2O emissions as well as ecologically relevant plant and soil constituents. The results of this 15-year trial confirm the possibility of ecological and energy-efficient production of various energy crop species.

Key words: Energy crop, Yield, Nutrients, Nitrogen, N_2O, Environment, Energy balance

INTRODUCTION

The generation of bioenergy has a key role in current EU strategies in order to contribute increasingly to climate protection and energy security. Energy from biomass offers considerable potential to fulfil these targets due to a wide variety of feedstock, especially energy crops, and conversion technologies. Energy farming on surplus agricultural area presents an opportunity to create alternative income sources aside from food production, to strengthen added value and employment in rural areas. In general, energy crops should have characteristics like high yields, low production inputs and high energy values to make the production of energy from biomass even more economically efficient and to optimise the environmental benefits.

MATERIALS AND METHODS

In order to select environmentally friendly plant species an experimental field was established in northwest Potsdam on a loamy sand soil. The field is divided into 10 long plots of 0.25 ha, which are subdivided into 4 blocks of 624 m^2 each. Block A receives basic mineral fertilisation and 150 kg N ha^{-1}. On blocks B and C, wood- and straw ashes as well as 75 kg N ha^{-1} each are applied. Block D is not fertilised. No plant protection products are used on the entire area (Fig. 1). As fertilisers, 540 or 270 kg ha^{-1} of calcium-ammonium nitrate and 520 kg ha^{-1} of potash-magnesia/super-phosphate mixture, as well as 660 kg ha^{-1} of coarse ashes each from a wood- and a straw combustion plant are used (Scholz, Krüger, Höhn, 2001; Scholz, Ellerbrock, 2002).

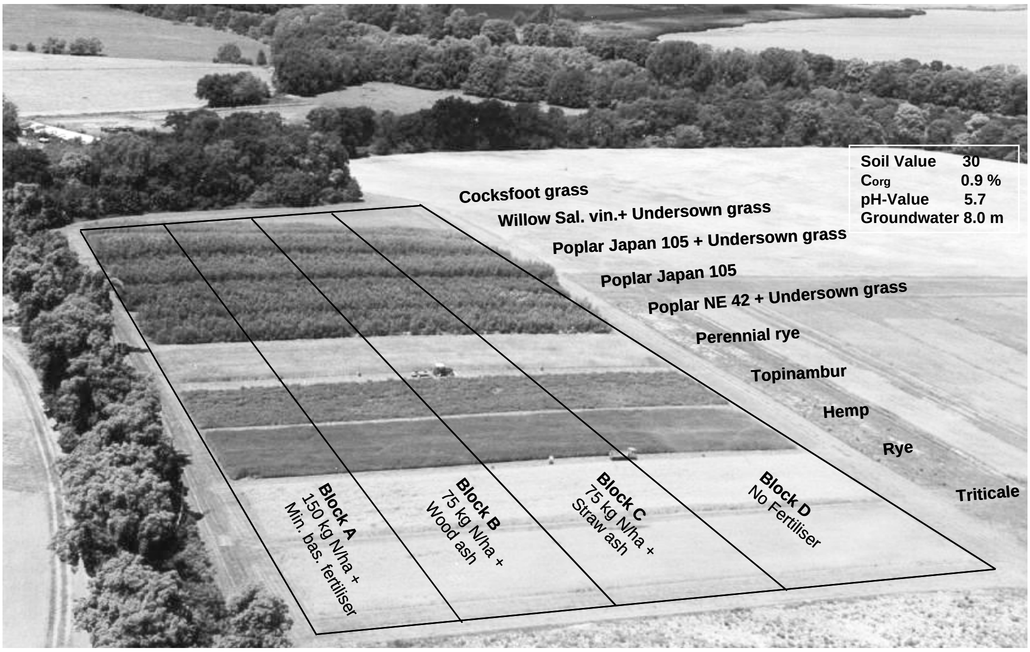

Figure 1. Experimental field

RESULTS AND DISCUSSION

Yield

The yield is the most important parameter determining the environmental and energetic efficiency of the production of energy crops. Related to the measuring period of 8–15 years the highest dry matter (DM) yields in total were measured on the poplar plot Japan 105 (9.1–10.1 t_{DM} ha^{-1}). The undersown grass reduces the average yield by 10–25%. On the intensively fertilised blocks (A), hemp, rye, and triticale also achieve, with 8.3–9.8 t_{DM} ha^{-1}, acceptable whole-crop yields. The originally promising topinambur haulm (Jerusalem artichoke) shows the lowest yield of all crops (Table 1).

The reduction of nitrogen fertiliser causes a loss of yield in all haulm-type crop species. In relation to the conventional N application rate of 150 kg N ha^{-1} the yields of rye and triticale decrease by approximately 10–15% at 75 kg N ha^{-1}, and the complete omission of fertiliser leads to a loss of 30–40% after 15 years. In contrast to these crops, the yields of short rotation coppices (SRC) were reduced only within the first 5–10 years. Later there is nearly no difference between the blocks. The reasons for this ecologically very useful phenomenon have not yet been clarified (Fig. 1).

Even though the use of plant protection products was consistently dispensed with, pest infestation and plant diseases stayed within limits and did not cause any detectable yield depression. Since weeds are usually harvested in total with the energy plants, yield losses in comparison with a weed-free culture are insignificant (Karpenstein-Machan, 2000).

Table 1. Average dry matter yield of the investigated energy crops from 1994–2009.

Plant species	**Number of years** (y)	**Dry matter yield (t (ha^{-1} y^{-1}))**			
		Block A 150 kg N ha^{-1}	Block B 75 kg N ha^{-1}	Block C 75 kg N ha^{-1}	Block D 0 kg N ha^{-1}
Cocksfoot grass	10	8.0	7.2	7.3	5.4
Willow*, Salix 21	14	8.1	7.1	8.0	7.1
Poplar*, Japan 105	14	7.8	7.9	8.7	7.6
Poplar, Japan 105	14	9.9	10.0	9.5	10.1
Poplar*, NE 42	10	5,4	6.5	6.9	6.9
Perennial rye	5	8.5	8.0	7.4	6.1
Topinambur	7	4.2	4.1	3.9	3.3
Hemp	8	9.8	9.1	9.0	7.5
Winter rye	15	8.7	8.1	7.9	6.7
Winter triticale	9	8.3	8.0	7.8	6.0

* with undersown grass

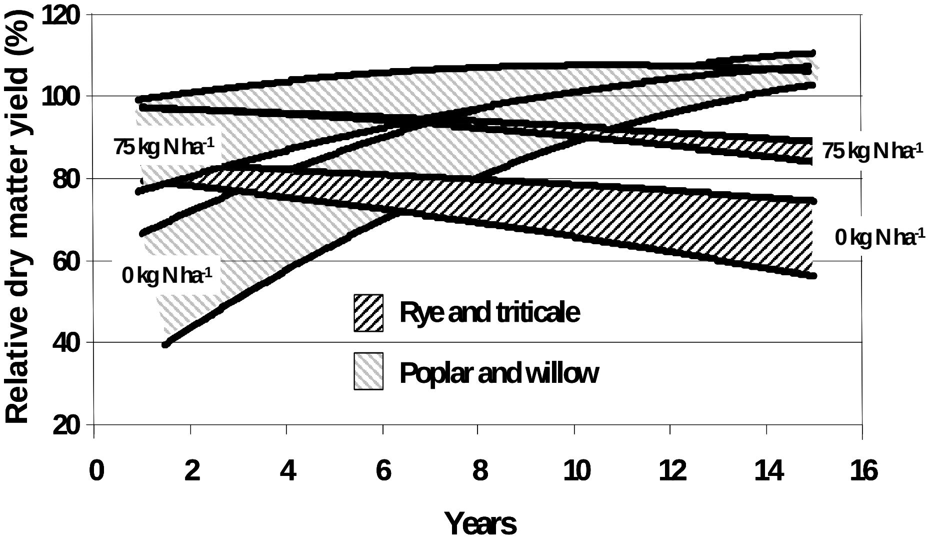

Figure 2. Development of SRC and cereal yield depending on N application rate (related to corresponding yield of 150 kg N ha^{-1})

Environmentally Relevant Plant Nutrients

The environmental relevance of plant nutrients results from both the ecological effects of the fertilisers on the plant and the soil and the emissions during combustion. In order to minimize detrimental effects, different regulations provide limits for environmentally harmful nutrients and heavy metals.

Nitrogen plays an important part in this context because its surplus enters into the ground water, causing the eutrophication of water, and because it emits nitrogenous oxides during cultivation and combustion. The nitrogen (N_t) contents of the investigated crop species exhibit an extraordinary range of variation. Cocksfoot, grain, and hemp reach the highest average N_t contents (0.9 to 1.9%). With 0.4–0.7%, the contents of trees and topinambur haulm are considerably lower (Fig. 3).

The contents of sulphur (S) and chlorine (Cl) are within the range of the values given in the literature (Obernberger 1997; Hartmann, Strehler, 1995; Maier, et.al., 1997; Anonymus, 2000). Only the sulphur content of cocksfoot is higher. In addition, this culture is also characterised by very high chlorine content. The winter-annual grain species and hemp also reach rather high values of 0.11–0.14% sulphur and 0.09–0.13% chlorine. Among all energy plants, the trees have the lowest contents of approximately 0.05% sulphur and 0.01% chlorine.

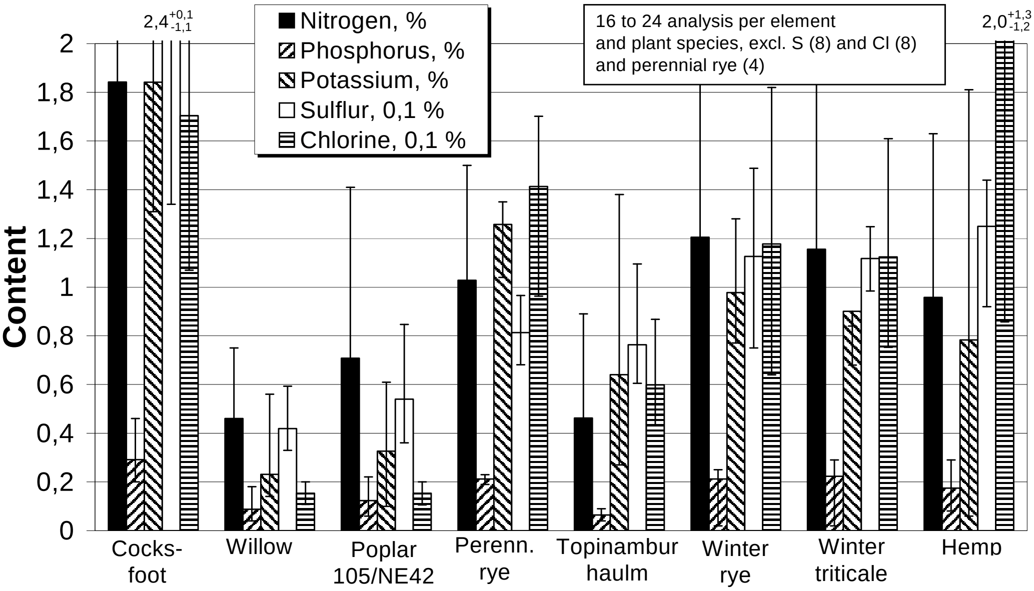

Figure 3. Contents of relevant macro- and micro-nutrients in the investigated energy crops.

Fertiliser-Induced Emissions

There are two sources of gaseous emissions caused by fertilisers: the first is the emissions relevant substances in plants such as nitrogen, phosphorus, sulphur and chlorine. The application of 150 kg nitrogen per hectare causes an average increase in the N_t content of plants of 0.1–0.3% (Scholz, Ellerbrock, 2002). This leads to an increase of nitrous oxide emissions (NO_x) of 10–50 mg m^{-3} during combustion

(Obernberger, 1997), which is significant compared with legal limits ranging from 250–400 mg m^{-3}.

Potassium (P), Sulphur (S) and Chlorine (Cl) also correlate more or less significantly with the amount of fertiliser. During combustion, the sulphur incorporated in the plants enters into the gaseous phase while forming sulphur oxides (SO_2 and SO_3). Depending on combustion conditions, chlorine can result in chloric acid (HCl), different chlorinated hydrocarbons (CHC), and highly toxic polychlorinated dibenzodioxines and dibenzofuranes (PCDD/F). Moreover, both elements favour the corrosion of the heat exchanger pipes in the boiler.

The other source of gaseous emissions caused by nitrogenous fertiliser occurs on the field. As a result of the activity of microorganisms the nitrogen forms nitrous oxide (N_2O), the global warming potential of which is about 300 times more powerful than CO_2. As shown by gas measurements carried out on the mentioned experimental field over several years, the application of 150 kg N ha^{-1} causes an additional quantity of up to 2 kg N_2O-N per hectare and year to be emitted from the soil (Hellebrand, Kern, Scholz, 2003). There is also an influence of the plant species, which partially may be explained by the soil management. Poplar and willow cause significantly less N_2O emissions than cereals. Therefore non-fertilised SRC fields emit only 15–30% N_2O of conventionally fertilised cereal fields (Fig. 4).

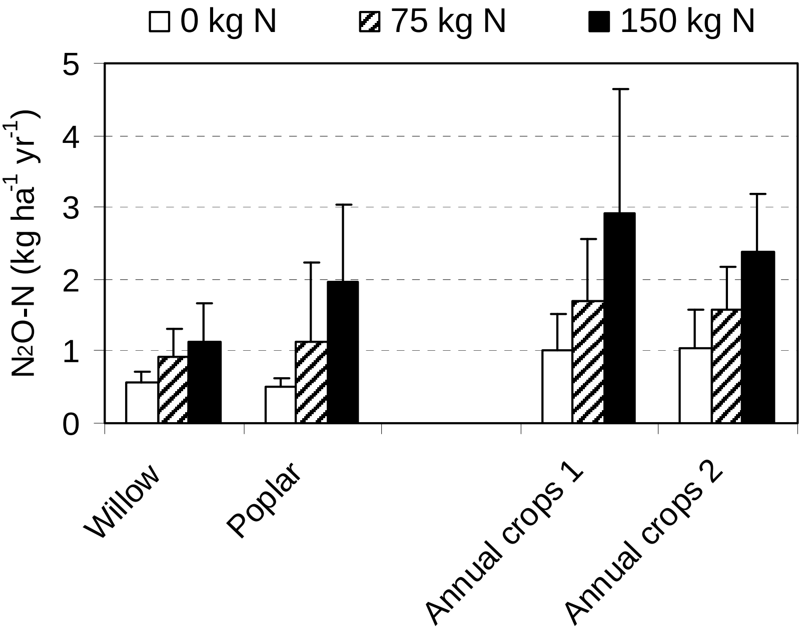

Figure 4. Long-term N_2O emissions of SRC and cereals (1999–2007).

Energy Gain

For the determination of the energetic efficiency and the energy gain of the production and utilization of energy plants, energy requirements and -yields must be established and compared. The cumulated energy demand (ED) is determined using a method which takes all direct and indirect primary energy requirements into account (Scholz, Berg, Kaulfuss, 1998).

The energy yield (EY), which is calculated based on the yield, the calorific value, and the water content of the storable plant material, is dependent upon the plant species, the undersown crop, and the fertilisation. If those experimental plants whose yield is extremely low, such as topinambur haulm and field trees with undersown crops, are disregarded, the energy yield ranges from 100–190 GJ (ha^{-1} y^{-1}) (Tab. 3).

Table 3. Energy demand (ED) and energy yield (EY) of energy crops as a function of fertilisation.

Plant species	**Energy (GJ ha^{-1} y^{-1})**					
	Block A 150 kgN ha^{-1}		Block B/C 75 kgN ha^{-1}		Block D 0 kgN ha^{-1}	
	ED	EY	ED	EY	ED	EY
Cocksfoot grass	13	141	8	130	3	100
Willow*, Salix 21	10	126	5	119	1	90
Poplar*, Japan 105	10	119	5	126	1	112
Poplar, Japan 105	10	178	5	166	1	173
Poplar*, NE 42	10	85	5	112	1	107
Perennial rye	11	147	7	133	2	105
Topinambur	12	71	8	68	2	55
Hemp	13	191	9	176	4	152
Winter rye	14	154	9	144	4	121
Winter triticale	14	153	9	151	5	116

* cultivated with undersown grass

In contrast to other renewable energy sources, however, the decisive criterion in the case of energy plants is energy gain rather than the input/output relation because the availability of cultivation areas is limited. Independent of the fertilisation variant, the annual (net-) energy gain (EG), which results from the difference of energy demand (ED) and -yield (EY), ranges between 97–178 GJ ha^{-1} y^{-1} for grain, cocksfoot, and hemp. With 161–172 GJ ha^{-1} y^{-1}, the poplar clone Japan 105 without undersown grass also achieves rather high energy gains. With the exception of poplar, the energy gain without fertilisation (block D) is only up to 24% lower as compared with intensive fertilisation (block A). The differences between intensive and reduced fertilisation (block B/C) are even smaller.

CONCLUSIONS

The results of a 15-year field trial with various energy crop species on a poor sandy soil in Germany show that fertiliser application can be reduced significantly and pesticides can generally be dispensed with. On a high fertilisation level, the mean yields of above-ground biomass range between 4.2–9.9 t_{DM} ha^{-1}. Hemp, poplar and whole crop cereals reflect the highest yields. If fertiliser application is reduced from 150 to 75 kg N ha^{-1}, the yield diminishes by 10–15% after 15 years, and without any fertilisation, it is reduced by approximately 30–40%. Poplar and willow (SRC) show a contrary trend: they need some N fertiliser only in the first few years. The poplar clone Japan 105 guarantees high, secure yields of about 10 t_{DM} ha^{-1} y^{-1} even without fertiliser.

From the environmental and the energetic point of view, the application of 150 kg N ha^{-1}is generally inefficient. However, sustainable high energy yields are realised by applying 75 kg N ha^{-1} and in some cases (SRC) even less. With the exception of topinambur haulm and trees with undersown crops, the net energy gains, achieved with reduced nitrogen fertilisation, range between 122 and 167 GJ ha^{-1} y^{-1}, corresponding to 2.9–4.0 tOE (tonnes oil equivalent) per hectare and year. In the unfertilised block, poplars reach approximately 172 GJ ha^{-1} y^{-1} (4.1 tOE ha^{-1} y^{-1}).

In addition to their high energy yield and their low demand for fertilisers and pesticides, SRC provide a set of further advantages. With mean contents of $\leq$ 0.7% nitrogen, $\leq$ 0.06% sulphur, and $\leq$ 0.01% chlorine, they belong to those energy crop species which cause the lowest environmentally harmful emissions during combustion and gasification. Furthermore they cause less climate effective nitrous oxide emissions during cultivation. Non-fertilised SRC fields emit only 15–30% of the N_2O of conventionally fertilised cereals.

Labour-management-related and economic advantages of SRC are the harvest time in winter, the free choice of the harvest intervals between two and 20 years. The relevant advantage, however, is that wood is a fuel for which proven combustion technologies with minimised emission rates are already available on the market.

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