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Comparative Performance of Annual and Perennial Energy Cropping Systems Under Different Management Regimes

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To the polar bears of this world

Contents

Summary

The theme of this thesis was chosen against the background of the necessary substitution of fossil fuels and the need to reduce greenhouse gas emissions. One major solution for these topics may be the energy generation from domestically produced biomass. The overall aim of this thesis was the identification of one or more efficient energy cropping systems for Central Europe. The target was set to supply high quality biomass for existent and currently developing modern conversion technologies.

Renewable energy production is thought to be environmentally benign and socially acceptable. The existence of diverse production environments necessitates further diversification and the identification of several energy crops and the development of energy cropping systems suited to those diverse environments.

This thesis starts with an introductory essay (chapter 1), which provides the background for renewable energy production, its features, demands and potentials, and the scientific basis of this thesis. Chapters 2 to 6 consist of five manuscripts to be published in reviewed journals (Papers I, II, IV and V) or in a multi-author book (Paper III). Subsequently, the results from all papers are discussed in a general setting (chapter 7), from which a general conclusion is formulated (chapter 8).

The basis of the research formed four field experiments, which were conducted at the experimental sites Ihinger Hof, Oberer Lindenhof and Goldener Acker of the University of Hohenheim, in south-western Germany.

Paper I addresses the overall objective of this thesis. Selected cropping systems for this experiment were short rotation willow, miscanthus, switchgrass, energy maize and two different crop rotation systems including winter oilseed rape, winter wheat and winter triticale with either conventional tillage or no-till. The systems were cultivated with three different nitrogen fertilizer applications. An energy balance was calculated to evaluate the biomass and energy yields of the different cropping systems. Results indicate that perennial lignocellulosic crops combine high biomass and net energy yields with low input and potential ecological impacts. Switchgrass, which produced low yields at the study site, may better perform on marginal sites. Switchgrass is an example of the need to grow site-adapted energy crops. The annual energy crop maize required the highest input, but at the same time yielded the most. The two crop rotation systems did not differ in yield and energy input, but the system with no-till may be more environmentally benign as it has the potential to sequester carbon.

The objective of **Paper II** was the optimization of crop cultivation through the differentiation of input parameters to enhance the quality of the energy crop triticale, without influencing the biomass yield. The intention was to minimize the content of combustion-disturbing elements (potassium and chlorine) and the ash residue of both aboveground plant

parts (grain and straw). It was done through different straw and potassium fertilizer treatments. It could be shown that the removal of straw from the previously cultivated crop and no additional potassium fertilizer could reduce the amount of combustion-disturbing elements. A high influence must also be expected from site and weather conditions.

Papers III to V address the supply of different high quality biomasses, with the focus on maize for anaerobic digestion. The objective of **Paper III** was the assessment of the requirements of biogas plants and biomass for anaerobic digestion. It introduces potential energy crops, along with their advantages and disadvantages. Alongside maize, many other biomass types, which are preserved as silage and are high in carbohydrates and low in lignocelluloses, can be anaerobically digested. The development of potential site-specific crop rotation systems for biomass production are discussed.

The objective of **Papers IV and V** was the identification of suitable biomass and production systems for the anaerobic digestion. The focus lay on the determination of (i) suitable energy maize varieties for Central Europe, (ii) optimal growth periods of energy crops, (iii) the influence of crop management on quality parameters and (iv) environmentally benign crop rotation systems. Differently maturing maize varieties were grown in six different crop rotation systems (continuous maize with and without an undersown grass, maize as a main crop partially preceded by different winter catch crops and followed by winter wheat) and tested at two sites. Additional factors were sowing and/or harvest dates. Maize and cumulative biomass yields of the crop rotation systems were compared. Specific methane yield measurements were carried out to evaluate the energy performance of the tested crops. Quality was assessed either by measurements of the dry matter content or by using the near infrared reflectance spectroscopy for the determination of chemical composition. Results indicate that an environmentally benign crop rotation system requires nearly year-round soil cover to minimize nitrogen leaching. This can be achieved through the cultivation of undersown or catch crops and additional main crops alongside maize, such as winter wheat. Late maturing maize varieties can be cultivated at a site where the maize can build adequate dry matter contents due to a long growth period (late harvest date). The energy generation in terms of methane production was primarily dependent on high biomass yields. It could be further shown that the specific methane yield of maize increased with increasing starch content, digestibility and decreasing fiber content.

To conclude, selected site-specific energy crops and crop rotation systems, with suitable crop management, (fertilizer and soil tillage) can produce high quality biomass and the highest net energy return. Lignocellulosic biomass can be optimized for combustion. Wet biomass is an optimal substrate for anaerobic digestion. Profitable energy production is characterized by a high land and energy use efficiency and especially high net energy yields.

Zusammenfassung

Das Thema der vorliegenden Arbeit wurde vor dem Hintergrund der derzeit stark nachgefragten und begünstigten Produktion erneuerbarer Energieträger gewählt. Einheimische Biomassebereitstellung kann einen Beitrag zur Ergänzung endlicher fossiler Energieträger und zur Minderung des Ausstoßes klimarelevanter Gase leisten. Das zentrale Ziel der Arbeit war es, qualitativ hochwertige Biomasse für existente und sich in der Entwicklung befindliche moderne Energiekonversionsverfahren zur Verfügung zu stellen. Unterschiedliche Standortbedingungen erfordern differenzierte Lösungsansätze. Die Ermittlung von standort-angepassten Kulturen und Fruchtfolgesystemen stellte einen wichtigen Punkt zur nachhaltigen Produktion hoher Biomasse- und Nettoenergieerträge dar.

Das einleitende Kapitel zur Arbeit erläutert die Hintergründe für die Produktion erneuerbarer Energierohstoffe, seine Besonderheiten, Voraussetzungen und Potentiale. Die wissenschaftliche Fragestellung wird formuliert. Die Arbeit basiert auf fünf Manuskripten, die zur Veröffentlichung in internationalen Fachzeitschriften (Manuskript I, II, IV und V) und in einem Lehrbuch (Manuskript III) vorgesehen sind. In der anschließenden Diskussion (Kapitel 7) und Schlussfolgerung (Kapitel 8) werden die gewonnenen Ergebnisse zusammengefasst und in einer abschließenden Stellungnahme bewertet.

Die Basis der Untersuchung bildeten vier Feldversuche, die auf Versuchsstationen der Universität Hohenheim (Ihinger Hof, Oberer Lindenhof und Goldener Acker) durchgeführt wurden.

Das **Manuskript I** behandelt das allgemeine Thema dieser Arbeit. Ausgewählte Anbausysteme für die Untersuchung waren Kurzumtriebsweide, Miscanthus, Rutenhirse, Energiemais und zwei unterschiedliche Fruchtfolgen mit Winterweizen, Wintertriticale und Winterraps mit konventioneller Bodenbearbeitung oder Direktsaat. Die Kulturen wurden mit drei unterschiedlich hohen Stickstoffgaben gedüngt. Die Bewertung der Biomasse- und Energieerträge wurde anhand einer Energiebilanz durchgeführt. Die Ergebnisse zeigen, dass mehrjährige lignocellulosehaltige Kulturen hohe Biomasse- und Nettoenergieerträge bei wenig Input und ökologischen Auswirkungen liefern können. Rutenhirse mit geringer Ertragsleistung an dem getesteten Standort ist ein Beispiel für die Voraussetzung des Anbaus standortangepasster Kulturen. Die einjährige Art Energiemais erzielte die höchsten Biomasseerträge, benötigte aber auch hohen Energieinput. Die zwei Fruchtfolgesysteme unterschieden sich nicht im Ertragsverhalten und den Nettoenergieerträgen.

Das Ziel von **Manuskript II** war die Optimierung von Qualitätseigenschaften von Energietriticale durch unterschiedliche Bestandesführung. Die Intention war die Minimierung von verbrennungsrelevanten Inhaltstoffen wie Kalium, Chlor und Asche beider Pflanzen-

partien (Korn und Stroh) durch unterschiedliche Stroh- und Kaliumbehandlungen. Es konnte gezeigt werden, dass die Abfuhr von Stroh der Vorfrucht und keine weitere Kaliumdüngung zu reduzierten Inhaltsstoffen in beiden Erntegütern führte.

Die **Manuskripte III** bis**V** befassen sich mit der Bereitstellung von Biomasse für die anaerobe Vergärung. Das Ziel von **Manuskript III** war die Erfassung der Anforderungen an Biomasse für die anaerobe Vergärung und die Vorstellung potentieller Kulturarten. Biomassen mit hohen Gehalten an Kohlenhydraten und geringen Gehalten an lignocellulosehaltigen Verbindungen sind geeignet. Das Kapitel schließt mit der Entwicklung standortangepasster Fruchtfolgen.

Das Ziel der **Manuskripte IV** und **V** war die Ermittlung geeigneter Biomassen für die anaerobe Vergärung. Der Fokus lag auf der Bestimmung von (i) geeigneten Maissorten für Mitteleuropa, (ii) optimalen Wachstumsperioden der getesteten Energiepflanzen, (iii) Einflüssen pflanzenbaulicher Maßnahmen auf Qualitätseigenschaften und (iv) umweltverträglichen Anbausystemen. An zwei Standorten wurden sechs Fruchtfolgesysteme (Mais Monokultur, Mais mit Untersaat, Mais mit Winterzwischenfrüchten und Winterweizen) und unterschiedlich reifende Maissorten geprüft. Saat- und Erntezeitpunkte wurden variiert im Hinblick auf differenzierte Biomassequalität und –quantität. Spezifische Methanertragsmessungen der geprüften Kulturen wurden zur energetischen Bewertung herangezogen. Die Qualität der Biomasse wurde über den Trockensubstanzgehalt und über Inhaltsstoffmessungen mittels der Nahinfrarot-Spektrometrie ermittelt. Die Ergebnisse zeigen, dass eine intensive Fruchtfolgegestaltung mit Winterzwischenfrüchten, Mais und Winterweizen über eine möglichst ganzjährige Bodenbedeckung ökologische Probleme wie Erosion und Nitratauswaschung mindern kann. An Standorten mit ausreichend langer Vegetationsperiode sind spät reifende Maissorten mit der Bildung optimaler Trockensubstanzegehalte den früh reifenden Sorten überlegen. Der Energieertrag (Methanertrag) ist hauptsächlich von einem hohen Biomasseertrag abhängig. Die Inhaltsstoffanalyse zeigte, dass mit zunehmender Verdaulichkeit, steigendem Gehalt an Stärke und abnehmendem Gehalt an Fasern der spezifische Methanertrag von Mais anstieg.

Abschließend lässt sich festhalten, dass ausgewählte standort-spezifische Energiepflanzen und Fruchtfolgesysteme mit entsprechenden pflanzenbaulichen Maßnahmen zu einer guten Nutzung der eingesetzten Ressourcen, hoher Biomassequalität und hohen Nettoenergieerträgen führen. Lignocellulosehaltige Biomasse eignet sich besonders für die Verbrennung oder neue innovative Konversionsverfahren, während feuchte Biomasse gut für die anaerobe Vergärung genutzt werden kann.

Eine wirtschaftliche Energieproduktion ist durch eine hohe Land- und Energienutzungseffizienz, sowie durch hohe Nettoenergieerträge gekennzeichnet.

1. Introduction

The world's fossil fuel reserves are limited. Global warming is proceeding considerably faster than long thought (IPCC, 2007). Anthropogenic carbon dioxide emissions must be reduced to at least 5 % below the 1990 level (KYOTO PROTOCOL, 1998). Sustainable systems are needed to reduce overall mitigation costs and to increase reductions in greenhouse gas emissions (IPCC, 2005). Finding a solution for these problems is not impossible. Since millennia, biomass has been known to be an abundant, renewable, energy source. Newly produced biomass takes up CO_2 from the ambient air. During usage of the produced energy carriers, a certain percentage of the carbon, which is emitted, stems from formerly crop-absorbed carbon. Knowledge about renewable energies was nearly lost over the course of the last century, due to the abundance of fossil fuels. The context of biomass production has changed considerably over the years and is, today, totally different than it was a century ago.

Against this background, the theme of this thesis was chosen: Energy production from domestic biomass cultivation with the overall aim of identifying one or more efficient energy cropping systems for Central Europe. The target was to supply high quality biomass for existent and currently developing modern conversion technologies.

1.1. Policies and background for renewable energy production

The production of agricultural biomass is one means with which to meet the rising demand of renewable energy sources. Agriculture is thought to have a huge potential to supply biomass for energy generation (Table 1.1). Biomass can be converted into electricity, heat and transport fuel, thus it is able to contribute to all energy needs (CEC, 1997). The implementation and expansion of renewable energy production is strongly promoted by the EU (CEC, 1997, 2000, 2003, 2005a, 2005b, 2006). It has set an indicative target to raise the overall share of renewable energy sources of the total energy consumption in the EU to 12 % by 2010. The market share of transportation biofuels is targeted to be 5.75 %, whereas the share of renewable energies in electricity generation is targeted to be 21 %. Meeting the target of 12 % of the 1606 mtoe (million tonnes of oil equivalent) gross inland consumption in the EU-25 by 2010 means that approximately 7 to 13 % more agricultural land will be needed for bioenergy production than is used today (JENSEN, 2003).

Renewable energy production has many different faces. It is not only a substitution for fossil fuels, but also has the potential to mitigate global environmental problems.

Table 1.1
Biomass consumption in mtoe [a] and environmentally-compatible [b] biomass production potential in the EU-25 (EEA, 2005)

mtoe [a]	2003 (Biomass consumption)	2010 (Potential)	2020 (Potential)	2030 (Potential)
Forest wood (increment and residues)	67 [c]	43	39-45	39-72
Organic wastes, wood industry residues, agricultural and food processing residues, manure		100	100	102
Energy crops from agriculture	2	43-46	76-94	102-142
Total	69	186-189	215-239	243-316

[a] Million tonnes of oil equivalent.
[b] No additional pressures on biodiversity and soil and water resources, further reduction in greenhouse gas emissions.
[c] Figure as a sum of both forest wood and wastes/ residues.

Renewable energy production is thought to be environmentally benign and socially acceptable. Greenhouse gas (GHG) emissions are identified as the leading cause of global warming (IPCC, 2001). The substitution of fossil fuels with renewable energy sources has a major potential to reduce GHG emissions (PAUSTIAN et al., 1998; SAUERBECK, 2001; SCHNEIDER and MCCARL, 2003; DORNBURG et al., 2005; DORNBURG et al., 2007). Energy production from agricultural land is also seen as an instrument for carbon sequestration. The potential for sequestration and mitigation is promoted not only through the substitution of fossil fuels, but also through diverse agricultural management procedures, such as the cultivation of perennial energy crops and the adoption of no-till agricultural systems (SMITH et al., 2000; SMITH et al., 2001; ZAN et al., 2001; VLEESHOUWERS and VERHAGEN, 2002; BARAL and GUHA, 2004). Environmental benefits of biofuel production will become more apparent when agricultural management is adjusted to energy production and not continued as it is today. Then, energy can be produced without major environmental impacts (HILL, 2007). Economic development of rural areas and energy supply security is thought to be enhanced by biofuel production (IEA, 2004). At the same time, pressure on agricultural land will rise with increasing biomass production and the resulting competition with food and fodder production (KEITH, 2001). According to VENTURI and VENTURI (2003), renewable energy production will not be limited by energy input parameters or by conversion technologies but by limited land. Prices for food and fodder may rise when land is removed from fodder production (IEA,

2004). Intensive renewable energy production is economically favorable but may have ecological impacts. It was observed by GREEN et al. (2005) that with increasing yields, biodiversity declines, but at the same time a decrease in the conversion of natural areas to agricultural land has been observed.

Modern renewable energy production is primarily driven by policies (see the different policy papers of the EU) and has a regional orientation. The production of biofuels is promoted differently by individual European member states. This has resulted in biodiesel production in Germany and bioethanol production primarily in the southern European countries (SLINGERLAND and VAN GEUNS, 2005). Today, most of the production is of first-generation biofuels, which rely on long-established forage crops that are rich in sugar, starch or oil and only make use of some of the plant's parts (Fig. 1.1.). Biofuels made out of these crops are not cost-competitive with fossil fuels and rely on fossil fuels to be converted into biofuels. Future prospects include new conversion technologies (Fischer-Tropsch-Synthesis) and second-generation biofuels that are based mainly on lignocellulosic crops whose total aboveground biomass can be used (CEC, 2006; FAAIJ, 2006) (Fig. 1.1.). However, these crops will only have a notable share of biofuel production after 2010.

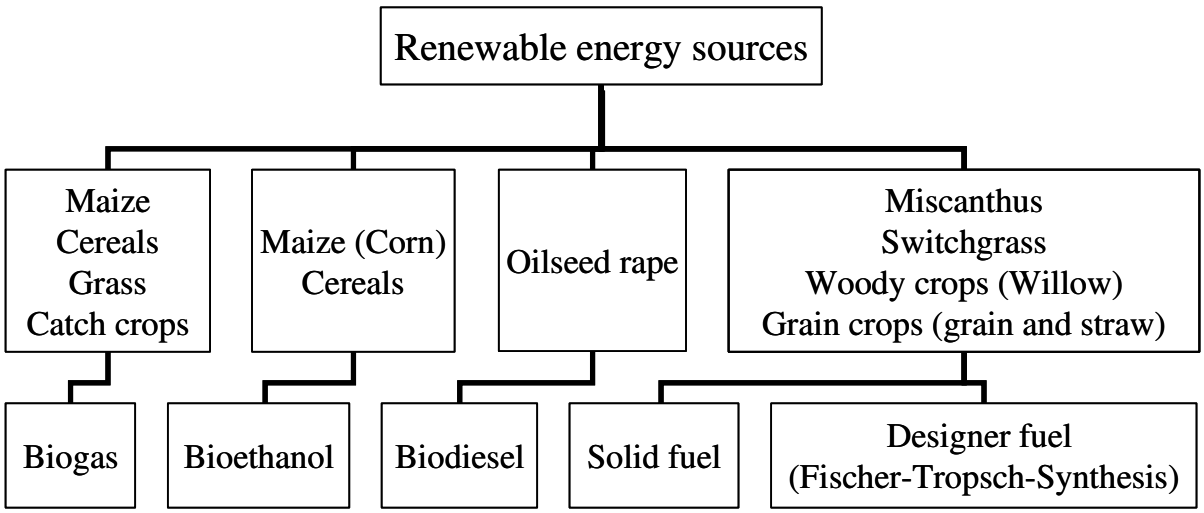

Fig. 1.1. Energy crops and corresponding possible energy types that can be produced in Central Europe. All these energy crops were grown in the field experiments.

Germany was identified as a state in the EU that is highly effective in renewable energy production through the application of feed-in tariffs (CEC, 2005a; GAN et al., 2007). With amendment and commencement of the Act on Granting Priority to Renewable Energy Sources (Renewable Energy Sources Act) in Germany, on 1st August 2004, a new incentive

was created for German farmers to become energy suppliers by generating heat and power via biogas production and a combined heat and power unit. Since the commencement of the implementation of the act, the number of biogas plants and the accumulated power of combined heat and power units has increased manifold and with it the need for substrates for anaerobic digestion. Today, silage maize is primarily used as a co-substrate, alongside liquid manure. Due to ecological concerns with continuous maize production, there is a demand for other energy crops for anaerobic digestion (HERRMANN and TAUBE, 2006). KARPENSTEIN-MACHAN (1997; 2002) developed the so-called "double-cropping systems" that produce high biomass yields with low inputs and have the potential for year-round soil cover. These systems are supposed to be environmentally benign and to maintain biodiversity (KARPENSTEIN-MACHAN, 2004).

1.2. Optimizing energy production from agriculture

The European countries are heterogeneous in many ways and differ in their opportunities for biomass production. Thus, bioenergy production must be investigated and optimized on a regional level. The potential biomass supply from agricultural land has been found to be greater than from forest land. Currently, forest biomass is dominating the supply, but it will be outpaced by agricultural biomass in the near future (ERICSSON and NILSSON, 2006).

The improvement of site-specific cropping systems is a key factor for the realization of efficient energy crop production (SMEETS et al., 2007). Biomass production for first-generation biofuels must be further improved and at the same time biomasses for second-generation biofuels must be optimized and evaluated for the future bioenergy supply. The question, which energy crop in which cropping system is best suited for Germany and Central Europe, becomes very important. The answer cannot consist of only one crop or cropping system because of the many different conversion technologies that exist and the different energy types that must be supplied. The existence of diverse production environments necessitates further diversification and the identification of several energy crops and the development of energy cropping systems suited to those diverse environments. This need is the scientific basis for this study.

Potential suitable energy crops for Central Europe are:

- Perennial C_4 rhizomatous grasses (such as miscanthus and switchgrass) have high yield potentials (LEWANDOWSKI et al., 2003a; HEATON et al., 2004).

- Woody crops, grown as short rotation coppice, such as willow and poplar, are sustainable in productivity and enhance biodiversity and rural development (KAUTER et al., 2003; VOLK et al., 2004).
- Silage maize (energy maize) was recently discovered as a high-yielding energy crop for anaerobic digestion. (HERRMANN and TAUBE, 2006; AMON et al., 2007).
- Oilseed rape is a long-established energy crop in Europe. Broad knowledge about its production, easy recovery of the oil-containing plant parts and acceptable oil quality have made it the leading oil crop for biodiesel production in Germany (KÖRBITZ, 1999; UFOP, 2007).
- Cereals such as winter wheat and triticale are widely established food and fodder crops that can be grown in a wide range of environments, while delivering average biomass yields (ALBRECHT, 1998; KAUTER et al., 2002; LOYCE et al., 2002).

In a crop rotation system, factors such as the different crops and varieties grown and the cultivation management applied, can be altered. Tillage is recognized to have major impacts on the performance of crop rotation systems. No-till systems have, in the middle to long term, no influences on the yield (EHLERS and CLAUPEIN, 1994), but might be more energy, time and cost saving compared to systems with conventional tillage (KÖLLER, 2003). No-till systems have the potential to improve soil qualities and increase soil fauna (SHUSTER and EDWARDS, 2003). These attributes correspond well with the mentioned targets of renewable energy production.

A further step in the optimization process is to evaluate the selected energy crops and crop rotation systems. Different instruments can be used to assess the suitability of a crop or crop rotation system:

- Conduction of a field experiment: This is the first means with which to assess the site-specific biomass yield, and to determine the ideal production intensity and the appropriate crop management procedures for the different biomass quality parameters.
- Calculation of an energy balance: This indicates whether a production system returns more energy than it consumes and shows how much input is required for one unit of energy output. The net energy yield can be assessed.
- Analysis of the biomass composition: This includes the determination of the dry matter content of the biomass, in order to ensure an unproblematic transport and a long shelf life and the determination of the chemical composition. Diverse chemical elements are wanted or unwanted in the subsequent energy conversion.

1.3. Research focus and objectives

This research focused on high quality and sustainable biomass production for energy generation in Germany and Central Europe. The general aim was to identify energy crops (annual and/or perennial) and crop rotation systems that are highly productive in biomass and energy yield and that have acceptable environmental impacts. Their suitability as contributors to the renewable energy supply was tested with the given site-specific soil and climate conditions. Variable parameters of crop management were fertilizer supply and tillage, to assess the optimal energy requirements and crop qualities.

The objectives of this study were:

- The direct comparison of the performance of different perennial and annual energy cropping systems under different management intensities for modern conversion technologies (Paper I).
- The evaluation of energy cropping systems through the calculation of an energy balance (Paper I).
- The optimization of cultivation through the differentiation of input parameters to either enhance the productivity (Paper I) or the quality of harvested biomass (Paper II) of energy cropping systems.
- The assessment of the overall requirements of biomass for anaerobic digestion (Paper III).
- The identification of an environmentally benign and sustainable crop rotation system for the supply of biomass for anaerobic digestion (Paper IV).
- The simultaneous optimization of the quality and quantity of biomass (energy maize) for anaerobic digestion (Papers IV and V), using near-infrared reflectance spectroscopy (Paper V).
- The assessment of the potential energy yield (methane) from anaerobically digested biomass (Papers IV and V).

Four field experiments were conducted in south-western Germany at three sites (Ihinger Hof, Oberer Lindenhof and Goldener Acker). Different potential perennial and annual energy crops and cropping systems were tested. All selected major energy crops and cropping systems are introduced in Paper I. Papers II , IV and V focus on special attributes of single or multiple energy crops based on the selection made in Paper I. Paper III introduces further energy crops, which have not been tested in field experiments. Selected species and varieties were as follows:

- Short rotation willow coppice (*Salix schwerinii* E. Wolf x *viminalis* L.) 'Tora'
- Miscanthus (*Miscanthus* x *giganteus* Greef et Deu.)
- Switchgrass (*Panicum virgatum* L.) 'Kanlow'
- Winter oilseed rape (*Brassica napus* L. ssp. *oleifera*) 'Elektra'
- Winter wheat (*Triticum aestivum* L.) 'Transit', 'Hybred'
- Winter triticale (*Triticale* x *triticosecale* Wittmack) 'Lamberto'
- Energy maize (*Zea mays* L.) varieties 'Gavott', 'Mikado', 'KXA5226', 'Deco', 'Lucatoni', 'Méridienne', 'Doge', 'Pollen', 'Mahora', 'PR39F58', 'PR37D25', 'PR36K67', 'Eminent'
- Italian ryegrass (*Lolium multiflorum* Lam.) 'Jeanne'
- Winter turnip rape (*Brassica rapa* L.) 'Lenox'
- Winter rye (*Secale cereale* L.) 'Protector'
- Perennial ryegrass (*Lolium perenne* L.) 'Barylou', 'Lisuna'
- Forage millet (*Sorghum bicolor* (L.) Moench) 'Rona 1'.

1.4. Introduction to the Papers

This study is based on the five papers that make up chapters 2 to 6. Each paper presents the objectives, materials and methods and results of the experiments. They are closed with a discussion of and conclusion based on the obtained results. A list of the cited references is attached to each paper. The papers are to be published in peer reviewed Journals (Papers I, II, IV and V) or in a multi-author book (Paper III). Subsequently, the results from all papers are discussed in a general setting (chapter 7) and a general conclusion is formulated (chapter 8). A list of all cited references is included (chapter 9).

The numeration of the sections, tables and figures of the five manuscripts (introduction to conclusion) was retained in the original order for every paper and may differ from the overall layout.

Paper I

Comparing annual and perennial energy cropping systems with different management intensities

Motivation: Different annual and perennial energy cropping systems have not previously been grown at one site and compared with different management intensities.

The aim of this field experiment was the comparison and evaluation of biomass and net energy yields of perennial (willow, miscanthus and switchgrass) and annual (energy maize, winter wheat, winter triticale and winter oilseed rape) energy cropping systems at one site. The crops were grown with three different levels of nitrogen fertilization to identify the optimum level between input (nitrogen fertilizer, energy consumption) and output (biomass or net energy yield). The annual energy crops, with the exception of maize, were grown in two crop rotation systems with either conventional tillage or no-till in order to test which of these systems can best contribute to environmentally-benign, renewable energy production. The biomass yield was assessed over the course of the four years of the field experiment. The energy consumption of the energy crops was calculated and weighed against the energy yield (estimated with the lower heating value). An energy balance was calculated to compare the energetic performance of the different energy cropping systems. Results indicate that perennial energy crops are high yielding and have relatively low demands for input. Energy maize as an annual energy crop supplied the highest yields but consumed moderate quantities of fossil fuel energy for its production.

Paper II

Triticale as an annual energy crop for solid fuel use – how can the quality demands for combustion of grain and straw be achieved through crop management?

Motivation: There is a lack of knowledge about the production of high quality aboveground plant parts (grain and straw) of triticale for combustion.

Triticale, as a long-established energy crop for the production of solid fuels, was chosen as a representative of the annual energy crops, which has the potential to be optimized in terms of biomass quality for combustion. The quality of both aboveground plant parts (grain and straw) was thought to be optimized through different fertilization management strategies, without exerting an influence on the biomass yield. The field experiment was conducted in Germany, where the soils are rich in potassium. Two straw and four potassium fertilizer treatments were applied, in order to measure whether there is a potential to lower the

combustion-disturbing elements potassium and chlorine, and the ash residue. Results indicate that the element contents of the biomasses can be lowered to a certain extent, but a high influence must be expected from the site and weather conditions.

Paper III

Energiepflanzen für die Biogaserzeugung (Energy plants for anaerobic digestion)

Motivation: Provide information about substrates that can be used for anaerobic digestion.

This manuscript is part of a book and functions, in this thesis, as a review of energy crops for anaerobic digestion. The first part summarizes the requirements of biogas plants and of biomass for anaerobic digestion. The second part introduces the potential energy crops and their advantages and disadvantages. Currently, primarily biomass from energy maize is used as a substrate, alongside liquid manure, for digestion in biogas plants. But, many other biomass crops can be used, especially herbaceous energy crops. The last part discusses the development of site-specific crop rotation systems for biomass production. Data obtained from field experiments that are presented in Papers IV and V, as well as yet unpublished data from a field experiment with *Sorghum bicolor* (L.) Moench, are integrated into the manuscript.

In this manuscript, references are made to tables and chapters, which are not part of this thesis, but are part of the book.

Paper IV

High quality production of energy maize (*Zea mays* L.) in crop rotation systems – biomass and methane yields and environmental impacts

Motivation: Energy maize, as a rather new annual energy crop, is currently the primary biomass source for anaerobic digestion throughout Germany. But, little is known about which variety should be used (early or late maturing), and how crop management can be optimized to obtain high biomass yields with high quality (dry matter content).

This paper focuses on highly productive and environmentally benign biomass production systems with the main focus on energy maize cultivation in different crop rotation systems. Four differently maturing maize varieties (early to late maturing) were grown in six different crop rotation systems. Two yield strategies were developed to obtain possibly divergent biomass yields and qualities. Biomass yields and dry matter content of the tested crops were measured to identify the optimal variety and crop rotation system. The biomass yields of all

crops in a crop rotation system (additional crops were winter wheat and the catch crops winter turnip rape, winter rye and Italian ryegrass) were added to compare the cumulative biomass yields of the systems over a two-year period. Specific methane yields were measured for further evaluation of the biomass yields. Results indicate the advantageousness of early maturing varieties at the study site in a crop rotation system with different crops and an almost year-round soil cover. Specific methane yields of maize differed significantly, but no recommendation for a particular maize variety could be given.

Paper V

Quality parameter estimation of energy maize (*Zea mays* L.) biomass and prediction of specific methane yield

Motivation: To determine if there are methods, other than digestion experiments, that can be used to predict the specific methane yield of maize.

The aim of this paper was the identification of parameters that determine the quality of energy maize biomass in terms of specific methane production. A three year field experiment was conducted, which was very similar to the one in Paper IV, with nine differently maturing maize varieties, six crop rotation systems and three successive harvest dates each year. The maize yields and cumulative biomass yields of the crop rotation systems were compared to determine the optimal variety, harvest date and crop rotation system. The question, with regard to quality, was whether it is possible to determine specific methane yields of maize through the determination of quality parameters such as starch, fiber and digestibility by using near infrared reflectance spectroscopy. Results indicate that continuous maize systems are advantageous at the tested site when growing late maturing varieties, which can be harvested relatively late in the season. The specific methane yields of maize are moderately correlated to tested quality parameters. A prediction of specific methane yield can be made more accurately for late maturing varieties than for early maturing varieties.

2. Paper I

Comparing annual and perennial energy cropping systems with different management intensities

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Comparing annual and perennial energy cropping systems with different management intensities

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Abstract

Given the political targets, it can be expected that in Europe, energy production from agricultural land will increase and that improved systems for its production are needed. Therefore, a four year field trial was conducted on one site in south-western Germany to compare and evaluate the biomass and energy yield performance of important energy crops. Six energy cropping systems with the potential to produce biomass for first and second-generation biofuels were selected. The systems were short rotation willow coppice, miscanthus, switchgrass, energy maize and two different crop rotation systems including winter oilseed rape, winter wheat and winter triticale. The two crop rotation systems were managed in either conventional tillage or no-till soil cultivation systems. The second test parameter was three different crop-specific nitrogen application levels. The performance of the energy cropping systems was evaluated by measuring the biomass yields and calculating the energy yields, as well as through an energy balance and nitrogen budget. Results show the superiority of the annual energy crop maize in dry matter yield (DMY) and primary net energy yield (PNEY = difference between the primary energy yield (DMY × lower heating value) and the energy consumption) performance with peak values at the highest N-application level of 19.1 t DM ha^{-1} a^{-1} and 350 GJ ha^{-1} a^{-1}, respectively. The highest yielding perennial crop was miscanthus with 18.1 t ha^{-1} a^{-1} DMY and a PNEY of 277 GJ ha^{-1} a^{-1}, followed by willow with 15.2 t ha^{-1} a^{-1} and 258 GJ ha^{-1} a^{-1}, at the highest N-application level. Switchgrass showed the lowest yields of the perennial crops with 14.1 t ha^{-1} a^{-1} DMY at the highest N-application level. The yields of the two crop rotation systems did not differ significantly and amounted to 14.6 t ha^{-1} a^{-1} DMY of both grain and straw at the highest N-application level. Willow showed the significantly highest energy use efficiency (output (PNEY):input (energy consumption)-ratio) with 99 GJ energy output per GJ fossil energy input at the lowest N-application level (no fertilizer). The two crop rotation systems had the lowest energy use efficiency with 20 GJ GJ^{-1} for the production of total aboveground biomass. Energy maize gave the best energy yield performance but at a relatively high energy input, whereas willow and miscanthus as perennial energy crops combine high yields with low inputs. Results suggest that no-till systems had no negative impact on biomass and energy yields, but that there was also no positive impact on energy saving.

Keywords: Energy crops; Crop rotation system; Biomass; Energy balance; Nitrogen

1. Introduction

Energy production from agricultural land is an important means with which to generate renewable energy. About 4% of the total energy consumption in the EU is currently covered by biomass production and this sector has the potential to more than double its contribution by 2010, with an anticipated production of about 185 mtoe (million tonnes of oil equivalent) (CEC, 2005).

The EU has set a target that 5.75% of the consumed fuel in Europe be produced from biomass by 2010 (CEC, 2003). Currently, about 90% of the European biofuel consump-

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tion is covered by domestic raw materials, which are grown on about 1.9% of the 97 million hectares of the EU-25's total arable land (CEC, 2005). To reach the target set for 2010 would require that between 4 and 13% of the arable agricultural land in the EU-25 be dedicated to energy crops for biofuel production. The exact amount of land needed depends on the type and yield potential of energy crops chosen, production intensity and technological development (Jensen, 2003).

Presently, so-called first-generation biofuels, such as biodiesel from oilseed rape and bioethanol from cereals, dominate the European biofuel sector and make up about 1.5 mtoe, of which over 80% is biodiesel (EUBIA, 2006). First-generation biofuels can be used in low-percentage blends with conventional fuels and can be distributed through the existing infrastructure. Today, these fuels are not competitive with fossil fuels and can be seen as an intermediate step to reduce GHG (greenhouse gas) emissions and to diversify transport energy sources. In the future, a shift towards second-generation biofuels, produced primarily from lignocellulosic biomass, is expected and encouraged by the EU (CEC, 2006). However, these second-generation biofuels will not make a significant market contribution until 2010, or later.

The above mentioned political goals will create an increased demand for agricultural land for the production of biofuels, if these are to be produced domestically. Consequently, competition may arise between different land use systems for food, feed, biomass production, and nature protection and landscape conservation, as well as between the production of different biofuel feedstocks. These developments demand an optimization of agricultural procedures for energy crop production at the most sustainable level. The choice of the best suited energy crop is crucial for the development of strategies that allow for the highest land use efficiency, substitution of fossil energies and the reduction of GHG emissions. These crops should have a high energy yield potential, along with only minimal environmental impacts. The Biomass Action Plan of the EU (CEC, 2005) strives for energy crop production systems that are advantageous from an environmental point of view. Energy production on agricultural land is likely to have significant environmental impacts, for example when permanent grassland is converted into arable land or when the use of agrochemicals increases with the intensity of production (Lantz et al., 2001; Guo and Gifford, 2002). Positive impacts, on the other hand, can come from the plantation of perennial crops by enhancing soil coverage and carbon sequestration (Paustian et al., 1998; Clifton-Brown et al., 2004; Deckmyn et al., 2004) and by supporting biodiversity (Hope and Johnson, 2003). Also, the production of annual crops can become more environmentally benign when the tillage in a crop rotation system is reduced to a minimum and the soil can function as a carbon sink (Smith et al., 1998). Such systems require less energy input because of the reduced number of soil tillage, but can also result in lower biomass yields and thus lower energy yields (Arman, 2003).

With regard to the energy consumption of agricultural production, the highest single energy input is fertilization, especially nitrogen fertilizer (Biermann et al., 1999; Monti and Venturi, 2003). Increasing nitrogen supply through fertilization triggers yield increases until an optimum level is reached (Lewandowski and Kauter, 2003; Lewandowski and Schmidt, 2006). Efficient cultivation of energy crops should operate in an optimal range that considers nitrogen fertilization, yield performance and net energy supply.

An energy balance is an adequate instrument to identify an efficient energy crop. Many energy balances have been devised for energy crops, but these analyses were either:

- based on literature instead of field trial data: Kaltschmitt et al. (1997), Hanegraaf et al. (1998), Scholz et al. (1998), Bullard and Metcalfe (2001), Venturi and Venturi (2003).
- applied to only one or a few energy crops: Scholz and Ellerbrock (2002), Lewandowski and Schmidt (2006), Rathke and Diepenbrock (2006).
- not applied to different management interactions: Venturi et al. (1999), Matthews and Mortimer (2000).

Hence, the need for information about the energy balances of the currently most important energy crops initiated our research. Although, energy use efficiency is an important criteria for the selection of the most suitable energy crop, it is not the only criteria. Depending on the kind of biofuel to be produced and the status of the conversion technology different kinds of crops, including oil, starch or lignocellulosic crops are needed. Therefore, the whole range of first and second-generation biofuel energy crops common in Central Europe were taken into consideration.

The aim of this study is to compare and evaluate the dry matter and energy yield and selected environmental impacts of different energy cropping systems, cultivated at different management intensities. For this purpose a field trial was conducted in south-western Germany with six energy cropping systems, at three different crop-specific nitrogen application levels over the course of four years. The selected cropping systems were short rotation willow coppice, miscanthus, switchgrass, energy maize and two different crop rotation systems that included winter oilseed rape, winter wheat and winter triticale, and varied in their soil cultivation. The energy consumption, nitrogen budget and energy use efficiency of all systems were calculated. Some attention was also paid to land and nitrogen fertilizer use, as a contribution to the further validation of the cropping systems.

2. Materials and methods

The first part of this study is based on a field trial and the results obtained from it over a period of four years. The second part consists of the calculations of the energetic evaluation, which were based on the data set obtained from the field trial and from additional data obtained from other

authors. For the calculations, the agronomic procedures were scaled up from the technologies used in the field trial management to practical farm management technologies. The equipment outfit of a model farm was assumed according to Kaltschmitt and Reinhardt (1997).

2.1. Site

The field trial was performed at the experimental station "Ihinger Hof" of the University of Hohenheim in southwestern Germany. The preparation of the field trial started in August 2001. Yield measurements were performed during the years 2002–2005. The station is located at 48°44′N latitude, 8°56′E longitude and at about 480 m above sea level. The long-term average annual air temperature and total precipitation are 8.1 °C and 693 mm, respectively. Climate data are shown in Table 1.

The soil is considered a Haplic Luvisol with a silty clay texture with an overlay of loess. Soil N_t and soil C_t were measured in Spring 2004 and ranged from 0.92% to 1.07% and 0.10% to 0.11% of dry soil, respectively. Before the trial, the site was used as arable land with winter triticale being the crop preceding the two crop rotation systems. Mustard was sown as a winter catch crop before the perennial crops were planted.

2.2. Experimental parameters

The trial had a randomized complete split plot design with six cropping systems as main plots (S1 to S6, see Fig. 1) and three nitrogen (N) application levels as subplots, each in four replications. Subplot size was 20 m × 8 m. Selected crops, varieties and crop rotation systems (CRS) for the field trial were as follows:

S1: Short rotation willow coppice (*Salix schwerinii* E. Wolf × *viminalis* L.) 'Tora'.
S2: Miscanthus (*Miscanthus* × *giganteus* Greef et Deu.).
S3: Switchgrass (*Panicum virgatum* L.) 'Kanlow'.
S4: Energy maize (*Zea mays* L.) 'Gavott' (2003) and 'Mikado' (2004 and 2005).
S5: Crop rotation system with conventional tillage (plough): winter oilseed rape (*Brassica napus* L. ssp. *oleifera*) 'Elektra' (2002 and 2005) – winter wheat (*Triticum aestivum* L.) 'Transit' (2003) – winter triticale (*Triticale* × *triticosecale* Wittmack) 'Lamberto' (2004).
S6: Crop rotation system with no-till: crops and varieties same as S5.

The perennial crops were planted (willow and miscanthus) and sown (switchgrass) in spring 2002. Energy maize was sown yearly at the end of April/beginning of May. In the crop rotation systems, winter oilseed rape was sown at the end of August 2001 and 2004, whereas winter wheat and winter triticale were only sown once at the beginning of January 2003 and at the end of September 2004, respectively.

For cropping system S4 the perennial crop reed canary grass (*Phalaris arundinacea* L.) was first selected and was sown in May 2002, but did not establish. Energy maize

Table 1
Annual and seasonal climate of the years 2002 2005 at the experimental site Ihinger Hof

Year	Average temperature (°C)		Precipitation (mm)		Global radiation (MJ m^{-2})	
	Year	Season[a]	Year	Season[a]	Year	Season[a]
2002	9.4	14.1	937	543	4249	3566
2003	9.7	16.7	539	282	4915	3643
2004	9.3	14.6	622	346	4384	3301
2005	8.8	14.6	604	382	4395	3220

[a] Season is between 1st April and end of September.

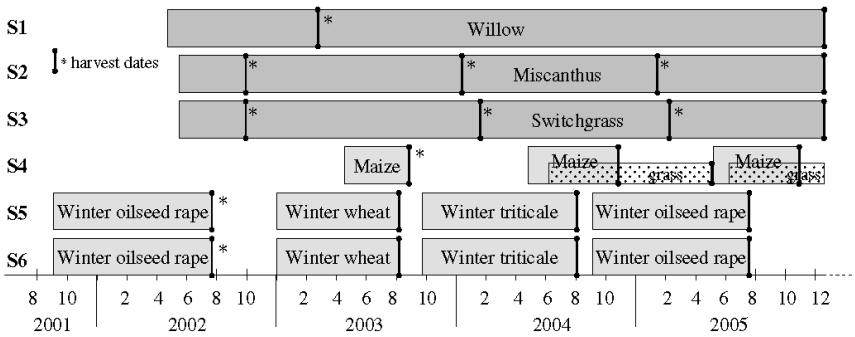

Fig. 1. Six selected cropping systems for the field trial.

was sown in spring 2003, instead reattempting reed canary grass, because of the rising importance of maize as an energy crop.

From 2004 onwards, the energy maize was cultivated with an undersown grass of *Lolium perenne* L. variety 'Lisuna', which was sown in June on an annual basis. The grass was grown as a catch crop to reduce potentially negative ecological impacts of maize cropping such as nitrogen leaching and soil erosion.

The second test parameter was the nitrogen fertilizer application at three different crop-specific levels (Table 2). The N-application levels were chosen according to the need of the different crops as reported by Mitchell et al. (1999) for willow, by McLaughlin and Kszos (2005) for switchgrass, by KTBL (2005) for energy maize, oilseed rape, winter wheat and winter triticale and by Lewandowski and Schmidt (2006) for miscanthus.

At the application level N0, no N fertilizer was given, at level N1, a medium crop-specific amount of N was given, and at level N2, a high crop-specific amount of N was applied. Nitrogen fertilizer was applied to the perennial crops annually in April. The first nitrogen treatments of the perennial crops were applied in 2003, which was the second year of establishment. Applications to the annual crops in the CRS were split with the first application in March and the second in April. N fertilizer application to energy maize took place in April and June.

Before establishing the field trial, 2.5 t ha^{-1} quicklime was applied to all plots in August 2001. Potassium was given to all plots as K_2O in August 2001 at a rate of 160 kg ha^{-1}. Further potassium was applied to energy maize in April 2003 and 2004 with 100 kg and 80 kg ha^{-1}, respectively. In addition, the fertilizer Rhe-Ka-Phos ($10\%P_2O_5 + 21\%K_2O + 4\%MgO + 6\%S$) was applied in March 2003 to energy maize with 1000 kg ha^{-1}, to winter wheat and switchgrass with 700 kg ha^{-1} and to willow and miscanthus with 350 kg ha^{-1}. In March 2004, 1300 kg ha^{-1} Rhe-Ka-Phos was applied to energy maize and in March 2005, 700 kg fertilizer ha^{-1} was applied to switchgrass, miscanthus and maize.

The crops were not irrigated, except for miscanthus, which was irrigated during the first year after planting. Pesticides were applied when the infestation pressure warranted such measures. Mechanical weed control was performed after willow harvest. Biological control in maize employed trichogrammids (*Trichogrammatidae*) to fight the European corn borer (*Ostrinia nubilalis* (Hübner)).

Biomass yield was assessed by cutting an area of between 6 m^2 and 20 m^2 (160 m^2 for willow) per plot. The sizes of the harvested areas were determined by the canopy density. The cutting height was 20 cm for willow and energy maize, 15 cm for miscanthus and switchgrass, and 10 cm for wheat, triticale and oilseed rape. Harvest dates were chosen according to the water content of the biomass, which means that cereals were harvested at Zadoks growth stage 92 (caryopsis hard), energy maize was cut during Zadoks growth stage 83–85 (dough ripeness) (Zadoks et al., 1974), and the perennial crops were harvested during the wintertime when the aboveground biomass had senesced (miscanthus and switchgrass) or leaves had fallen off (willow). Each year, three stools of all willow plots were cut to determine the annual growth rate. Dry matter weight was determined by drying the samples at a temperature of 105 °C to constant weight.

2.3. Calculations for the energy balance

The primary net energy yield (PNEY) was calculated as the difference between primary energy yield (PEY) and energy consumption. The primary energy yield was assessed by multiplying the dry matter yield (DMY) and the corresponding lower heating values (Table 3). Energy use efficiency (EUE) was calculated as the output:input-ratio of PNEY and energy consumption.

Energy consumption was calculated using the methodological approach and the basis data set for energy and fuel use established by Kaltschmitt and Reinhardt (1997). In case the data for particular types of machinery operations was not available then the data was taken from other

Table 2
Three nitrogen (N) application levels (N0, N1 and N2) for the cropping systems, applied amount per level (kg N ha^{-1} a^{-1})

Energy crop	N0	N1	N2
Willow[a,b]	0	(40 kg N ha^{-1} $3a^{-1}$) 13.3	(80 kg N ha^{-1} $3a^{-1}$) 26.7
Miscanthus[a]	0	40	80
Switchgrass[a]	0	40	80
Energy maize[c]	0	120	240
Winter oilseed rape[d]	0	(80 in 2002) 120	(160 in 2002) 240
Winter wheat[d]	0	80	160
Winter triticale[e]	0	80	160

[a] Nitrogen application as KAS (27%N, thereof 13.5%NO_3 N and NH_4 N + 12%CaO).
[b] Treatment only after rotation each three years.
[c] Nitrogen application as ENTEC 26 (26%N, thereof 7.5%NO_3 N and 18.5%NH_4 N + 13% S + DMPP).
[d] Application one third as ASS (26%N, thereof 7%NO_3 N and 19%NH_4 N + 13%S) at beginning of vegetation period and two thirds as KAS at Zadoks growth stage 29 31.
[e] Application 50% as ASS and 50% as ENTEC 26.

Table 3
Lower heating values (MJ kg^{-1} DM) of biomasses of the selected energy crops

Energy crop	Whole crop	Grain	Straw
Willow	18.4		
Miscanthus	17.6		
Switchgrass	18.3[a]		
Energy maize	19.3[b]		
Winter oilseed rape		26.5	17.1
Winter wheat		17.0	17.2
Winter triticale		16.9	17.1

After Hartmann (2001).
[a] Scurlock (2005).
[b] KTBL (2005).

sources. KTBL (2005) data was used for the 4-furrow plough, seed bed combination, Cambridge roller, conventional and direct seed-drilling machine, precision airplanter, lime distribution, swather and transportation systems. Energy consumption for seed production and transport for switchgrass and energy maize was calculated according to Spatari et al. (2005) and Diepenbrock et al. (1995), respectively. Data for miscanthus plantlet production and transportation was derived from Lewandowski et al. (1995). Input data for the production of magnesium and sulphur fertilizers was calculated based on Moerschner and Gerowitt (1998). The energy content of diesel fuel was assumed to be 42.7 MJ kg^{-1}.

In addition, the calculations were done on the basis of the following assumptions: The model farm, as a scale up of the field trial and experimental station, has an average field size of five hectares (140 m × 357 m) and the mean distance from the field to the farm is two kilometers. The agricultural machinery for such a farm includes two tractors (Fendt Vario 714 and Fendt Vario 409) and the above mentioned soil cultivation, planting, sowing and direct seed-drilling machines, a fertilizer distributor with a width of 15 m (capacity 2000 kg) and a pesticide sprayer that contains 2200 l. The harvest is thought to be done by a farm contractor, who uses the following harvest technologies: forage harvester Claas Jaguar 870 Green eye with maize header RU 600 (for maize), forage harvester Claas Jaguar 870 Green eye with cutter bar Direct Disc 520 (for winter oilseed rape straw), front mounted drum mower Claas Corto 3100 FC with conditioner (for miscanthus and switchgrass), Claas Jaguar 870 Green eye with special 1-double-row header for wood chopping (for willow), combine Claas Lexion 550 (for winter wheat and triticale), combine Claas Lexion 530 (for winter oilseed rape) and a baler Claas Quadrant 2200 R for square bales.

The transport of the grain crops was realized with a three-way-tippable wagon that can haul 13.5 t, and waited at the field edge to be loaded. For transporting the chopped energy maize, winter oilseed rape straw and willow material, a loader wagon with a volume of 40 m^3 was used. The straw from winter wheat and winter triticale was first swathed, baled into square bales (1.2 m × 0.7 m × 2.2 m) and then put onto a trailer with a front loader. Harvested material from miscanthus and switchgrass was also baled. All harvested crops were brought to the farm for storing or further transportation.

Irrigation was only applied to miscanthus twice in the first year after planting, at a rate of 5 l m^{-2}, and was applied using a 10,000 l volume slurry tank and adjacent hose applicators.

The assumptions are made to describe practical energy crop production technologies. After the year of establishment (perennial crops), the same operations were performed annually. The rootstocks and rhizomes of the perennial crops must be removed after completion of their lifecycle. This is assumed to be done by a farm contractor with a AHWI forest mulcher FM700, and afterwards the soil is loosened with a grubber. The energy consumption for land clearing is evenly allocated to the lifecycle period.

The lifecycle of the perennial crops is set to 16 years, which seems to be a realistic but conservative estimate according to Lewandowski et al. (2000), Keoleian and Volk (2005) and McLaughlin and Kszos (2005). The lifecycles of the other cropping systems were adjusted to the perennial crops to ensure the comparability of the cropping systems. Energy consumption for the whole lifecycle for all cropping systems was calculated by multiplying the consumption of the years 2003 to 2005 by five and adding the energy consumption value for the year 2002 (year of establishment). The total DMY for the cropping systems over the lifecycle were calculated as follows:

- *Miscanthus and switchgrass*: Stable yields of miscanthus and switchgrass were obtained by Christian et al. (2002) and Clifton-Brown et al. (in press) from the fourth or fifth year, while McLaughlin et al. (1999) and Clifton-Brown et al. (2001) found stable yields starting in the second or third year. Therefore, the mean DMY from the third and fourth year after establishment (2004 and 2005) were chosen to represent the DMY of the lifecycle from the third year on. The yields from the first and second year (2002 and 2003) were added to complete the lifecycle.
- *Willow*: The DMY was calculated by multiplying the DMY harvested after the three-year rotation period by five, and adding the DMY from the year of establishment (2002).
- *Annual crops*: The DMY was calculated by multiplying the mean DMY from the years 2003–2005 by five, and adding the DMY from the year of establishment (2002).

The biomass and energy yields of the six cropping systems were calculated for the lifecycle period of 16 years but are shown as annual values.

The land use was calculated for each cropping system and N-application level as the quotient from one land unit (1 ha) and the DMY or the PNEY. The nitrogen fertilizer use was calculated for each cropping system and N-application level as the quotient from the nitrogen recovery (kg ha^{-1}) and the DMY or the PNEY.

2.4. Nitrogen budget

The nitrogen budgets of the six cropping systems were calculated as the difference between the amount of nitrogen fertilizer applied each year and the recovered nitrogen in the harvested DMY. The nitrogen content in dried plant tissue was measured using the Dumas combustion method through the macro analyzer Vario Max CNS.

2.5. Statistical analysis

The total DMY, PEY, PNEY and EUE properties of the six cropping systems were evaluated as means over

the lifecycle period of 16 years, with an analysis of variance by using the SAS procedure PROC GLM (SAS version 8.2, SAS Institute Inc., Cary, NC, USA). The grain and straw yields from both CRS were analyzed based on the annual field trial data. Mean values for the energy crops were compared at $P < 0.05$.

3. Results

3.1. Biomass yield

The results show a significant difference in DMY between the cropping systems and the nitrogen application levels (Table 4 and Fig. 2). In general, the DMY of the energy cropping systems increased with higher nitrogen application rates from level N0 to N2. Energy maize DMY at N-application levels N1 and N2 and miscanthus DMY at level N2 were significantly higher than the DMY from the other energy cropping systems and the N-application levels.

Table 4
Analysis of variance with GLM-model, effects of replication, energy crop and N-application level on dry matter yield

Source	DF[a]	SS[b]	MS[c]	*F*-value	*P*-value	Sig.
Replication	3	2258.50	752.83	4.02	0.03	*
Energy crop	5	53221.63	10644.33	56.89	0.00	*
N-application level	2	31424.83	15712.41	126.56	0.00	*
Energy crop* N-application level	10	11516.99	1151.70	9.28	0.00	*
Energy crop* replication	15	2806.62	187.11	1.51	0.15	n.s.[d]

[a] Degrees of freedom.
[b] Sum of squares.
[c] Mean square.
[d] Not significant.
* Significance level at 0.05%.

The total DMY of both CRS consists of grain and straw DMY (Fig. 3). Among the four crops in the two CRS, winter triticale had the significantly highest DMY at N-application level N2. The yields of all crops increased significantly from N-application level N0 to N1 and N2.

3.2. Nitrogen budget

The results of the nitrogen budget (Table 5) ranged between −230 and 98 kg N ha^{-1} a^{-1}. A value beneath zero indicates that the energy crop withdrew more nitrogen than was applied as fertilizer. A positive value indicates that the crop took up less nitrogen than was applied as fertilizer. The mean values for the entire two CRS indicate a generally higher uptake of nitrogen than was applied, whereas the values of the single crops show that winter oilseed rape did not use the full amount of nitrogen fertilizer. In contrary, winter wheat and winter triticale took up more than supplied.

3.3. Energy consumption

The energy consumption of the energy cropping systems was very crop-specific and depended primarily on the amount of nitrogen fertilizer applied (Fig. 4). The nitrogen fertilizer had a share of 41–64% of the energy consumption for the production of annual crops, and a share of 17–45% for perennial crops. For miscanthus, the highest energy demand came from plantlet production, which amounted to 2.92 GJ ha^{-1} a^{-1} due to its energy intensive cultivation in the greenhouse. The use of pesticides was crop-specific and resulted in nearly no energy demand for willow and between 0.18 and 0.69 GJ ha^{-1} a^{-1} for the other crops. Tractor-pulled operations for the perennial crops consumed little energy (0.30 and 0.38 GJ ha^{-1} a^{-1}) due to the fact that the main operations took place in the year of establishment, but were evenly allocated to the lifecycle of 16 years. Due to the fewer soil operations in the no-till

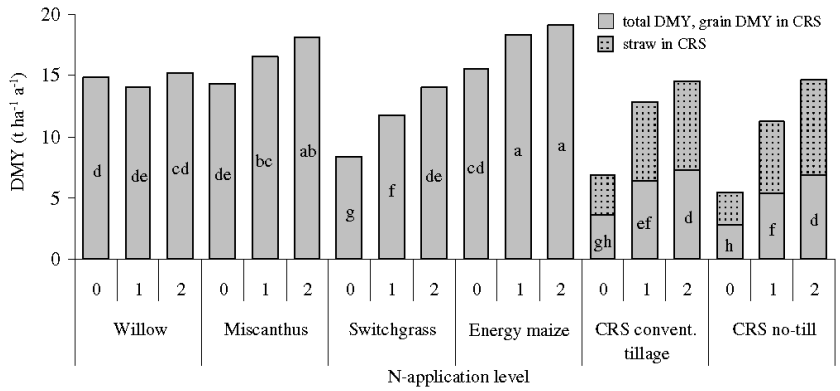

Fig. 2. Dry matter yield (DMY) of the six crop rotation systems (CRS) and three N-application levels as means over the lifecycle period of 16 years, presented as annual values, basis data for the energy balance, significant differences are indicated by different letters ('a' to 'h') for total aboveground DMY.

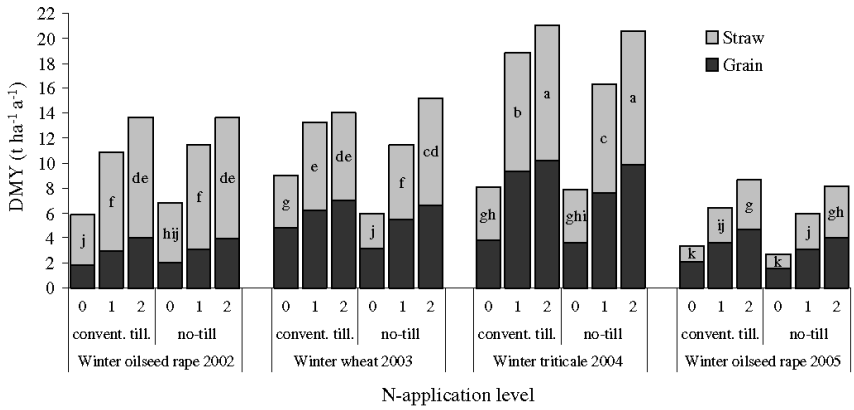

Fig. 3. Grain and straw dry matter yield (DMY) of the crops in the two CRS, significant differences are indicated by different letters ('a' to 'k') for total aboveground DMY.

Table 5
Nitrogen budgets (kg N ha^{-1} a^{-1}) of the six cropping systems and N-application levels (N0 to N2), means over the lifecycle period of 16 years and annual budgets for the crops in the two crop rotation systems (CRS)

Energy crop	N0	N1	N2
Willow	−52.1	−51.0	−34.9
Miscanthus	−31.3	11.6	52.7
Switchgrass	−32.0	−8.2	15.3
Energy maize	−230.1	−160.1	−37.7
CRS conventional tillage	−69.4	−41.2	−26.7
CRS no-till	−55.4	−18.7	−14.9
Annual crops in the two CRS			
CRS convent. till. Winter oilseed rape	−68.2	−41.0	−23.3
CRS no-till Winter oilseed rape	−80.7	−39.3	−12.9
CRS convent. till. Winter wheat	−96.5	−69.8	−71.2
CRS no-till Winter Wheat	−59.4	−33.4	−73.1
CRS convent. till. Winter triticale	−57.4	−74.9	−80.3
CRS no-till Winter triticale	−59.2	−51.5	−70.8
CRS convent. till. Winter oilseed rape	−54.5	21.0	70.6
CRS no-till Winter oilseed rape	−42.5	32.9	98.9

CRS, the energy consumption for soil cultivation and crop management was about 1 GJ ha^{-1} a^{-1} lower for this system than in the other CRS. In all six cropping systems, the energy demand for soil cultivation and crop management, as well as for harvest and transport, rose from N-application level N0 to N2, primarily because more N fertilizer was applied and a higher amount of biomass had to be harvested and transported. Land clearing is only necessary for perennial crops and resulted in an energy consumption of 0.13–0.16 GJ ha^{-1} a^{-1}.

3.4. Primary energy yield and primary net energy yield

The primary energy yield (PEY) reached the significantly highest values in the annual crop energy maize at N-application levels N1 and N2 (Table 6). Like the DMY, also the PEY and the PNEY showed a response to nitrogen and increased with increasing nitrogen application. The exception was willow, which showed no response to nitrogen application. The CRS with conventional tillage showed higher values for both PEY and PNEY than the CRS with no-till, but the differences were not significant (Table 6). In both CRS, the grain and straw yield is considered to be the total DMY, whereas the straw from winter oilseed rape is often not used for energy generation and is left on the field. By not harvesting the winter oilseed rape straw, the energy consumption of the two CRS is lowered to 93–98%. The DMY, PEY and PNEY drop to 87–91%. The DMY, PEY and PNEY from N-application level N0 are in this case significantly different from the other treatments of the two CRS, but the significance levels of N1 and N2 remain (data not shown).

The larger the difference between PEY and PNEY, the higher is the energy consumption of a cropping system. This relationship can best be expressed through energy use efficiency.

3.5. Energy use efficiency and land and nitrogen fertilizer use

The energy use efficiency (EUE) of a cropping system needs to be higher than 1 to produce more bioenergy than is consumed by biomass production processes. This value was achieved by all systems but with different characteristic values. Willow production without nitrogen application had the significantly highest EUE in this trial (Table 6) with a value of 99 GJ energy output per GJ fossil energy input. The significantly lowest EUE were attained in the two CRS and in energy maize at N-application level N2, with only about one fifth of the value reached in willow production. In all six energy cropping systems, the EUE decreased with increasing rates of nitrogen application.

The land and nitrogen fertilizer use (Table 7) were calculated for the biomasses from each cropping system at the N-application level, which turned out to be the optimum for the site. The optimum is defined as the combination between the N-application level with the lowest input and the significantly highest biomass yield level. For example,

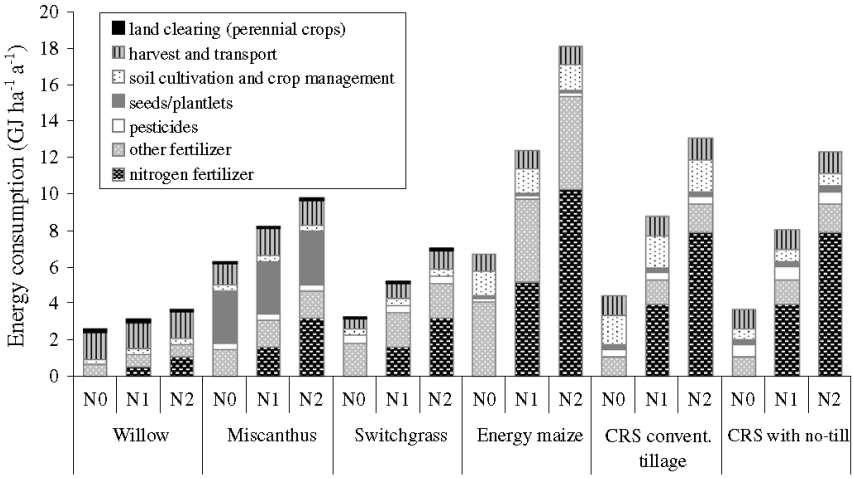

Fig. 4. Annual energy consumption for the production of the six cropping systems at three N-application levels, means over the lifecycle period of 16 years.

Table 6
Primary energy yield (PEY), primary net energy yield (PNEY) and energy use efficiency (EUE) of the six energy cropping systems at three different N-application levels

Energy crop	PEY (GJ ha^{-1} a^{-1})			PNEY (GJ ha^{-1} a^{-1})			EUE (GJ GJ^{-1})		
	N0	N1	N2	N0	N1	N2	N0	N1	N2
Willow	259	246	266	257	243	263	99	78	72
	cdef	defg	cd	cde	defg	cd	a	b	c
Miscanthus	231	263	287	224	255	277	36	32	29
	fgh	cde	bc	fg	cde	bc	f	fgh	ghi
Switchgrass	143	198	237	140	193	230	44	38	34
	j	i	efg	i	h	efg	de	ef	fg
Energy maize	300	354	368	293	342	350	45	29	20
	b	a	a	b	a	a	d	ghi	k
CRS with conventional tillage									
WOR WW WT[b] (g + s)[a]	122	229	262	118	220	249	27	26	20
	jk	gh	cde	ij	gh	cdef	hi	hijk	k
CRS with no-till									
WOR WW WT[b] (g + s)[a]	100	203	263	97	195	251	27	25	21
	k	hi	cde	j	h	cdef	hij	ijk	jk

Analysis of variance (letters 'a' to 'k') separately for each factor PEY, PNEY and EUE.
[a] Grain and straw.
[b] WOR: winter oilseed rape, WW: winter wheat, WT: winter triticale.

Table 7
Comparison of land and nitrogen fertilizer use of the six energy cropping systems at the optimal nitrogen application level, values show the consumption of land and nitrogen per tonne dry matter yield (DMY) or per GJ primary net energy yield (PNEY)

Energy crop	Optimal N-application level	Land use		Nitrogen fertilizer use	
	kg N ha^{-1} a^{-1}	(m^2 t^{-1} DM)	(m^2 GJ^{-1} PNEY)	(kg N t^{-1} DM)	(kg N GJ^{-1} PNEY)
Willow	0	710	39.0	3.7	0.20
Miscanthus	40	669	39.3	1.9	0.11
Switchgrass	80	771	43.4	5.0	0.28
Energy maize	120	545	29.3	15.3	0.82
CRS conventional tillage	160 (winter wheat and winter triticale); 240 (winter oilseed rape)	692	40.2	14.7	0.85
CRS no-till	see CRS convent. till.	686	39.9	13.7	0.80

the optimal level for energy maize was 120 kg N ha^{-1} a^{-1} because the next higher level did not trigger a significantly higher yield. The optimal level for the other energy crops was 0 kg N ha^{-1} a^{-1} for willow, 40 kg N ha^{-1} a^{-1} for miscanthus, 80 kg N ha^{-1} a^{-1} for switchgrass, 160 kg N ha^{-1} a^{-1} for winter wheat and winter triticale, and 240 kg N ha^{-1} a^{-1} for winter oilseed rape. An efficient cropping system has low values for land and nitrogen fertilizer use per tonne dry matter and per GJ primary net energy yield. Miscanthus was a crop with a high efficiency to use the supplied nitrogen with 1.9 kg N t^{-1} dry matter, whereas maize showed the highest efficiency in land use. Maize needed an area of 545 m^2 to build one tonne of dry matter.

4. Discussion

This field trial has shown – in accordance with other studies (Börjesson, 1996; Lewandowski et al., 2003; Lewandowski and Schmidt, 2006) – that perennial lignocellulosic crops are among the highest yielding energy crops. Lignocellulosic biomasses, as well as features such as the C_4-photosynthetic pathway, seem to be advantageous for energy production at this site. Here, willow, miscanthus and energy maize were most productive with respect to biomass and energy yield potential per land unit (Table 7).

4.1. Aspects of no-till crop rotation systems

Perennial crops have the potential to contribute to carbon sequestration and to an improvement of soil qualities (Clifton-Brown et al., 2004; Deckmyn et al., 2004). Annual crops also have this potential if they are cultivated with reduced soil cultivation or no-till methods (Lal, 2003). This fact was the main motivation for testing annual energy crops in no-till soil cultivation systems. In our trial, we found no evidence that the biomass or energy yields in no-till soil cultivation systems were reduced in comparison to cropping systems that included intensive soil cultivation. However, the energy saving effect of reducing soil cultivation intensity was negliable in this study. Systems with no-till have the further advantage of being less time and cost consuming (Al-Kaisi and Yin, 2004), because of the reduced cultivation operations, while returning the same yields as crop rotation systems with conventional tillage. As a consequence of reduced tillage, a lower rate of mineralization occurs, which leads lo lower mineralized nitrogen contents in the soil in spring and thus less nitrogen leaching (Harrach and Richter, 1992) and less erosion (Pekrun et al., 2003). According to Arman (2003), higher nitrogen application levels would be needed for systems with reduced tillage to produce the same yields as systems with conventional tillage. During the transition period from a system with conventional tillage to a no-till system, it may be advisable to apply extra nitrogen fertilizer to compensate for the reduced mineralization rates (Baeumer and Köpke, 1989). Ehlers and Claupein (1994) showed that there were no differences after eight years of the application of reduced tillage. Since we found no differences in yield between the two systems, the results from Hoffmann and Koch (1998), who found no interactions between soil cultivation and nitrogen fertilization, would also be valid for our trial.

Problems arise in both crop rotation systems with generating energy from all aboveground material. Winter oilseed rape straw is often not considered for energy generation and even left on the field, which will lead, in this case, to lower dry matter and energy yields of the two crop rotation systems.

4.2. Dry matter yield

Switchgrass, like miscanthus, is also a perennial C_4-crop. However, it only achieved yields on the same low levels as the annual energy crops in the two CRS tested in this trial. This result is associated with results from Heaton et al. (2004), who compared miscanthus and switchgrass yields from different sites and years. Results of their analysis show about twice the DMY for miscanthus than for switchgrass. Miscanthus yields in this trial were significantly higher than switchgrass yields, however not to the extent observed by Heaton et al. (2004). Reasons for this result could be related to soil characteristics. Switchgrass can develop relatively better on marginal sites (McLaughlin and Kszos, 2005). Moreover, other switchgrass field trials conducted in Southern Germany indicate that switchgrass performs better on light and sandy soils than on heavy clay soils (Lewandowski, 1998). Heavy soil prevails at the field trial site, and this might therefore be a primary reason for the poor performance of switchgrass. Another reason could be an inappropriate choice of variety. Results of trials investigating different switchgrass varieties on sites from Central to Southern Europe showed that the performance of switchgrass varieties depends on the latitude of their origin in the USA and that different varieties should be chosen for different sites in Europe (Elbersen et al., 2000). Hence, better switchgrass varieties might be found for south-western Germany.

Miscanthus was identified to have a high biomass yield potential (up to 25 t DM ha^{-1} a^{-1}) in Central Europe with global radiation and average temperatures being about 3500–3900 MJ m^{-2} and 7.3–8.0 °C, respectively. Yields were reported to be even higher at sites with higher temperatures and water supply. Genotypes also have a considerable influence on the yield, but *M.* × *giganteus*, as used in this trial, is the most productive genotype in Central Europe (Lewandowski et al., 2000).

The yields of short rotation willow coppice were found to be highly variable and site-dependent. The annual productivity was reported to vary from 7 to 14 t DMY ha^{-1} a^{-1} after two to four years rotation of a young plantation. Yields were found to be highest at sites with loamy soil (similar to the study site). Limiting factors for willow growth may be shallow soil, site exposure, flooding or animal damage (Beale and Heywood, 1997), which could not be demonstrated in this trial.

The choice of the energy maize cropping system, with the undersown grass, appears to be a very reliable system due to its soil-conserving features and high productivity. The undersown grass had no negative effects on energy maize yields in this trial, when yields from year 2004 and 2005 (maize with undersown grass) were compared to the yield from 2003 (maize without grass). This was also observed by Aufhammer and Kübler (1997). The grass itself can also be harvested and used for energy production if biogas is to be produced. Expected DMY can reach up to 6 t ha^{-1} a^{-1} (Boehmel et al., 2005). Furthermore, the grass can contribute to soil cover in winter, whereby it can be expected that the undersown grass will effectively reduce one of the most critical environmental impacts of maize production, which is soil erosion. Attention must be paid to light soils and areas with low precipitation, because here the main crop and grass will compete for the limited water supply (Kreuz et al., 1988).

4.3. Influences of the nitrogen fertilizer management

Cropping systems with higher biomass yields, attained through higher nitrogen fertilizer levels, consumed more energy per land unit (especially true for energy maize), but this higher energy input was compensated for by the higher energy yields. The main parameter for determining energy input, for all energy cropping systems, was fertilization, particularly nitrogen fertilization. The energy use efficiency of a system was primarily defined by its demand for nitrogen fertilizer, because of the high impact of the N-application level on the energy consumption of the six cropping systems.

A general observation in this field trial was that especially energy crops with a high nitrogen demand, like energy maize, withdrew far more nitrogen than was applied (Table 5). Early spring measurements of plant available mineral nitrogen contents in the soil (highest values measured were below 40 kg N ha^{-1}), did not indicate a high additional soil nitrogen supply during the winter. The undersown grass in energy maize plots has the ability to take up a certain, even though a small, amount of nitrogen and reduce mineral nitrogen in soil during the winter (Aufhammer and Kübler, 1997), but this does not apply to the other cropping systems. Maize showed the largest deviation between the amount of nitrogen fertilizer supplied and the amount recovered in harvested biomass. The high amounts of recovered nitrogen that were not derived from fertilizer, may be derived from additional mineralization during the vegetation period or from atmospheric nitrogen deposition, but which only amounts to about 10-17 kg ha^{-1} a^{-1} in Central Europe (Stevens et al., 2004; Phoenix et al., 2006; Verhagen and Van Diggelen, 2006).

The low nitrogen application levels used on willow, maximum 27 kg ha^{-1} a^{-1}, makes both the comparison of the nitrogen fertilizer use and energy use efficiency difficult. Therefore, a nitrogen budget was included, showing the actual withdrawal of fertilized nitrogen by the above-ground biomass. The amounts withdrawn from willow were in the medium range and should be compensated for by mineralization occurring in the soil during the vegetation period (Salinas-Garcia et al., 1997; Zihlmann et al., 2006). According to Mitchell et al. (1999), willow yields will not decrease because of an absence of fertilizer applications, during the first ten years of cultivation on previously used farmland. This supports our theory that willow will grow vigorously on this fertile site, without any higher inputs and consequently with minimal environmental impacts. A reason for low mineral nitrogen demands of willow might be the supply of nutrients, especially nitrogen and phosphor, by ectomycorrhizal symbiosis that occurs in willow growth (Tibbett and Sanders, 2002).

Nevertheless, the significantly highest yields of willow, miscanthus and maize were not derived from the highest N-application level, which leads to the conclusion that the nutrient supply was sufficient. Attention has to be drawn on miscanthus rhizomes, which have the ability to store nutrients over winter and re-translocate them in spring. Thus, miscanthus is having a high nitrogen use efficiency and only a minor demand of extra nutrient supply (Beale and Long, 1997).

To identify the total potential of mineral nitrogen dynamics and supply to the crops, especially the soil supply, more soil analyses are necessary. This may lead to a better understanding of the nitrogen source and supply in the soil.

4.4. Energy yield and energy use efficiency

Total biomass yield has been shown to be a good indicator for the net energy yield and the energy use efficiency of energy cropping systems. The results from the primary net energy yield and the energy use efficiency show a clear ranking of the tested energy crops (ranking for the crops of the PNEY: energy maize > miscanthus > willow > both CRS > switchgrass). Hanegraaf et al. (1998) found similar rankings of the energy budgets of the crops, with the highest values for maize followed by miscanthus, willow, winter wheat and winter oilseed rape. Bullard and Metcalfe (2001) compared perennial grasses and reported higher energy ratios (like the EUE in this trial) for miscanthus than for switchgrass, which was not true for this trial. A reason for the relatively low EUE of miscanthus, compared to the EUE of switchgrass, might be the high energy input needed by miscanthus, especially for plantlet production.

For miscanthus, a high share of the energy input was a result of plantlet production. Here, a conservative approach for assessing the energy demand for plantlet production of miscanthus was chosen and a high share of the energy consumption is associated with the heating of the greenhouses needed to raise the plantlets (Lewandowski et al., 1995). Miscanthus establishment by rhizome propagation, as commonly performed today, will significantly reduce the costs for miscanthus establishment (Venturi et al., 1999), but not the energy input (Bullard and Metcalfe, 2001).

Bullard and Metcalfe (2001) also stated that the energy ratios of the perennial grasses were higher than for short rotation coppice and annual crops. This relation was only found for the perennial grasses and annual crops in this trial since willow showed the highest EUE. The particularly high EUE for willow was the result of the low rates of nitrogen fertilization applied to it, due to the triennial fertilizer application cycle.

5. Conclusion

Among all energy crops tested in this trial, the perennial lignocellulosic crops, willow and miscanthus, best combine high biomass and energy yields with high land and energy use efficiency, nitrogen fertilizer use and environmentally benign production methods, on this specific site.

Energy maize has a comparatively high demand for nitrogen for the production of one tonne dry matter or 1 GJ. On the other hand, it produces very high biomass yields per land unit and can therefore contribute to very efficient land use. Potentially negative environmental impacts of maize, like erosion and nitrogen leaching, can be minimized by introducing an undersown grass at sites where there is sufficient water supply.

No-till crop rotation systems can be recommended primarily for the production of annual energy crops for first-generation biofuels, because no-till systems can reduce the environmental impacts of crop production, such as soil erosion, improve the carbon sequestration potential and enhance soil fertility without jeopardizing biomass and energy yield production targets.

In this trial, energy crops were evaluated by comparing biomass and energy yields. Land and energy use efficiencies, as well as nitrogen fertilizer use, contribute to the further validation of the crops, which was shown in this study. However, additional aspects, such as pesticide use and biodiversity, must also be considered, in order to gain a more complete perspective of the effects of energy production on agricultural land.

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3. Paper II

Triticale as an annual energy crop for solid fuel use – how can the quality demands for combustion of grain and straw be achieved through crop management?

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Abstract

Triticale (grain and straw) production presents one opportunity to supply the rising demand for solid biofuels when the use of forest biomass comes to its limit. But high amounts of combustion-disturbing elements, such as potassium, chlorine and ash in both grain and straw present a quality constraint. Here, the present study classifies into the context. These combustion-disturbing elements were sought to be reduced through crop management procedures. A three-year field trial, with two different straw and four different potassium fertilizer treatments, was performed in Germany. Treatments were chosen against the background of soils rich in potassium and the assumption that the crop management procedures will not have an influence on the grain and straw yield. This assumption could be confirmed by the results. It was further shown that the removal of straw from the previously cultivated crop and no additional potassium fertilizer could reduce the amount of combustion-disturbing elements. But a high influence must also be expected from year and site conditions. Results indicate that it is possible to optimize the production of grain and straw at the same time.

Keywords: Energy triticale; Biomass; Quality; Solid fuels; Fertilization; Potassium; Straw; Chlorine; Chemical elements

1. Introduction

Solid biofuels are one means with which to reduce the dependency on fossil fuels. Sources of solid biofuels are not necessarily limited to forestry, but may also be found in agriculture. Agriculture can contribute to biofuel supply through perennial grasses or annual grain crops.

The twofold use of grain crops, through their grain and straw, and the different energy types that can be produced with these crops make them a multipurpose plant. Biomass intended for combustion must meet several quality standards in order to ensure an environmentally benign combustion with low emissions and to prevent technical problems during combustion. It is understood that woody biomass is well suited for combustion due to its low content of combustion-disturbing and ash-forming elements (HARTMANN, 2001; SCHOLZ and ELLERBROCK; 2002; OBERNBERGER et al., 2006), but the demand for solid biofuels is continually rising and therefore further biomass sources must be evaluated to supply the demand. Annual grain crops with a high production rate of straw, in addition to the production of grain, are of great interest due to their widespread cultivation in Europe (OLSSON, 2006). The concentration of disturbing elements, such as potassium (K) and chlorine (Cl), is far higher in grain and straw than in wood. But the annual grain crops offer a good opportunity for solid biofuel supply in supplementation to the utilization of wood.

For the fuel characterization and standardization a suitable method (HÄRDTLEIN and ELTROP, 2004), as well as a quality management system is needed (LANGHEINRICH and KALTSCHMITT, 2006). To establish such standards, a consolidated knowledge of the chemical composition of different types of biomass is required to facilitate the processing and postharvest management of the biomass. The chemical composition of a biomass can be influenced during its growth on the field through crop management (LEWANDOWSKI and KAUTER, 2003). The concentration of the disturbing elements potassium and chlorine can be lowered through the application of an adequate fertilization management program. It should not be underestimated, in this context, the importance of reducing fertilizer use in order to lower greenhouse gas emissions and leaching, and improving the energy balance. A further advantage of the cultivation of annual energy crops is the possibility to integrate them into the established crop rotation systems of a farm and that farmers usually already have the necessary knowledge for crop management.

Triticale is among the highest yielding annual grain crops (ELLEN, 1993). Moreover, it is a hybrid plant that does not serve the food supply and thus ethical concerns can be avoided. Lower harvest losses, in comparison to other grain crops, can be expected due to a firm grain seat (ALBRECHT, 1996). Most importantly, triticale has initially lower chlorine contents compared to other annual grain crops (VETTER, 2001), which is a good basis for its selection as an annual energy plant. Many experiments have been conducted to evaluate the potassium, chlorine and ash concentrations of various energy crops, but often the species of the analyzed crop was not defined and the management systems were optimized for different goals:

- straw production: SANDER (1997) (no triticale); HARTMANN and BÖHM (1999) (no species); HARTMANN and MAIER (2000) (no species); HERNÁNDEZ ALLICA et al. (2000) (wheat straw); HERNÁNDEZ ALLICA et al. (2001) (wheat straw);. SCHOLZ and ELLERBROCK (2002) (triticale but not clear whether only straw or total biomass was harvested); OBERNBERGER and THEK (2004) (straw pellets, no species).
- grain production: FEIL and FOSSATI (1995) (triticale not for fuel use); OBERNBERGER et al. (1997) (triticale grain and wheat straw, only general recommendation for low values of K and Cl).

While triticale has been identified as a suitable annual energy crop, there is still a lack of knowledge about how to optimize crop management for quality and yield of both grain and straw. Relevant crop management procedures include fertilizer management and harvest strategies (LEWANDOWSKI and KAUTER, 2003).

The aim of this study was to optimize the cultivation management of both triticale plant parts (grain and straw) in order to obtain a biomass of high quality for the use as a solid biofuels. Different crop management procedures were introduced to reduce the concentration of combustion-disturbing elements, such as potassium and chlorine, and to reduce the ash residue. A field experiment was performed in Germany based on the condition that the soil is rich in potassium, due to historically high application rates (SCHEFFER and SCHACHTSCHABEL, 1998). The question was, if it is possible on that condition to reduce the chemical elements in the aboveground plant biomass through the application of different potassium fertilizer management programs and through the removal of the straw from previously cultivated cereals. It was assumed that the treatments will not have an influence on the grain and straw yield.

2. Methods

2.1. Site conditions

The field experiment was conducted at the experimental station “Ihinger Hof” of the University of Hohenheim, located in the southwest of Germany (48°44’ N, 8°56’ E, altitude 480 m asl). The region is characterized by a warm-temperate rainy climate. The long-term average annual air temperature and total precipitation are 8.1°C and 693 mm, respectively. For monthly mean air temperature and sum of monthly precipitation see Table 1. The soils of

the farm are Haplic Luvisols with an overlay of loess. The soils contained average amounts of plant nutrients (Table 2).

Table 1
Weather conditions during the three years of the field experiment (Autumn 2002 to summer 2005), mean monthly air temperature (°C) and sum of monthly precipitation (mm)

	2002		2003		2004		2005	
Month	(°C)	(mm)	(°C)	(mm)	(°C)	(mm)	(°C)	(mm)
January	0.0	11.2	-0.7	75.3	0.2	101.3	0.6	0.6
February	4.9	61.1	-1.4	13.9	2.1	17.7	0.2	0.3
March	5.7	76.1	6.4	26.2	3.9	37.3	8.1	8.0
April	8.0	32.3	8.8	36.9	9.6	23.9	8.8	9.0
May	12.4	146.9	14.0	84.9	11.7	48.4	15.7	15.7
June	17.7	43.5	21.2	44.5	16.3	29.4	21.0	20.8
July	17.2	108.7	19.4	61.8	17.8	70.7	16.6	16.7
August	16.9	119.6	22.7	24.4	18.1	100.2	15.6	15.6
September	12.1	91.9	14.1	29.6	14.2	73.2	14.6	13.7
October	9.0	91.3	6.5	75.7	10.6	88.2	10.9	11.8
November	6.5	116.5	5.9	40.8	4.0	28.4	1.3	0.5
December	2.5	37.7	0.1	25.4	2.9	3.7	1.9	1.7

Table 2
Soil analyses of initial nutrient contents (mg kg^{-1} dry soil) of the field experiment of the three years

Year	P_2O_5	K_2O	Lime	Mg	S	Boron
2003	213	202	415	35	11	0.90
2004	192	153	273	31	16	0.40
2005	168	220	320	42	10	0.40

2.2. Field experiment management

The field experiment comprised a two-factorial randomized complete split-plot design in four replications (Fig. 1). Factor one (main plot) consisted of two different treatments of straw from the previous crop summer barley as a source of nutrients for the following crop. The second factor (subplot) consisted of four different potassium fertilizer treatments (Table 3). Subplot size was 8.6 x 4 m. The selected crop for the experiment was winter triticale (*Triticosecale* Wittm.), variety 'Lamberto'. Yield and nutrient measurements in plant material and soil were performed during the years 2003 to 2005.

The plots were ploughed after harvest of the previous grain crop and prior to planting triticale with a seed driller. The seeding rate was 280 fertile seeds m^{-2}. The plots received 70 kg mineral nitrogen ha^{-1} at the growth stage 'beginning of tillering' and the same amount at the stage 'beginning of stem elongation'. The mineral nitrogen content of the soil at the time of planting in all years in the upper soil layer (0-30 cm depth) was below 10 kg ha^{-1}. No other fertilizer was applied. Plots with treatments of potassium (K) fertilizer received 60 kg ha^{-1} of the corresponding kind. For dates of fertilizer application and sampling see Table 4.

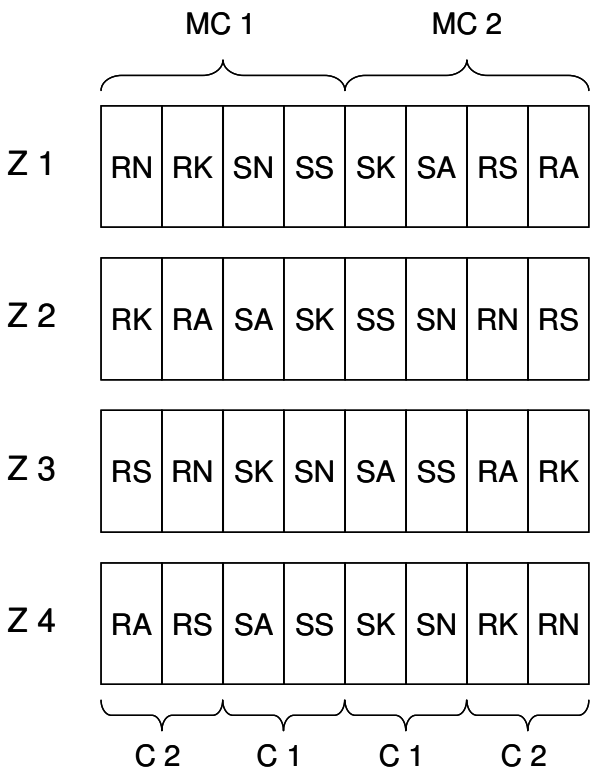

Fig. 1. Split plot design of the field experiment, Z = row, MC = main column, C = column, treatment combinations as in Table 3.

Table 3
Straw and potassium (K) fertilizer treatments and their combinations for the field experiment

Treatments	Straw from previous crop remains on the field (S)	Straw from previous crop is removed from field (R)
KCl in autumn (A)	SA	RA
KCl in spring (S)	SS	RS
K_2SO_4 in spring (K)	SK	RK
No K fertilization (N)	SN	RN

Pest management was carried out through the application of fungicides each year during the growth stages ‘beginning of stem elongation’ and ‘beginning of inflorescence emergence’. Herbicides were only applied in the first year at the growth stage ‘end of tillering’. Growth regulators were applied each year during growth stages ‘end of tillering’ and ‘flag leaf emergence’.

Harvest was initiated when the crop canopy reached the growth stage ‘over-ripeness’ (Table 4) and was conducted with a combine harvester. Fresh weights of grain and straw were determined before the samples were oven dried at a temperature of 105°C to constant weight to calculate the dry matter content. Samples for analyses of plant nutrients were oven dried at a temperature of 60 C and were then ground through a 1 mm sieve.

Soil samples were taken in three depths, up to 90 cm, each year at different dates to determine the potassium and chlorine contents (Table 4).

Table 4
Planting, harvest and sampling dates (soil samples) of the field experiment of the three years

Dates		2003	2004	2005
Planting		11.10.02	24.09.03	05.10.04
Harvest		23.07.03	18.08.04	19.08.05
K-fertilizer application autumn		09.09.02	20.08.03	12.08.04
K-fertilizer application spring		27.03.03	18.03.04	24.03.05
Soil samples	Planting	15.10.02	-	-
	Beginning of vegetation	25.02.03	03.03.04	22.03.05
	Beginning stem elongation	24.04.03	-	-
	Beginning inflorescence emergence	12.06.03	-	-
	Harvest	05.08.03	-	-

2.3. Potassium, chlorine and ash analysis

For all analyses finely ground plant or soil dry matter were used. The potassium content in the soil dry matter was measured by flame photometry (ELEX 6361, Eppendorf, Germany). The decomposition of the soil was done using the calcium-acetate-lactate (CAL)-method. The potassium content in the plant tissue was measured after pressure digestion using inductively coupled plasma – optical emission spectrometry (ICP-OES).

The samples for chlorine analyses were extracted with distilled water. Chlorine contents were determined using electrometric titration (Chloride meter, Slamed, Germany). The detection limit is 5 mmol l^{-1}. The chlorine content in the soil dry matter was below or just

above the detection limit and values could not be relied upon. Nearly no results could be obtained from the chloride analysis of the soil.

The ash content of the grain and straw dry matter was determined in a muffle-type furnace by loss of ignition at a temperature of 550°C.

2.4. Data analysis

The mean values of the total dry matter yield, the grain and straw dry matter yield, and the ash content in the dry matter for each of the three years, and the potassium content in the upper soil layer at five measuring dates in 2003 were compared at $P < 0.05$, with an analysis of variance using the procedure PROC MIXED by SAS (SAS version 9.1, SAS Institute Inc., Cary, NC, USA). The design of the field experiment had to be adjusted in response to the management practices, which necessitated an adjustment of the mixed model. The potassium fertilizer treatments were arranged in rows (Z) and the straw treatments in columns (C). Two straw treatments together formed one main column (MC). The model syntax is explained in PIEPHO and BÜCHSE (2003) and PIEPHO et al. (2003). An example of the split plot design is shown in Fig. 1.

The values of the chlorine and potassium contents in the grain and straw dry matter could not be analyzed statistically because there was only one measurement per plot.

3. Results

3.1. Yield and yield structure

Both the grain and straw, and the total dry matter yields (DMY) generally showed very few responses to the different straw and potassium fertilizer treatments of the three years (Fig. 2 and Table 5). In 2004, the total DMY showed a significant response to the interaction between straw and potassium fertilizer treatments. The treatment ‘straw removed’ had significantly higher yields compared to the treatment ‘straw remains’ at potassium fertilizer treatments ‘KCl in autumn’ and ‘no K’. Comparing the potassium fertilizer treatments within the treatment ‘straw remains’, the treatments ‘KCl in spring’ and ‘K_2SO_4’ showed significantly higher yields than the treatment without potassium fertilizer application (no K). The mean standard error of difference (MSED) for the comparisons in 2004 was 0.83.

In the year 2005, there was a significant effect from the interaction between the straw treatments and the row, which is a kind of block effect. Explanations of this effect might

include that there were influences from the neighboring plant canopy or from the soil. Influences are likely to be different in the plots at the experiment edge (columns C 2) than in plots in the middle of the experiment under columns C 1. In 2003 and 2005, the significant influences on the grain DMY were caused by the block effect as mentioned above, where in 2004, the grain DMY showed a significant response to the straw treatments. The MSED was 0.32. Comparing the two different straw treatments within a potassium fertilizer treatment, the treatment 'straw removed' had significantly higher grain yields within treatment 'no K'. The only significant influence on the straw DMY is caused by the interaction between straw and potassium fertilizer treatments in 2004. Within the straw treatment 'straw removed' the treatment 'no K' had the significantly highest yields and the treatment 'K_2SO_4' showed the significantly lowest yields. The MSED was 0.68. A significant response in 2004 was also caused by the interaction between the straw treatments and the row, which related to the already mentioned block effect. In 2005, the main column showed an influence which is also a block effect and can only be explained by influences from the soil or the neighboring plant canopy.

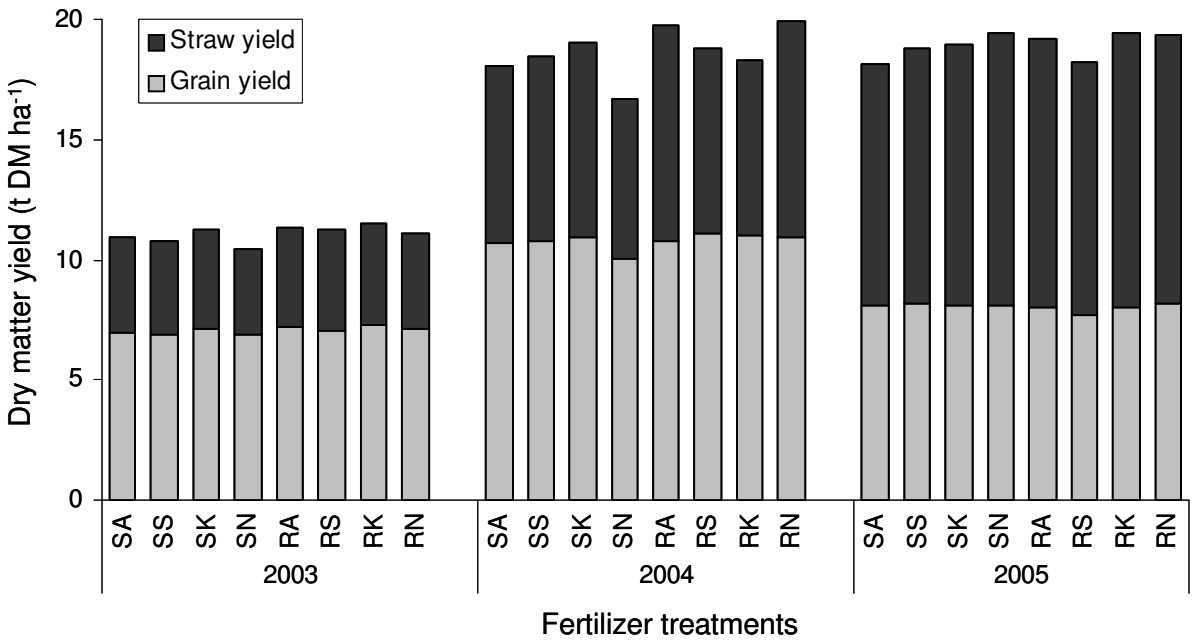

Fig. 2. Grain and straw dry matter yield (DMY) of all treatments and years (treatments, first letter: S = straw remains; R = straw removed; second letter: A = KCl in autumn; S = KCl in spring; K = K_2SO_4; N = no fertilization).

The harvest indices indicate the share of grain of the total dry matter yield and were highest in 2003 and decreased in subsequent years (Table 6). A harvest index above 0.5

indicates a relatively high grain yield compared to the total DMY. The composition of the total DMY is of relevance when the different plant parts are intended for different uses or combustion furnaces. The dry matter content of grain and straw must be at a high level to ensure an unproblematic harvest and storage (Table 6). This was true for the years 2003 and 2005. But in 2004, dry matter contents, especially the straw, were considerably lower than in the other two years. The low dry matter content in the straw indicates that it was still green and had not died back in comparison to a dried grain.

Table 5
Analysis of variance for total, grain and straw dry matter yield (DMY) of the three years

Effect		2003		2004		2005	
on total DMY	DF [a]	F-value	Pr > F	F-value	Pr > F	F-value	Pr > F
Straw (S)	1	7.63	0.2212	7.69	*	0.22	0.7234
Potassium (K)	3	2.78	0.0747	0.23	0.8751	1.87	0.1753
S*K	3	0.31	0.8172	4.37	*	0.28	0.8409
Main column	1	0.19	0.7412	0.41	0.5314	15.00	0.1609
S*Row	6	1.93	0.1382	2.52	0.0623	3.77	*
on grain DMY							
Straw (S)	1	4.04	0.2939	5.08	*	0.27	0.6926
Potassium (K)	3	1.90	0.1707	2.40	0.1036	0.44	0.7306
S*K	3	0.18	0.9064	1.59	0.2282	0.79	0.5173
Main column	1	0.08	0.8240	1.39	0.2553	0.81	0.5329
S*Row	6	2.83	*	1.93	0.1342	3.31	*
on straw DMY							
Straw (S)	1	3.87	0.0658	5.36	*	1.78	0.2002
Potassium (K)	3	2.94	0.0631	0.33	0.8058	1.92	0.1646
S*K	3	0.49	0.6913	4.72	*	0.45	0.7232
Main column	1	0.11	0.7406	1.75	0.2036	32.84	***
S*Row	6	1.37	0.2832	3.83	*	2.62	0.0552

[a] Degrees of freedom.
$p < 0.05$ = *; $p < 0.001$ = ***.

Table 6
Mean harvest indices and dry matter content (DM) of grain and straw at harvest of the three years

	2003	2004	2005
Harvest index	0.64	0.58	0.43
DM grain (% of fresh matter)	89.1	79.5	87.7
DM straw (% of fresh matter)	82.1	47.7	87.5

3.2. Chemical composition of the dry matter

The chlorine content in the straw DM was higher than in the grain dry matter (DM) (Fig. 3). In the years 2003 and 2005, the average value of the chlorine content in the grain DM was at the same level of about 450 mg kg^{-1} DM. The chlorine content in the grain DM in 2004 averaged at a value of 370 mg kg^{-1} DM. The average chlorine content in the straw DM was about 6, 3.5 and 2 times higher than the contents in the grain DM of the years 2003, 2004 and 2005, respectively. A general observation was that the lowest chlorine content in the grain DM was obtained from straw treatment level 'straw remains', whereas there was no influence from potassium fertilizer treatments observed. In the year 2003, the chlorine content in the straw DM was more than twice as high than in 2004, and about 3.5 times higher than in 2005. The highest chlorine content in the straw DM was measured in the potassium fertilizer treatments 'KCl in spring' and 'KCl in autumn'. The straw treatments did not seem to have an influence.

The potassium content in the grain DM ranged between 4710 and 6221 mg kg^{-1} DM (Fig. 4). There was observed an increase in potassium content in the grain DM from 2003 to 2005. The values of the potassium content in the grain DM were lower in all three years in the straw treatment 'straw removed' than in treatment 'straw remains'. The potassium fertilizer treatments did not seem to have an influence on the potassium content in the grain DM. The potassium content in the straw DM was highly influenced by the year and ranged at two levels. In 2003, the values averaged at 19425 mg kg^{-1} DM, whereas in 2004 and 2005, the values were about half as high and averaged at 9800 and at 8994 mg kg^{-1} DM, respectively (Fig. 4). The lowest potassium content in the straw DM was generally measured in all three years from potassium fertilizer treatments 'no K' and 'K_2SO_4'. No other influences were observed.

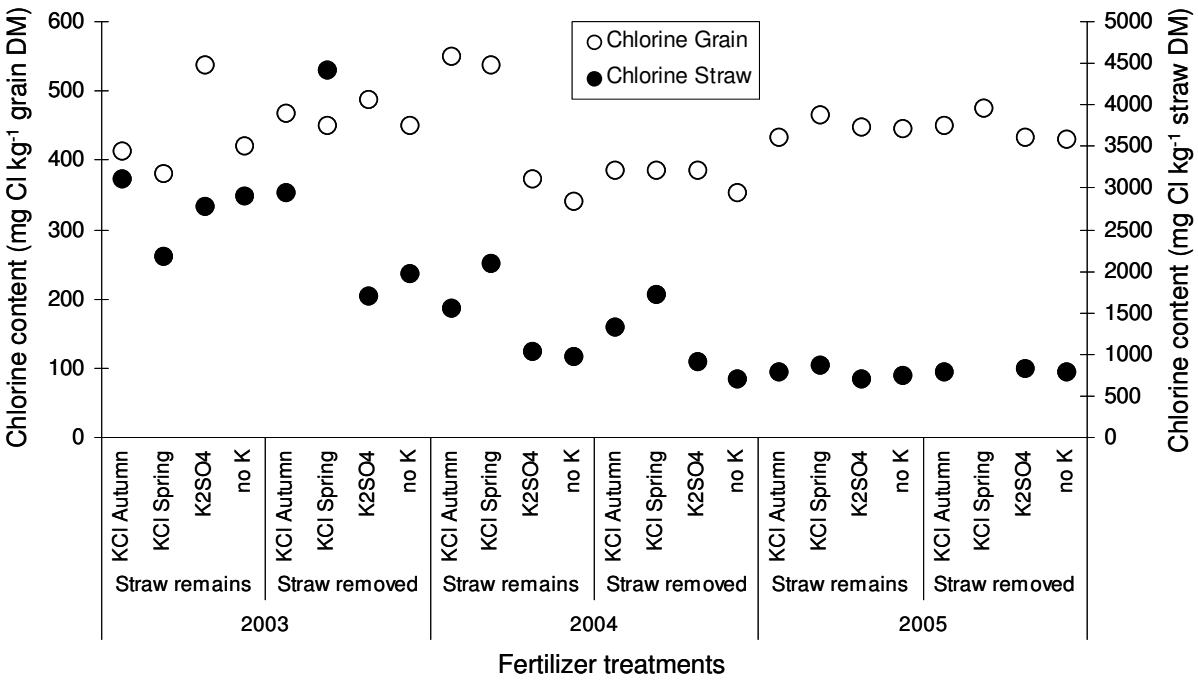

Fig. 3. Chlorine (Cl) content in grain and straw dry matter (DM) of all treatments and years.

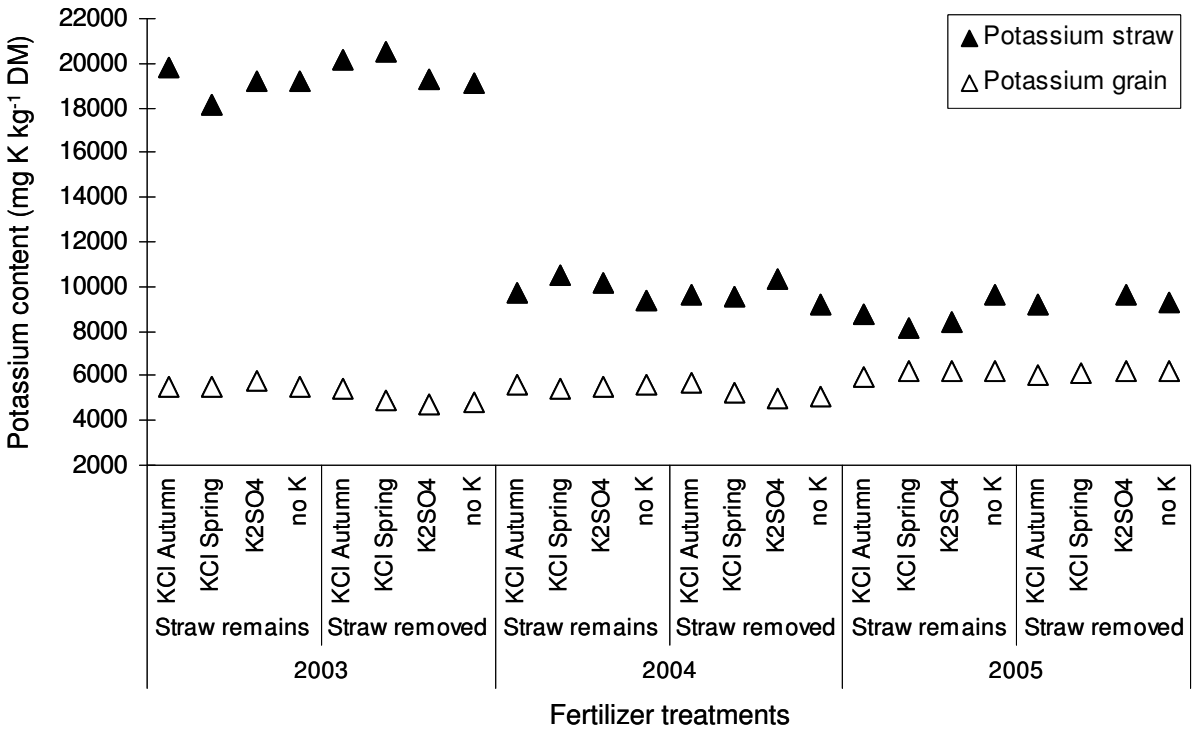

Fig. 4. Potassium (K) content in grain and straw dry matter (DM) of all treatments and years.

The average values of the ash content in the DM of all years were 1.91 and 5.89 % in grain and straw, respectively (Fig. 5). The levels of the ash content were equal in 2003 and 2005, but lower in 2004. The ash content in the grain and straw DM, in general, did not respond to the straw and potassium fertilizer treatments. Only in 2003, there was observed a

significant influence from the potassium fertilizer treatments to the ash content in the straw DM. The potassium fertilizer treatment 'KCl in autumn' showed, with both types of straw treatments, significantly higher ash contents than the potassium fertilizer treatment 'K_2SO_4'. The MSED was 0.12. In 2004, the significant differences of the ash content in the grain DM were caused by the interaction between the straw and potassium fertilizer treatments. In combination with straw treatment level 'straw remains' the potassium fertilizer treatment 'no K' had a significantly higher ash content in the grain DM than in treatment 'KCl in spring', whereas at straw treatment level 'straw removed' the potassium fertilizer treatment 'KCl in autumn' had a significantly higher ash content in the grain DM than in treatment 'no K'. The MSED was 0.09.

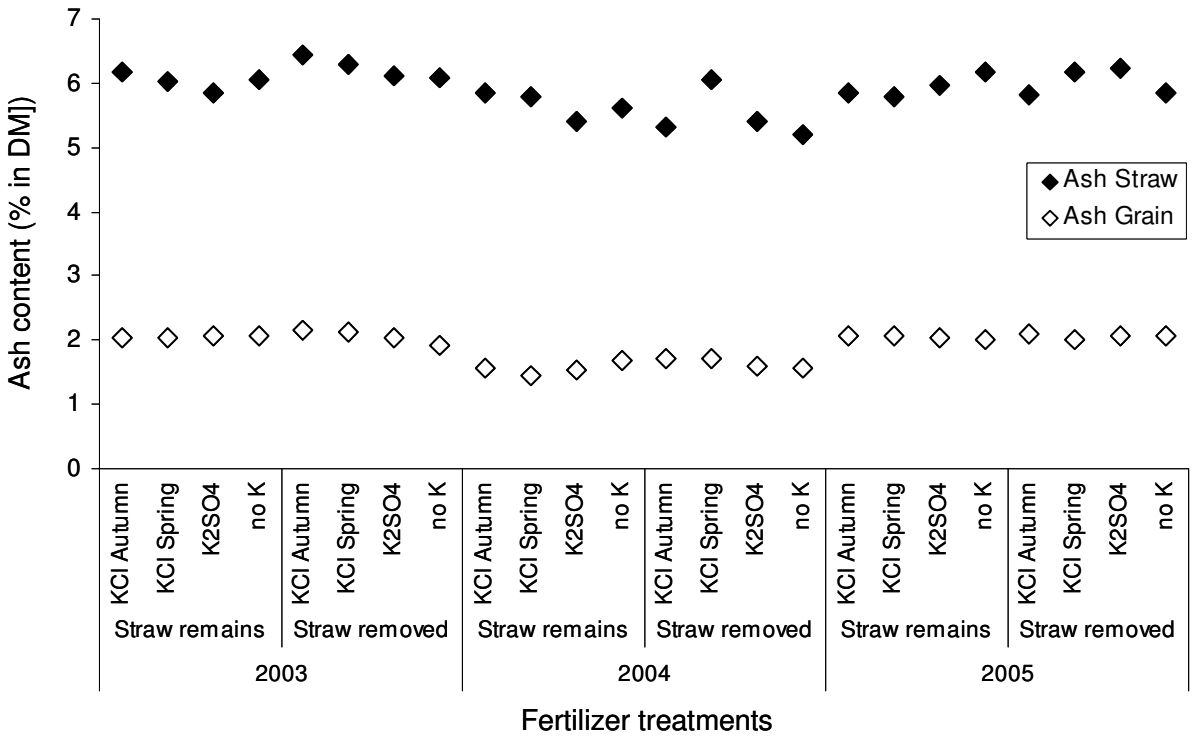

Fig. 5. Ash content in grain and straw dry matter (DM) of all treatments and years.

3.3. Potassium contents in the soil

Results of the potassium content in the soil are only shown for the upper soil layer (down to 30 cm depth) because there was no additional information obtained from values of the lower soil layers. The plant available potassium content in the upper soil layer showed a significant response to the measuring date (Table 7). In all treatment combinations the content was highest between the end of February and the end of April, in other words between the dates 'beginning of vegetation' and the plant growth stage 'stem elongation' (Fig. 6). No

other influences were observed. The MSED for comparisons between measuring dates was 18.1.

The plant available potassium content in the soil at the beginning of vegetation showed a response to the year (Fig. 7). In 2005, the values for all treatment combinations were higher than in the other two years. In general, the potassium fertilizer treatment 'KCl in autumn' caused the highest potassium content. No other influences were found.

Table 7
Analysis of variance for potassium content in the upper soil layer at five dates during the vegetation period in 2003

Effect	DF [a]	F-value	Pr > F
Date (D)	4	7.58	***
Straw (S)	1	0.27	0.6942
Potassium (K)	3	1.09	0.3577
D*S*K	28	0.78	0.7721
S*K	3	0.76	0.5181
Main column (MC)	1	48.71	0.0906
S*Row (Z)	6	2.03	0.0675

[a] Degrees of freedom.
$p < 0.05$ = *; $p < 0.001$ = ***.

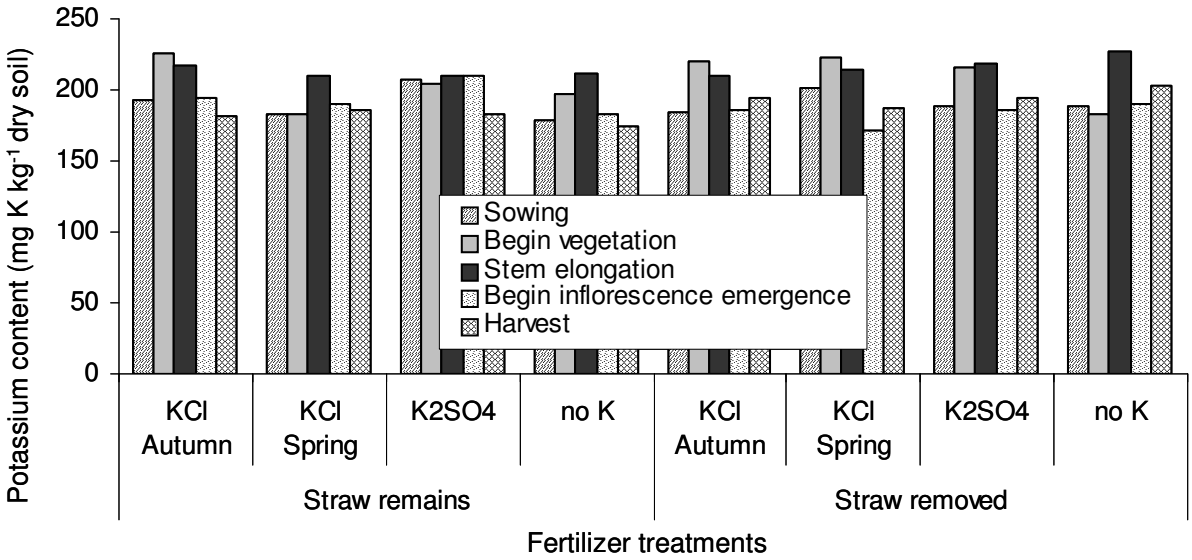

Fig. 6. Plant available potassium (K) content in the upper soil layer (0-30 cm depth) at five dates during the vegetation period in 2003.

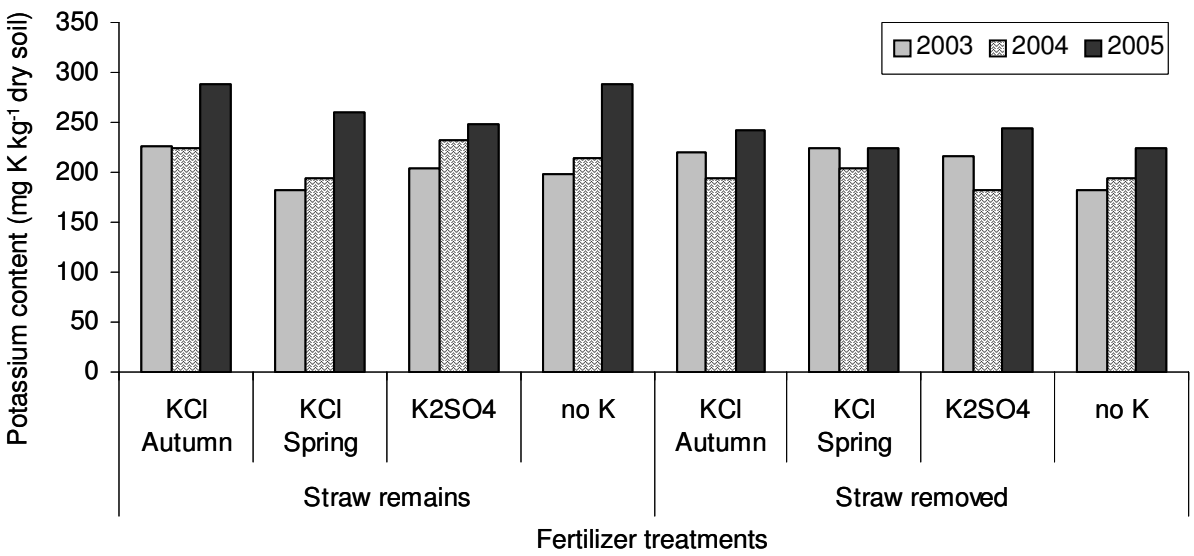

Fig. 7. Plant available potassium (K) content in the upper soil layer (0-30 cm depth) at the beginning of vegetation of the three years.

4. Discussion

4.1. Yield and yield structure

The field experiment was conducted with the assumption that the different straw and potassium fertilizer treatments would not have an influence on the yield. The results confirmed this assumption and correspond to results obtained by WULFF et al. (1998), who found no influence on the yield even when supplying different amounts of potassium fertilizer. Nevertheless, negative effects on the yield could be seen from the straw treatment 'straw remains'. This might be the result of the immobilization of nutrients during the process of organic matter decomposition of the previously ploughed straw, which means that nutrients were missing when needed for the development of new plant biomass.

The different levels of grain and straw DMY for each of the three years were caused by different weather conditions. The year 2003 was extremely warm and yields were reduced by too high temperatures. Also, the yield structure was influenced by the year, which resulted in different harvest indices. ELLEN (1993) found harvest indices averaging 0.45. Values at this level were only measured in this experiment in the year 2005, whereas in the other two years, the harvest indices were higher, resulting in a higher grain yield compared to the total DMY. Cereals intended for food or fodder supply are desired to have a high harvest index for a high share of grain yield. But in the context of solid fuel use and the use of both aboveground plant

parts, a high total biomass yield is desired. The advantage of the calculation of the harvest index is the amount of energy that can be gained from each of the plant parts.

4.2. Chemical composition of the dry matter

The potassium content in grain and straw responded to a couple of influences. The generally lower potassium content of grain in comparison to straw makes it advantageous for the utilization as a solid biofuel. The absence of an effect of the potassium content in the soil on the potassium contents of grain and straw shows similarities to results obtained by FEIL and FOSSATI (1995), SANDER (1997) and KAUTER et al. (2002).

According to SCHEFFER and SCHACHTSCHABEL (1998), a plant available potassium content over 50 mg kg^{-1} soil dry matter is not yield limiting. The additional supply of potassium from the soil, by values ranging from 50 to 90 mg K kg^{-1}, is recognized to be sufficient to obtain optimal yields. The amount of fertilizer applied each year would then have to be calculated after the potassium removal by the plant. Calculated values of the potassium removal after KTBL (2005) range from 90 kg K ha^{-1} a^{-1} in 2003 and 200 kg K ha^{-1} a^{-1} in 2005, for the production of grain and straw dry matter. These calculated fertilizer amounts are about 1.5 to 3.3 times higher than the actual amount of applied potassium fertilizer. But according to WULFF et al. (1998) it is sufficient for optimal plant growth to maintain a plant available potassium content in the soil of about 40 mg kg^{-1} soil. In our experiment, the potassium content in the soil was on average about 5 times higher. These values and calculations show the high demand of triticale grain and straw for potassium supply on the one hand, but on the other hand that the potassium content in the soil is even higher than is needed to maintain optimal yields. The calculated potassium demand did not exceed the soil supply, but since the potassium supply from the soil can drop to about one fifth of its current value and still be sufficient according to SCHEFFER and SCHACHTSCHABEL (1998), there exists a potential to save fertilizer, which should be emphasized. The values indicate a luxury consumption as a result of the general absence of a yield response.

According to FEIL and FOSSATI (1995), there appears to be an influence from year, site and variety on the potassium content in grain dry matter. They also reported that increasing grain yield is responsible for reduced mineral content in the grain dry matter. The correlation might explain the decreasing potassium content with increasing yields in 2004 and 2005, in comparison to 2003.

HERNÁNDEZ ALLICA et al. (2001) reported an increasing chlorine content with increasing KCl fertilizer, which cannot be verified by results from our experiments. SANDER (1997)

found a correlation between the potassium and chlorine content in straw, which is also generally true for our results, even if the chlorine contents seem to be quite unbalanced. A potential reduction of the chlorine content can be obtained by the substitution of KCl fertilizer with K_2SO_4 fertilizer. It would reduce the chlorine input but at the same time increase the sulphur input. According to SANDER (1997) the additional sulphur in the soil does not raise the sulphur content in the straw dry matter. But the chance persists that the additional sulphur might increase the sulphur content in the plant tissue, which also has negative impacts on the combustion process (OBERNBERGER et al., 2006). In addition, K_2SO_4 fertilizer is much more expensive than KCl fertilizer. But according to OBERNBERGER et al. (2006) chlorine concentrations below 0.1 % of dry matter are unproblematic for combustion. Values below this range were found in all grain measurements and in straw measurements in 2005.

An interesting observation was made by HERNÁNDEZ ALLICA et al. (2000; 2001). They observed that the potassium and chlorine content in the grain dry matter can be lowered considerably through the leaching of the elements during grain maturation as a result of precipitation. According to their results, 50 to 80 mm of cumulated precipitation seem to be sufficient. In the years 2004 and 2005, the precipitation amounted to over 50 mm during the time of grain maturation, which indicates that the leaching process might have also occurred in our experiments.

Potassium is a key element determining the amount of ash produced during combustion. Decreasing the content of potassium in the plant dry matter leads to a lower quantity of ash, which could be shown in 2004. Increasing the ash content in straw leads to deceasing lower heating values (HARTMANN and MAIER, 2000), which results in the potassium content gaining further importance. Another important aspect is the resultant high ash accumulation in the furnace, which must then be emptied frequently. In this context, OBERNBERGER and THEK (2004) recommend straw only for medium to large-scale combustion plants due to its high ash content, as well as high potassium and chlorine content. However, there is one, though perhaps small, advantage of a high potassium content in the ash, which is its potential to be used as fertilizer for other crops (HARTMANN and BÖHM, 1999).

5. Conclusion

The experiment has shown that crop management can partially influence the concentrations of combustion-disturbing elements, such as potassium and chlorine, and ash in triticale grain and straw. However, high variations must be expected from varying year and site conditions. The high quality production of grain and straw can be optimized at the same time. Results indicate that even if the soil is rich in potassium it generally has no influence on the yield and potassium content of the aboveground plant parts. Somewhat higher yields and a lower potassium content in grain on plots where the straw of the previously cultivated crop was removed from the field leads to the recommendation that the harvested straw should be used for a purpose and not be left on the field. No further potassium fertilization is recommended due to the absence of a yield response and the partially lower content of chlorine and potassium in straw dry matter. The accumulation of ash can only be reduced by a lower potassium content in the plant parts. To conclude, the possibility to reduce combustion-disturbing elements is low by cultivating triticale on well nutrient (potassium) supplied soils. It leads to the recommendation to optimize the cultivation procedures with regard to obtain high biomass yields and to optimize the process management for combustion.

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4. Paper III

Energiepflanzen für die Biogaserzeugung

Constanze Böhmel

This manuscript is part of a new chapter of the book 'Energie aus Biomasse', which will be published in 2008 as a revised second edition.

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1 Energiepflanzenproduktion

1.5 Energiepflanzen für die Biogaserzeugung

In modernen Biogasanlagen wird neben Gülle und Festmist heute vielfach Biomasse von meist einjährigen Energiepflanzen anaerob vergoren. Energiepflanzen stellen das Co-Substrat zu Gülle und Festmist dar. Die momentane Gesetzeslage sieht für Deutschland und Österreich einen extra Bonus für Biogasanlagen vor, die ausschließlich speziell angebaute Energiepflanzen als Co-Substrat zu Gülle nutzen. Auf dieser Grundlage werden im Folgenden Pflanzenarten behandelt, die unter die Kategorie der für Biogasanlagen bonus-berechtigten Energiepflanzen fallen.

1.5.1. Anforderungen an pflanzliche Biomasse zur Co-Fermentation

Die Biomasse sehr unterschiedlicher Energiepflanzen kann als Co-Substrat in einer Biogasanlage eingesetzt werden. Grundsätzlich gilt, dass alles, was ein Wiederkäuer (z.B. eine Milchkuh) als Futter nutzen kann auch für eine Biogasanlage gut geeignet ist. In der Biogasanlage finden mehrere biochemische Prozesse statt, die nicht einfach zu kontrollieren und zu beeinflussen sind. Die in der Biogasanlage aktiven Mikroorganismen (hauptsächlich unterschiedliche Arten von Bakterien) setzen Biomasse unter anaeroben Bedingungen zu Biogas mit einem Methananteil von ca. 50 bis 70 % um. Unterschiede zwischen Biogasanlage und Wiederkäuer bestehen unter anderem in der Umsetzung und Verwertung der Energie. Der Wiederkäuer braucht die über das Futter aufgenommene Energie überwiegend für den Stoffwechselprozess, während die eingesetzte Energie in einer Biogasanlage (pflanzliche Biomasse + Gülle) über einen vierstufigen Abbauprozess (siehe Kapitel 15.1.2) in Biogas umgesetzt wird. Ein Wiederkäuer bevorzugt protein- und energiereiche Nahrung, wohingegen in einer Biogasanlage der Proteingehalt möglichst niedrig und der Anteil an energiereichen Substanzen (Kohlenhydrate und Fette) möglichst hoch liegen sollte. Ein weiterer entscheidender Unterschied liegt in der Verweildauer. Ein Wiederkäuer muss innerhalb eines halben bis ganzen Tages die Energie aus dem Futter möglichst effizient umsetzen, während in einer Biogasanlage die Verweildauer mindestens 30 Tage, meistens aber 60 bis 90 Tage, oder auch bis zu 120 Tagen, beträgt.

Die generellen Anforderungen an Biomasse zur Co-Fermentation in einer Biogasanlage lassen sich vom Prozess der Methanbildung und der Funktionsweise einer Biogasanlage

ableiten. Biogasanlagen können mit unterschiedlichen Temperaturbereichen und Beschickungssystemen gefahren werden. Da momentan die meisten Biogasanlagen in einem mesophilen Temperaturbereich arbeiten (ca. 37°C) und kontinuierlich beschickt werden, beziehen sich die folgenden Ausführungen auf die Bereitstellung von Biomasse für eine im mesophilen Bereich arbeitende Biogasanlage.

Gut geeignete Co-Substrate sind Biomassen, die für die Mikroorganismen in der Biogasanlage leicht aufzuschließen und umzusetzen sind, die einen guten Nährwert für die Mikroorganismen (zum Aufbau der Population) haben und möglichst hohe Energiegehalte aufweisen. Kohlenstoffreiche Biomassen liefern den Grundbaustein für das Methan (CH_4). Biomassen mit hohen Anteilen an Kohlenhydraten (Zucker, Stärke, Cellulose und Hemicellulose) und/oder Fetten sind gut geeignet. Die Biopolymere müssen zunächst in Oligo- oder Monomere gespalten werden. Je weniger komplex und strukturiert ein Substrat ist, das heißt, je stärker die Biopolymere schon abgebaut sind, desto schneller und besser kann es umgesetzt werden. Proteinhaltige Biomassen sind in geringer Mischung (siehe unten: C:N-Verhältnis) mit anderen Biomassen einsetzbar. Dabei muss auf den Schwefel- und Stickstoffgehalt geachtet werden. Der in Biogasanlagen aus Sulfaten gebildete Schwefelwasserstoff, bzw. dessen Oxidationsprodukte wirken korrosiv auf die gasführenden Bauteile. Aus einem Überschuss an Stickstoff kann störendes Ammoniak entstehen. Das C:N-Verhältnis der eingesetzten Substrate (pflanzliche Biomasse + Gülle) und auch die Verhältnisse zu Phosphor und Schwefel spielen eine wichtige Rolle für die Methanproduktion. Bei zu weitem Verhältnis wird der Kohlenstoff nicht umgesetzt. Hohe Proteingehalte der eingesetzten Substrate können zu hohen Ammonium-N-Konzentrationen im Fermenter und dadurch zur Wachstumshemmung der Mikroorganismen führen. Ein günstiges C:N:P:S-Verhältnis liegt im Bereich von 600:15:5:1 /1-15/. Lignifizierte Pflanzenbestandteile (Lignin-inkrustierte Cellulose) lassen sich von Mikroorganismen schwer bis gar nicht aufschließen und tragen daher nicht zur Methanbildung bei und können zudem die Umsatzrate mindern. Daher sind stark lignifizierte Biomassen, wie z.B. ausgereifte Miscanthus-Biomasse oder auch Stroh nicht für die Biogasanlage geeignet.

Prinzipiell können alle Biomassen, die den oben genannten Anforderungen entsprechen, in einer Biogasanlage vergoren werden. Dazu gehören unter anderem der gesamte oberirdische Aufwuchs von z.B. Mais, Getreide, Futtergräsern und -leguminosen, unterirdische Pflanzenteile wie Sprossknollen von z.B. Topinambur und Kartoffeln, sowie Abfallstoffe wie Getreideausputz und Futter- und Speisereste. Unter förderungsrechtlichen

Gesichtspunkten spricht man dabei nur dann von Energiepflanzen, wenn das Hauptprodukt der Pflanze und nicht nur ihr Nebenprodukt (z.B. Zuckerrübenblatt) verwertet wird.

Der optimale Erntezeitpunkt einer Biomasse wird unter anderem von ihrem Trockensubstanzgehalt bestimmt. Allerdings weisen nicht alle Biomassen zum optimalen Erntezeitpunkt denselben Trockensubstanzgehalt auf. Der optimale Trockensubstanzgehalt (TS) wird auch nicht immer bei maximalem Aufwuchs der Energiepflanzen erreicht. Wird Korngut als Co-Substrat verwendet, so muss dieses zur Ernte möglichst trocken (ca. 86 % TS) und damit drusch- und lagerfähig sein. Die Lagerfähigkeit der Biomassen ist ein sehr wichtiges Kriterium, da die Biogasanlage das ganze Jahr kontinuierlich mit Substrat beschickt werden muss, die Biomassen aber konzentriert zu bestimmten Zeitpunkten im Jahresverlauf anfallen. Daher ist das meist verwendete Substrat in der Biogasanlage die Silage von Biomassen unterschiedlicher Energiepflanzenarten. Der Prozess der Silagebereitung ist nicht nur ein Mittel zur Konservierung und Lagerung der Biomasse, sondern verbessert auch die Eigenschaften als Co-Substrat (siehe unten). Für eine gute Silagebereitung liegt der optimale Trockensubstanzgehalt der frisch geernteten Biomasse, je nach Art, zwischen 25 und 40 %.

Die Aufbereitung einer Biomasse vor der Beschickung der Biogasanlage ist von großer Bedeutung für deren Umsetzbarkeit. Zum Beispiel liefern gequetschtes Korngut und silierte Biomasse höhere spezifische Methanertragspotentiale als frische und unbehandelte Biomasse /1-5/, /1-11/. Durch die Verletzung des Korns quillt dieses besser, die Mikroorganismen haben eine bessere Angriffsfläche und können die Kornbiomasse schneller umsetzen. Diese Prozessbeschleunigung spielt besonders eine Rolle bei kurzen Verweilzeiten der Biomasse in der Biogasanlage. Während des Silageprozesses wird der pH-Wert herabgesetzt und Inhaltsstoffe der Biomasse, wie z.B. Zucker, werden zu Säuren abgebaut, was sich günstig für die erste Stufe des Biogasprozesses (siehe Kapitel 15.1.2) auswirkt. Es können generell auch frische Biomassen in der Biogasanlage verwertet werden, doch ist deren Einsatz auf die Zeit (Stunden) unmittelbar nach der Ernte beschränkt, da frische Biomassen nur sehr begrenzt lagerfähig sind.

Werden mehrere Substrate zusammen in den Fermenter gegeben, so muss der Gesamttrockenmassegehalt der Mischung berücksichtigt werden. Die Masse muss zum einen rührfähig sein und zum anderen den Mikroorganismen gute Beweglichkeit gewährleisten. Die Trockensubstanzgehalte sollten unter 15 %, idealer Weise bei 8 bis 10 % liegen. Ein geeigneter Gesamttrockensubstanzgehalt kann durch entsprechende Zugabe von Gülle oder Prozesswasser zu den Co-Substraten erreicht werden.

1.5.2 Abschätzung des Methanertragspotentials einer Biomasse

Die Abschätzung des spezifischen Biogas- und Methanertragspotentials einer Biomasse ist wichtig unter anderem im Hinblick auf das Mischungsverhältnis und die Substratmenge bei der Beschickung einer Biogasanlage. Die Mikroorganismen setzen die Biomasse am besten und schnellsten bei gleich bleibender Qualität und Quantität um. Veränderungen der Substratzusammensetzung sollten nur langsam vorgenommen werden. Des weiteren darf eine Biogasanlage nicht mit Biomassen, die hohe spezifische Methanertragspotentiale aufweisen, überlastet werden. Es kann dann unter Umständen die Pufferkapazität für den pH-Wert überlastet werden, die erste Stufe des Biogasprozesses vermehrt ablaufen (siehe Kapitel 15.1.2) und als Folge wird viel Kohlendioxid und weniger Methan produziert.

Einen Hinweis auf die Eignung einer Biomasse für den Einsatz als Co-Substrat und das mögliche Methanertragspotential kann der Futterwert liefern. Die Werte, welche die Verdaulichkeit für einen Wiederkäuer bestimmen (Analyse nach Tilley und Terry), sowie der Rohprotein- und Rohfasergehalt lassen jedoch keinen eindeutigen Rückschluss auf das substratspezifische Methanertragspotential zu. Die spezifischen Methanertragspotentiale einzelner Stoffklassen können in Gärversuchen genau gemessen werden, doch sind die in Tabelle 1.17 genannten Stoffklassen in der Biomasse in Strukturen eingebunden, die erst aufgeschlossen werden müssen, so dass meist nicht die gesamte Substanz einer Stoffklasse umgesetzt werden kann.

Tabelle 1.17 Spezifisches Methanertragspotential und Methangehalt von Substraten unterschiedlicher Stoffklassen /1-2/

Stoffklasse	Substrat	Methanertrag in Nm^3 CH_4/ kg oTS [a]	Methangehalt im Biogas in %	Theoretischer Methanertrag in Nm^3 CH_4/kg oTS /1-14/
Kohlenhydrate	Stärke	0,349	46	0,375
	Cellulose	0,392	48	
Fette	Sonnenblumenöl	0,861	67	1,003
	Rapsöl	1,000	67	
Proteine	Gelatine	0,437	62	0,480
	Casein	0,457	63	

[a] Nm^3 Norm Kubikmeter (Normbedingungen: 1013,25 hPa und 273,15 K); oTS: organischer Trockensubstanzgehalt

Die Abschätzung des Methanertragspotentials über die Nahinfrarotspektroskopie liefert bisher nur Anhaltswerte zur Einstufung der Substrate. Das Modell befindet sich in der Validierungsphase, so dass in näherer Zukunft eine Methode zur Abschätzung erwartet werden kann /1-8/. Momentan gibt es keine genaue Bestimmungsmethode, die eine Biomasse als Co-Substrat bestimmter Qualität einstufen und darüber deren spezifisches Methanertragspotential identifizieren kann. Eine genaue Analyse mit Rückschlüssen auf die Gärqualität der Biomasse ist derzeit nur mit Biogasertragstests möglich. Anhand des Hohenheimer Biogasertragstests (vgl. /1-6/, /1-14/) kann das spezifische Methanertragspotential ermittelt werden.

Die tatsächliche Methanausbeute in einer Biogasanlage wird jedoch gegenüber dem Potential vermindert unter anderem durch die Bindung von Substrat für den Aufbau der Mikroorganismenpopulation (3 bis 10 % Substanzverlust für die Biogasproduktion) /1-14/ und die unterschiedlich schnelle Umsatzrate der Substrate zu Biogas. Bei nicht ausreichend langer Verweildauer in der Biogasanlage kann sich ein Restgaspotential von ca. 10 bis 15 % ergeben /1-12/.

Doch besonders bei grün geernteter Biomasse mit Silagequalität konnte gezeigt werden, dass das spezifische Methanertragspotential von untergeordneter Bedeutung ist. Das wesentliche Kriterium ist hier das Methanertragspotential pro Hektar, das in direkter Abhängigkeit zur Höhe des Trockenmasseertrages steht (Abb. 1). Das Methanertragspotential kann anhand folgender Gleichung berechnet werden (1-1).

Methanertragspotential pro Hektar (Nm^3 CH_4/ha) = Biomasseertrag (t Trockenmasse/ha) • spezifisches Methanertragspotential (Nm^3 CH_4/kg TS) • 1000 (1-1)

Je höher das Biomasseertragspotential einer für die Biogasproduktion geeigneten Art oder Sorte ist, desto höher ist auch das Methanertragspotential pro Hektar.

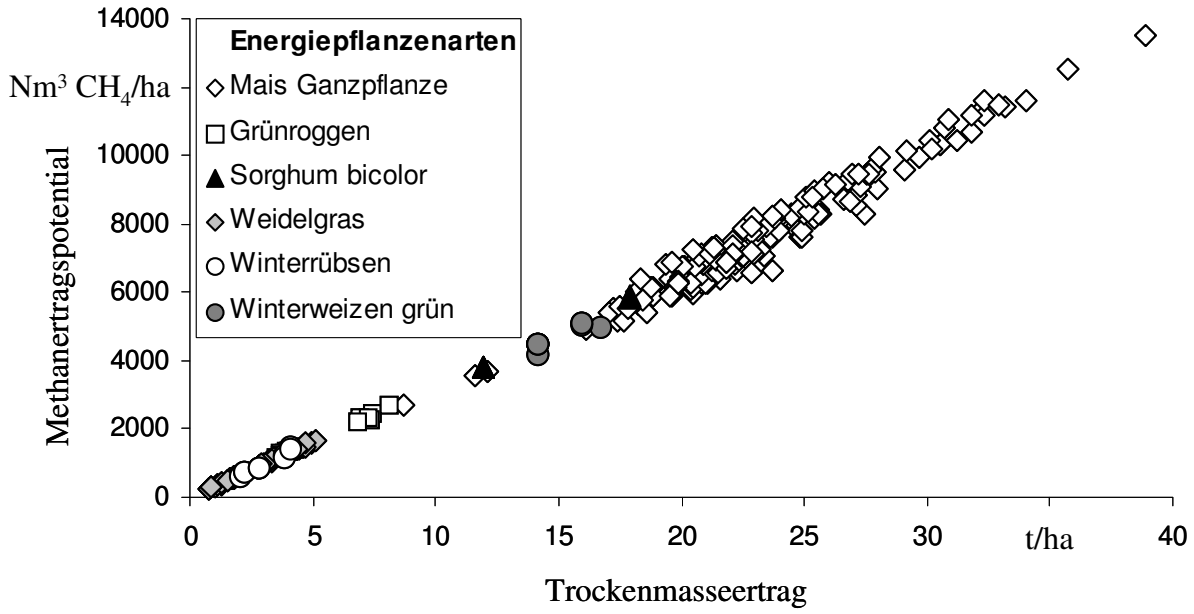

Abb. 1 Methanertragspotential pro Hektar in Abhängigkeit des Trockenmasseertrages pro Hektar

1.5.3 Auswahl geeigneter Arten zur Biomasseproduktion

Die Auswahl geeigneter Arten, deren Biomassen als Co-Substrat in einer Biogasanlage zum Einsatz kommen können, richtet sich neben Biomassequalitätskriterien hauptsächlich nach dem Biomasseertragspotential. Das Biomasseertragspotential definiert die Menge an Biomasse (Tonnen (t) Trockenmasse (TM)), welche eine Energiepflanze je Hektar (ha) und Jahr (a) bilden kann. Im Folgenden werden die derzeit wichtigsten Energiepflanzen für die Produktion von Biomasse zur Biogasgewinnung und deren energetische Eigenschaften beschrieben (Tabelle 1.18). Die Einordnung und Bedeutung von Fruchtfolgen, das heißt, der zeitlichen Abfolge unterschiedlicher Energiepflanzen auf dem Feld, erfolgt in Kapitel 1.5.4.

Neben dem momentan für die Biomasseproduktion größtenteils angebauten Mais können eine Vielzahl weiterer Biomassen in Form von Silage als Co-Substrat eingesetzt werden. Hierzu zählen unter anderem die unterschiedlichen Getreidearten, Gräser (hauptsächlich *Lolium*-Arten), Zwischenfrüchte, *Sorghum*-Arten, Sonnenblume und Topinambur. Auch die Sprossknollen von Topinambur können als Co-Substrat genutzt werden. Das Korngut von Getreide, Körnerleguminosen und Raps findet ebenfalls Verwendung. Körnerleguminosen und Raps haben allerdings nur eine sehr geringe Anbaubedeutung für die Biomasse-produktion, da sie aufgrund ihres hohen Proteingehaltes nur in geringen Mischungsanteilen der Biogasanlage zugeführt werden können. Außerdem bringen sie nur geringe Kornerträge und es gibt für ihre Nutzung ökonomisch attraktivere Alternativen.

Mais. Der Silomais (*Zea mays* L.) als Biomasselieferant zählt zu den Arten mit dem höchsten Biomasseertragspotential. Je nach Standort und Wasserversorgung sind Erträge von bis zu mehr als 25 t/(ha a) möglich. Das Ertragspotential ist neben optimalen Wachstumsbedingungen auch von dem Sortentyp und dem Abreifeverhalten abhängig (Abb. 2). Die Erreichung einer kritischen Temperatursumme (Summe der täglichen Temperaturmittelwerte oberhalb einer Basistemperatur von 6°C in einer bestimmten Periode, z.B. von Aussaat bis Ernte) und die standortspezifische Länge der Vegetationszeit bestimmt die Sortenwahl. In Mitteleuropa können Silomaissorten mit Siloreifezahlen von 180 bis 300 standortangepasst sicher angebaut werden. Für eine Sorte mit einer Siloreifezahl von z.B. 250 ist eine Temperatursumme von 1490 bis 1540°C erforderlich, um ca. 32 bis 35 % Trockensubstanz bilden zu können. Je höher die erreichbare Temperatursumme eines Standortes, desto später reifende Sorten, das heißt, Sorten mit einer höheren Siloreifezahl, können gewählt werden. Eine standortgeeignete Sorte mit entsprechender Siloreifezahl gewährleistet einen Ertrag zu optimalen Trockensubstanzgehalten für die Silierung (Tabelle 1.19). Für den Energiemaisanbau werden momentan Sorten mit Siloreifezahlen, die 30 bis 50 Punkte über dem Standortoptimum für die Futtermaisproduktion liegen, empfohlen. Dadurch erhöht sich das Biomasseertragspotential, was jedoch mit Risiken verbunden sein kann, wenn Frühfröste drohen oder der Mais durch ungünstige Witterung nicht abreifen kann. Bei nicht ausreichender Abreife der Ganzpflanze kann es zu Problemen mit der Silierung kommen, wenn die Trockensubstanzgehalte unter 28 % liegen.

Das Anbauverfahren konzentriert sich auf die Maximierung des Ganzpflanzenertrages, wobei der Kolbenanteil, abhängig von der Sorte und dem Erntetermin, sehr schwanken kann. Der Kolben- bzw. Kornanteil stellt ein entscheidendes Kriterium für den Trockensubstanzgehalt zum Nutzungszeitpunkt dar. Die Ernte sollte im Stadium der Milchreife bis frühen Teigreife des Kolbens durchgeführt werden. Das stärkereiche Korn hat ein höheres spezifisches Methanertragspotential als die Restpflanze (Tabelle 1.18), was sich im Gesamtmethanertragspotential dadurch auswirkt, dass mit verzögerter Ernte der Kornanteil und damit auch der Methanertrag steigt. Silomais zur Biomasseproduktion, hier Energiemais genannt, wird derzeit sehr stark züchterisch bearbeitet. Neue Energiemais-Sorten versprechen ein höheres Biomasseertragspotential über eine verlängerte vegetative Phase und vermehrte Blattmassebildung.

Silomais und desgleichen Energiemais wird bislang wenig von Krankheitserregern und Schädlingen befallen (vgl. Kapitel 3.3.2.4). Die Stickstoffdüngung richtet sich nach dem erwarteten Ertragspotential und sollte aufgrund erwünscht hoher Gesamtbiomasseerträge

nicht unter 150 kg/(ha a) liegen. Nährstoffe aus organischen Düngemitteln, wie Gülle und Gärreste der Biogasanlage, werden vom Mais sehr gut aufgenommen, was auch im Nährstoffkreislauf mit der Ausbringung der Gärreste von Bedeutung ist. Die Phosphor- und Kaliumdüngung wird in Kapitel 3.3.2.4 beschrieben.

Die Ernte wird mit reihenabhängigen oder -unabhängigen Maishäckslern durchgeführt. Die Häcksellänge sollte möglichst kurz sein (ca. 1 cm), um im Silo eine gute Verdichtung und einen optimalen Verlauf der Gärung (Silageprozess) zu gewährleisten. Kurze Häcksel bieten auch den Mikroorganismen in der Biogasanlage eine bessere Angriffsfläche. Nach Einbringung der Häcksel in ein Silo, Verdichtung und luftdichter Abdeckung setzt unter anaeroben Bedingungen die Milchsäuregärung der Biomasse ein. Während des Prozesses wird Zucker aus der Biomasse zu Säure abgebaut. Die Bildung der Milchsäure lässt den pH-Wert bis auf einen Wert von ca. 4 absinken und dient gleichzeitig als Konservierungsmittel. Nach ca. sechs Wochen ist der Prozess abgeschlossen und in diesem Zustand ist die Silage bis zu einem Jahr lagerfähig.

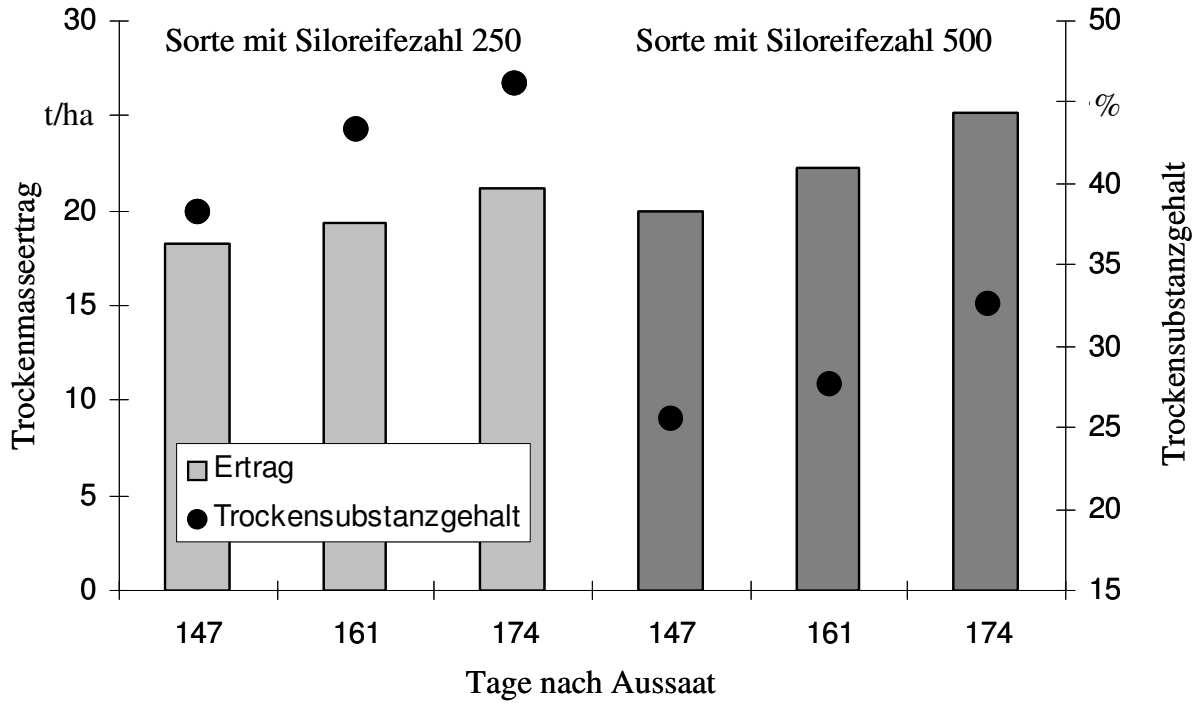

Abb. 2 Trockenmasseertrag und Trockensubstanzgehalt von zwei unterschiedlich reifenden Maissorten (Sorten mit einer Siloreifezahl von 250 gelten als angepasst an den Versuchsstandort, eine Sorte mit der Siloreifezahl 500 ist sehr spät reifend) an drei Ernteterminen (147 bis 174 Tage nach Aussaat), Standort Stuttgart-Hohenheim.

Getreide. Getreide zur Verwertung in der Biogasanlage wird entweder als Ganzpflanze zur Silagegewinnung oder zur Kornproduktion angebaut. Meist angebaute Arten sind Roggen (*Secale cereale* L.), Triticale (*Triticosecale* Wittmack) und Weizen (*Triticum aestivum* L.). Zur Silagegewinnung wird das Getreide bei TS-Gehalten in der Ganzpflanze um die 30 % im Stadium der Milch- oder Teigreife geerntet. Zur Gewinnung von Korngut wird im Stadium Totreife bei TS-Gehalten von ca. 86 % gedroschen (Tabelle 1.19). Das anfallende Stroh kann dann nicht in der Biogasanlage verwertet werden. Die Erträge liegen bei Ganzpflanzenernte von Weizen zwischen 8,0 und 18,0 t/(ha a), je nach Standort und Sorte. Kornerträge belaufen sich auf 4,0 bis 9,5 t/(ha a) (vgl. Tabelle 3.6). Bei der Auswahl der Sorte wird weniger auf Qualitätsmerkmale als auf hohe Biomasseerträge geachtet.

Das grundsätzliche Produktionsverfahren für Getreide wird in Kapitel 3.1.6 beschrieben, während hier nur auf die spezifischen Anforderungen für Biogasanlagen eingegangen wird.

Nachdem sich der Getreidebestand etabliert hat, sind zur Silageproduktion teilweise weniger Herbizide notwendig als zur Korngutproduktion, denn auch die Unkrautbiomasse kann einen Beitrag zur Biomasseproduktion leisten. Die Behandlung mit Wachstumsregulatoren zur Halmverkürzung und Stabilisierung der Standfestigkeit ist hauptsächlich nur dann erforderlich, wenn sonst Lager und Ertragsausfall drohen. Während der Korngutproduktion muss auf die Pflanzengesundheit geachtet werden, da sonst Mindererträge zu erwarten sind. In der Ganzpflanzenproduktion kann weitgehend auf die Behandlung von Krankheiten verzichtet werden. Die der Biomasse anhaftenden Krankheitskeime können in der Biogasanlage abgetötet werden /1-4/, so dass die Gärreste risikolos als Dünger eingesetzt werden können. Das Düngemanagement sollte sich auf die Maximierung des Biomasseertrages ausrichten. Die Stickstoffdüngermenge wird in zwei Gaben aufgeteilt und richtet sich nach der Höhe des Entzuges (Tabelle 3.5). Erhöhte Stickstoffgaben erhöhen die Proteingehalte in der Biomasse, was aufgrund ungünstiger Auswirkungen in der Biogasanlage vermieden werden sollte.

Die Ernte zur Silageproduktion wird mit einem Feldhäcksler oder Mähwerk durchgeführt. Die Anforderungen und Durchführung zur Silageproduktion sind ähnlich denen der Maissilageproduktion. Der optimale Erntetermin und eine kurze Häcksellänge sind entscheidend für die Silagequalität. Bei der Korngutproduktion wird das Korngut im Mähdrusch geerntet und dann trocken gelagert.

Gräser und Grünlandaufwuchs. Das Anbauverfahren für Acker-, bzw. Futtergräser wird in Kapitel 3.1.5 beschrieben, unterscheidet sich jedoch von dem dort Genannten in den

Anforderungen an das Erntegut und dem damit verbundenen Schnittzeitpunkt. An ertragreichen, das heißt, niederschlagsreichen Standorten können Gräser mehrschnittig genutzt werden. Die Nutzung von Grünlandaufwüchsen ist ebenso denkbar, doch ist in beiden Fällen der Mehraufwand durch die Schnitte dem Energieertrag gegenüberzustellen. Unter den Gräsern sind Weidelgräser (*Lolium* spp.) die ertragreichsten Arten und liefern Trockenmasseerträge bis zu 17 t/(ha a). Grünland liefert bei 3 bis 5 Schnitten pro Jahr zwischen 7,5 und 12 t TM/(ha a). Die Schnitthäufigkeit richtet sich nach den Standortverhältnissen. Die Sortenwahl erfolgt nach Vegetationsdauer (ein- oder mehrjährige Nutzung) und Biomasseertragspotential. Der Schnittzeitpunkt ist ein wichtiges Kriterium für die Verdaulichkeit. Je länger der Schnitt nach dem Ährenschieben hinausgezögert wird, desto höher ist der Rohfaseranteil und desto geringer ist die Verdaulichkeit, bzw. die Umsetzbarkeit in der Biogasanlage. Pflanzenschutzmaßnahmen sind bei Gräsern meistens nicht notwendig. Die Stickstoffdüngung richtet sich nach der Schnitthäufigkeit und der Höhe der Ertragserwartung und kann bei intensiv genutzten Grasbeständen bis zu 300 kg/(ha a) betragen. Bei dreimaligem Schnitt und mittlerer Ertragserwartung liegt der Stickstoffbedarf bei ca. 170 bis 200 kg/(ha a). Die Ernte erfolgt mit rotierenden Mähwerken. Durch die relativ geringen Trockensubstanzgehalte zur Ernte (Tabelle 1.19) muss das Erntegut auf dem Feld angewelkt werden, um durch Verdunstung von Wasser die Trockensubstanzgehalte auf Werte von optimaler Weise 35 % zu erhöhen. Die Silagebereitung erfolgt dann wie bei Mais.

Zwischenfrüchte. Zu den Zwischenfrüchten zählen Arten wie Rübsen, Futterleguminosen, Kleegras (Gemenge aus Klee und Gras), Getreidearten wie Roggen (Grünroggen – früh geernteter Roggen) und auch Gräser. Zwischenfrüchte werden häufig als ausgleichendes Glied in Fruchtfolgen angebaut. Vielfach dienen sie zur Auflockerung der Fruchtfolge, zur Verbesserung von Bodeneigenschaften, zur Minderung von Erosion und Nitratauswaschung, werden aber auch zur Futternutzung geschnitten. Wenn sie nicht zu Ertragszwecken geerntet werden, wird die oberirdische Biomasse gemulcht und in den Boden eingearbeitet. Zwischenfrüchte werden im Sommer oder Winter zwischen den Hauptfrüchten einer Fruchtfolge angebaut. Sie liefern bei ausreichend langer Wachstumszeit gute Biomasseerträge. Je nach Standort, Wasserangebot und Witterung können diese Arten zum Gesamtbiomassepotential beitragen, jedoch muss auch immer wieder mit Ausfällen bei ungünstiger Witterung gerechnet werden. Bei Beerntung der oberirdischen Biomasse verlieren sie meist die bodenverbessernden Eigenschaften und dienen nur als Biomasselieferant. Die Trockenmasseerträge von Grünroggen und Futterleguminosen

erreichen Werte bis maximal 10 t/(ha a). Weidelgräser liefern als Zwischenfrucht Erträge von bis zu 6 t TM/(ha a), während die meisten Arten bis maximal 4 t TM/(ha a) erbringen. Die Sortenwahl bei Zwischenfrüchten erfolgt nach Jahreszeit (Winterfestigkeit ist zu beachten), Vegetationsdauer und Biomasseertragspotential. Bei Futterleguminosen ist ebenso wie bei Gräsern der Schnittzeitpunkt ein wichtiges Kriterium für die Verdaulichkeit. Der Nutzungszeitpunkt der anderen Zwischenfrüchte richtet sich zum einen nach optimalen Siliereigenschaften (Tabelle 1.19), zum anderen aber auch nach der Stellung in der Fruchtfolge und der dafür eingeräumten Zeitspanne. In einer Fruchtfolge wird häufig nicht der optimale Nutzungszeitpunkt der Zwischenfrüchte erreicht, da das Anbauverfahren der Hauptfrüchte Vorrang hat. Wird bei zu niedrigen Trockensubstanzgehalten geschnitten, muss das Erntegut wie im Grasanbau angewelkt werden.

Gräser, Futterleguminosen und Kleegras können auch als Untersaat, z.B. im Mais, angebaut werden. Die Saat erfolgt idealer Weise im Sechs-Blatt-Stadium des Maises und der Aufwuchs der Untersaat wird vor der Aussaat der Folgefrucht geschnitten.

Pflanzenschutzmaßnahmen sind bei Zwischenfrüchten meistens nicht notwendig. Bei Futterleguminosen wird kein Stickstoff gedüngt. Den anderen Zwischenfrüchten reicht häufig Reststickstoff der Vorfrucht und die Nachlieferung mineralisierten Stickstoffs aus dem Boden. Bei guter Witterung werden N-Gaben von bis zu 60 kg/(ha a) gut in Ertrag umgesetzt. Geerntet wird mit Mähwerken und die Silierung wird wie bei Mais durchgeführt.

Sorghum. Sorghum-Arten wie *Sorghum bicolor* (L.) Moench (Zucker- oder Futterhirse) und *Sorghum sudanense* (Piper) Stapf. (Sudangras), sowie Kreuzungen dieser zwei Arten gestalten sich im Anbau ähnlich wie Mais. Die Ertragserwartung liegt bei 12 bis 30 t/(ha a) trockener Biomasse. Die Sortenwahl erfolgt nach Standort, Vegetationsperiode und hohen Biomasseertragspotentialen. Die Futterhirse wird einmal im Herbst bei Erreichen der Silagequalität geschnitten (Tabelle 1.19), während das schnell lignifizierende Sudangras meistens zweischürig (zwei Schnitte pro Jahr) genutzt wird, was allerdings nicht zur Ertragssicherheit beiträgt. Der erste Schnitt schwächt die Pflanze, was zu Pflanzenausfällen und Minderertrag zur zweiten Ernte führen kann. Als relativ anspruchslose, wärmeliebende und trockenheitsverträgliche C_4-Pflanze können diese Arten auf Mais-, sowie Maisgrenzstandorten angebaut werden. Für einen hohen Biomasseertrag sind hohe Stickstoffgaben von mindestens 150 kg/(ha a) erforderlich. Eine zu hohe Stickstoffgabe sollte vermieden werden, da sonst die Standfestigkeit gemindert wird und es zu Lager und Fäulnis

kommen kann. Pflanzenschutzmaßnahmen sind meist nicht notwendig (vgl. Kapitel 3.3.1.2). Die Ernte erfolgt mit einem Feldhäcksler oder Mähwerk. Die Silierung erfolgt wie bei Mais.

Sonnenblume. Wüchsige Genotypen der Sonnenblume (*Helianthus annuus* L.) können als Alternative z.B. zum Mais angebaut werden. Die Sonnenblume kann den Bodenwasservorrat gut erschließen, was auf trockenen Standorten einen Vorteil gegenüber dem Mais bedeutet. Es lassen sich Gesamttrockenmasseerträge von bis zu 14 t/(ha a) realisieren. Bei der Sortenwahl ist auf biomassebetonte Genotypen zu achten, wobei hohe Ölgehalte zu einer hohen Methanausbeute beitragen. Die erste Energiesonnenblumensorte zur Biomasseproduktion steht kurz vor der Zulassung. Der Nutzungszeitpunkt richtet sich nach der Silierfähigkeit, die im Stadium der Milchreife der Körner bei Trockensubstanzgehalten von 25 bis 30 % erreicht ist (Tabelle 1.19). Die Notwendigkeit zur Durchführung von Pflanzenschutzmaßnahmen kann teilweise über die Bestandesführung und gute Einordnung in die Fruchtfolge minimiert werden (vgl. Kapitel 3.2.2). Eine angepasste Stickstoffdüngung von bis zu 120 kg/(ha a) erhöht das Biomasseertragspotential, aber gleichzeitig die Krankheitsanfälligkeit und senkt die Standfestigkeit. Geerntet wird die Sonnenblume mit einem reihenunabhängigen Feldhäcksler oder Mähwerk. Die Silagebereitung erfolgt wie bei Mais.

Topinambur. Allgemeine Daten zum Anbau von Topinambur (*Helianthus tuberosus* L.) werden in Kapitel 3.3.2.2 beschrieben. Topinambur kann ein- oder mehrjährig angebaut werden und zur Biomasseproduktion auf zweierlei Weise genutzt werden. Zum einen kann die oberirdische Biomasse siliert, zum anderen können die unterirdischen Sprossknollen genutzt werden. Im einjährigen Anbau kann die gesamte Biomasse geerntet werden. Die Sortenwahl richtet sich nach der Nutzungsrichtung (Kraut oder Knolle) oder, bei gleichzeitiger Nutzung von Kraut und Knolle, nach möglichst hohen Gesamtbiomasseerträgen, wobei bei Doppelnutzung nicht der optimale Nutzungszeitpunkt beider Pflanzenpartien erreicht werden kann. Spätreifende Sorten haben ein höheres Gesamtbiomasseertragspotential. Die Sorten sind teilweise sehr alt und haben häufig noch Wildpflanzencharakter. Im mehrjährigen Anbau wird das Kraut einmal jährlich im Herbst geschnitten und liefert bei ca. 30 bis 40 % TS Trockenmasseerträge bis zu 20 t/(ha a). Im einjährigen Anbau kann die gesamte Biomasse oder auch nur die Knollenmasse geerntet werden. Mittlere Knollenerträge liegen bei ca. 9 t TM/(ha a) (Tabelle 1.19). Je später im Jahr geerntet wird, desto niedriger ist der Krautertrag und desto höher der Knollenertrag. Die Stickstoffdüngung sollte bei der Knollenproduktion 80 kg/ha nicht übersteigen, da erhöhte N-Gaben nicht in Knollenmasse umgesetzt werden können. Zur Krautproduktion können bis zu

40 kg N/ha zusätzlich gegeben werden. Die Pflanzengesundheit kann mit guter Bestandesführung erhalten werden (vgl. Kapitel 3.3.2.2). Das Kraut wird mit einem Mähwerk oder Feldhäcksler geerntet und einsiliert (siehe Mais). Die Knollen lagern am besten im Boden und werden bei Bedarf mit einem Kartoffelroder geerntet. Knollen lassen sich außerhalb des Boden nur wenige Wochen lagern.

Tabelle 1.19 Erntekriterien und Lagerungsformen von Biomassen für die Co-Fermentation

Biomasse	Erntekriterium	Lagerung/Behandlung
Mais	Stadium Milch- bis Teigreife, TS-Gehalt[a] von 28-35 %	Silage
Getreide (Weizen) Korn	Stadium Totreife, TS-Gehalt ca. 86 %	Korngut/schroten oder quetschen
Getreide (Weizen) Ganzpflanzensilage	Stadium Milch- bis Teigreife, TS-Gehalt von 30-35 %	Silage
Ackergräser und Grünlandaufwuchs	ab Stadium Ährenschieben, Verdaulichkeit und Rohfaseranteil, TS-Gehalt von 15-22 %	anwelken[b], Silage
Zwischenfrüchte	TS-Gehalt ab ca. 20-25 %	anwelken, Silage
Sorghum-Arten	TS-Gehalt von 25-35 %	Silage
Sonnenblume	Stadium Milchreife, TS-Gehalt ca. 30 %	Silage
Topinambur (Kraut)	TS-Gehalt von 30-40 %	Silage
Topinambur (Knolle)	oberirdische Biomasse abgestorben, ab Ende Oktober	Knolle im Boden/evtl. quetschen
Silphie	TS-Gehalt ca. 30 %	Silage
Knöterich	TS-Gehalt von 25-30 %	Silage

[a] TS-Gehalt: Trockensubstanzgehalt der Frischmasse zur Ernte; [b] Anwelken: Maßnahme zum Wasserverlust zur Erhöhung der TS-Gehalte

Weitere Arten zur Biomasseproduktion. Arten, die kaum bis gar nicht züchterisch bearbeitet sind und auch nur in sehr begrenztem Umfang bisher angebaut wurden, können unter Umständen sehr interessant für die Biomasseproduktion werden. Diese Arten lockern die Fruchtfolge auf, haben meistens nur einen sehr geringen Unkraut- und Schaderregerdruck und auch nur geringe Standortansprüche. Zu diesen Arten zählen zum Beispiel die Durchwachsene Silphie (*Silphium perfoliatum* L.) und Arten der Gattung *Reynoutria* (*R. japonica* Houtt – Japanischer Staudenknöterich und *R. sachalinensis* (F. Schmidt) Nakai – Sachalin-Knöterich).

Die Silphie gehört zur Familie der Korbblütler und ist in den gemäßigten Regionen Nordamerikas heimisch. Der Anbau der ausdauernden und rhizombildenden Pflanze ist nicht sehr arbeitsintensiv. Nach der Saat oder Pflanzung beschränken sich die Maßnahmen

hauptsächlich auf die jährlichen Düngegaben. Die Silphie benötigt etwa dieselben Mengen an Stickstoff wie Mais. Die Ertragserwartung liegt zwischen 13 und 20 t TM/(ha a) ab dem zweiten Standjahr. Die Ernte erfolgt bei den zur Silagebereitung günstigen Trockensubstanzgehalten (Tabelle 1.19) mit einem Mähwerk oder Feldhäcksler.

Der Knöterich zählt zu der Familie der Knöterichgewächse und stammt aus Japan. Der Anbau dieser ebenfalls mehrjährigen und rhizombildenden Art gestaltet sich ähnlich wie bei der Silphie. Der Knöterich wird entweder gesät oder über Rhizome gepflanzt und jährlich mit ca. 80 kg/ha Stickstoff gedüngt. Der Knöterich wird bis zu dreimal jährlich ab einem Trockensubstanzgehalt von ca. 25 % (Tabelle 1.19) mit Mähwerk oder Häcksler geschnitten. Es lassen sich Erträge zwischen 10 und 25 t TM/(ha a) realisieren. Der Silageprozess beider Arten erfolgt wie bei Mais.

1.5.4 Fruchtfolgen und Anbauverfahren zur Bereitstellung von Biomasse zur Biogasproduktion

Die Fruchtfolgegestaltung für die Biomasseproduktion hat das Ziel, eine hohe Flächenproduktivität mit der Nachhaltigkeit eines Anbausystems zu kombinieren. Eine Fruchtfolge definiert sich als geregelte zeitliche Abfolge unterschiedlicher, meist einjähriger Kulturarten auf einem Feld. Ihre Gestaltung orientiert sich an den folgenden Aspekten:

- Hohes Gesamtbiomasseertragspotential: Mit dem Gesamtbiomasseertrag steigt die Effizienz eines Anbauverfahrens. Je höher der Ertrag pro Flächeneinheit, desto höher ist auch das Methanertragspotential und desto weiter ist das energetische Output:Input-Verhältnis.
- Ausnutzung der Wachstumsperiode: Die produktivste Zeit während des Jahres sind die Sommermonate, doch viele Feldfrüchte wie Getreide nutzen diese Periode nicht aus, da sie vor Ende des Sommers geerntet werden. Energiepflanzen wie Mais und Hirsen, die zudem als C_4-Pflanzen eine sehr hohe Wassernutzungseffizienz aufweisen, haben dagegen ihre Hauptvegetationsperiode in den Sommermonaten und deshalb ein hohes Biomasseproduktionspotential.
- Auftreten von Krankheiten und Schädlingen: Monokulturen fördern das Auftreten spezialisierter Krankheitserreger und Schädlinge. Über eine abwechslungsreiche Fruchtfolge kann der Schaderregerdruck minimiert werden.

- Ganzjährige Bodenbedeckung: Im Hinblick auf die Minderung von Erosion und Nitratauswaschung ist eine möglichst ganzjährige Bodenbedeckung wünschenswert. Dies kann z.B. durch den Anbau von Zwischenfrüchten realisiert werden.
- Abstimmung der Saat- und Nutzungstermine: Eine gute Abstimmung des Anbaus aufeinander folgender Früchte sichert ein hohes Biomasseertragspotential der Fruchtfolge, die Ausnutzung der Wachstumsperiode und eine möglichst ganzjährige Bodenbedeckung.
- Wasserversorgung: Die Wasserversorgung kann ein ertragslimitierender Faktor sein. Daher muss die Fruchtfolge dem standortspezifischen Wasserangebot angepasst werden, um Ertragsausfälle zu vermeiden.

Mögliche Fruchtfolgeschemata für den Energiepflanzenanbau zur Versorgung einer Biogasanlage sind in Abb. 3 gezeigt. Fruchtfolge FF1 stellt eine Monokultur (Sommerung) dar, für die typischerweise Mais gewählt wird. Der Mais gehört zu den Kulturen, die selbstverträglich (Sensibilität einer Kultur gegenüber Krankheitserregern, die kulturartenspezifisch durch mehrmaligen Anbau verstärkt auftreten) sind, aber nach langjähriger Monokultur teilweise Mindererträge aufweisen. Die Vorteile der Monokultur sind die Möglichkeiten der optimalen Bestellung, Etablierung und Bestandesführung einer Kultur. Der Wasserhaushalt wird von keiner weiteren Kultur beansprucht, was in Regionen mit Wasserknappheit von Bedeutung wird. Nachteilig wirkt sich das potentiell verstärkte Vorkommen von bestimmten Krankheiten und Schädlingen, die einseitige Beanspruchung und die über Winter lange Zeit unbedeckte Oberfläche des Bodens aus. Während der Brachezeit können Nährstoffe (besonders Nitrat) ausgewaschen werden und der Boden ist empfindlich gegenüber Wind- und Wassererosion. Der Anbau einer Monokultur ist für nicht erosionsgefährdete Gebiete, aber hauptsächlich für Regionen mit knappem Wasserangebot mit Niederschlägen unter ca. 500 bis 550 mm und geringer Wasserhaltekraft des Bodens (sandige Böden) zu empfehlen. Bei höherem Wasserangebot ist in jedem Fall eine Zwischenfrucht oder Untersaat zu empfehlen. Der Arbeitszeitbedarf einer Monokultur ist vergleichsweise gering.

In Fruchtfolge FF2 (Abb. 3) ist die Hauptfrucht mit einer Untersaat bestellt. Als Untersaat dienen häufig Gräser, Kleegras und Futterleguminosen, die in den etablierten Bestand der Hauptfrucht gesät werden und entweder über Winter abfrieren und eingearbeitet werden oder deren Aufwuchs bei guter Witterung im Frühjahr vor der Aussaat der Folgefrucht geerntet wird. Zu den Vorteilen einer Untersaat gehört die Minderung von Erosion und Nitratauswaschung durch die Bodenbedeckung und die Möglichkeit den

Gesamtbiomasseertrag auf der Fläche zu erhöhen. Erträge von Grasuntersaaten lassen sich bei ausreichend langer Wachstumszeit bis 6 t TM/(ha a) realisieren. Anstelle der Untersaat kann auch eine Zwischenfrucht gewählt werden, die nach der Ernte der Hauptfrucht gesät wird. Diese Fruchtfolgevariante FF2 ist für Regionen geeignet, die ausreichend Niederschläge (> 600 mm) aufweisen, in denen aber das Wachstum durch die Länge der Vegetationsperiode (z.B. Höhenlagen ab ca. 500 m) beschränkt wird.

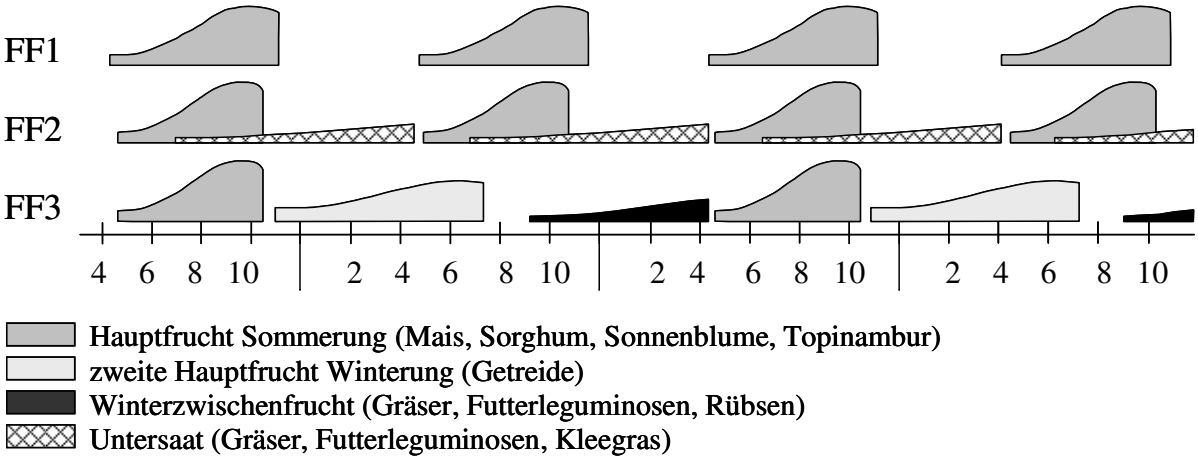

Abb. 3 Drei Anbauschemata von Fruchtfolgen zur Biomasseproduktion (Abszisse stellt die Monate des Jahres dar)

Intensivere Fruchtfolgen mit fast ganzjähriger Bodenbedeckung setzen ausreichend Niederschläge (> 700 mm) und eine lange Vegetationsperiode voraus. Eine intensive Fruchtfolgegestaltung mit zwei unterschiedlichen Hauptfrüchten (Sommerung und Winterung) und einer Winterzwischenfrucht ist in der dritten Fruchtfolge (FF3) abgebildet. Der Wechsel von Winterung und Sommerung und C_3- und C_4-Pflanzen mit einer möglichst ständigen Bedeckung des Bodens stellt eine gute Grundlage für einen intensiven, aber nachhaltigen und umweltfreundlichen Energiepflanzenanbau dar. Innerhalb dieser Fruchtfolge müssen die Saat- und Erntetermine folgender Früchte aufeinander abgestimmt werden. Wird z.B. Mais als Hauptfrucht im Sommer gewählt, so kann er auf guten Standorten bei später Saat Mitte Mai gegenüber einer drei Wochen früheren Saat bis zum selben Erntetermin trotz kürzerer Vegetationszeit gleich hohe Biomasseerträge bilden. Winterzwischenfrüchte können bei guter Witterung im Frühjahr relativ hohe Biomasseerträge liefern und zu einem hohen Gesamtbiomasseertrag beitragen /1-1/.

Eine gut aufeinander abgestimmte Fruchtfolge sichert neben der Pflanzengesundheit und der Erhaltung der Bodenfruchtbarkeit ein hohes Biomasseertragspotential, muss aber an den jeweiligen Standort und das verfügbare Wasserangebot angepasst werden.

Tabelle 1.18 Anforderungen und Eigenschaften unterschiedlicher Biomassen zur Co-Fermentation /1-3/, /1-7/, /1-9/, /1-10/, /1-13/

Biomasse	Wachstumsperiode (min. und max.)	N-Düngung in kg/ha	Biomasseertragspotential in t Trockenmasse/(ha a)	Methanertragspotential in Nm^3 CH_4/kg oTS	C:N:P:S-Verhältnis
Mais Ganzpflanze	Mitte 04/Ende 05 bis Anfang 09/Anfang 11	150-240	12,0- >25,0 (30,0)	0,295-0,380	600:16:3:1,5 bis 600:21:5:3
Mais Korn			5,8-14,5	0,366-0,417	C:N = 600:19
Mais Spindel			1,6-3,1	0,283-0,333	
Mais Lieschen			1,0-3,0	0,297-0,349	
Mais Restpflanze			5,8-16,3	0,300-0,326	
Getreide (Weizen) Korn	Mitte 09/Ende 10 bis Ende 07/Ende 08	100-180	4,0-9,5	0,355-0,370	600:31:10:2 bis 600:34:7:3
Getreide (Weizen) Ganzpflanzensilage	Mitte 09/Ende 10 bis Mitte 06/Anfang 07	100-140	9,0-18,5	0,310-0,350	600:19:4:2
Ackergräser	Anfang 07/Mitte 09, ein- oder mehrjährig, bis zu 5 Schnitte/Jahr	120-320	7,0-17,0	0,320-0,370	600:34:4:5 bis 600:45:6:11
Grünlandaufwuchs	Anfang 07/Mitte 09 für Gründlanderneuerung	120-300	7,0-12,0	0,300-0,350	600:24:1:0,3
Zwischenfrüchte	je nach Einordnung in die Fruchtfolge, Sommer- oder Winterzwischenfrucht	0-80	2,0-10,0	0,310-0,380	
Sorghum-Arten	Anfang 05/Anfang 06 bis 09/Mitte 10	150-220	10,0-25,0	0,300-0,360	N:P:S = 20:8:3 bis 20:3:3
Sonnenblume	Ende 04/Mitte 05 bis Anfang 08/Ende 09	60-120	9,0-14,0	0,280-0,325	
Topinambur (Kraut)	Anfang 03/Mitte 04 bis Ende 08/Ende 09	80-100	7,0-20,0	ca. 0,290	N:P:S = 20:6:17
Topinambur (Knolle)	Anfang 03/Mitte 04 bis Ende 11/Anfang 03	80	4,0-13,5	ca. 0,390	N:P:S = 20:13:4
Erbse	Anfang 03/Ende 03 bis Anfang 07/Ende 07	0	2,4-5,0	ca. 0,270	600:51:6:3
Ackerbohne	Ende 02/Ende 03 bis Ende 08/Mitte 09	0	3,5-7,0	ca. 0,270	600:83:7:4
Raps	Mitte 08/Ende 08 bis Mitte 07/Ende 07	180-240	2,8-4,8	0,540-0,630	600:27:7:2 bis 600:39:9:5
Silphie	Mitte 04/Ende 04, mehrjährig	150-200	13,0-20,0	ähnlich Mais	
Knöterich	Anfang 05/Ende 05, mehrjährig	80	10,0-25,0		

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5. Paper IV

High quality production of energy maize (*Zea mays* L.) in crop rotation systems – biomass and methane yields and environmental impacts

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Abstract

The biogas production is a growing sector in Germany and an outcome of the improvement of renewable energies demanded by the EU. Biogas plants, which use co-substrates such as maize and cereal silage next to liquid manure are financially supported. Silage maize became one of the most favored energy crops. In this context here it is called energy maize. Currently, energy maize is bred for new high biomass yielding varieties, but there is little-known about their environmental impact and the influences of crop rotation systems. A two-year field trial was conducted to get more knowledge about energy maize. Six crop rotation systems, with the main crop being energy maize, partially preceded by three different winter catch crops (winter rye, winter turnip rape and Italian ryegrass) and followed by winter wheat, were cultivated in south-western Germany to identify their biomass yield potential and possible environmental impacts. The second test parameter were four differently maturing potential energy maize varieties (FAO-rating between 250 and 700). Third test parameter were two yield strategies. The strategies differed in the sowing and harvest dates of the crops and possibly vary in yield and quality. Quality aspects in terms of dry matter content at harvest and specific methane yields were measured for all crops for further evaluation. The Results show that the crop rotation system with maize in monoculture had the highest yield (20.5 to 28.2 t dry matter $ha^{-1}a^{-1}$), but also had the highest possible environmental impacts, such as nitrogen leaching and erosion. The crop rotation system with winter rye as a catch crop, followed by maize and winter wheat (harvested at milk ripeness) seemed to be a system with high biomass yields (mean value 17.9 t dry matter $ha^{-1}a^{-1}$) and at the same time it had only minimal environmental impacts. Here, the treatment with late sown and early harvested maize was advantageous because of higher catch crop yields, but it showed similar maize yields in comparison to the treatment with an early sowing and late harvest of the maize. A

site-adapted early maturing variety was advantageous, compared to a late maturing variety, due to the early development of biomass and adequate dry matter contents. The dry matter content increased with increasing maturity rate of the maize varieties (expressed by FAO-rating) and a later harvest date, and ranged between 18.9 and 47.3 % of fresh matter. Specific methane yields among the maize varieties ranged between 0.333 and 0.363 Nm^3 CH_4 kg^{-1} volatile solids. The primary factor in the evaluation of the energy performance was the biomass yield, with higher biomass yields resulting in higher methane production per hectare.

Keywords: Maize; Energy crop; Catch crops; Crop rotation system; Biomass; Methane

1. Introduction

With the directive on electricity generation from renewable energy sources (CEC, 2001), the EU set the target of 22.1 % indicative share of electricity produced from renewable energy sources in the EU-25 by 2010. Germany was identified as high effective in renewable energy production by applying feed-in tariffs in the EU (CEC, 2005a; GAN et al., 2007). Within the scope of the directive, Germany strives towards the promotion of electricity generation through combined heat and power units via biogas production. With commencement of the update of the Act on Granting Priority to Renewable Energy Sources (Renewable Energy Sources Act) on August 1, 2004, Germany offers its stakeholders good incentives to invest in new biogas plants. A large number of new biogas plants arose because Germany promotes primarily small-scale plants (CEC, 2005a). Higher incentives for biogas plants, which use specially grown energy crops as co-substrates to liquid manure, strongly promoted the production of energy crop cultivation. Due to this fact the production of silage maize, in particular, increased in Germany. At the end of 2005 about 450 MW accumulated power was installed in heat and power units in Germany. If this power is to be served by biogas plants using only maize as a co-substrate, about 1.5 % of the agricultural area in Germany must be used for maize cultivation. However, the number of biogas plants is still rising and the policies favor the utilization of a variety of co-substrates in addition to silage maize, such as grass and whole grain crops. These crops yield less per unit area than silage maize, therefore, the demand for agricultural land for biomass production will increase. But, land is in short supply and other uses, such as food and fodder production are in direct competition with energy crops. Furthermore, the supply of land for biomass production is not only limited by food and fodder crops, but also by crops for different energy sources in addition to biogas, such as liquid and solid biofuels.

The targets of the EU can only be achieved by doubling the current supply of biomass for heat and electricity generation in the EU-25 to about 130 million tonnes of oil equivalent by 2010 (CEC, 2005b). The amount of agricultural land in Germany, like in most member states, cannot be increased and domestic food production cannot be affected. Therefore, the biomass and energy yield per unit area must be sustainable at a high level to meet all the demands on available farmland. In addition, energy cropping must be environmentally benign to maintain the basic ideas of renewable energy production (HILL, 2007). Within this context, so-called double-cropping systems were developed with the aim of producing high biomass yields with minimum inputs and maximum soil cover throughout the year. The biomasses are harvested before physiological maturity during a stage of high biomass dry matter accumulation (KARPENSTEIN-MACHAN, 1997; 2002). These systems are supposed to be more environmentally benign and are thought to enhance biodiversity (KARPENSTEIN-MACHAN, 2004).

Intensive maize breeding programs currently release new genotypes that are supposed to have special features with respect to high biomass production and are intended to open up a new class of maize varieties. The so-called energy maize varieties are bred to maximize biomass yields under Central European conditions, which can be achieved by a later maturation and increased development of vegetative biomass (SCHMIDT, 2006).

Taking these aspects into account and the fact that currently little is known about energy maize production (HERRMANN and TAUBE, 2006), we focused our research on the optimization of the cultivation of energy maize.

The aim of our study was to investigate whether it is possible to produce high biomass yields in an environmentally benign energy crop rotation system. Our work concentrated on the following questions: (i) Can a crop rotation system with continuous maize production be highly productive and at the same time having acceptable environmental impacts? Are there other crop rotation systems that should be favored? (ii) Is there a maize variety (early or late maturing) that can be recommended for energy maize production? (iii) Which quality (in terms of dry matter content) of harvested biomass is produced and can it be influenced by the production management or harvest date? and (iv) Which methane yield potentials do the crops have in the crop rotation systems?

To find answers to these questions, we conducted a field trial in south-western Germany with four differently maturing energy maize varieties and additional crops, such as winter wheat and three different winter catch crops (winter rye, winter turnip rape and Italian

ryegrass). Crops were grown in six different crop rotation systems and two different yield strategies to optimize the biomass production.

2. Materials and Methods

2.1. Experimental site

The field trial was performed at the experimental station "Ihinger Hof" of the University of Hohenheim in south-western Germany. The station is located at 48°44' N latitude, 8°56' E longitude and at about 480 m above sea level. The long-term average annual air temperature and total precipitation are 8.1°C and 693 mm, respectively. The soil is considered to be a Haplic luvisol with a silty clay texture. The field trial started in September 2003. Yield measurements were performed during the years 2004 to 2005.

2.2. Experimental design

The trial had a 3-factorial randomized complete split plot design, with two yield strategies as main plots, six two-year crop rotation systems (CRS) as subplots, and four different maize varieties as sub-subplots, in three replications. The sub-subplot size was 8.6 m x 4 m. The crop rotation systems contained energy maize (*Zea mays* L.) as a main crop, partially preceded by three different winter catch crops (Italian ryegrass – *Lolium multiflorum* Lam., winter turnip rape – *Brassica rapa* L. and winter rye – *Secale cereale* L.), and followed by winter wheat (*Triticum aestivum* L.) or an undersown grass (perennial ryegrass – *Lolium perenne* L. + Italian ryegrass – *Lolium multiflorum* Lam.) (Fig. 1.). All selected crops are thought to support the energy production. The two yield strategies were chosen to obtain divergent biomass yields and qualities, and were realized through differing sowing and harvest dates:

- Yield strategy "long maize": The maize was sown early and harvested late to maximize the vegetation period for maize cultivation.
- Yield strategy "short maize": The maize was sown late and harvested early to give the other crops in the crop rotation systems a possibly longer vegetation period.

For exact sowing and harvest dates and established canopy density see Table 1. The maize varieties were chosen to represent a wide range of different maturing rates, using the FAO-rating system (Table 2). They were selected based on a high biomass yield performance and

on the potential to be released by breeders as special energy maize varieties. The new varieties (all except Gavott) have not been tested under different growth conditions and crop rotation system influences, and therefore their performance in the field cannot yet be predicted.

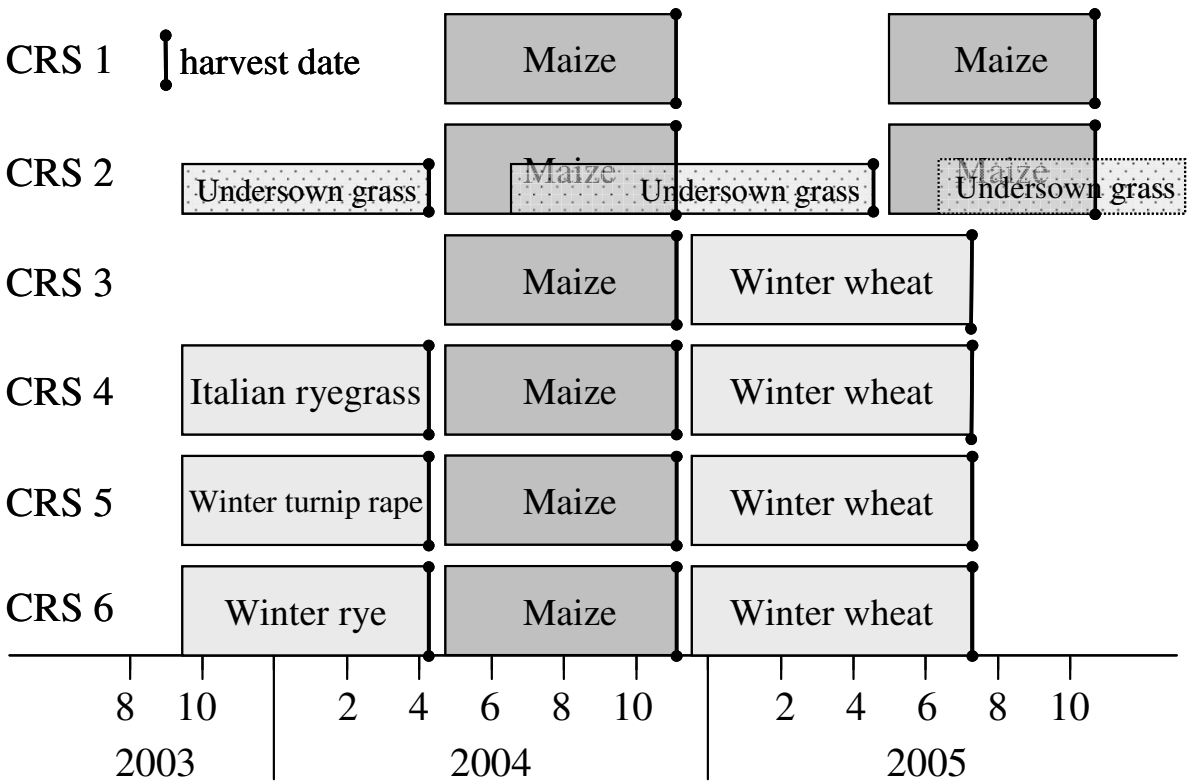

Fig. 1. Energy crops for the selected six two-year crop rotation systems (CRS 1 to 6) for the field trial, all crops are intended for biogas production.

Total aboveground maize biomass was harvested with a single row forage harvester by cutting 9 m^2 per plot. All other crops were harvested manually by cutting 1 m^2 per plot. The winter wheat was cut during the growth stage 'milk ripeness', whereas the other crops were harvested according to the chosen dates in the two yield strategies and therefore had different growth stages at harvest. Harvested material was oven dried at a temperature of 60°C to constant weight. Fresh and dry matter weight was measured. The dry matter content of the different crops and varieties was measured because it is a key factor in the following silage process used to preserve and store the biomass.

Soil preparation was carried out with a cultivator for winter catch crops and winter wheat. In addition to the cultivator, a plough was used for winter wheat. A spring-tine harrow was used before maize cultivation. Phytosanitary measures were carried out according to

infestation pressure. The nutrient supply status of the soil was determined at the beginning of the trial. Fertilization of potassium and phosphor was not necessary due to a good soil supply. Mineral nitrogen (N) fertilizer (containing 26 % N, thereof 7.5 % NO_3-N and 18.5 % NH_4-N + 13 % S + nitrification inhibitor DMPP) was applied to the winter catch crops at the beginning of February 2004, at a rate of 40 kg N ha^{-1}. After sowing, the maize plots received 230 kg N ha^{-1} in 2004 and 240 kg N ha^{-1} in 2005. Nitrogen fertilization of winter wheat was divided into three applications and was applied at the beginning of April, May and June 2005, with rates of 80 kg N ha^{-1}, 50 kg N ha^{-1} and 50 kg N ha^{-1}, respectively. The undersown grass received 80 kg N ha^{-1} at the beginning of February 2005.

The maize plant density was counted in 2004 and 2005 on all plots of both yield strategies. Measurements were done on 2 m^2 size plots on the 26.05.04 for yield strategy "long maize" and on the 14.06.04 for yield strategy "short maize". In 2005, counting took place on the 14.06.05 for both yield strategies.

Table 1
Sowing and harvest dates and sowing density of energy maize, winter catch crops, winter wheat and undersown grass

	Sowing and harvest dates		
	Yield strategy		
Crop management	"long maize"	"short maize"	Sowing density
Sowing catch crops	10./12.09.03	10./12.09.03	Italian Ryegrass: 40 kg ha^{-1} Winter rye: 160 kg ha^{-1} Winter turnip rape: 10 kg ha^{-1} Grass underseed: 15 kg ha^{-1} Italian ryegrass + 10 kg ha^{-1} Perennial ryegrass
Harvest catch crops	20.04.04	04.05.04	
Sowing maize	26.04.04	14.05.04	10 seeds m^{-2} in rows with 0.75 m distance
Sowing grass	28.06.04	28.06.04	15 kg ha^{-1} Italian ryegrass + 10 kgha^{-1} Perennial ryegrass
Harvest maize	02.11.04	04.10.04	
Sowing winter wheat	16.11.04	22.10.04	220 seeds m^{-2}
Harvest grass	22.04.05	10.05.05	
Sowing maize	30.04.05	13.05.05	10 seeds m^{-2} in rows with 0.75 m distance
Sowing grass	19.07.05	19.07.05	35 kg ha^{-1} Italian ryegrass
Harvest winter wheat	17.08.05	17.08.05	
Harvest maize	25.10.05	27.09.05	

Table 2
Selected differently maturing (early (FAO 250) to very late maturing (FAO 700)) energy maize varieties for the field trial, years 2004 and 2005

Variety	Variety-no.	FAO-rating	2004	2005
Gavott	1	250	x	x
Deco	2	ca. 300		x
Lucatoni	4	ca. 400		x
Méridienne	2	ca. 400-450	x	
Mikado	3	ca. 500	x	x
Doge	4	ca. 700	x	

2.3. Soil mineral nitrogen analysis and water budget calculation

The mineral nitrogen contents of the soil were measured to quantify possible environmental impacts. The plant available mineral nitrogen content in the soil was determined by measuring the nitrate (NO_3^-) content. Three soil samples per plot were taken down to a depth of 90 cm. The samples were oven dried at a temperature of 60°C to constant weight, ground through a 2 mm sieve and then analyzed for nitrate content of the soil dry matter using the method of Kjeldahl.

The water budget calculation was done for each crop rotation system and yield strategy as mean over the four maize varieties. The calculation was intended to give a general overview of the water supply of a crop rotation system. The water consumption of the two-year crop rotation systems was estimated by calculating the quotient of the total biomass yield of each system and the water use efficiency of the different crops based on McVetty et al. (1989) and Mueller et al. (2005). These values were summed up and the difference between them and the total precipitation during cultivation of the crop rotation systems indicates the water budget of a system. The values are only a benchmark.

2.4. Biogas analysis

The biogas analysis was performed for further validation of the harvested biomass yields and was done using a batch experiment, the Hohenheim Biogas Yield Test (HBT – Hohenheimer Biogasertragstest) (Helffrich and Oechsner, 2003). Methane yield was measured from oven dried and ground (1 mm sieve) samples for all maize varieties in CRS 1, for all catch crops, undersown grass and for winter wheat. Syringe samplers were filled with liquid manure, as inoculum, and dried plant material, and were then incubated for 35 days at a mesophilic temperature of 37°C. Biogas production was measured continuously and summed

up for a cumulative biogas yield after 35 days. The biogas volume, which was produced by the inoculum was subtracted from the cumulative yield in order to obtain the specific methane yield of the plant material. The methane volume was adjusted to norm conditions (273.15 K and 101.3 kPa). The yield was measured using a photometric sensor. For calculating the methane yield per unit area see equation 1.

2.5. Statistical analysis

The total dry matter yields, the maize dry matter yield in 2004, the maize plant density in 2004 and 2005 and the specific methane yields of winter catch crops and maize in 2004 and 2005 were evaluated with an analysis of variance by using the SAS procedure PROC MIXED (SAS version 9.1, SAS Institute Inc., Cary, NC, USA). Mean values were compared at $P < 0.05$.

The calculations for the coefficients of determination and the relation between dry matter yield and methane yield per hectare of all tested crops together were carried out using the SAS procedures PROC CORR and PROC REG. The calculations for the methane yield per hectare of the maize varieties in both years were done using the SAS procedure PROC MIXED and type one analysis. During the calculation, the mixed model was adjusted to results showing no significant differences between interactions of different parameters.

3. Results

3.1. Biomass yield, dry matter contents and plant density

The dry matter yields (DMY) of all crops in a crop rotation system were added to show the total yield potential of the different two-year crop rotation systems in both yield strategies (Fig. 2., Fig. 3., Table 3). The cumulated DMY, as mean over maize varieties and crop rotation systems, was significantly higher in yield strategy “short maize” than in yield strategy “long maize”. The cumulated DMY, as mean over the four maize varieties, was significantly highest of the trial in both yield strategies in CRS 1, with continuous maize, and in CRS 2, with an undersown grass. The lowest, though not significantly different, cumulated DMY were found in both yield strategies in CRS 4, with Italian ryegrass as a winter catch crop.

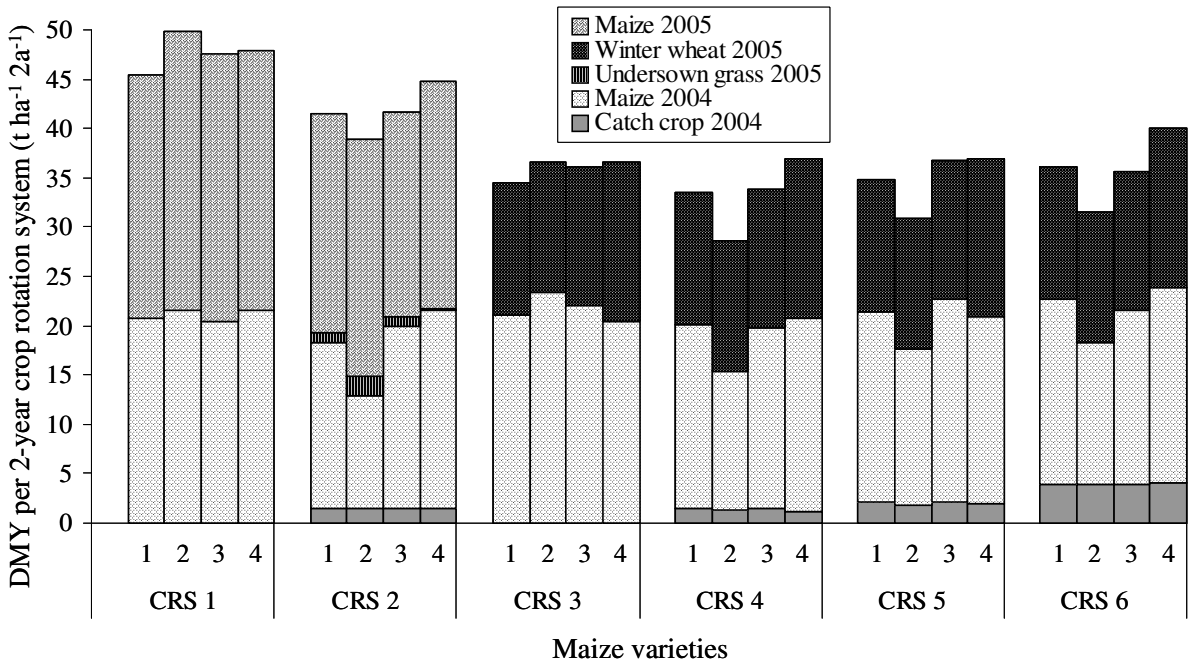

Fig. 2. Cumulated dry matter yield (DMY) of the six two-year crop rotation systems at yield strategy "long maize", differentiated to four maize varieties, LSD for comparing total DMY within a yield strategy = 4.45; LSD for comparing maize DMY in 2004 = 2.71.

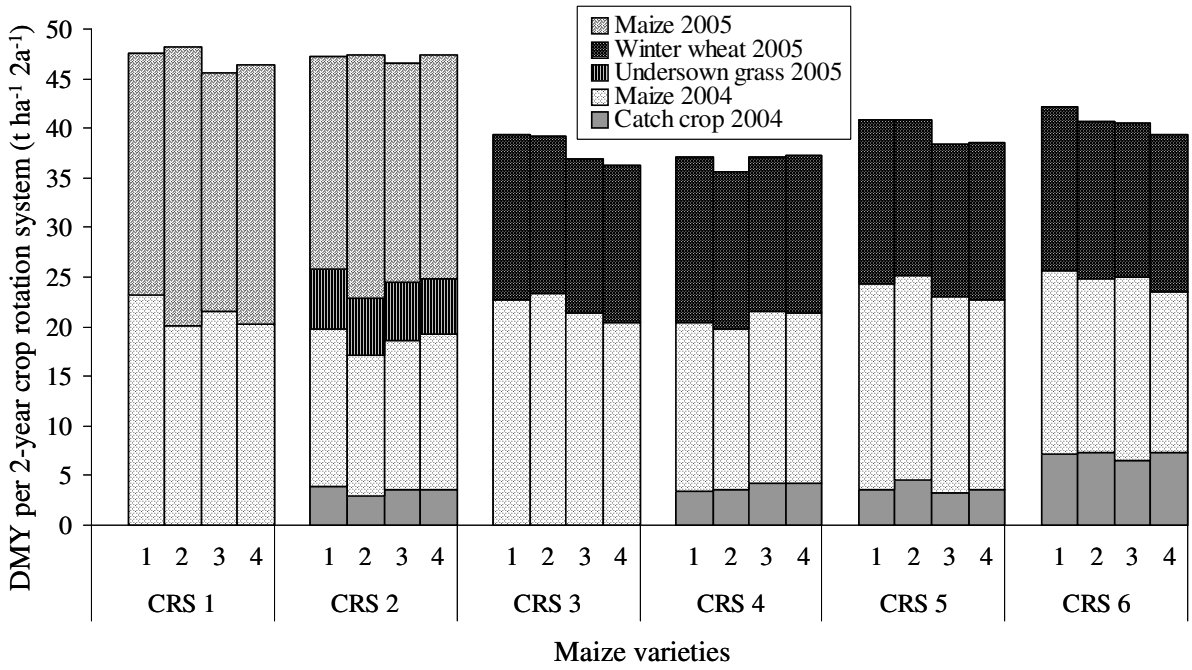

Fig. 3. Cumulated dry matter yield (DMY) of the six two-year crop rotation systems at yield strategy "short maize", differentiated to four maize varieties, LSD for comparing total DMY within a yield strategy = 4.45; LSD for comparing maize DMY in 2004 = 2.71.

Maize varieties showed a significant response to the crop rotation system and yield strategy in 2004 (Table 3). It is remarkable that the maize variety Méridienne showed

significantly lower yields than the other maize varieties in 2004, in the yield strategy "long maize" in the crop rotation systems, which followed winter catch crops or grass. The peak maize DMY value of 249 t DMY ha^{-1} a^{-1}, as a mean over maize varieties Méridienne and Deco, was reached in CRS 1, with yield strategy "long maize".

The DMY of the catch crops was at a significantly higher level in yield strategy "short maize" than in yield strategy "long maize". Winter rye showed, among the catch crops, the significantly highest yields with 7.1 t ha^{-1} a^{-1}.

Table 3
Analysis of variance for cumulated dry matter yield (DMY) of the two-year crop rotation systems and for maize DMY in 2004

		Cumulated DMY		Maize DMY 2004	
Effect	DF[a]	F-value	P-value	F-value	P-value
Maize variety (MV)	3	2.81	*	9.36	***
Crop rotation system (CRS)	5	53.05	***	33.47	***
Yield strategy (YS)	1	26.47	*	0.05	0.8484
YS*CRS	5	3.12	*	1.49	0.2383
YS*MV	3	8.78	***	9.77	***
CRS*MV	15	1.51	0.1240	3.61	**
YS*CRS*MV	15	0.81	0.6650	2.17	*
Replication	2	14.89	0.0629	12.16	0.0760

[a] Degrees of freedom.

The dry matter (DM) contents at harvest, of all crops, are presented as means over the six crop rotation systems for each yield strategy (Table 4). A general observation was that the dry matter contents of all crops were higher in yield strategy "long maize" than in yield strategy "short maize". The dry matter content decreased continuously from early maturing maize varieties (Gavott) to late maturing varieties (Doge or Mikado). At the time of harvest, the catch crops had just started stem elongation and the build-up of fresh matter and therefore had the lowest DM contents of the trial.

Maize plant density, counted in 2004, showed a significant response to maize variety, crop rotation system and yield strategy (data not shown). Especially the maize varieties Méridienne and Mikado had significantly lower plant densities than the other two varieties with the lowest value of 6 plants m^{-2} in crop rotation systems, which followed grass or winter rye. The highest average values were reached with 12 plants m^{-2}, as a mean over maize varieties, in crop rotation systems, which followed bare fallow. In 2005, the maize plant density showed no significant differences among maize varieties.

Table 4
Dry matter content (%) at harvest of the tested crops in the two yield strategies, means over the six crop rotation systems

Crop (year)	Yield strategy "long maize"	Yield strategy "short maize"
Italian ryegrass	21.9	19.9
Winter rye	19.2	19.0
Winter turnip rape	13.0	15.1
Undersown grass	22.0	20.7
Winter wheat	30.7	31.7
Gavott (2004)	41.1	34.2
Méridienne (2004)	31.5	27.2
Mikado (2004)	24.0	21.5
Doge (2004)	19.7	18.9
Gavott (2005)	47.3	32.1
Deco (2005)	44.6	28.4
Mikado (2005)	28.5	21.9
Lucatoni (2005)	37.2	23.9

3.2. Soil mineral nitrogen and water budget

The measured values of the mineral nitrogen content are a snapshot of the amount of nitrogen that was available at the time of measurement to the different crops in each crop rotation system and in both yield strategies (Fig. 4. and 5.). The time series of measurements showed the changes of the nitrogen availability in the different crop rotation systems. A general observation was that the amount of residual nitrogen from a preceding crop was still available after the following crop. Fertilizer applications were not adjusted to the amount of residual nitrogen in the soil. Between the maize harvest in 2004 and the end of March 2005, the residual nitrogen content in the soil doubled to quintupled, without any further applications of nitrogen fertilizer. In the spring of 2005, the CRS 5 with winter turnip rape in yield strategy "short maize" had a mineral nitrogen supply that was about 38 % higher than in CRS 4 with Italian ryegrass. Most of the nitrogen was found in the deepest soil layer (data not shown), which indicates that nitrogen leaching was occurring.

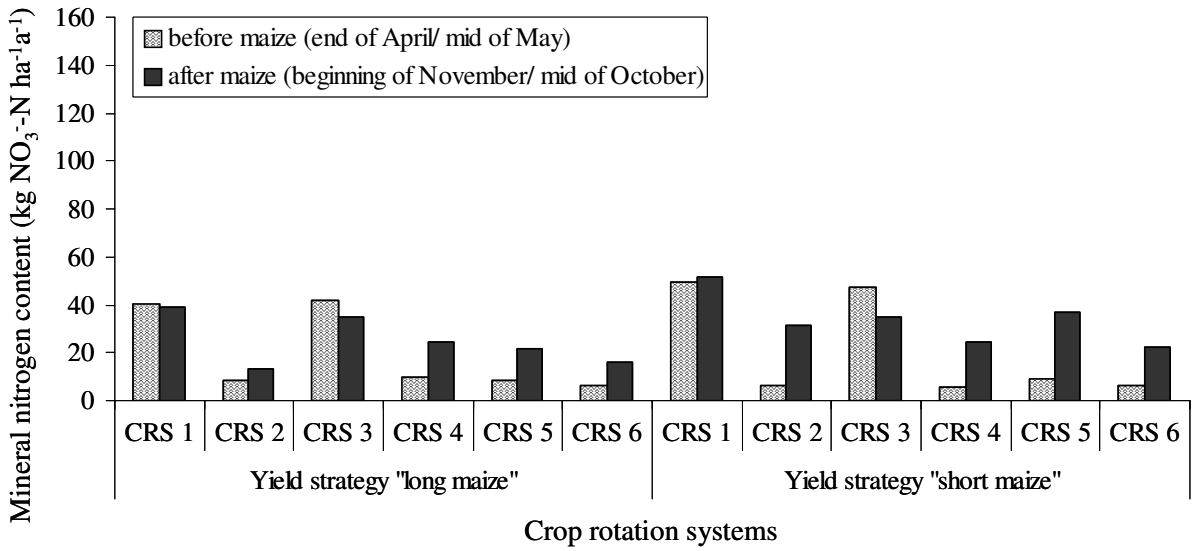

Fig. 4. Plant available mineral nitrogen content in the soil down to a depth of 90 cm in all crop rotation systems (CRS) and both yield strategies in 2004.

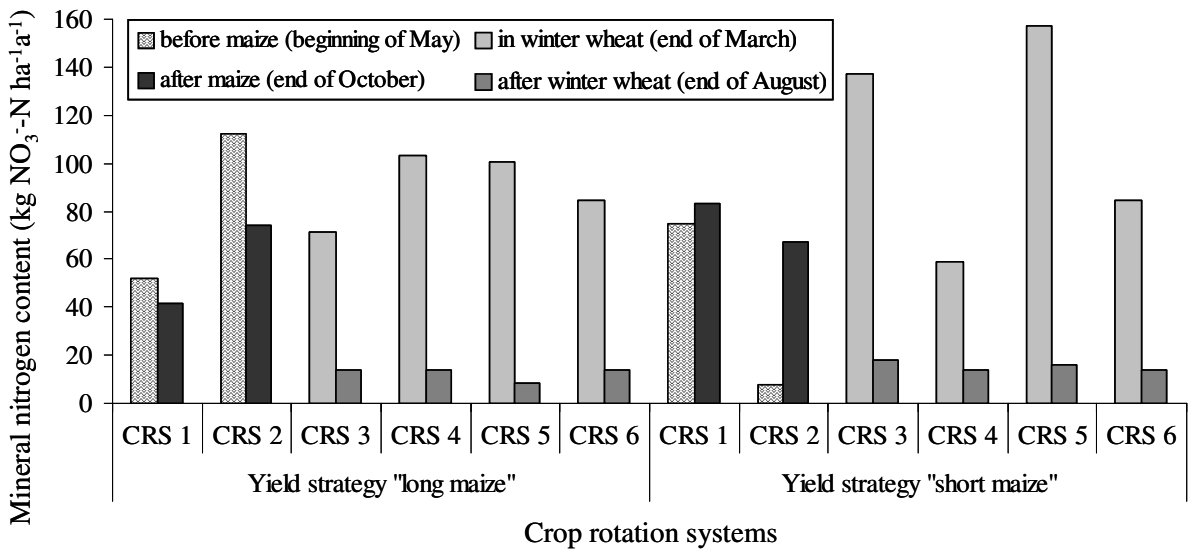

Fig. 5. Plant available mineral nitrogen content in the soil down to a depth of 90 cm in all crop rotation systems (CRS) and both yield strategies in 2005.

The estimated water budgets for the two-year crop rotation systems were calculated to increase the amount of information available on the water supply of the total cultivation period of the crop rotation systems (Table 5). The values of the water budgets only give an indication of whether there was a general surplus or deficit in water supply. The values suggest that there was sufficient water to supply the different crops in the crop rotation systems, with the exception of CRS 2 (with an undersown grass) in yield strategy “short maize”, which appeared to have had a deficiency after the two-year rotation.

Table 5
Estimated water budget (mm) of the six crop rotation systems (CRS) in both yield strategies, values indicate a surplus or deficiency after the rotation of two years

CRS	Yield strategy "long maize"	Yield strategy "short maize"
1	40	60
2	150	-90
3	300	240
4	350	210
5	290	130
6	280	130

3.3. Methane yield

The specific methane yields represent the potential of the different biomasses to produce methane per kg volatile solids (Table 6). A general observation was that there were no significant differences between the two yield strategies. The specific methane yields of the winter catch crops showed a significant difference between the crop rotation systems, which in this context means that there were differences between the different winter catch crops themselves.

The datasets of the analyzed crops indicated a strong relationship between the methane yield per hectare and the dry matter biomass yield of a crop (Fig. 6.). The higher the biomass yield, the higher was the methane yield of a crop per hectare.

The methane yield per hectare (MYH; $Nm^3\ CH_4\ ha^{-1}a^{-1}$; Norm cubic meter methane per hectare) can be calculated as follows:

$$MYH = DMY \times SMY \times 1000 \quad (1)$$

where the DMY is the dry matter biomass yield ($t\ ha^{-1}\ a^{-1}$) and SMY is the specific methane yield per kg dry matter content ($Nm^3\ CH_4\ kg^{-1}$ DM).

The methane yield per hectare of the maize varieties in both years showed a significantly different ranking of the maize varieties (Fig. 7., data only shown for 2004). An observation was that the level of methane yield per hectare was generally higher in 2005 than in 2004. But there was no uniformity of the variety rankings for the two years. The rankings were not arranged according to the FAO-ratings (i.e. maturing rates). The analysis of variance shows the calculations from the original mixed model and from the adjusted model (Table 7). Model

adjustment was made possible because no significant differences were found between the interactions of the different parameters.

Table 6
Specific methane yields of the tested crops per kg volatile solids (Nm^3 CH_4 kg^{-1} vs) (SCHUMACHER et al., 2006)

Crop (year)	Yield strategy "long maize"	Yield strategy "short maize"
Italian ryegrass	0.360	0.357
Undersown grass	0.356	0.353
Winter rye	0.365	0.350
Winter turnip rape	0.348	0.353
Winter wheat	0.340	0.345
Gavott (2004)	0.334	0.358
Méridienne (2004)	0.355	0.355
Mikado (2004)	0.339	0.344
Doge (2004)	0.348	0.363
Gavott (2005)	0.341	0.342
Deco (2005)	0.345	0.341
Mikado (2005)	0.335	0.338
Lucatoni (2005)	0.338	0.333

Nm^3: Norm cubic meter.
LSD for comparing specific methane yields of catch crops = 0.012; LSD for comparing specific methane yields of maize in 2004 = 0.020; LSD for comparing specific methane yields of maize in 2005 = 0.010.

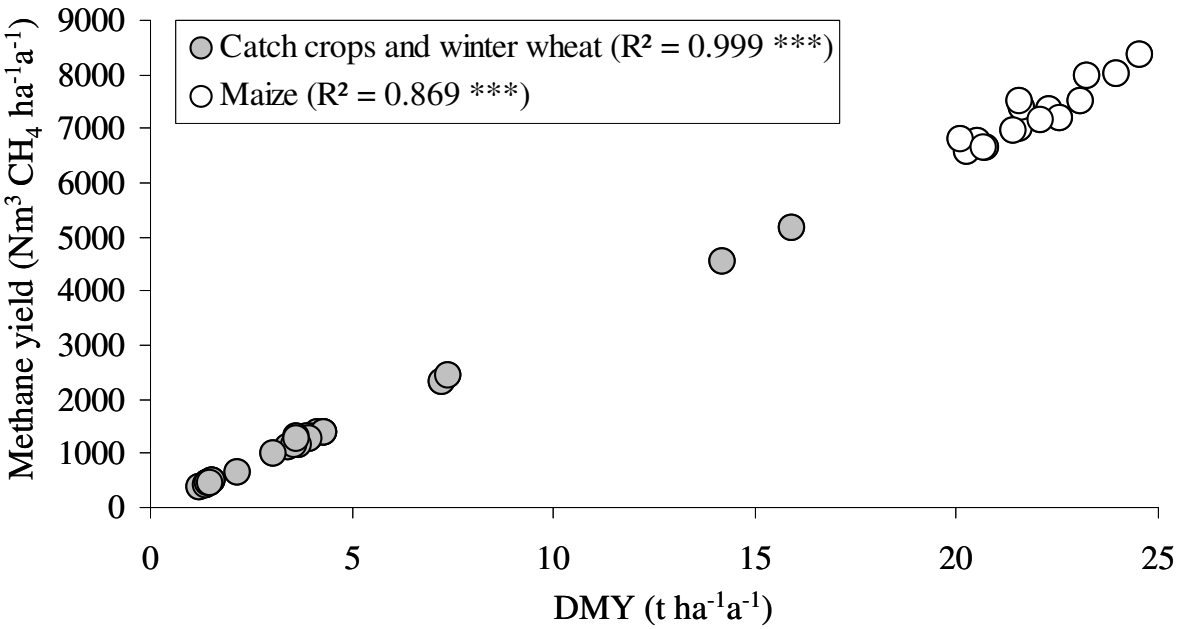

Fig. 6. Relation between dry matter yield (DMY) and methane yield per hectare of all tested crops.

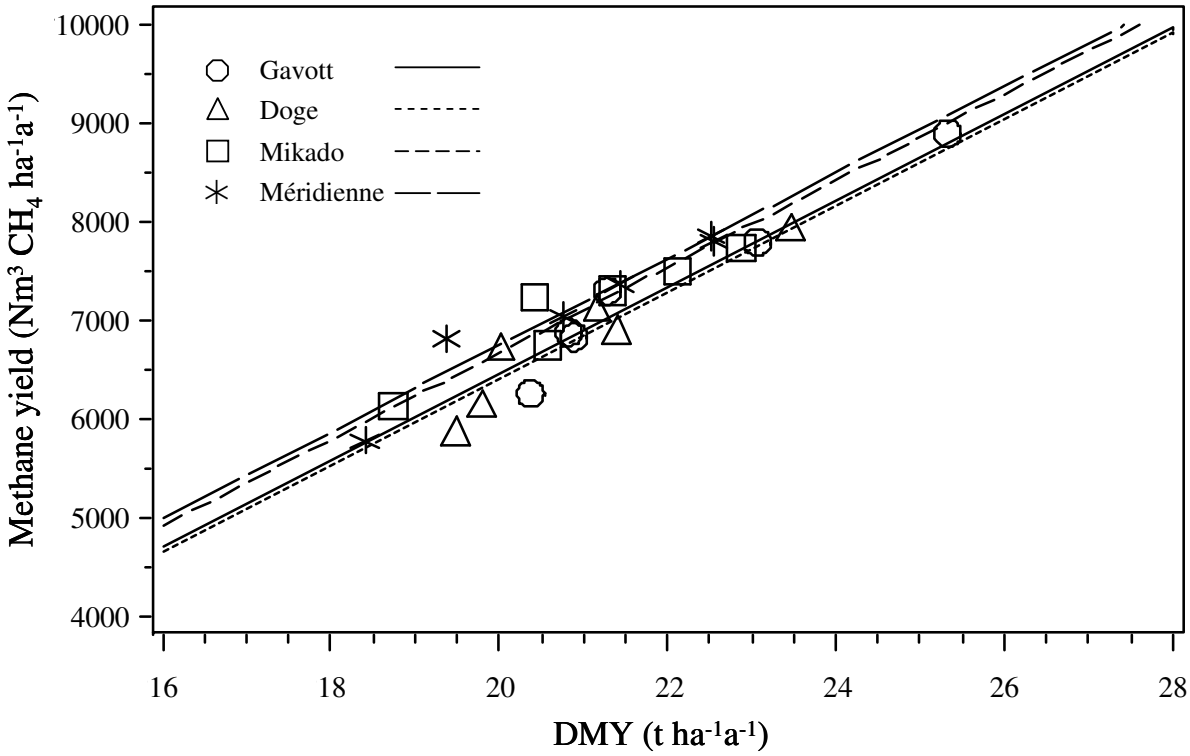

Fig. 7. Relation between dry matter yield (DMY) and methane yield per hectare of the different maize varieties in 2004. The lines show the regression line for each variety and symbol the measured values.

Table 7
Analysis of variance for methane yield per hectare of the different maize varieties in 2004 and 2005, calculation after original mixed model and adjusted model after there occurred no significant differences between parameter interactions

		Original model				Adjusted model			
		2004		2005		2004		2005	
Effect	DF[a]	F-value	P-value	F-value	P-value	F-value	P-value	F-value	P-value
Replication	2	27.10	**	397.59	*	0.81	0.5482	1.93	0.1816
Maize variety (MV)	3	6.41	*	97.38	*	4.58	*	8.73	**
Yield strategy (YS)	1	7.75	*	0.99	0.5014	1.66	0.3271	2.84	0.1142
MY*YS	3	27.52	***	24.52	*	-	-	-	-
Dry matter yield (DMY)	1	99.87	***	437.16	**	236.52	***	4584.47	***
DMY*MV	3	1.12	0.4119	0.52	0.6963	-	-	-	-
DMY*YS	1	0.30	0.6008	0.06	0.8194	-	-	-	-
DMY*MS*YS	3	1.20	0.3864	0.44	0.7394	-	-	-	-

[a] Degrees of freedom.

4. Discussion

4.1. Biomass yield, environmental impacts and the role of nitrogen and water supply

Crop rotation systems with continuous maize or with an undersown grass in both yield strategies were, with regard to biomass dry matter production, the best systems. It was expected that the maize in yield strategy "long maize" would be more productive than the maize in yield strategy "short maize", because of the almost six weeks longer growth period. Maize, as a plant with a C_4-photosynthetic pathway, is able to use the higher solar radiation of summer in combination with only moderate water requirements to build high biomass yields. Contrary to the expectation, the maize in the yield strategy "long maize" was not able to build more biomass, as was also observed by DARBY and LAUER (2002). The yield potential seemed to be already fully utilized at this site within the vegetation period of the yield strategy "short maize". As a result the selection of a yield strategy should be carried out with regard to other aspects. Quality, in terms of dry matter content, gains importance as does the yield performance of further crops in the crop rotation systems, especially when the systems with winter catch crops and winter wheat are considered. The yield strategy "short maize" seemed advantageous because of a more homogenous composition of the yield structure. Also the dry matter contents of most of the crops were in an adequate range for the subsequent silage process. The cumulated biomass yield in a crop rotation system with different crops is divided into the several components of the crop rotation system. More harvest times a year lead to a reduced risk of yield losses due to bad weather conditions or pests and diseases.

Environmental impacts of continuous maize production, such as erosion and nitrogen leaching, are thought to be enhanced when production extends over a longer period of time. The impact can be diminished by cultivating catch crops or an underseed, but this might also affect the maize yield performance (SCHÄFER, 1986; GOECK and GEISLER, 1989; STEMANN et al., 1993; VYN et al. 1999). Maize biomass yields, independent of the variety and yield strategy, showed a clear response to the preceding crop. Lower mineral nitrogen contents after catch crop growth or undersown grass may influence the following maize growth (KUO and JELLUM, 2002). KARPENSTEIN-MACHAN and STUELPNAGEL (2000) recommend a legume catch crop preceding maize, which could solve the nitrogen problem. No additional fertilizer would be needed but the leguminous crops cannot be used as a single substrate in a biogas plant due to their chemical composition (BOEHMEL, 2007), thus lowering their potential.

The highest residual nitrogen values, before maize sowing in CRS 1 (continuous maize), were found in the deepest soil layer (data not shown), which was not true for plots in CRS 2 (maize with undersown grass). This indicates a potential for diminishing nitrogen leaching by undersowing maize with a grass crop. Clayey and loamy soil, as predominantly present at the site, shows lower nitrogen leaching than other soils (KOLENBRANDER, 1969; BERNTSEN et al., 2006), but cannot totally limit the leaching process. Early-sown cover crops or an undersown grass, with a short winter dormancy, have the potential to reduce residual nitrogen and nitrogen leaching by covering the soil for most of the winter time (MARTINEZ and GUIRAUD, 1990; LEMOLA et al., 2000; MACDONALD et al., 2005).

The lower yields in CRS 2 (maize with undersown grass) compared to continuous maize growth in CRS 1 cannot be explained by a lack of mineral nitrogen, but might be due to limited water supply. The water budget calculation indicates that, at least in CRS 2 in yield strategy "short maize", water was one of the limiting factors. ABDIN et al. (1998) found interactions between maize and undersown crops when there was a competition for water. In this trial, the grass may not have affected the maize yield in the same year, because it accumulates biomass dry matter primarily after the maize harvest. However, the maize following grass may be provided with less soil moisture in comparison to continuous maize.

Another explanation for reduced maize growth after catch crop cultivation could be the presence of phytotoxic compounds in the soil, secreted by the catch crops and the grass. This occurrence, referred to as allelopathy, can be responsible for inhibited germination and growth of the following crop (MASON-SEDUN et al., 1986; EINHELLIG, 1996). The values from the maize plant density measurements could be an indication of the existence of allelopathy. In both years, maize plant density was higher in plots after bare fallow, rather than after catch crops or undersown grass. The very different responses of the maize varieties may indicate the differing sensitivities of the varieties to conditions during germination. Though, phytotoxic compounds may not only affect maize growth after catch crop cultivation, but also during continuous maize cultivation (EINHELLIG and LEATHER, 1988). During the performance of this trial, no evidence existed for eventual decreasing maize yields, but based on EINHELLIG and LEATHER'S research, one would expect decreasing yields in future years in continuous maize production.

Energy maize production in crop rotation systems with monoculture is highly productive, but leads to a higher risk of nitrogen leaching and erosion. According to RAIMBAULT et al. (1990) and the results from our trial, a crop rotation system with winter rye as a catch crop next to maize cultivation seems to form a sustainable and environmentally benign system for

biomass production. The CRS 6, with maize as the main crop, preceded by the catch crop winter rye and followed by a second main crop such as winter wheat, was a promising crop rotation system that can combine high yields with an acceptable level of environmental impacts. It should be considered that with the removal of all produced aboveground biomass of a crop rotation system, the soil humus content might decrease over time (NARDI et al., 2004). A basis assumption for the cultivation of an intensive crop rotation system is a sufficient water supply and a climate that ensures maize maturation during the vegetation period between April to October.

4.2. Maize varieties and quality

It was thought that alongside the crop rotation systems and yield strategies, the different varieties of maize would also influence biomass yield. In the context of the cumulated biomass yield of the two-year crop rotation systems, a differentiation between the varieties can only be made in the yield strategy "long maize", where late maturing maize varieties seemed favorable. New breeding programs for special energy maize varieties, such as Deco and Lucatoni, promise high biomass yields (SCHMIDT, 2006). These varieties yielded more biomass than the other varieties, but particularly the late maturing variety Lucatoni was not entirely satisfactory. Decisive, besides the biomass DMY, is the dry matter content. The variety Deco was the fastest growing variety of the trial and had sufficient dry matter content already at the early harvest date. The fast growth and build-up of dry matter yield is advantageous when an early harvest is desired. A harvest date past mid-October cannot be recommended for this variety, because at that point the dry matter content is too high for an optimal silage.

The appropriate dry matter content at harvest is a fundamental requirement for the subsequent silage process, which serves as an instrument for preservation and storage. An adequate dry matter content is between 28 and 35 % of fresh matter. Prevailing weather conditions in late summer and autumn are of importance for the development of the dry matter content. The dry autumn in 2005 led to a faster drying of the plant canopy of all varieties in yield strategy “long maize” and so to an overall higher dry matter content. Another explanation for the different performances of the varieties might be their different genetic backgrounds. The late maturing varieties Mikado and Doge originate from much warmer regions in southern Europe, and thus have a different growth habit and yield development. The varieties Deco and Lucatoni originate from the energy maize breeding

program. Their performance is different from that of adapted silage maize varieties and must be further analyzed.

4.3. Methane yield

The methane yield per hectare and the biomass yield of a crop showed a strong correlation, resulting in the choice of a crop and crop rotation system that produces high biomass yields. However, a distinction must be made amongst the different maize varieties. Specific methane yields had an influence on the methane yield per hectare. It could be shown that some maize varieties yielded more methane even when they produced the same amount of biomass. The same rankings that were derived from the means of the specific methane yields were also noticeable from the means of the methane yields per hectare of the maize varieties. However, the rankings did not correspond with the maturing rates of the varieties, the growth stage or the dry matter content at harvest. A further, as yet unknown method, must be found and applied to classify the different maize varieties for their potential to produce methane.

Observations of the specific methane yields of the winter catch crops showed that crops in the yield strategy "long maize" seemed advantageous, especially winter rye. This is not easily explained, because of the low dry matter contents of the catch crops. The catch crops harvested at an early growth stage did not contain substances such as oils or sugars, which have a high potential to build specific methane yields (CZEPUCK et al., 2006). The plant structure at this growth stage is not yet complex with high water contents and the plant material might be easily digestible by microorganisms.

The measured specific methane values represent only potentials because in practice the biomass is fed continuously to a biogas plant, whereas the HBT is a batch-essay at laboratory scale and here the specific methane yield is likely to be higher (GRUBER et al., 2004; KAISER et al., 2005). In a biogas plant, 5 to 10 % of the dry matter of the substrate's biomass (plant biomass and liquid manure) is used by the microorganisms to build their own matter. A further decrease of the specific methane yield potential is due to the presence of indigestible structures in the biomass (ANGELIDAKI and SANDERS, 2004). The biomass was tested as dried material in our experiments, but not as ensiled biomass, which is the usual material fed to a biogas plant. HEIERMANN et al. (2002) and AMON et al. (2007) found even higher specific methane yields for ensiled material than for fresh biomass. They attributed the higher yields to the predecomposition of the organic compounds during the silage process.

5. Conclusion

The careful selection of an energy crop rotation system is an important basis for sustainable and environmentally benign energy cropping to supply substrates for biogas production. Environmental impacts of the six different crop rotation systems, such as nitrogen leaching and erosion, were discussed. Results lead to the recommendation of a system with a possible year-round soil cover, which can be realized when a winter catch crop is cultivated before maize, which is then followed by winter wheat. Among the tested catch crops, winter rye was a high yielding crop when harvested relatively late in the season (beginning of May). A basis requirement of an intensive crop rotation system is a sufficient water supply. Early maturing varieties, up to a FAO-rating of 300, seemed advantageous compared to very late maturing varieties, because of the early development of biomass and dry matter content. This is an advantage in years with bad weather conditions and in an intensive crop rotation system, because the maize can be harvested early and the soil can be cleared for the following crop. Differently performing maize varieties in terms of specific methane yield and methane yields per unit area did not support the choice of one variety. In general, a high yielding variety and diversified crop rotation system should be chosen until further information is available of the methane production. The continuing breeding programs raise expectations for improved energy maize varieties in the near future.

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6. Paper V

Quality parameter estimation of energy maize (*Zea mays* L.) biomass and prediction of specific methane yield

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Abstract

Silage maize production is a widespread method of supplying the growing numbers of biogas plants in Germany with substrates for anaerobic digestion. To study the affect of different varieties of silage maize and crop rotation systems on the production of high quality biomass, nine differently maturing maize varieties were tested in six different crop rotation systems (additional crops were winter wheat, and the winter catch crops winter rye, winter turnip rape and Italian ryegrass) for three years. The key research questions were whether it is possible to produce high maize yields in crop rotation systems other than continuous maize systems, and to qualify the influence of the factors maize variety and harvest date on quality parameters such as starch, fiber and digestibility. A further question was whether these parameters can be used to determine the specific methane yields of maize. Results show that the highest yielding system, with an average yield of 20.9 t dry matter ha^{-1} a^{-1}, was the continuous maize system with the cultivation of a late maturing variety and a late harvest date (174 days after sowing). Crop rotation systems, in which maize is followed by winter wheat and a winter catch crop represent an environmentally benign system with adequate dry matter yields of between 16.1 and 19.2 t dry matter ha^{-1} a^{-1}. Specific methane yields of maize ranged from 307 to 370 m^3 CH_4 kg^{-1} volatile solids, and were moderately related to the starch and fiber content, and digestibility. Increases in starch and digestibility, and decreases in fiber resulted in increased specific methane yields. These parameters better determine the methane yields of late maturing varieties than of early maturing varieties.

Keywords: Energy maize; Crop rotation system; Biomass; Harvest date; Near infrared reflectance spectroscopy; Starch; Fiber; Digestibility; Methane; Anaerobic digestion

1. Introduction

Silage maize production has become a widespread method of supplying the growing numbers of biogas plants in Germany with substrates for anaerobic digestion. After liquid manure, plant biomass is currently the primary substrate fed to biogas plants on a daily basis [1]. The increasing area of silage maize production throughout Germany is sometimes thought to increase ecological problems associated with agriculture such as nitrogen leaching and erosion. Additional energy crops and environmentally benign cropping systems are needed to minimize the negative ecological impacts of continuous maize cropping. Generally all crops that can be preserved as silage or that are rich in carbohydrates such as sugar and starch and poor in lignocellulosic material can be fed into biogas plants. Grain crops can be harvested around the milkline stage to be preserved as silage or at full ripeness, at which the grain and partially the straw can be used as a substrate [2, 3]. Forage grasses and catch crops can be grown and preserved as silage and than used as a substrate [4, 5]. However, silage maize is recognized as the highest yielding annual energy crop for the supply of biomass for anaerobic digestion [6]. In this context, silage maize is called energy maize and is currently being bred to be particularly suitable as an energy crop. These new varieties are intended to be higher yielding in both biomass and specific methane yield [7]. The methane yield per area is thought to be dependent on the biomass yield [8 – 10]. Previous research has not yet been proven, which chemical composition of a biomass is especially advantageous for methane production [5]. Merely single substrates could be analyzed in isolated form [11].

The quality of maize production for fodder is well analyzed and can be expressed with different parameters, such as starch or protein content, fiber and digestibility. These parameters are either measured by wet chemistry or near infrared reflectance spectroscopy (NIRS) [12 – 15]. The NIRS analysis is recognized as an appropriate method of measuring forage quality parameters [16, 17]. Digestibility of the whole plant, as a primary parameter of forage quality, increases with higher amounts of digestible starch in the maize grain, until the digestibility of the stem and leaves is too low and the digestibility of the whole plant decreases [18, 19]. This suggests that with increasing maturity and digestibility, the methane yield will also increase. It has also been shown that digestibility can be improved genetically [20, 21], which gives the impetus for further breeding in order to produce better energy maize varieties.

However, the question arises whether these aforementioned quality parameters are also valid for methane production, because the process of anaerobic digestion in a biogas plant is somehow similar to the digestion that occurs in a ruminant [22].

The lack of knowledge in quality parameter determination for energy maize and the demand for an environmentally benign cropping system initiated our research. We focused our study on the following questions: (i) Are there cropping systems other than the continuous maize system that can be utilized for energy maize production? (ii) How great is the influence of the energy maize variety and harvest date (the maturity) on the dry matter yield and on quality parameters? (iii) Is it possible to determine the specific methane yield of maize through the determination of starch, fiber and digestibility, by using the near infrared reflectance spectroscopy?

For this purpose, a three-year field experiment was conducted in south-western Germany. It tested nine maize varieties, with different maturation rates, in six different crop rotation systems with additional crops winter wheat and the catch crops winter rye, winter turnip rape, and Italian ryegrass. Maize biomass was harvested at three different harvest dates to determine the influence of maturity. NIRS analyses were conducted to measure the quality parameters starch and fiber concentration and digestibility. All selected crops have the potential to contribute to methane production.

2. Materials and Methods

2.1. Site and experimental design

The field experiment was conducted at the experimental site Goldener Acker of the University of Hohenheim in south-western Germany. The site is located at 48°42’ N latitude, 9°13’ E longitude and at an altitude of 400 m above sea level. Soil type is a Typic Luvisol. The preceding crop on the site was summer wheat, which was followed by *Phacelia* as a winter catch crop. The mean annual air temperature and total precipitation are 8.8°C and 698 mm, respectively. Yield measurements were performed during the years 2004 to 2006.

The field experiment consisted of a two-factorial randomized complete split plot design in three replications. The first factor (main plot) consisted of six three-year crop rotation systems (CRS) (Fig. 1.) and the second factor (subplot) consisted of nine differently maturing energy maize varieties (Table 1). The maturing rates of the maize varieties varied between 250 (early) and 700 (very late), according to FAO-ratings. Subplot size was 7 m x 4 m. Tested crops in the crop rotation systems were, in addition to maize (*Zea mays* L.): winter wheat (*Triticum aestivum* L.), winter rye (*Secale cereale* L.), winter turnip rape (*Brassica rapa* L.),

Italian ryegrass (*Lolium multiflorum* Lam.) and a mixture of Italian ryegrass and perennial ryegrass (*Lolium perenne* L.) as an undersown grass.

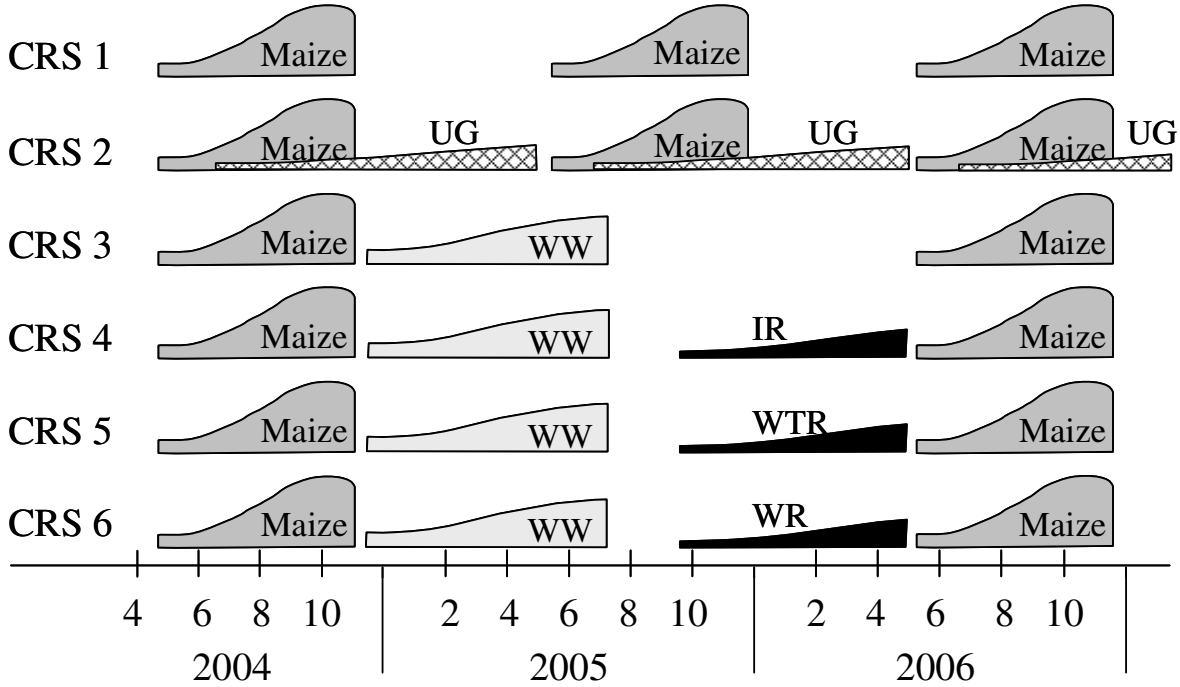

Fig. 1. Six selected three-year crop rotation systems (CRS) for the field experiment during the years 2004 to 2006 (WW, winter wheat; UG, undersown grass; IR, Italian ryegrass; WTR, winter turnip rape; WR, winter rye).

Sowing of maize took place each year (2004 to 2006) at the end of April and the beginning of May. Harvest of maize took place at three successive dates; about 148, 161 and 174 days after sowing. The first harvest date was chosen in response to the sufficient maturation of the earliest maturing variety. The subsequent harvest dates followed at intervals of about 14 days. The underseed was sown each year during the first half of June, and was harvested about ten days before the following maize crop was sown. The winter wheat was sown after the last maize harvest in mid-November 2004, and harvested at the growth stage 'milk ripeness' at the beginning of June in 2005. Winter catch crops were sown in mid-September 2005, and harvested before the maize was sown in 2006. All crops in the crop rotation systems are intended for biogas production. 5 m^2 per plot of total aboveground maize biomass was harvested using a single-row forage harvester. The other crops were harvested manually and 1 m^2 was cut per plot. Harvested biomass of all crops was oven dried at a temperature of 60 °C to constant weight. Fresh and dry matter weight was measured. Dried matter was ground with a Cyclotec 1093 sample mill through a 1 mm sieve.

Table 1
Energy maize varieties for the field experiment, FAO-rating (250 – early maturing to 700 – very late maturing) and year of cultivation. Varieties that were cultivated each year were selected for presentation of results

Maize varieties	FAO-rating	Cultivation year
Gavott	250	2004, 2005, 2006
KXA5226	260	2005, 2006
PR39F58	260	2004, 2005, 2006
Eminent	270	2004
Pollen	300	2004, 2005, 2006
Deco	ca. 300	2005, 2006
PR37D25	330	2004
PR36K67	ca. 370-400	2005, 2006
Méridienne	ca. 400-450	2004
Lucatoni	ca. 400	2005, 2006
Mahora	440	2004, 2005, 2006
Mikado	ca. 500	2004, 2005, 2006
Doge	ca. 700	2004

A plough was used for soil preparation at the beginning of the experiment in 2004, and before the sowing of winter wheat. A rotary harrow or cultivator was used in all other plots and years. The mineral nitrogen fertilizer application (containing 26 % N, thereof 7.5 % NO_3-N and 18.5 % NH_4-N + 13 % S + nitrification inhibitor DMPP) amounted to 230 kg $ha^{-1}a^{-1}$ and was broadcast each year soon after the maize was sown. Thomaskali (containing 10 % P, 15 % K and 3 % Mg) was applied at a rate of 1000 kg ha^{-1}, at the beginning of the field experiment. Phytosanitary measures were applied according to the infestation pressure. In 2005, the stubble of undersown grass was only mechanically processed and not sprayed before the following maize crop was sown. In 2006, the stubble of the catch crops and undersown grass was sprayed.

2.2. Biogas analysis

The biogas analysis was done using a batch assay, the Hohenheimer Biogas Yield Test (HBT – Hohenheimer Biogasertragstest) [23]. Syringe samplers were filled with specially prepared inoculum, based on digested liquid cattle manure (30 ml) and ground, dried plant material (400 mg). The mixture was then incubated for 35 days at a mesophilic temperature of 37 °C. Biogas production was measured continuously and summed up for a cumulative biogas yield after 35 days. The biogas volume was corrected in terms of humidity and norm

conditions (273.15 K and 101.3 kPa). The biogas volume, which was produced by the inoculum was subtracted from the cumulative yield in order to obtain the specific yield of the pure plant material. The methane content was measured using a photometric sensor. Specific methane yield was measured for all maize varieties in CRS 1 in 2004 and for variety Gavott in CRS 1 in 2005.

2.3. Analysis using NIRS

Near-infrared reflectance spectroscopy (NIRS) was used for the chemical composition analysis. All maize varieties in CRS 1 in 2004 were measured. Samples were prepared according to VDLUFA [24] and the recommendation of LOVETT et al. [25]. Prior to scanning, the samples were dried again to remove residual moisture. Two replications of the maize samples were analyzed with a NIR-Systems 5000 monochromator, over a wavelength range of 1032 to 2561 nm. All spectra data were recorded as log (1/R), where R is the reflectance. The software for scanning and mathematical processing was supplied with the instrument by Infrasoft International. The calibration, which is used in a round-robin and updated and validated each year was calculated by VDLUFA (DMK-FAL-Kalibration) [24]. Outliers were not used for parameter estimation and were detected by ranking the samples on the basis of the standardized Mahalanobis-distance. Results are given as H-values, and samples with values above 3 were dropped. Analyzed parameters were (in % of dry matter): crude starch (XS), acid detergent fiber (ADF, cellulose + lignin) and *in vitro* digestible organic matter (IVDOM). Other analyzed parameters included sugar, protein and different values for the determination of the fiber content, but these parameters did not improve prediction of the specific methane yield in this study and are therefore not presented in the results section. Values obtained by NIRS measurements were not confirmed by wet chemistry analysis, because the used NIRS calibration is thought to be sufficiently accurate.

2.4. Statistical analysis

The analysis of variance and F-Tests of fixed effects of the total dry matter yield of the six crop rotation systems, of the dry matter content of maize and of the specific methane yields of maize were performed according to the experimental design using the SAS procedure PROC MIXED (SAS version 9.1, SAS Institute Inc., Cary, NC, USA). Mean values were compared at $P < 0.05$. A mixed model with repeated autoregressive measurements was used for analysis.

The calculations for the coefficients of determination and the relation between the specific methane yield and quality parameters (starch and fiber content, and digestibility) of maize varieties were carried out using the SAS procedure PROC REG. Calculations were split to early (FAO 250 to 330) and late (FAO 400 to 700) maturing varieties.

3. Results

3.1. Dry matter yield and dry matter content

Five maize varieties, that were grown throughout the three years of the field experiment, were selected for the presentation of dry matter yields (DMY). The results of the other varieties did not increase information. Increased time between sowing and harvesting significantly increased the total DMY of all six crop rotations, as means over the three years of the rotations (Table 2, Fig. 2, Fig. 3, Fig. 4).

Table 2
Analysis of variance for total dry matter yield of the three-year crop rotation systems, for maize dry matter content in 2004 and for specific methane yield of maize varieties in 2004

	Dry matter yield		Dry matter content		Methane yield	
Effect	F-value	P-value	F-value	P-value	F-value	P-value
Maize variety (MV)	11.38	***	871.11	***	5.23	***
Crop rotation system (CRS)	36.26	***	1.81	0.1943	-	-
Days after sowing (DAS)	32.66	***	531.56	***	6.09	**
MV*DAS	5.21	***	17.49	***	1.95	*
MV*CRS	1.57	*	0.97	0.5221	-	-
CRS*DAS	2.08	0.0784	0.62	0.7781	-	-
MV*CRS*DAS	1.91	***	0.82	0.8411	-	-
Replication	4.67	*	0.56	0.5849	6.50	**

Early maturing maize varieties were highest yielding at the first and second harvest dates, whereas the late maturing varieties were highest yielding at the third harvest date. Maize DMY, as means over the nine maize varieties, six crop rotation systems and three harvest dates were highest in 2005, with a value of 22.6 t dry matter ha^{-1} a^{-1}, and lowest in 2006, with a value of 15.4 t dry matter ha^{-1} a^{-1}.

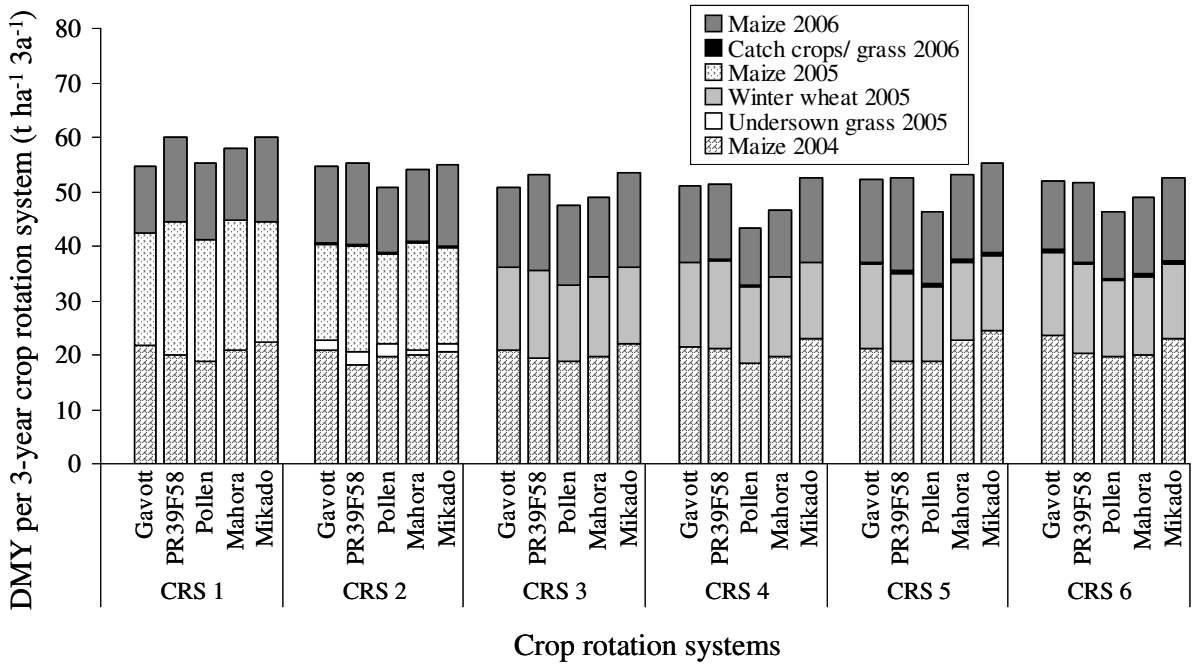

Fig. 2. Total dry matter yield (DMY) of the six three-year crop rotation systems (CRS), differentiated to selected maize varieties; harvest of maize 148 days after sowing. LSD for comparisons between interactions of maize variety and harvest date was 3.32.

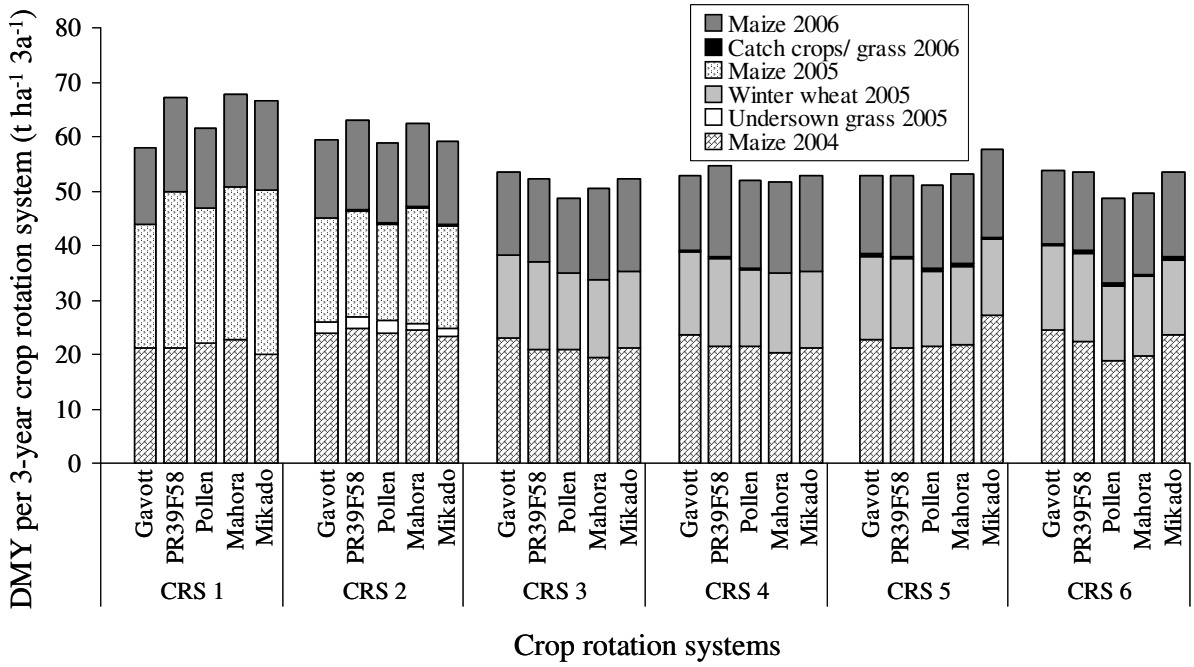

Fig. 3. Total dry matter yield (DMY) of the six three-year crop rotation systems (CRS), differentiated to selected maize varieties; harvest of maize 161 days after sowing. LSD for comparisons between interactions of maize variety and harvest date was 3.89.

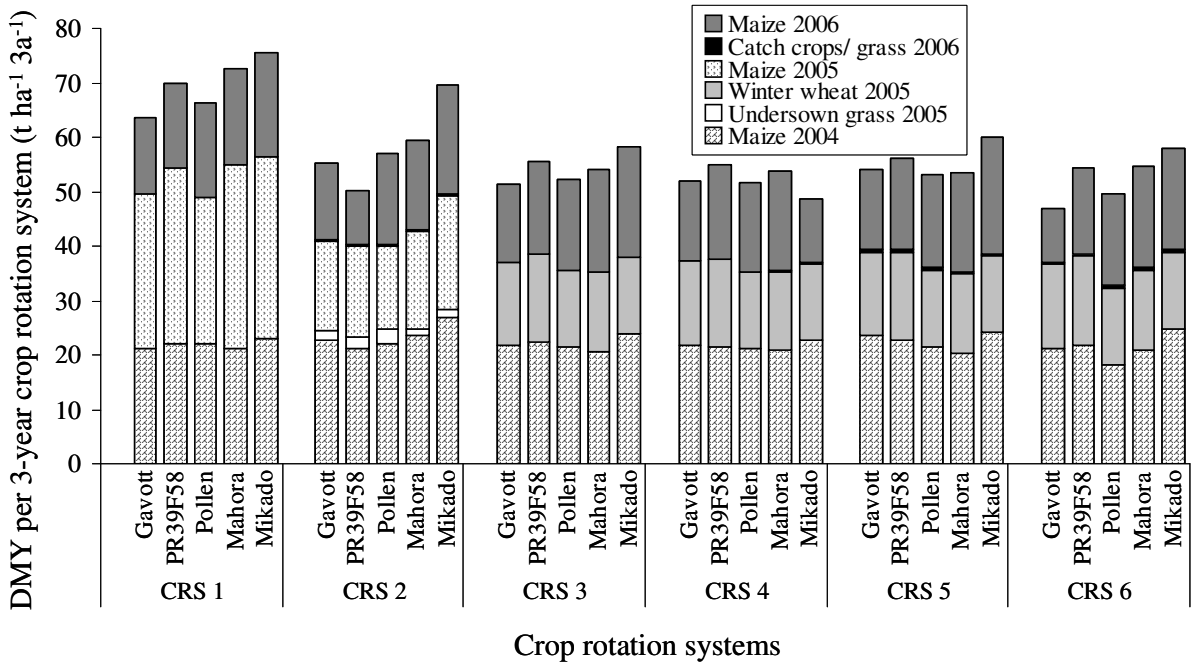

Fig. 4. Total dry matter yield (DMY) of the six three-year crop rotation systems (CRS), differentiated to selected maize varieties; harvest of maize 174 days after sowing. LSD for comparisons between interactions of maize variety and harvest date was 4.14.

The undersown grass significantly reduced the following maize growth in 2005. The remaining grass stubble was quite vigorous and impeded the growth of the young maize plants. The biomasses of the three different winter catch crops were not harvestable with a mower and thus the realistic yields amounted to nearly zero. It was only possible to harvest some biomass through a manual cut.

The dry matter content of the five selected maize varieties, over the three years, increased significantly from late (Mikado) to early (Gavott) maturing varieties and from the early harvest date (148 days after sowing) to the late harvest date (174 days after sowing) (Table 2 and Table 3).

Table 3
Dry matter content (%) at harvest of five selected maize varieties in crop rotation system 1 (continuous maize) at three harvest dates (148, 161 and 174 days after sowing) during the three years of cultivation

	2004			2005			2006		
Variety	148	161	174	148	161	174	148	161	174
Gavott	36.4	43.3	45.9	41.3	42.8	47.4	37.2	43.8	45.3
PR39F58	34.9	40.0	45.0	30.8	32.5	38.4	38.9	44.1	49.7
Pollen	31.2	37.4	43.1	35.7	36.8	42.2	31.8	37.0	43.1
Mahora	28.4	33.3	37.4	32.6	34.5	41.5	29.3	34.5	42.2
Mikado	24.0	26.6	30.3	26.8	27.3	33.2	25.8	29.3	34.3

3.2. Specific methane yields

The specific methane yields of the tested maize varieties in 2004 showed a significant response to the maize variety and harvest date (Table 2 and Table 4). Particularly the late maturing varieties showed increasing methane yields with prolonged growth periods. The level of the specific methane yields was generally higher in 2005 than in 2004 (data only shown for variety Gavott).

Table 4
Specific methane yields per kg volatile solids (Nm^3 CH_4 kg^{-1} VS) of maize varieties in CRS 1 in 2004 and additional variety Gavott in 2005

	Days after sowing		
Variety	148	161	174
Gavott	0.340	0.349	0.339
PR39F58	0.346	0.334	0.346
Eminent	0.337	0.351	0.345
Pollen	0.337	0.338	0.339
PR37D25	0.336	0.338	0.340
Méridienne	0.340	0.339	0.345
Mahora	0.330	0.337	0.341
Mikado	0.331	0.333	0.338
Doge	0.307	0.322	0.342
Gavott (2005)	0.367	0.369	0.370

Nm^3, norm cubic meter.
LSD = 0.013.

3.3. Chemical composition and digestibility analysis

Parameters for analysis with NIRS were selected according to their relevance for anaerobic digestion in a biogas plant. The measurements of the relationship between the chemical composition (starch and fiber) or digestibility and the specific methane yields were split between early maturing varieties (FAO 250 to 330) and late maturing varieties (FAO 400 to 700). The results suggest that no such relationship existed for early maturing varieties, but that a significant relationship existed between the parameters and specific methane yield for late maturing varieties (Table 5, Fig. 5). For the late maturing varieties, the results show that with increasing starch content and digestibility, and with decreasing fiber content the specific methane yield increased. The third harvest date showed no significant influence on the relationship between the three parameters and the specific methane yield (data not shown). There was a significant strong relationship (R^2 from 0.62 and 0.92) between the three measured parameters and the dry matter content at harvest of the maize varieties. The starch content and digestibility increased with increasing dry matter content, whereas the fiber content (ADF) decreased.

Table 5
Analysis of variance for regression between analyzed parameters through NIRS (starch, fiber and digestibility) and specific methane yield of all maize varieties in 2004

Parameter	Days after sowing	R^2	Parameter Estimate	Standard Error	T-Value	Sig.
XS (early v.)	148	0.02	0.0003	0.000482	0.56	n.s.
XS (late v.)	148	0.49	0.0012	0.000399	3.08	*
XS (early v.)	161	0.00	0.0000	0.00113	0.05	n.s.
XS (late v.)	161	0.51	0.0010	0.000297	3.25	**
ADF (early v.)	148	0.05	-0.0008	0.000950	-0.86	n.s.
ADF (late v.)	148	0.61	-0.0028	0.000711	-3.92	**
ADF (early v.)	161	0.08	-0.0021	0.00219	-0.98	n.s.
ADF (late v.)	161	0.58	-0.0021	0.000570	-3.68	**
IVDOM (early. v.)	148	0.06	0.0007	0.000764	0.89	n.s.
IVDOM (late v.)	148	0.66	0.0037	0.000826	4.45	**
IVDOM (early. v.)	161	0.22	0.0029	0.00166	1.78	n.s.
IVDOM (late v.)	161	0.54	0.0022	0.000648	3.44	**

XS, starch; ADF, acid detergent fiber; IVDOM, *in vitro* digestible organic matter.
v., variety; early maturing varieties from FAO 250 to 330; late maturing varieties from FAO 400 to 700.
R^2, coefficient of determination.
n.s., not significant.

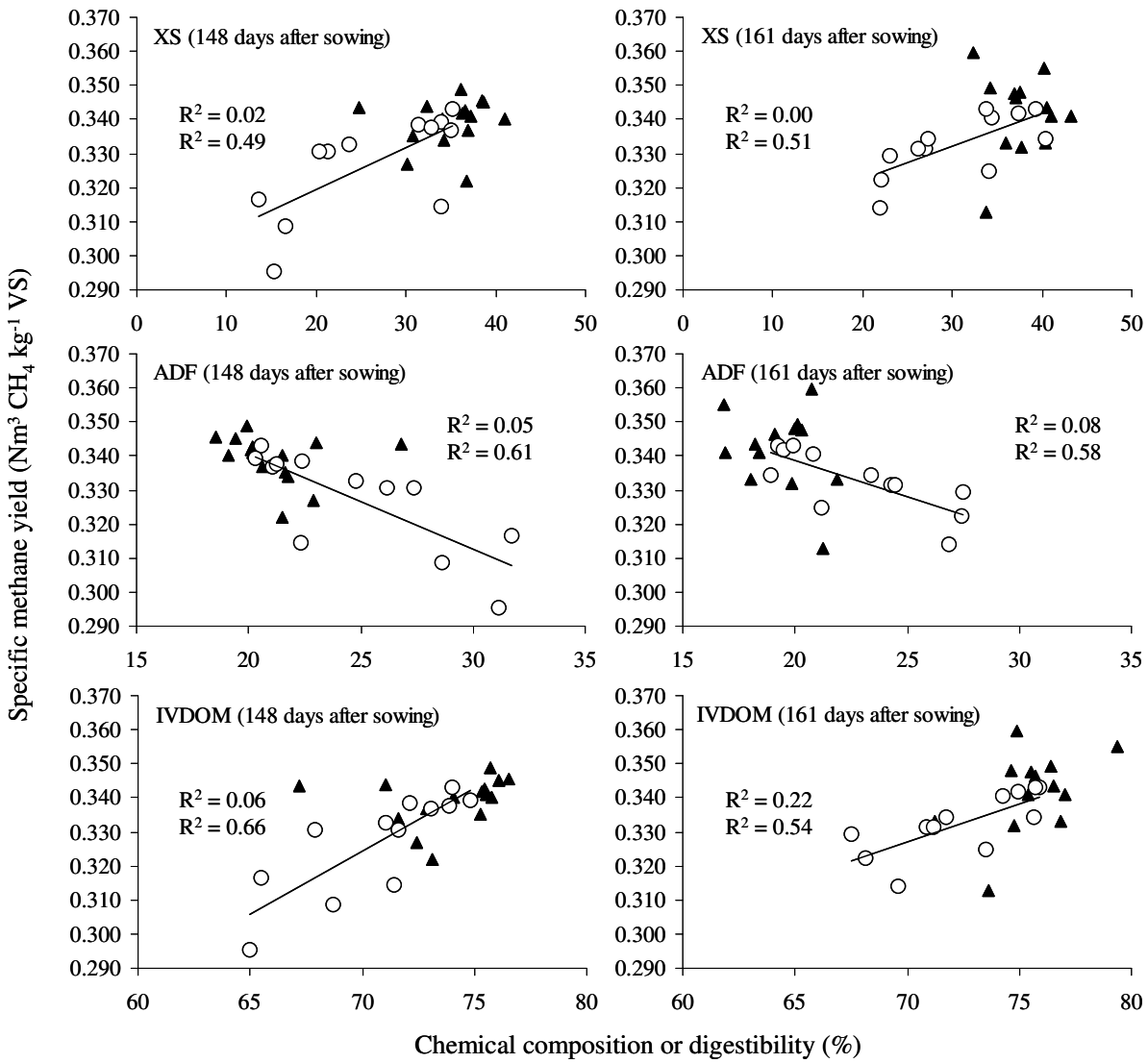

Fig. 5. Relation between chemical composition (XS, starch; ADF, acid detergent fiber) or digestibility (IVDOM, *in vitro* digestible organic matter) and specific methane yield per kg volatile solids in 2004, triangles show values of the early maturing varieties (FAO 250 to 330) and circles show values of the late maturing varieties (FAO 400 to 700), lines show the regression line for late maturing varieties, coefficients of determination in upper line for early maturing varieties and in lower line for late maturing varieties.

4. Discussion

4.1. Optimizing the crop rotation system and biomass yield

The results of the DMY analysis of the different maize varieties show that the yields were generally high, but influenced by the year. The results of other authors [6, 26] confirm the high yield potential, but no one has previously highlighted the interactions between year and yield. In average years (2004) to bad years (2006), the DMY of the different varieties did not

differ to the extent observed in a very good year (2005), which had evenly distributed precipitation and a dry autumn. In such a good year, the late maturing varieties had a clear advantage because of the long growth period.

The dry matter yields of the six crop rotation systems demonstrated that especially at the first harvest date the system with continuous maize (CRS 1) was not advantageous compared to the other systems that had winter wheat as a second main crop. With successively later maize harvest dates the yield of the late maturing varieties rose, because of their ability to utilize the longer growth period for producing more vegetative biomass and for starting the grain filling stage at a later time. The dry matter content becomes important when the biomass is intended to be preserved as silage. An optimal dry matter content ranges from 28 to 35 %. It is therefore recommended that early maturing varieties be harvested 150 days after sowing at the latest. In contrast, late maturing varieties require at least about 160 days to mature.

In 2005, the maize yields in CRS 2, with an undersown grass, were affected by the grass. The grass grew back quickly because the stubble was only treated mechanically (tilled with a cultivator), and therefore inhibited the growth of the young maize plants. This growth reduction was responsible for the late plant development and low yields. The crop rotation systems 3 to 6 did not differ in their yield performance because the varied component of these systems, the different catch crops, yielded nearly nothing. The long winter in 2006 did not allow the catch crops to grow before they were cut to ensure an early sowing of maize. However, the catch crops and the undersown grass covered the soil from autumn to spring. This method lowers erosion and nitrogen leaching, which is likely to occur in continuous maize production with bare winter fallows [27, 28]. Thus, the cultivation of cover crops or an undersown crop might be instruments in more environmentally benign energy cropping systems. In years with good weather conditions, the catch crops are able to build a DMY of up to 7 t ha^{-1} a^{-1} in spring, and therefore add to the total biomass yield of the crop rotation systems [29]. The undersown grass must be sprayed, as was done in 2006, to ensure that the growth of the following maize crop is not inhibited.

4.2. Assessing and optimizing quality parameters for methane production

The analyses of the chemical composition and digestibility of maize via NIRS measurements have shown that the specific methane yields are moderately correlated to these parameters. The distinction between early maturing varieties (FAO 250 to 330) and late maturing varieties (FAO 400 to 700) must be made, because the correlation was only observed in the late maturing varieties. The prediction of mature maize biomass via NIRS

analyses is well established but it could be shown that NIRS analyses were much more accurate for the prediction of vegetative biomass than for generative biomass (cobs), however no explanation for this was given [30]. The late maturing varieties were harvested at a very early stage of grain filling and maturity, and therefore the proportion of the vegetative DMY was much higher than that of the early maturing varieties. Our results confirmed those of JOHNSON et al. [12], who concluded that the harvest date, respective the maturity and variety, had an effect on the chemical composition of maize.

The increasing starch content and digestibility with the rising dry matter content was also shown by other authors [31, 32]. The early maturing varieties might already have had adequate starch contents at the first harvest date, and the further increase in starch content might not have contributed to an increase in specific methane production, because the digestibility had already reached its optimum. When the biomass can no longer be digested, methane production stops because there is no further release of the chemical elements needed for methane production, namely carbon and hydrogen. The level of specific methane production somehow plateaued with high digestibility, high starch and low fiber contents without showing an obvious negative influence on the specific methane production.

The digestibility of the cell wall is moderately influenced by the variety and growth conditions, but it has to be related to the cell contents, such as sugars and starch, to obtain reliable results [33]. Thus, the analyses of starch and digestibility must be combined in order to be able to make a valid conclusion about the analyzed biomass.

According to AMON et al. [6] the starch content showed no contribution to the specific methane yield of maize. Instead, he found high positive influences from protein and cellulose. This cannot be confirmed by our results. The relationship between protein concentration and specific methane yield could not be shown (data not shown). AMON et al. [6] did his analyses by wet chemistry, which might result in slightly different values.

The ADF values for fiber analysis include cellulose and lignin content. Cellulose can be digested by the microorganisms in biogas plants but not lignin. It might be that with increasing maturity of the maize varieties the share of lignin increased relatively more than the share of cellulose of the ADF. However, AMON et al. [6] could show a relatively low positive correlation between specific methane yield and lignin content. NDF content that contains ADF and hemicelluloses was in relation very similar to ADF but on a higher level (data not shown), which can be confirmed by WIERSMA et al. [32]. Cellulose was identified to be able to produce a moderately high specific methane yield [11], hence the influence of the

composition of celluloses, hemicelluloses and lignin in biomass on specific methane yield needs further examination.

LOVETT et al. [34] challenge the total reliability of NIRS to predict *in vitro* digestibility and recommend further validation of NIRS calibration and better sample preparation methods. The calibration used for this study is validated each year with hundreds of samples and is believed to be sufficiently accurate.

5. Conclusion

Silage maize production for energy generation via a biogas plant can be designed in an environmentally benign way when a site-specific crop rotation system is chosen. Continuous maize systems had the highest biomass yields but are vulnerable to nitrogen leaching and erosion. Further crops in crop rotation systems, such as catch crops, undersown crops and different main crops have the potential to minimize ecological problems. Thus, maize cannot be cultivated each year, but other crops in a crop rotation system, such as winter wheat or winter catch crops, which can also be used as a substrate for anaerobic digestion. Yields of crop rotation systems with different crops other than maize will be lower but the systems are more environmentally benign. At a site where late maturing varieties can build an adequate dry matter content due to a long growth period (a late harvest date), these varieties are advantageous because they produce higher biomass yields.

Furthermore, it could be shown that the specific methane yield can be estimated based on starch, fiber and digestibility measurements. Methods used to qualify the quality of biomass for animal nutrition, such as the near infrared reflectance spectroscopy, are also valid for predicting the methane production of maize, to a some extent. High contents of starch and high values of digestibility positively influence the specific methane production whereas increasing fiber (ADF) decreased specific methane production. The quality of maize biomass at an early stage of maturation can be predicted more accurate than further matured biomass (grain maturation). The role of fiber content needs further clarification.

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7. General discussion

This discussion section presents an overview of all obtained results in the context of the optimization of energy cropping for Central Europe. The area is classified as one climate region, but the weather and site conditions in Central Europe vary considerably between the coast and the Alps. Crops with similar requirements can be grown throughout a region but different varieties, crop management procedures and crop rotation systems must be found to optimize the performance of the crops. Bearing in mind that energy crops produce biomass for different energy types such as solid biofuel, liquid biofuel or biogas, they can be compared at the level of their bioenergy production potential.

The possibility to produce biomass domestically and the many different perennial and annual, woody and herbaceous crops that can be cultivated as energy crops make biomass a multipurpose renewable energy source. A sustainable, environmentally benign, energy efficient and innovative agricultural energy production system is sought to secure the energy supply and to increase the competitiveness of biofuels with fossil fuels in the future.

7.1. Energy cropping

The European Union (EU-25) is recognized as being able to meet its biomass targets of 12 % of the total energy consumption by 2010. The required 5.6 EJ a^{-1} of energy can be produced without any resource limitations. However, it is unlikely that the goal of meeting this target in the time frame by 2010 can be met, unless immediate action is taken. A greater knowledge of energy crop production is needed as a key factor for the improvement of biomass supply as soon as possible (ERICSSON and NILSSON, 2006). Such basis data for energy production can be provided by this present study. Major potential energy crops and crop rotation systems for Central Europe have been tested and evaluated in terms of biomass quality and quantity. A recommendation for optimized energy cropping can be made. Table 7.1 gives an overview of the selected energy crops, the required input parameters and the key factors for production.

Table 7.1
Input parameters and key factors of production of the selected and tested energy crops; combined results from all five papers and additional data

Crop	Nitrogen kg N ha^{-1} a^{-1}	TC [a] l H_2O kg^{-1} DM	LUE [b] m^2 t^{-1} DM	Further parameters	Yield t DM $ha^{-1}a^{-1}$
Willow (first rotation)	0	300-700	710	low pesticide requirement	14.8
Miscanthus	40	150-350	669	low pesticide requirement	16.5
Switchgrass	80	150-300	771	low pesticide requirement	14.1
Energy maize	120	150-300	296-1026		19.1
Winter wheat [c]	160	400-800	603-758 [d]	no-till	14.6
Winter triticale [c]	160	400-800	503-956	no-till, no K fertilization	16.2
Winter oilseed rape [c]	240	400-800		no-till	11.0
Winter catch crops			1354-5322	reduce N leaching	3.7
Grass (*Lolium* spp.) Catch crop or underseed			2325-8192	reduce N leaching	2.5

[a] TC: Transpiration coefficient (EL BASSAM, 1998).
[b] LUE: Land use efficiency; amount of land (m^2) needed for the production of one tonne DM.
[c] Grain and straw.
[d] Values for winter wheat harvested at stage 'milk ripeness'.
DM: Dry matter.

7.2. Biomass performance of perennial energy crops

Generally, the perennial lignocellulosic crops combine high biomass productivity with low requirements for inputs, such as nitrogen fertilization, pesticides, tillage operations and water supply. These findings are confirmed by the findings of other authors (BÖRJESSON, 1996; MATTHEWS, 2001; LEWANDOWSKI et al., 2003; LEWANDOWSKI and SCHMIDT, 2006). Willow and miscanthus could corroborate the hypothesis of high biomass yields. Willow yields are still expected to increase after the first rotations (MATTHEWS, 2001).

Miscanthus and switchgrass, are plants with a C_4-photosynthetic pathway and are therefore able to convert solar radiation into dry matter very efficiently. This seems to be advantageous at the study site, where the vegetation period is long enough for biomass accumulation. But, switchgrass produced comparatively low yields and it was found that

switchgrass might perform better on marginal sites with light and sandy soils (LEWANDOWSKI, 1998; MCLAUGHLIN and KSZOS, 2005). In addition, many different switchgrass varieties exist and their performance is primarily dependent on their place of origin in the USA (ELBERSEN et al., 2000), which suggests that better varieties might be found for the study site. This emphasizes the need for site-specific management to fully utilize the biomass production potential of a site.

Outline:

- Perennial lignocellulosic energy crops have the potential to produce high yields, but they must be selected according to site conditions.
- C_4 crops have a high yield potential, which can be advantageous for biomass production.

7.3. Biomass performance of annual energy crops

Energy maize has been shown to be the highest yielding energy crop of this study. Dry matter yields are highly dependent on the variety (maturing rate) and the time elapsed between sowing and harvesting. Maize requires high nitrogen fertilizer input, but as a plant with a C_4-photosynthetic pathway it is very water and solar-energy-use efficient. Differently maturing maize varieties have different biomass yield potentials. It could be shown, with the results obtained in Papers IV and V, that late maturing varieties have much higher yield potentials at a late harvest date than early maturing varieties. These late maturing varieties form a basis for current energy maize breeding programs. New varieties are being developed that are thought to be high yielding. They are considered to build adequate dry matter contents by the typical harvest time frame in Central Europe, which ranges from mid-September to the end of October. The potentially high-yielding, late-maturing varieties are combined with traits such as cold-tolerance and short-day reaction to develop new high yielding energy maize varieties suitable for Central Europe (SCHMIDT, 2006). The tested varieties KXA5226, Deco and Lucatoni stem from such breeding programs. They are characterized by early biomass development, but require, according to their maturing rate, different growth periods to build adequate dry matter yields.

Long established energy crops are winter wheat, winter triticale and winter oilseed rape. These crops are adapted to Central European conditions but vary in their requirement for input parameters such as fertilization and pesticide application. They only produce moderately high yields but have the advantage that they can be cultivated throughout Europe in varying

climates. The required production technologies are widely known (JØRGENSEN et al., 2007). Cereals such as wheat and triticale can be harvested either at the growth stage 'milk ripeness' to be preserved as silage, or at the stage 'full ripeness' to allow for the separate use of the grain and straw fractions.

Outline:

- Energy maize is currently the highest yielding energy crop, but even higher yields can be expected in the future as a result of the ongoing breeding programs for new varieties.
- Late maturing maize varieties have a higher yield potential than early maturing varieties.
- Grain crops are multi-purpose plants that are widely adapted and known.

7.4. Biomass quality

Biomass quality can be influenced during cultivation through crop management and during harvest and postharvest handling (SANDER, 1997; LEWANDOWSKI and KICHERER, 1997; DARBY and LAUER, 2002a,b; LEWANDOWSKI et al., 2003b; LEWANDOWSKI and KAUTER, 2003; ADLER et al., 2006). The quality of the different biomasses was determined in different ways, each appropriate to the particular energy conversion technology the biomass was destined for.

A key quality factor is the dry matter (DM) content at harvest. The DM content of perennial and annual crops intended for solid fuel use is supposed to be as high as possible to ensure unproblematic storage and energy conversion (combustion or Fischer-Tropsch-Synthesis). Amongst others, a high DM content can be achieved through a late harvest date (LEWANDOWSKI and HEINZ, 2003). The perennial crops are preferably harvested in spring, before resprouting starts. Thus, the quality of the biomasses from the tested perennial crops has the potential to be increased. Annual grain crops are best harvested between the growth stages 'full ripeness', and 'dead ripeness' but the harvest cannot always be delayed due to weather conditions or the sowing date of the next crop. The optimal DM content of energy maize and other crops, which are preserved as silage (winter wheat, catch crops, grass), ranges from 30 to 40 % of fresh matter (HARRIS, 1993). The DM content of these herbaceous energy crops can be influenced by altering the sowing and harvest date, as well as by the choice of the variety. Many differently maturing maize varieties exist for regions with short to long vegetation periods. Maize varieties with a FAO-rating of 250 are adapted to the experimental sites used in this study (Ihinger Hof and Goldener Acker). A chosen adequate

maturing rate of a variety for one site ensures that the maize biomass can be harvested at an optimal dry matter content for the subsequent silage process. The cultivation of late maturing varieties in Central Europe leads to a late development of biomass yield and a relatively low dry matter content at the latest possible harvest date, which is just before the first frost. The prevailing weather conditions during maturation were also shown to have an influence. A dry autumn led to a more rapid drying of the biomass and thus to higher dry matter contents earlier in the season.

Furthermore, the chemical composition of biomass plays an important role when it comes to the conversion technologies, such as combustion or anaerobic digestion in a biogas plant. For combustion, low contents of disturbing elements, such as potassium and chlorine, and low residual ash contents are preferred. Potassium and chlorine contents in both grain and straw can be lowered through crop management (no application of potassium chloride fertilizer). The ash residue can be reduced primarily by decreasing the potassium content in the biomass. Weather conditions also have an influence on the potassium and chlorine contents. Increasing yield, which might be the result of better weather conditions, led to decreased mineral contents in grain (FEIL and FOSSATI, 1995), and especially, lower potassium contents in this study. High precipitation during grain maturation was observed to lower potassium and chlorine contents in other studies (HERNÁNDEZ ALLICA et al., 2000; 2001), which might also apply to the results of this study.

It is recognized that the concentration of combustion-disturbing elements is much lower in wood than in grain and straw, but the demand for wood is rapidly increasing in Europe and therefore alternative energy crops are becoming more important (OLSSON, 2006).

Anaerobic digestion requires a different biomass composition. The herbaceous wet biomass must be digested by microorganisms to release the elements that are needed for the formation of methane – carbon and hydrogen. A high digestibility, as well as compounds that are rich in carbon, are required. The digestion in a biogas plant functions similarly to the digestion that occurs in a ruminant. Therefore, the same methodology used for the characterization of forage biomass was also applied to energy crops, namely the near-infrared reflectance spectroscopy (NIRS). It was thought that with increasing digestibility and amounts of carbon-rich compounds, such as starch, the specific methane yield could be increased. But, only a moderately strong correlation could be demonstrated between the specific methane yield of maize and the quality parameters. However, a distinction must be made between early and late maturing maize varieties. The correlation could only be substantiated for late maturing varieties that produce primarily vegetative biomass in Central Europe. VOLKERS et

al. (2003) discovered that the NIRS analysis is much more accurate for the prediction of vegetative biomass and JOHNSON et al. (2002) found an effect related to the maturity at harvest, which might explain our observation. The early maturing varieties might already have reached the optimum digestibility, and without any further digestion of the biomass, the elements for methane production cannot be further released.

Outline:

- The quality of biomass must be seen in relation to the conversion technology.
- Dry matter content is a good parameter for quality determination.
- Quality can be influenced by crop management (choice of harvest date and fertilization), but also by prevailing weather conditions.
- Maturity of a crop is an important factor for the determination of quality parameters.

7.5. Crop rotation systems and environmental impacts

Energy cropping is required to be sustainable and environmentally benign. These demands can best be satisfied by site-specific crop rotation systems. Different site conditions, such as soil properties and the length of the vegetation period, must be considered before a system is established. Furthermore, crop management parameters can have major impacts on the development of a crop rotation system. Different parameters are shown in Fig. 7.1.

Perennial crops cannot be integrated into crop rotation systems as they form systems themselves. The predicted lifetime of a plantation is 15 to 20 years (LEWANDOWSKI et al., 2003a). During this time, the soil is nearly undisturbed and can function as a carbon sink (CLIFTON-BROWN et al., 2004; DECKMYN et al., 2004). The aboveground biomass can contribute to biodiversity by providing habitat for mammals, birds and insects (GÖRANSSON, 1994; MAKESCHIN, 1994). Furthermore, perennial crops are nutrient-use efficient. Miscanthus and switchgrass, as rhizomatous perennial grasses, are able to store a certain amount of nutrients in the underground plant parts and therefore need less fertilizer than other crops (VENENDAAL et al., 1997; LEWANDOWSKI et al., 2003). Willow requires very low nitrogen fertilization during the first years on land formerly used for field crops (MITCHELL et al., 1999), because it is able to store some nutrients in the woody biomass and to recycle other nutrients through leaf litter. Therefore, willow received very little nitrogen fertilizer but could nonetheless produce high yields.

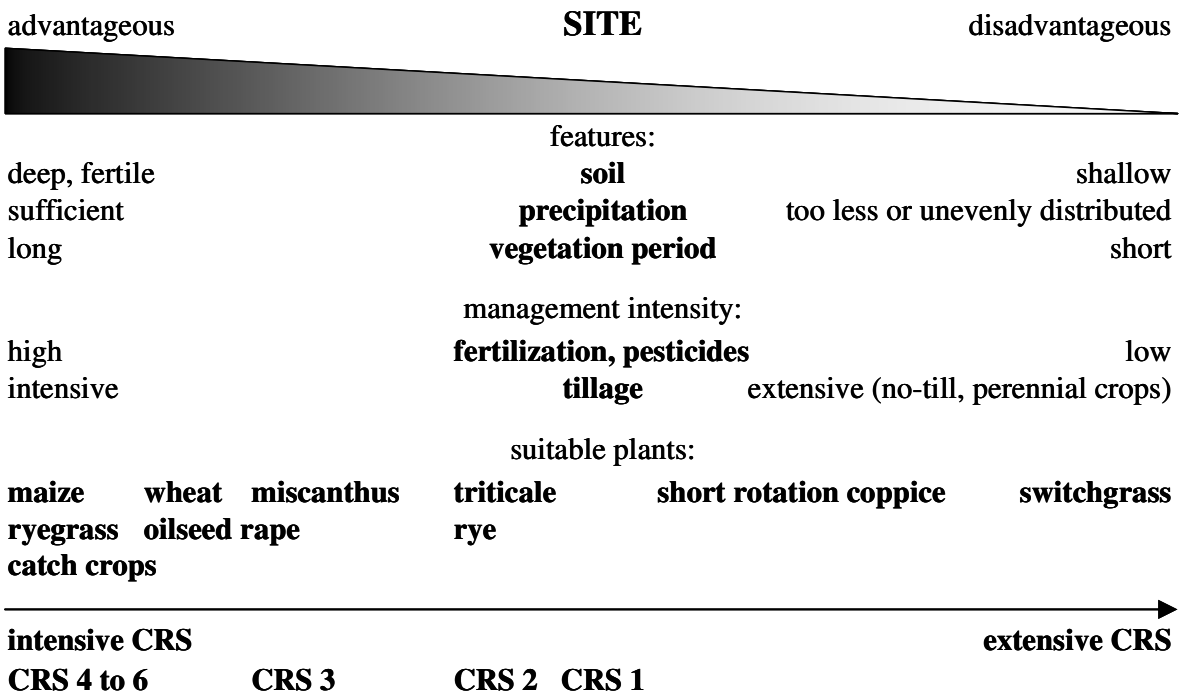

Fig. 7.1. Requirements of site-specific energy cropping: parameters for the characterization of a site and potential energy crops for sites differing in quality and vegetation period. Crop rotation systems (CRS) that were introduced in papers IV and V are suggested for differing environments (CRS 1 continuous maize, CRS 2 maize with undersown grass, CRS 3 maize followed by winter wheat, CRS 4 to 6 maize preceded by catch crops and followed by winter wheat).

Annual energy crops are best cultivated in crop rotation systems as they can benefit from the synergetic effects of such systems, such as nutrient accumulation and lower pest and weed infestation pressure (KARPENSTEIN-MACHAN, 2004).

A number of different parameters can be altered in a crop rotation system; soil cultivation is only one example. As presented in Paper I, the tillage operations were either plough tillage or no-till. The motivation to test a no-till system was that these systems have the potential to contribute to carbon sequestration (LAL, 2003) and to the improvement of soil properties (PEKRUN et al., 2003). The application of no-till must be carefully adapted to site conditions. Heavy and silty soils tend to siltation, which has erosion as a consequence. A slight reduction in yield might be expected during the transition period (BAEUMER and KÖPKE, 1989; ARMAN, 2003), which could not be confirmed by the results obtained in this study. The crop rotation with no-till, which included winter oilseed rape, winter wheat and winter triticale, seems to be an environmentally benign system for the production of solid or liquid biofuels in Central Europe.

Another parameter that can be altered in a crop rotation system is the choice of cultivated energy crops. Different crops are arranged in chronological order to optimize the yield and minimize ecological impacts of the total crop rotation system. The sowing and harvest dates of succeeding crops must be adjusted to fully utilize the vegetation period and to cover the soil for as much of the year as possible. A nearly year-round soil cover minimizes the potential for leaching and erosion, and can be achieved through the cultivation of catch crops (winter and/or summer) and undersown crops (MARTINEZ and GUIRAUD, 1990; LEMOLA et al., 2000; MACDONALD et al., 2005). Results obtained in Papers IV and V confirmed these observations. The different cultivated winter catch crops (winter rye, winter turnip rape and Italian ryegrass) in CRS 4 to 6 (catch crop – maize – winter wheat) were able to lower the residual mineral nitrogen content in the soil. Negative impacts of the cover crops and undersown grass on the following maize crop were also observed. Lower nitrogen and water supply after catch crop cultivation could be excluded as a cause, but the catch crops might exude phytotoxic compounds that inhibit the germination and growth of the following crop (MASON-SEDUN et al., 1986; EINHELLIG, 1996). Secondly, the catch crop stubble must be carefully sprayed to avoid rapid regrowth, which can significantly impede the following maize growth. The winter hardiness of the catch crops should be considered in Central Europe, when they are intended to be harvested and used as energy crops. A potentially short winter dormancy is also advantageous. Thus, winter catch crops are able to contribute to a high cumulative biomass yield in crop rotation systems.

Energy maize is able to produce very high yields in continuous systems where there is no competition for water or nutrient sources. Continuous maize systems have the disadvantage that the soil is uncovered from autumn to spring and is therefore vulnerable to nitrogen leaching and erosion. Thus, continuous maize cultivation should be avoided on sites with unfavorable soil structures and in climates that allow for more intensive crop production. The careful cultivation of an undersown crop (grass) has the potential to minimize these ecological effects without much interference with the main maize crop.

The intensity of production of an energy crop or a crop rotation system usually has the potential to increase with the use of higher amounts of nutrient and pesticide applications and more harvest operations in a given time frame. Increasing yields result in increasing recovery of nutrients in the biomass. This leads to the requirement that the nutrients in the soil be replenished through higher fertilization rates. The higher input must be compensated for through higher net energy returns to be energetically- and economically-efficient and to achieve acceptance.

Outline:

- Energy cropping must be adapted to the particular site conditions, including water supply, soil properties and length of vegetation period.
- Perennial energy cropping systems require low input and contribute to carbon sequestration.
- Annual energy crops are best grown in site-specific crop rotation systems.
- No-till systems contribute to carbon sequestration without lowering yields in comparison to systems with plough tillage.
- Different crops in a crop rotation system have the potential to minimize negative ecological effects and can add to the total biomass yield.

7.6. Energy evaluation

An energy balance was calculated for the evaluation of the tested energy crops. The calculated energy use efficiency (EUE) shows the ratio of renewable energy output to fossil fuel energy input. It could be shown that willow, with very low energy input in terms of nitrogen fertilizer, had the highest EUE. In general, the perennial energy crops had a higher EUE than the annual crops. The energy use efficiency of a system was defined by its energy consumption in relation to the biomass yield. Regardless of the high input requirements, energy maize also had a high EUE. The other annual crops were less efficient because of lower biomass yields combined with high energy inputs. There was no energy saving effect observed in the no-till crop rotation system.

The primary energy yield was calculated by multiplying the biomass yields with the lower heating values. The primary net energy yield (PNEY) is the primary energy yield less the energy consumption. The PNEY is the key factor for the evaluation. Results show the following ranking of the tested energy crops: energy maize > miscanthus > willow > both crop rotation systems (winter oilseed rape - winter wheat - winter triticale with either plough tillage or no-till) > switchgrass. Energy maize as an annual crop requires management and tillage operations several times each year. But the decisive factor is the high yield potential, which outweighs the energy consumption. With decreasing yield the energy consumption carries more weight in the value of PNEY.

A comparison of energy yield between the tested energy crops can be made because of the application of the same methodology for assessing biomass and energy yield. Although, it must be remembered that not all of the energy crops can be used for the same conversion

technology because of the different biomass features. Furthermore, a differentiation and the supply of different energy sources is desired. Table 7.2 gives an overview of the tested energy crops and their potential utilization and requirements for conversion.

Lignocellulosic crops, such as the perennial crops and straw from wheat and triticale, are best used as solid biofuel due to their biomass composition. These crops can also be used for the Fischer-Tropsch-Synthesis to produce a liquid biofuel. This conversion technology requires the same biomass features as does combustion.

Winter oilseed rape, a crop with high oil content, is suitable for liquid biofuel (Biodiesel) production. However, it is low yielding and not competitive with liquid fossil fuels. Biodiesel belongs to the first generation of biofuels, which are characterized by production methods that are long established and derived from food and fodder production technologies. Currently, these biofuels are still produced, but are now seen as a transitional solution on the way to the second generation of biofuels. Second-generation biofuels primarily include lignocellulosic biomasses. These biofuels are thought to be competitive with fossil fuels when accompanied by improved conversion technologies.

Table 7.2
Suggested energy conversion of the selected energy crops and requirements for conversion.

Crop	Suggested energy conversion	Requirements for conversion
Willow	Solid fuel, Fischer-Tropsch[a]	lignocellulosic biomass, low water content and concentration of N, K and Cl in biomass
Miscanthus	Solid fuel, Fischer-Tropsch	lignocellulosic biomass, low water content and concentration of N, K and Cl in biomass
Switchgrass	Solid fuel, Fischer-Tropsch	lignocellulosic biomass, low water content and concentration of N, K and Cl in biomass
Energy maize	Biogas	30-40 % dry matter content for the silage process, rich in carbohydrates
Winter wheat and triticale (grain and straw)	Solid fuel	lignocellulosic biomass, low water content and concentration of N, K and Cl in biomass
Winter wheat and triticale (green biomass)	Biogas	>30 % dry matter content for the silage process
Winter oilseed rape	Liquid fuel (Biodiesel)	high oil content
Winter catch crops and grass	Biogas	>25 % dry matter content for the silage process

[a] The Fischer-Tropsch-Synthesis is used to liquefy solid biomass, designed biofuels can be produced (WU et al., 2006).

Anaerobic digestion, as a methodology for the conversion of wet biomasses to biogenous gases, is currently a widespread and still-expanding technology in Central Europe. It is applied in biogas plants to generate heat and power via a combined heat and power unit. Nearly all biomasses that are rich in carbohydrates and low in lignocelluloses can be efficiently digested in a biogas plant. An efficient methane production is dependent on high biomass yields on the one hand and on the chemical composition on the other hand. Maize is currently the leading biomass for anaerobic digestion because it combines high yields with a suitable chemical composition. The resultant methane of the anaerobic digestion is primarily converted to heat and power through a heat and power unit but can also be cleaned and used as a natural gas substitute. The methane that is removed from digested biomass and liquid manure through the biogas process is no longer available for global warming process and thus shows a further potential to contribute to environmentally benign renewable energy production.

Outline:

- Perennial as well as selected annual energy crops can produce high net energy yields with a high energy use efficiency (renewable energy output to fossil fuel energy input).
- Lignocellulosic biomasses contribute to second-generation biofuels.
- Today, the production of biodiesel produced from oilseed rape is considered to be inefficient. But the biodiesel as a first-generation biofuel is currently seen as a transitional solution on the way to second-generation biofuels.
- Maize as a leading biomass for anaerobic digestion combines two features that are decisive for methane production: high biomass yield and suitable chemical composition.

8. Conclusion

Agricultural production is optimized for food and fodder production in Central Europe but now has to meet the demand for sustainable, innovative, renewable energy production. The question arises whether net renewable energy can be produced with the given agricultural tools.

The challenge was to find a high yielding site-specific energy crop and crop rotation system that is capable of providing the high quality biomass needed for renewable energy production for different modern conversion technologies. Energy cropping must be environmentally benign to ensure sustainable production. The following points must be considered when examining the results obtained in the five papers:

- One energy crop can best be produced for one energy type and the corresponding conversion technology.
- On the basis of the chosen conversion technology, the energy crop can be optimized for its quality.
- Agricultural practices must be adapted to the renewable energy production need, and not continued in the current manner with the imposition of agriculture to produce energy.

The perennial lignocellulosic crops willow and miscanthus combine high biomass and energy yields with low input parameters such as nitrogen fertilizer and pesticides. The production of perennial crops can be designed to be environmentally benign and at the same time to sequester carbon. Switchgrass, a C_4 plant like miscanthus, might be better cultivated on marginal land where no other energy crops can compete. Lignocellulosic biomass can be used for combustion or converted into liquid biofuels via the Fischer-Tropsch-Synthesis. The latter conversion technology produces biofuels, which are second generation technologies. It is thought that these technologies will be competitive with fossil fuels in the short to middle term.

C_4 plants are advantageous because of their high biomass yield potential. This has also been shown to be true of the annual energy crop maize. Maize is currently the highest yielding energy crop but simultaneously demands high levels of inputs. High yields imply efficient land use. Maize is often produced in continuous systems, which have considerable ecological impacts. These impacts can be minimized through the cultivation of undersown crops or catch crops with the aim of having the soil covered nearly year-round.

Environmentally benign and sustainable energy cropping includes the cultivation of crop rotation systems, which allow for synergistic effects such as lower infestation pressure and nutrient accumulation. Intensive crop rotation systems imply good site conditions and crop management (water and nutrient supply). Crop rotation systems using no-till techniques contribute to carbon sequestration, but they are not energy saving. Site-specific energy cropping is possible when site conditions are known and can be responded to.

Usually, annual energy crops are lower yielding in Central Europe compared to perennial crops, but their production methods are widely known. They can be easily converted into first-generation biofuels and distributed through existing infrastructure. Grain crops can contribute to the rising need for biomasses for combustion or for anaerobic digestion. Wet biomass produced by annual energy crops can be efficiently converted into heat and power via anaerobic digestion in biogas plants. Two prerequisites for efficient methane production are high yields and a suitable chemical composition.

The quality of biomass can be determined through dry matter content and chemical composition. Both quality parameters can be influenced by crop management (choice of species and variety, fertilization, harvest date). Influences from site and year must also be considered. All crop management procedures can be performed without jeopardizing the main target, which is a high biomass and net energy yield.

For a comprehensive overview of renewable energy production from agricultural land, additional aspects must also be considered, which could not be covered by the present study. They include the following questions:

- What is the long term perspective for farmers – perennial or annual energy crops? Perennial crops will determine the land use for 15 to 20 years, whereas annual energy crops can be changed annually.
- Site-specific energy cropping is demanded but what can be produced from marginal land alongside switchgrass? Are there crops that can be grown? Is it cost and energy-efficient to irrigate energy crops when water is the limiting factor?
- Breeding of energy crops has only recently begun. Are there further features to be expected that will substantially improve renewable energy production?
- What will the effect be on biodiversity of the increased production of a few crops?
- If global warming continues to proceed rapidly, then the climate in Central Europe will probably change to a more subtropical type with a generally warmer climate throughout the year. Thus, additional energy crops that need warmer climates to produce high yields

can be considered. Plants with a C_4 photosynthetic pathway, which have been identified as having the potential to be high yielding at appropriate sites, will be one way to meet future challenges.

Agriculture can contribute to the production of renewable energy without significantly changing its tools. Energy farming has the potential to produce crops for all energy types in an environmentally benign and sustainable way. Crop rotation systems contribute to the sustainability of agriculture. The basis of successful renewable energy supply is very efficient production.

9. References

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Abbreviations and glossary

a	Year
asl	Above sea level
C	Carbon
C_3	Plant with a C_3 photosynthetic pathway, first stable products of the photosynthesis are 3-carbon compounds
C_4	Plant with a C_4 photosynthetic pathway, first stable products of the photosynthesis are 4-carbon compounds
CH_4	Methane
Cl	Chlorine
CRS	Crop rotation system
DF	Degrees of freedom
DM	Dry matter
DMY	Dry matter yield
EU	European Union
EUE	Energy use efficiency
EJ	Exa Joule (10^{18} Joule)
FAO-rating	System to classify maize varieties (early to late maturing)
FF	Fruchtfolge (crop rotation system)
GHG	Greenhouse gases
GJ	Giga Joule
ha	Hectare
HBT	Hohenheimer Biogasertragstest (Hohenheimer Biogas Yield Test)
K	Potassium
LSD	Least significant difference
MJ	Mega Joule
MSED	Mean standard error of difference
mtoe	Million tonnes of oil equivalent
MW	Mega Watt

N	Nitrogen
NIRS	Near infrared reflectance spectroscopy
Nm^3	Norm cubic meter (gases at 1013,25 hPa and 273,15 K)
oDM	organic dry matter
oTS	organische Trockensubstanz (organic dry matter)
P	Level of significance
PEY	Primary energy yield
PNEY	Primary net energy yield
R^2	Coefficient of determination
t	tonne
TM	Trockenmasse (dry matter)
TS	Trockensubstanz (dry matter content)
VS	Volatile solids

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