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Modelling of biomass utilisation for energy purpose

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Institute of Technology and Life Sciences

Reviewer: Prof. Mariusz Stolarski, PhD. Eng.

Editors: Prof. Jan Pawlak, PhD. Eng.
Marek Hryniewicz

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Preface

The EEA- and the Norwegian Financial Mechanism are important instruments in strengthening the scientific relations between Poland and Norway. Developing new understanding and new concepts through collaboration, knowledge exchange and dialogue based on diverse experiences are essential in managing the complex challenges we are facing on the path towards sustainable development. The co-operation between Institute of Technology and Life Sciences (previous IBMER and IMUZ) and the partner institutes IHAR, IUNG and IGIK on the one hand, and Bioforsk on the other hand, is an example where the EEA Financial Mechanism has become an operational instrument. Co-operation has been established based on the project "Modelling of biomass utilization for energy purpose". The scope of the project, which is really in line with the overall political priorities worldwide, is to enhance the shift from non-renewable to renewable energy sources by generating knowledge on how to improve the utilization of terrestrial energy crops. This is a particular important issue in Poland, where coal constitutes a substantial part of the national energy supply.

Project activities include, inter alia, field studies of various aspects linked to energy crop production and related model calculations, state-of-the-art descriptions on the status of production of energy crops in different countries, and dissemination and exchange of information through seminars and study tours in Poland, Sweden and Norway. A number of publications are expected from the project.

I would like to take this opportunity to thank all partners involved in the implementation of the project, for the valuable contributions from researchers both at Polish and Norwegian side. Last but not least, I would also express my thankfulness for the opportunities provided by the EEA/Norwegian Financial Mechanism. It is my sincere wish that the project "Modelling of biomass utilization for energy purpose" has established a platform for long-term relations between Bioforsk and partner institutes in Poland within this important field of research.

Ås, Norway, 22.06.2010

Nils Vagstad
Director of Research
Institute Bioforsk

Introduction

The following natural conditions enable agriculture development: surface configuration, climatic conditions including insolation, temperature, rainfalls, winds and frost periods, soil conditions (fertility), water conditions. Water conditions are determined by sum of rainfalls, evaporation quantity and water transpiration by plants. Climatic conditions and soil conditions are decisive factors for agricultural land use. They determine plants selection for crop and expected yield level. Non-natural conditions are also important for agriculture development. The following factors belong to them: labour force, structure of the land ownership, farms size, fertilization, herbicides utilisation, farm mechanisation, education and skills of a farmer, EU and state agricultural policy. EU and Polish agricultural policy is characterized by protectionalism. It means a financial support system and preferential credits with implementation of other means for agricultural market protection.

Poland lies in the sphere of clashes between influences of continental climate (with quite dry summers and cold winters) and moderate Atlantic climate. These clashes are reason of unstable conditions for agricultural production. The annual average air temperature varies from 6.0 to 8.8°C. The length of the thermal vegetation period is about 220 days and only in South-West part of Poland exceeds 230 days. The annual sum of rainfall is about 500-600 mm on lowlands, 600-700 mm on highlands and it is above 1000 mm in mountains. Central Poland (Masovia, Great Poland, Kuyavia) belongs to European regions with the smallest rainfall sum which not exceeds 550 mm. Atlantic Ocean significantly influences on Polish climate from west side of Poland and Asia continent from east side of Poland. Rainfall is another significant factor. Western Europe has significantly higher rainfall in comparison with Poland. Polish agriculture is featured by: high amount of smallest farms in the overall farms structure, farms land distribution on several separate subfields for one farm, villages' overpopulation and very high employment in agriculture (about 27% of all employees in national economy works in agriculture). Farmers have low education level. In towns 34% of population has secondary education and in rural areas - only 15-16%. Less than 2% inhabitants of rural areas have higher education. The structure of land use is as follows: arable land **11.5**%, meadows and pastures 25.4%, forests 30.1%. Poland requires implementation of technical and technological progress for intensification of agricultural production. The reason of competition for agricultural land is maintenance of the current consumption level and allocation of part of agricultural production for energy purposes. Agricultural land is going to be key factor for biofuels production.

In this publication research results for the Project PL0073 "Modelling of energetical biomass utilization for energy purposes" have been presented. The Project was financed from the Norwegian Financial Mechanism and European Economic Area Financial Mechanism. The publication is aimed at moving closer and explaining to the reader problems connected with cultivations of energy plants and dispelling myths concerning these problems. Exchange of fossil fuels by biomass for heat and electric energy production could be significant input in carbon dioxide emission reduction. Moreover, biomass crop and biomass utilization for energetical purposes play important role in agricultural production diversification in rural areas transformation. Agricultural production widening enables new jobs creation. Sustainable development is going to be fundamental rule for Polish agriculture evolution in long term perspective. Energetical biomass utilization perfectly integrates in the evolution frameworks, especially on local level. There are two facts. The fist one is that increase of interest in energy crops in Poland has been observed since a few years. The second one is that biomass production from fast rotating crops is all the time promoted as a new agricultural production direction. In spite of the two facts, this direction is not developing.

Anna Grzybek
Assistant Professor, Institute of Technology - Life Sciences
06.09.2010, Warsaw, Poland

1

Significance and types of energy crops in the Nordic countries

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Lars Nesheim, Uffe Jørgensen

Introduction

Biomass is the largest renewable source of energy globally. Most biomass comes from residues from forestry and agriculture, while only a limited production of dedicated energy crops, where the main purpose is bioenergy production, has taken place so far. However, the ambitious goals stipulated in national and EU strategies of a substantial reduction in fossil fuel use, may require so much biomass that dedicated energy crops have to be produced. Also, specific quality criteria for certain bioenergy technologies can better be reached by dedicated energy crop production where the quality can be managed [Jørgensen and Sander 1997].

There is hardly any commercial growing of agricultural crops for energy purposes in Norway. Cereal straw is to some extent used as a solid biofuel. The agricultural area constitutes only 3 % of the total land surface in Norway, and the area is so far used for grassland (65 %) and arable crops for food and feed (35 %). There is no reason to believe that production of energy crops will increase significantly in Norway in the near future, partly due to political reasons. Production of feed and food is highly prioritized. Also in Iceland the proportion of agricultural land is very low (1.2 % of total land surface), and most of this land is used for hay and silage production [Björnsson 2007]. In Denmark, Finland and Sweden cultivation of energy crops has been commercial for several years. The objective of this chapter is to give a review of the current production of different energy crops in the Nordic countries, and to present some ideas on what may be the future for biofuels in these countries.

Crops for biodiesel

In Sweden, the area of spring oilseed rape is 90 000 ha, of which 3 % is used for biodiesel (about 3 000 ha). The potential area of rape (*Brassica napus* L. var. *oleifera* Metzg.) and turnip rape (*Brassica rapa* L. var. *oleifera* Sinsk.) in Norway is 28 000 ha, and winter types could be grown on about 10 % of this area. In the last five years the actual area of oil seed crops has been 6 000 ha on average. So far nothing is used for biodiesel. Figures for mean yield levels are not available. In variety trials in Norway the yield of seeds has been about 2 000 kg per ha for spring rape and about 3 300 kg for winter types [Abrahamsen *et al*. 2009].

The rape area in Denmark has been increasing over the last years and was approximately 171 000 ha in 2008. Mainly winter rape is grown in Denmark, and the mean seed yield is 3 200-3 700 kg per ha [Statistics Denmark]. During a period about 70 % of the Danish rape oil production was used for biodiesel production [Jørgensen *et al*. 2008], but there are no adequate statistics on the oil use. The Danish biodiesel production is exported as there is no significant tax reduction for biofuels in Denmark.

Phot. 1. Reed canary grass

Phot. Archive IBMER

Phot. 2. Experimental cultivation of miscantus in Denmark (Foulum)

Phot. Archive IBMER

Phot. 3. Miscantus and willow cultivation in Denmark

Phot. Archive IBMER

Phot. 4. The cultivation of willow in Sweden

Phot. Archive IBMER

For various reasons the area suitable for growing rape and turnip rape is limited in Norway. There are several other oil producing species, both cruciferous plants and others, but only a few of them have previously been investigated under Nordic climatic conditions. As a part of a project called "Opportunities for Norwegian production of biodiesel from agricultural crops" some alternative oil seed crops were grown on three sites in the years 2007 and 2008 [Nesheim 2009]. The sites were Apelsvoll and Vollebekk in South-Eastern Norway and Kvithamar in the Central part of Norway. The following species were investigated: Oil flax (*Linum usitatissimum* L.), sunflower (*Helianthus annuus* L.), sarepta mustard (*Brassica juncea* L.), camelina (*Camelina sativa* L.), crambe (*Crambe abyssinica* Hochst.) and blue lupine (*Lupinus angustifolius* L.). Also a cultivar of spring rape was included in the experiments. In the first year the oil seed yield was rather low for all crops on all sites. In 2008 the quality of the experiments was better, and particularly at Vollebekk and Kvithamar the yields were satisfactory. However, for sunflower the growing season was too short at the experimental sites, and for camelina, crambe and sarepta mustard the seed yields were rather low. Oil flax and spring rape produced about 2 400 kg oil seeds per hectare and for blue lupine the yield was about 3 700 kg of seeds.

Crops for bioethanol

In Sweden wheat from about 27 000 hectares is used for production of bioethanol. That constitutes about 7 % of total area of wheat. There is now one factory for bioethanol production in Sweden, and two or three more plants are planned. In the other Nordic countries there is no production of bioethanol from agricultural crops, but a large plant is planned to be build in Grenå in Denmark, where also grain from the world market can be shipped in. The plant is projected to convert 600 000 tonnes of wheat into 200 million litres of bioethanol, 150 000 tonnes protein fodder and 75 000 tonnes of fibre [www.danishbiofuel.dk].

Crops for solid biomass

Reed canary grass

In Finland reed canary grass (RCG) is now grown on 20 000 hectares, and the energy crop may be used in about 12 power plants in bales or as fuel-mix [Lötjönen *et al*. 2009]. This crop is well suited for Finland and Northern Sweden, where the winters are cold. There is also commercial growing of reed canary grass for biofuel in Sweden, but the area is much lower than in Finland (less than 1 000 hectares). The Ministry of Agriculture and Forestry in Finland has set a target to increase the area of energy crops to 100 000 hectares before 2016. The realistic yield level of RCG in Finland is 4-7 tonnes of dry matter (DM) per hectare, when harvest losses are taken into account. Because the energy content of RCG is about 4.5 MWh per tonne DM, the current production is about 450 GWh per year, if the yield level is set to be 5 tonnes per hectare. If the RCG area was increased to 100 000 hectares, the annual energy production would be about 2.25 TWh, or 0.6 % of the total energy consumption in Finland.

Reed canary grass is a winter hardy, highly productive and persistent grass crop. The oldest experimental fields have been productive more than 15 years in Finland [Lötjönen *et al*. 2009]. RCG grows well in all soil types, but the best yields have been recorded from moist mould and fine sandy soils. The crop is fertilized in the spring after harvest at 60-80 kg N per hectare. In Finland and Sweden RCG is harvested in spring after the snow melts because the crop is dry (moisture content of 10-15 %) and the fuel quality is high. The ash content is lower and the ash melting point is higher in spring harvested material compared to RCG harvested in autumn. Ash content can range between 2 and 10 %, according to fertilization and soil type. Round balers are currently the most commonly equipment used to harvest RCG in Finland, but because large square balers have a higher capacity and produce bales better suited for transportation, square balers are now becoming more common.

In Norway reed canary grass is grown to some extent for forage production, particularly on organic soils in the western parts of the country. So far there is no commercial growing of reed canary grass for energy, but some experiments have been carried out. In central parts of Norway it has been harvested in three years in April/May [Nesheim 2007]. The average DM yield has varied from 4 to 9 tonnes per hectare between years. The content of water at harvest has been very high in two out of three years (34 %). The yield contained on average 3.4 % ashes. A similar experiment was accomplished in the southern parts of the country [Henrik Kofoed Nielsen, pers. comm.]. Annual yields of RCG during five years varied from 6 to 9 tons per hectare, with a water content from 9 to 57 %. The content of ashes in spring was on average 2.5 %.

In Denmark, only a single experiment has been done on reed canary grass at a sandy soil at Research Centre Foulum [Mortensen and Jørgensen 2000]. A maximum yield of 8-10 tonnes of DM was obtained when the green grass was harvested in August. Waiting until spring harvest of dry grass in March-April reduced the dry matter yield to 5-6 tonnes. However, the natural habitat for reed canary grass is a moist organic soil, and new experiments were established on such a soil at Foulum in 2009.

Miscanthus

Miscanthus is a C_4 perennial grass which, compared to other C_4 crops, is very cold tolerant [Dohleman and Long 2009]. Still, it performs best in the warmer parts of the Nordic countries, where up to 20 tonnes of dry matter have been measured in experiments [Jørgensen 1997; Jørgensen et al. 2003] when harvesting green crops in autumn. If the harvest is delayed until spring, when dry straw can be directly baled, the yield is reduced by 30-50%. Miscanthus is still not a fully developed commercial crop and especially the crop establishment needs further development. The Danish company Nordic Biomass has developed a rhizome planter, which makes cheap and safe establishment possible [Jørgensen and Schwarz 2000] but more experience is needed before it is fully commercially viable. The most widely utilised miscanthus variety, *M.* X *giganteus* is prone to die back in the first winter after planting in cold climates [Clifton-Brown and Lewandowski 2000] , and this can be handled by planting large rhizomes, or choosing other genotypes. A miscanthus stand may last for 15-25 years. There is hardly any commercial growing of miscanthus in the Nordic countries. The area in Denmark is about 65 hectares, which is rather used for thatching of roofs than for bioenergy [www.miscanthus.dk]. In most regions of Norway the winter persistence of Miscanthus is probably too low.

Willow

Willow (*Salix*) may be harvested every 2-4 year in wintertime. The water content may be about or slightly over 50 %, and the yield potential per year is about 10 tonnes per hectare. However, yields in practise in Sweden have been much lower [Mola-Yudego and Aronsson 2008], despite even higher yields are reported in some cases [Lærke *et al.* 2010]. There is therefore still an important learning on how to optimise management as well as to recognise the large influence of water availability on willow yields [Lindroth and Båth 1999]. The content of ashes is approximately 1.6 %. A plantation may last for 25-30 years. The need of pesticides is low but it is very important to manage weeds (especially perennial weeds) during the establishment (year 1 and 2). Weed management can be done chemically or mechanically by row cultivation. A review of methods for harvest and handling of perennial energy crops in Denmark, mainly miscanthus and willow, is given by Fløjgaard Kristensen [2009].

In Sweden willow is grown on about 13 500 hectares of agricultural land [Xiong and Finell 2009]. The area is not increasing any longer, mostly due to reduced subsidies, but also to the abovementioned low yields and high costs of harvest. The breeding company SW Seed has released 25 varieties of willow during the last 20 years, which has increased the potential yield by up to 60 % [Lærke *et al.* 2010; www.agrobransle.se]. In Denmark, the area of willow is about 2 700 hectares with a significant planting taking place since 2009. In 2010 a subsidy scheme is established to support a total of almost 30 000 hectares perennial energy crops, which is expected to be mainly willow. In Finland and Norway there is no commercial production of willow for energy purposes.

Hemp

Hemp (*Cannabis sativa*) is an annual multipurpose plant that has been domesticated for the best fibre in the stem, oil in the seeds and content of a resin secret [Xiong and Finell 2009]. Most of the hemp grown in Europe is used for fibre production. Only EU certified “industrial hemp” varieties may be used, and these varieties have a tetrahydrocannabiol (THC) content of less than 0.20 %. In Norway, it is not allowed to grow hemp. There is some interest for this species in other Nordic countries, but so far the profitability has been low. In Sweden, hemp for solid biofuel has been harvested in wintertime on about 600 hectares. In Denmark and Finland, the area is lower.

Phot. 5. Hemp plant in Sweden

Phot. Archive IBMER

Crops for biogas production

During the last years the number of farm based biogas plants has increased strongly in Germany. And for most plants the input is animal manure and silage maize. In the Nordic countries there are some biogas plants based on animal manure, but till now only a few of these utilize energy crops. The most suitable crops for biogas production in the Nordic countries are probably whole crop silage of winter rye and grass silage from 2-3 harvests per year, but in Denmark and southern Sweden silage maize is also an option. However, the lower prices on biogas compared to Germany makes economic production of crop biomass for biogas difficult. Only in specific cases crop biomass may make economic sense under current conditions. For instance in organic farming a stable nutrient supply is essential for crop production, and this can be achieved from harvesting natural grassland or grass clover on farm and utilise it in a biogas plant. The nutrients will then be available in the biogas slurry and can be applied to the organic crop rotation in an optimal way. This secures a better nutrient use than ploughing under green manure in the organic crop rotation, and may increase yields [Jørgensen and Dalgaard 2004]. Recently a Danish organic farmer has established a biogas plant to utilise carrot tops, grass clover and grass from nature areas. And in the valley of Nørre harvesting of meadow grass for biogas is investigated with respect to the economy, practicality and environmental aspects of the concept as part of an inter-Nordic project [http://www.biom-kask.eu/].

In a Danish experiment, different potential crops for biogas were tested [Lærke *et al.* 2008] with yields ranging from 6 to 22 tonnes of dry matter per hectares. The convertibility of the crops for biogas was tested as well and calculated net energy surplus from producing biogas ranged from 100 to 250 GJ/ha. The crops tested were harvested green or constituted mainly easily convertible organic compounds as e.g. maize and beets. However, also more lignified crops may be used for biogas subject to a pre-treatment to break down the lignocellulosic structure. Calculations based on laboratory results from pre-treatment of lignocellulosic crops indicate that willow and miscanthus may be as cost-efficient or more efficient than the use of maize [Uellendahl *et al.* 2008]. This would in addition increase the environmental sustainability of crop production for biogas.

Energy crop production costs

A study by Ericsson *et al*. [2009] was carried out to calculate the indicative ranges of production costs and to assess the main sources of cost for a number of energy crops, both annual and perennial, on a regional level in Europe. The production costs were calculated in terms of the economic compensation required by the farmer in order to grow the crop, and therefore include not only the cost of cultivation, but also the costs of land and risk, which are often omitted in production cost calculations. The calculated energy crop production costs were found to be consistently lowest for short-rotation coppice (willow, poplar) and highest for annual straw crops. For short-rotation coppice the production costs were calculated to be 4-5 € per GJ under present conditions and 3-4 € per GJ under improved future conditions. The corresponding Figures for perennial grasses were 6-7 and 5-6 € per GJ, respectively. The production costs for annual straw crops were estimated to be 6-8 € per GJ under present conditions, with small potential for cost reductions in the future.

Environment

As it appears from the above, the economy of producing energy crops is not significantly better than the production of traditional agricultural crops. Thus, this does not provide much incentive for the farmers to establish new (and thus more or less uncertain) crops, often with a long investment period. However, Nordic agriculture faces significant challenges with respect to meeting the environmental demands set up in national and EU policies, such as the Water Framework Directive. Substantial reductions in nutrient losses may cause banning of traditional agricultural crops, or significant changes in management.

However, the production of perennial energy crops can significantly reduce nutrient losses, pesticide use and emissions of greenhouse gasses [Børjesson 1999; Danish Ministry of Food, Agriculture and Fisheries 2008]. For instance switching from grain crop rotations into perennial energy crops will reduce nitrate leaching by approximately 70 % [Jørgensen 2005]. This means that farmers can fulfil their obligations for environmental improvements by switching into another crop instead of taking land out of production and in this way keep a profitable business. This is the main reason for the recent high interest from Danish farmers in establishing perennial energy crops, and the reason for the Danish Government to promote the establishment by various measures in the new "Green Growth Packet".

Future perspectives

Phasing out fossil fuel use in the Nordic countries is a clear political focus even though the path to the goal is not yet defined in all countries. However, it seems clear that biomass will play a very significant role at least in the medium term within the next fifty years. This will be for heat and power but also the demands for increased biofuel use in the transport sector [EU Directive 2009/28/EC] will increase the demand for biomass dramatically. First choice should be sustainable utilization of biomass residues. But biomass residues cannot fulfil the future feedstock demand, at least not in heavily populated countries like Denmark. Growing dedicated energy crops is an option for delivering increased amounts of biomass. However, if this will decrease food production, indirect land use change in other parts of the world may lead to greenhouse gas emissions reducing the net effect [Searchinger 2008]. This can be counteracted if net productivity of crop production on the current agricultural land is raised to increase the resource for food, feed, chemicals and energy. Alternatively, the cultivation of energy crops on more or less marginal arable land, wetlands etc. could be an option.

Perennial energy crops, such as miscanthus and willow, are promising candidates for high-yielding, low emission production systems [Karp and Shield 2008]. These crops provide high net GHG reduction due to storage of carbon in the soil [Grelle *et al*. 2007], they have high N-use efficiency, and will significantly reduce nutrient losses and energy consumption for soil tillage [Uellendahl *et al*. 2008]. Compared to current grain crop production, approximately 50% yield increase can be obtained by employing perennial crops with an indeterminate growth, to exploit the prolonged growing season already available due to climate change [Dohleman and Long 2009]. If furthermore crops utilising C_4-photosynthesis, which has a 30% higher efficiency of light conversion, are employed, a doubling of biomass yield may be obtained [Heaton *et al*. 2008]. This may be an option in larger parts of the Nordic countries at further climate warming [Hastings *et al*. 2009].

To fully exploit the yield potential of lignocellulosic crops with an indeterminate growth, harvest of green crops before leaf fall must be in focus, which implies a need for new harvest, storage and conversion methods. Converting the biomass in a biorefinery will be an option for green biomass, and will create market flexibility to produce a portfolio of products for energy, feed, and chemicals. The Danish companies DONG Energy and Inbicon have build the so far largest 2^{nd} generation bioethanol plant at Kalundborg, Denmark, and the plant now converts straw into ethanol, animal feed (C_5-molasse) and lignin pellets for combustion [www.inbicon.com].

2

The effect of energy crops on soil enviroment

2.1 The production possibility of energy plants in Poland

Anna Grzybek, Marek Hryniewicz

Poland lies in the sphere of clashes between influences of continental climate (with quite dry summers and cold winters) and moderate Atlantic climate. These clashes are reason of unstable conditions for agricultural production. The annual average air temperature varies from 6.0 to 8.8°C. The length of the thermal vegetation period is about 220 days and only in South-West part of Poland exceeds 230 days. The annual sum of rainfall is about 500-600 mm on lowlands, 600-700 mm on highlands and it is above 1000 mm in mountains. Central Poland (Masovia, Great Poland, Kuyavia) belongs to European regions with the smallest rainfall sum which not exceeds 550 mm. Atlantic Ocean significantly influences on Polish climate from west side of Poland and Asia continent from east side of Poland. Rainfall is another significant factor. Western Europe has significantly higher rainfall in comparison with Poland. Climatic conditions and soil conditions are decisive factors for agricultural land use. They determine plants selection for crop and expected yield level.

Arable land in Poland has surface of 16.2 mil. hectares with relatively big production potential. It enables production diversification in spite of many insufficiencies in agrotechnology and agrotechnique.

Biomass resources for energy purposes can be divided, according to their origin, into following groups:

forestry biomass,

agricultural biomass,

organic wastes.

Energy crop plantations belong to agricultural biomass sources. Turnover of energy plants takes place according to determined procedure in Poland, by biomass sale to registered biomass processing companies. Biomass processing companies are registered by Agricultural Market Agency. The registration is done on the base of application of the first processing unit or purchasing company. The following types of plants are regarded as energy plants which can be cropped on agricultural land and processed into energy products:

annual plants (e.g. rape, turnip, rye, maize, flax),

sugar beets – on condition that each intermediate product is utilized for energy products production and each co-product or by-product with sugar is utilized according to Council Decision (WE) no 318/2006,

soya - on condition that each intermediate product, with exception of soya flour, is utilized for energy products production, perennial plants (e.g. thornless rose, Pennsylvanian mallow, Miscanthus giganteus, Jerusalem artichoke, Fallopia sachalinensis, reed canary grass),

forest coppices with short rotation period (e.g. energy willow, poplar, Robinia pseudoacacia),

plants cropped on agricultural land which are used as fuel for farms heating or for energy or biofuel production on farms, among others:

forest coppices with short rotation period (e.g. energy willow, poplar, Robinia pseudoacacia),

cereals,

oil plants seeds – broken soya seeds which are not predicted for sowing, rape, turnip with erucic acid low content, sunflower seeds (broken, not husked, in husk), sunflower seeds which are not predicted for sowing,

annual plants and perennial plants processed on biogas.

There are three basic groups of units which produce and process agricultural biomass for energy purposes in Polish production system. They are: farmers – biomass planters, biomass purchasing companies and biomass processing companies. Detailed requirements for each group are written in Act about payments to agricultural land and sugar payment from 2007 [Official Gazette 2007 No. 35 pos. 217], its amendments from 2008 [Official Gazette 2008 No. 44 pos. 262] and in appropriate executive directives for payments to energy crops.

Biomass purchasing companies and biomass processing companies are intermediate link between farmers – biomass planters and final agricultural biomass receivers: energy–heating companies. Activity of biomass purchasing and processing companies is subordinated to requirements of biomass final users - energy–heating companies. It includes requirements linked with quantity, structure, dead-lines and shape of supplied energy raw material. At the same time these requirements will be important for agricultural biomass producers. They will determine: harvest organization, implemented technology and profitability of energy plants production.

Table 1. Representative yields for selected energy plants in 2008

Species	Representative yield (dt dry matter per hectare)
Willow	80
Rosa multiflora	120
Pennsylvanian mallow	150
Miscanthus giganteus	200
Jerusalem artichoke	200
Spartina prairie	170
Grasses	100
Reed canary grass	80
Fallopia sachalinensis	200
Robinia pseudoacacia	80
Poplar	100
Alder	80
Birch	80
Hazel	80

Source: Regulation of Polish Ministry of Agriculture from 14 March 2008 for representative yields of energy plants (Journal of Laws No 44, pos. 267)

The Agency for Restructuring and Modernization of Agriculture (ARMA) is basic source of data about cultivated surface and species of energy plants in Poland. Polish support system for renewable energy development defines energy plants planter as a farmer who applies for payments to energy crop plantations.

Representative yields were defined by Regulation of Polish Ministry of Agriculture in 2008 (Table 1).

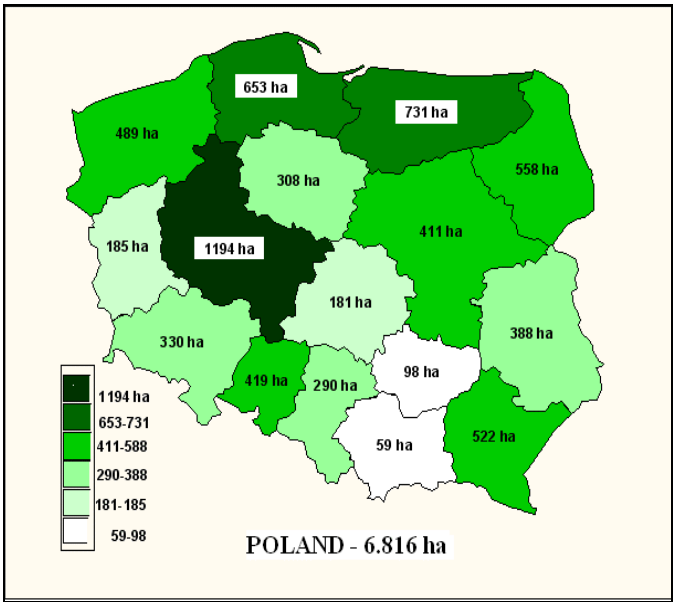


Figure 1. Surfaces of durable plantations of energy plants in Voivodeships in 2007
Source: own work, Grzybek, Muzalewski

Figure 2 presents average size of Polish energy willow plantations in 2007.

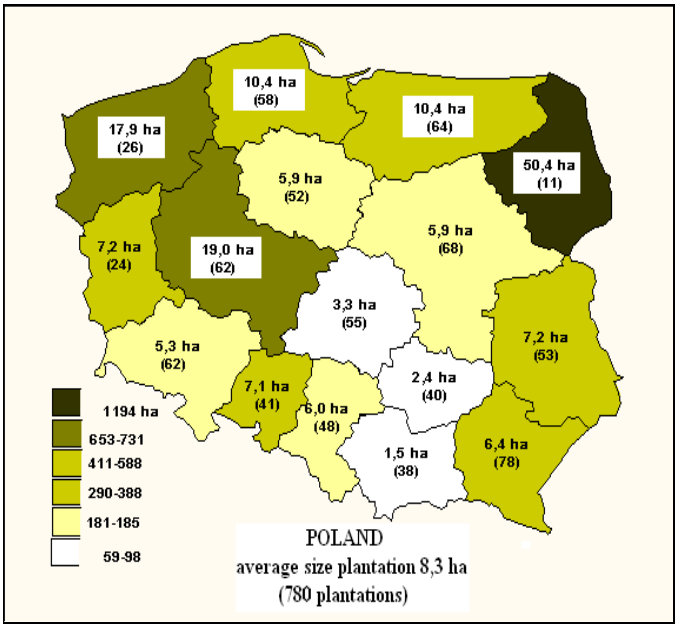


Figure 2. Average size of energy willow plantations in Poland for year 2007.
Source: own work, Grzybek, Muzalewski

In 2007, energy crops covered only 1.1% of arable land in Poland. Plants on durable plantations are cropped only on 6,816 ha - it is 3.9% of total surface of energy crops plantations and 0.42% of arable land in Poland. The highest share of durable plantations in total surface of energy crops plants was stated in Podlaskie Voivodeship (85.3%), Warmian-Masurian Voivodeship, Masovian Voivodeship and Pomeranian Voivodeship (relatively from 20.6% to 10.9%). The main agricultural biomass sources for energy sector are plants cropped on durable plantations (perennial). In 2007 the total area of land declared by farmers as energy crop plantations amounted to 175.381 ha. Figure 1 presents surfaces of durable plantations of energy plants in particular voivodeships in 2007. However, not all energy plants planters apply for payments.

The highest shares in energy plants crop structure have: oil plants (63.3%), cereals (20.4%) and maize (11%). The biggest surfaces of durable energy plants plantations, which are the main sources of agricultural biomass for energy sector, are in: Greater Poland Voivodeship (1,194 ha), Warmian-Masurian Voivodeship (731 ha) and Pomeranian Voivodeship (653 ha). The smallest surfaces are in Lesser Poland Voivodeship (59 ha) and Swietokrzyskie Voivodeship (98 ha).

Willow dominates on most of durable energy plants plantations (95% of surface of durable energy plants plantations). The biggest declared surface of energy willow was in Greater Poland Voivodeship (1 178 ha) in 2007. The smallest declared surface of energy willow was in Lesser Poland Voivodeship (58 ha) in 2007. Average surface for 780 willow plantations was 8.31 ha – from 1.53 ha in Lesser Poland Voivodeship to 50.38 ha in Podlaskie Voivodeship. Miscanthus declared crop surface amounted to 67.8 ha and of Pennsylvanian mallow 26.1 ha in 2007. Miscanthus plantations were localized mainly in Warmian-Masurian Voivodeship. Pennsylvanian mallow plantations were localized mainly in Warmian-Masurian and Pomeranian Voivodeships. In 2009 growth of energy plants crops was observed (Table 2).

Table 2. State of crop for perennial energy plants in voivodeships in 2009 [ha]

Voivodeship	Willow	Miscanthus	Pennsylvanian mallow	Perennial grass	Reed canary grass	Poplar
Lower Silesian Voivodeship	599.97	11.03				
Kuyavian-Pomeranian	197.99		1.30	281.63		0.50
Lublin	305.65	10.75	3.42		14.69	5.01
Lubusz	409.42			0.90		
Łódź	210.92	1.59				
Lesser Poland	61.83	9.48				
Masovian	762.44	1 200.04	30.13			0.23
Opole	226.50	7.51	1.00	28.65	19.11	2.02
Subcarpathian	651.63	42.13	12.68			45.24
Podlaskie	156.52		3.83			4.01
Pomeranian	394.43	17.37	0.20			487.70
Silesian	258.91	2.85	39.24	17.17		0.71
Świętokrzyskie	98.64		0.50	28.49		
Warmian-Masurian	571.03	382.09	26.70		8.31	5.61
Greater Poland	765.57	31.74		21.89	10.50	13.09
West Pomeranian	488.97	116.22	2.60	985.42		83.79
Poland	6 160.42	1 832.80	121.60	1 364.15	52.61	647.91

In 2009 total surface of durable energy crops plantations was 10 179.5 ha. Energy willow still dominated – 60.5% of the total energy crops surface. Surface of miscanthus crop increased up to 18% of the total energy crops surface.

Plants production for energy purposes is stimulated by demand of energy-fuel sector on one hand and payments to crops surface for energy plants on the other hand. Demand of energy companies for agricultural biomass is driven by duty of energy companies for selling energy from renewable sources. Cultivation of perennial plants has not developed so much since 2007. The main reason of this situation seems to be a lack of stable agricultural policy and missing guaranties for biomass price and market. Duty of electrical energy production from renewable sources has existed since 2003. This duty framework is actualized in consecutive Regulations issued by Minister of Economy. Energy company's duty was given in Regulation issued by Minster of Economy in 2008. It seemed that it could start multiyear biomass contracts and clear prices policy would be presented for biofuels. A boom for dedicated plantations establishment for green energy production was expected. Unfortunately, it has not happened. There is still stagnation with the establishment of perennial energy plants plantations. Other important reason were and still are: the attitude of farmers and producers towards new type plants (perennial, trees), the lack of machines and equipment for planting and harvesting, the lack of perspectives for biomass selling. In ordinance from 2008, current percentage rates for electric energy produced from renewal energy sources (RES) were established. According to project of ordinance of Ministry of Economy[1], the obligation to obtain required amount of certificates will be achieved if in a particular year amount of electric energy from RES, in total annual sale of electricity to final customers will be at level as shown on Figure 3.

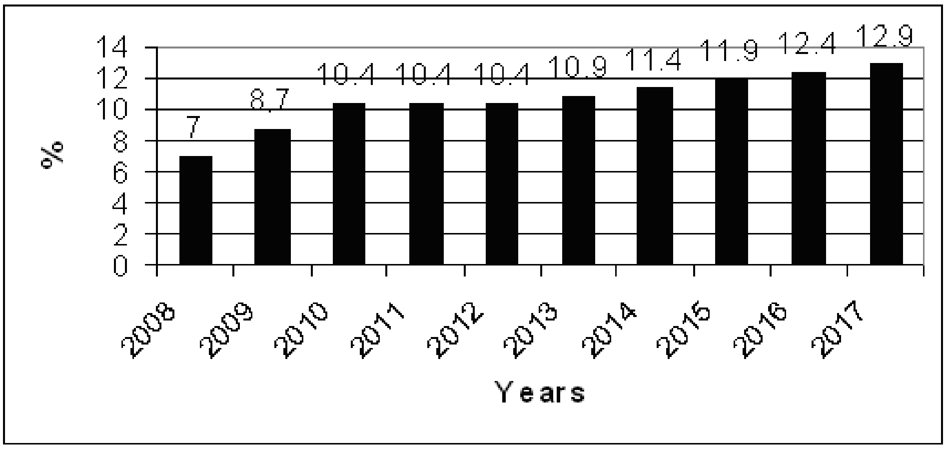


Figure 3. Required amount of electric energy from RES in following years, on basis of Ministry of Economy Ordinance, 2008

For co-firing of biomass and combustion using hybrid system, in power plants with total power over 5 MW, since 2008 the biomass from agriculture should be used. Required share of agricultural biomass is shown on figure 4.

[1] Ordinance of Ministry of Economy in scope of obligation to obtain and remit certificates of origin, substitute payment and purchase of electric energy and heat produced from RES, 2008

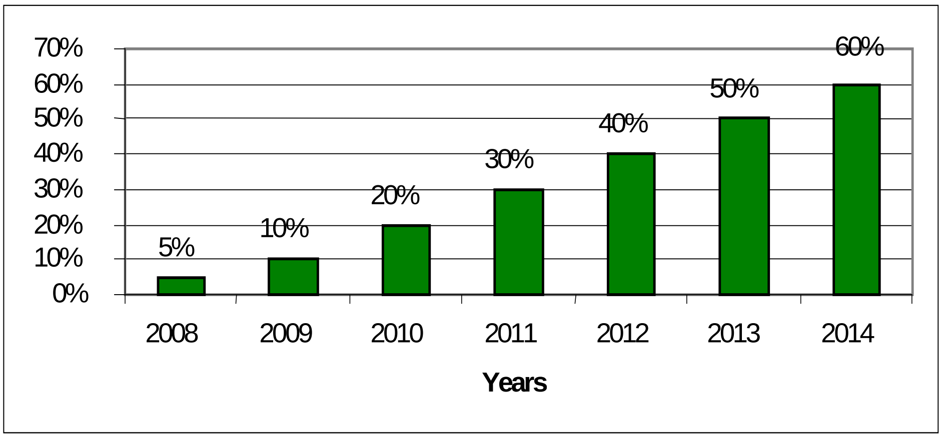


Figure 4. Required share of biomass from agriculture for electricity production purposes, on a basis of Ministry of Economy Ordinance, 2008

Demand for biomass, also from agriculture, for energy production till 2020 was calculated with following assumptions:

share of biomass in renewable energy sources balance will be 50%;

heating value of biomass is 10MJ/t, 40% of water content.

In Table 3 demand for biomass for energy production is presented.

Table 3. Demand for biomass for energy production

No.	Position / Year	2007	2008	2009	2010	2020
1.	Gross energy production forecast, TWh/a	154.8	159.3	163.8	168.3	201.7
2.	Share of energy from RES, %	4.8	6.0	7.5	9.0	20.0
3.	Share of energy from RES, TWh/a	7.4	9.5	12.3	15.1	40.3
5.	Share of energy from biomass, PJ/a	13.36	17. 2	22. 4	27. 2	72.6
7.	Demand for biomass, mln t/a	1.3	1.7	2.2	2.7	7.2
8.	Share of energy from agricultural biomass,%		5	10	20	60
9.	Share of energy from agricultural biomass, PJ/a		0. 86	2.2	5.4	43.6
10.	Demand for agricultural biomass, mln t/a		0.086	0.22	0.54	4.36

Source: own calculation

In a few projects potential possibilities of the cultivation of durable plantations of energy plants were determined. Poland can allocate from 1.0 to 4.3 mln ha for energy plants production until 2020 according to the out of Polish authors. Poland cannot be ranked among countries with very good conditions for the production of plants for energy purposes due to relatively small rainfalls and limited ground water resources.

Only soils with lower quality and less useful for food production can be allocated for perennial energy plantations. Cultivation of energy plants on such soils limits yield and the production profitability in consequence. One of many projects which estimated the theoretical and technical potential of energy crops in Poland was financed by EU project ,, Renewable fuels for Europe up to 2030” with acronym REFUEL [http://www.ieo.pl/downloads/26102007/Sylvia%20Prieler.pdf]. REFUEL report took as environmental criterions: advantageous CO_2 balance, country soil, water and climatic conditions. The report recommended for cultivation energy willow and Panicum virgatum. There was received an incredibly high technical potential of energy plantations. Panicum virgatum was taken as a representative of grass plants in REFUEL project. However, analyses in this project have not taken into consideration Polish environmental conditions and the structure of national agriculture. Due to these reasons the estimated technical potential of energy crops as 2 259 096 TJ (according to REFUEL project methodology) is incredible. Authors of another project (UE/IEE European Environmental Agency (EEA), Estimating the environmentally compatible bio-energy potential from agriculture" (Technical Report No. X/2007, Copenhagen, '2007, unpublished) have stated that 11.5 mil. ha of arable land could be excluded from food production and allocated for energy plants cultivation with conservation of food self-sufficiency. The technical potential of energy crops has been predicted as 1 011 000 TJ in 2020. There is an assumption for EU states majority (excluding very small and very dense populated countries) that in 2020 year perspective will be a big growth of energy crops. Poland was included to a group of countries where about 30% of arable land would be allocated for energy crops. The Report generated by the project stated that in Poland there are about 12% meadow type settlements protected in NATURE 2000 framework (EU average 16%). Their protection depends on maintenance extensive agricultural practices including in it grass mowing. It creates a potential for biomass but with strong environmental protection limits. When estimation of available space in 2020 year perspective for energy crops, terrains which in the nearest future are going to be allocated on other than agricultural purposes were taken into consideration. It means terrains for: urbanization, the development of infrastructure, for transport and environment (water treatment stations, wastes recycling), afforestations and tourism development. Poland has been taken into account to the biggest group of EU states where such terrains would take probably about 1% of contemporary agricultural land. The report qualifies energetically feasible arable land of 4 321 200 ha in 2020, as well as available grasslands of 492 300 ha. It gives the sum 4 813 500 ha. However, above mentioned values are in discrepancy with reality. There were taken not correct data. The work "Possibilities of Renewable Energy Sources utilization till to 2020 year" (an expertise of Polish Ministry of Economy, Warsaw, December 2007) stated that the surface of grasslands agriculturally utilized which would be available for biomass production on energy purposes was predicted as 100 000 ha. There has been estimated the technical potential of energy crops as 479 166 TJ including in it: lignocellulose crops – 208 888 TJ, starch and sugar crops – 81 027 TJ, rape – 73 514 TJ, maize and grasslands silage (for biogas) – 116 625 TJ.

However, authors stated further that macroeconomic estimations (made from the following points of view: available space balance, arable land balance for food production, energy crops intensity and national energy balance) must not be immediately transferred on farmers decisions. They stated also that Polish government influence on farmers' decisions would be limited. Moreover, analyses till 2020 year took into consideration only the first biofuels generation, whereas at the same time the second biofuels generation will be available on the market. Thus demand on arable land for energy crops could be slightly smaller than calculated and as a consequence the final shares of energy from Renewable Energy Sources in total energy balance are conservatively estimated. With any knowledge about support instruments for the second biofuels generation and assuming that till 2020 year current support instruments will be implemented it is difficult (according to the accepted method) estimate the share of second bi

2.2 The effect of energy crop on chemical soil properties

Jerzy Grabiński, Piotr Nieróbca, Edward Szeleźniak, Antoni Faber

Summary

In the paper the studies concern the evaluation of changes in the chemical properties of the soil under cultivation of different species of energy crops was described. The studies were carried out on 2-9 years old energy crop plantations of willow, miscanthus and Sida hermaphrodita, located on different soil types in Experimental Stations and on private farms in Poland. To analyze of changes of chemical soil properties, the samples were collected from different levels of the soil: 0-30 cm, 30-60 cm and 60-90 cm. On these layers pH, content of mineral nitrogen, available forms of phosphorus, potassium, magnesium were analyzed. For analyze the changes of organic carbon content in the soil samples were collected from levels 0-10 cm and 10-20 cm. The control treatments were set up 5-10 m from the border of the plantation, cultivated traditionally (fallow ground or sown grasses).

Introduction

There are many differences between perennial energy crops and typical arable, annual crops [Dimitrou et. al. 2009]. First of all, energy crops grow on the same field incessantly (even 20 and more years) but annual crops at most in few years monoculture. Technologies of energy crops characterize much lower intensity of control agrophages and typically much less fertilizing. The moment of high intensity of energy crop technology concern only year of plantation establishing, which is usually bounded with deep tillage and weeds control [Tolbert et al. 1995].

An important distinguishing feature of energy crops harvested every few years (e.g. willow) is a way of fertilization for long-term, which may create danger to the environment [Grabiński et al. 2006].

It should be added that perennial energy crops are deeper rooted and generally have a high water consumption compared with conventional crops [Dimitrou et. al. 2009].

Yields of crops cultivated for energy are often very high - even 20 and more ton of dry matter per hectare per year. With high yield, not so small quantity of nutrient is removed. Adegbidi et al. [2001] shown that with 15-22 t/ha of dry matter yield it is uptake from the soil of 75-86 kg nitrogen, 10-11 kg phosphorus, 27-32 kg potassium, 52-79 kg calcium and 4-5 kg magnesium.

Mentioned above information justify studies on defining the effect of energy crops on the environment. Especially, that according to many experts the interest in using biomass for energy production will increase. The aim of the study was evaluation of the effect of cultivation of different species of energy crops on chemical properties of the soil.

Methodology

The studies were carried out on 2-9 years old energy crop plantations, of willow, miscanthus and Sida hermaphrodita hermaphrodita, located on different soil types in Experimental Stations and in private farms (Table 4.). In the autumn, after the end of vegetation (usually in the second decade of November), samples were collected in order to analyze changes of chemical soil properties. The samples were taken from different levels of the soil: 0-30 cm, 30-60 cm and 60-90 cm. On these layers pH, content of mineral nitrogen, available forms of phosphorus, potassium and magnesium were analyzed. In the same term like mentioned above, the samples were collected from levels 0-10 cm and 10-20 cm for analysis of the changes in organic carbon content in the soil. All soil samples were taken from the middle part of interrows, 5-10 m from the border of the plantation. The control surfaces (fallow ground or sown grasses, cultivated traditionally) were located 5-10 m from the border of the plantation.

Fertilization of plantations was differentiated. Plantations located on silt clay and on slightly loamy sand were fertilized the most intensively: 75-80 kg N, 60-72 kg P_2O_5 and 72-90 K_2O per hectare per year. Willow, as a species harvested every three years, was fertilized using long term doses (in the year of harvest). Big plantation near Bydgoszcz, on which soils samples were collected from two types of soil (slightly loamy sand and light loam) was fertilized after harvest, every two years in doses 80 kg N/ha, 20 kg P_2O_5 and 40 kg/ha K_2O per hectare. On plantations localized on silty clay and silt loam fertilizers were not applied.

Table 4. List of plantations, on which samples were collected

Place names	Year of plantation establishment	Cultivated species	Soil texture group	Content in %		
				Sand	Silt	Clay
1. Experimental Station of IUNG PIB Osiny	2003	willow, miscanthus, Sida hermaphrodita	Heavy silt loam	15	34	51
2. Private farm near Zamość	2000	willow	Silt clay	3	47	50
3. Experimental Station of IBMER at Kłudzienko	2007	willow	Silt loam	30	43	27
4. Private farm near Bydgoszcz	2004	willow	Light loam	61	24	15
5. Experimental Station of IUNG PIB Osiny	2004	willow, miscanthus, Sida hermaphrodita	Heavy loamy sand	65	19	16
6. Private farm near Bydgoszcz	2004	Willow	Slightly loamy sand	83	9	8

The following methods of chemical analysis were applied:

-potentiometric - pH in KCl according to PN-ISO 10390: 1997

- Kieldahl – total nitrogen

-Egner-Riehm – available phosphorus

-Egner-Riehm – available potassium

-atomic absorption spectroscopy – available magnesium, according PN-R-04020:1994.

-spectrophotometric -N-NH_4 and N-NO_3, after extraction 1% K_2SO_4 –

- Tiurin-organic carbon.

The chemical analysis was made in authorized Central Laboratory of Chemical Analysis of IUNG PIB in Pulawy.

Results

Studies showed that after 5-9 years since establishing of willow plantations pH of soil decreased, as compared to control surfaces, in 0-30 cm layer on all types of soils except of slightly loamy sand soil. In deeper layers of soil 30-60 and 60-90 cm these reduction were observed on heavy silt loam, light loam and slightly loamy sand only (Table 5).

Table 5. Soil pH values on the surfaces of control and expressed as a percentage of control in the plantations of willow

Soil type	Layer of soil	Soil pH on control surface (grass, fallow)	Soil pH on willow plantation (as percentage of control surface)
Heavy silt loam	0-30 cm	4.23	90.8
	30-60 cm	4.51	96.3
	60-90 cm	4.80	97.4
Silt clay	0-30 cm	4.94	97.9
	30-60 cm	4.37	108.6
	60-90 cm	4.92	113.1
Light loam	0-30 cm	4.40	98.5
	30-60 cm	4.49	93.3
	60-90 cm	4.58	95.5
Heavy loamy sand	0-30 cm	4.78	98.6
	30-60 cm	4.72	108.7
	60-90 cm	5.54	112.6
Slightly loamy sand	0-30 cm	6.11	102.0
	30-60 cm	5.76	96.5
	60-90 cm	5.74	99.4
The average pH at different levels	0-30 cm	4.89	97.6
	30-60 cm	4.77	100.7
	60-90 cm	5.12	103.7

Source: own research

Examined plantations of miscanthus and Sida hermaphrodita were established on two types of soils: heavy soil (heavy silt loam) and on light soil (heavy loamy sand). Considerable decrease of pH, exceeding 10 %, on these species plantations, compared with soils from control surfaces were observed in the layer 0-30 cm. In deeper layers decline of pH was observed on Miscanthus plantation only.

In the range of abundance of nutrients quite a big differences between soils under energy crops and control surfaces in available phosphorus was confirmed. They consisted on increasing the amount of available phosphorus compared with control surfaces, in the range from a few to several percent, on plantations of willow, miscanthus and Sida hermaphrodita on heavy silt loam and silt clay, fertilized with that nutrient, but only in the layer 0-30 cm.

Differences in available forms of potassium in the soil from energy crop plantations and control area were rather small, but it should be noticed that reducing of this nutrient contents compared with control surfaces was observed on miscanthus plantation in the layer 0-30 cm (Table 6).

Table 6. The potassium contents in the soil on the control surfaces and expressed as a percentage of control on plantations of miscanthus and Sida hermaphrodita

Soil type	Soil layer	Miscanthus		Sida hermaphrodita	
		The potassium content on the control surface - grass, fallow [mg ·100 g^{-1} soil]	The potassium content on the energy plantation as percentage of control	The potassium content on the surface of the control grass, fallow [mg ·100 g^{-1} soil]	The potassium content on the energy plantation as percentage of control
Heavy silt loam	0-30 cm 30-60 cm 60-90 cm	16.0 4.6 2.3	79.8 110.2 100.0	16.2 8.9 4	100.9 88.3 92.1
Heavy loamy sand	0-30 cm 30-60 cm 60-90 cm	12.3 2.4 2.6	82.3 113.4 108.2	11.3 3.4 2.6	83.4 99.9 104.3

Source: own research

The observed ranges of differences in magnesium available content did not exceed 5%, on all plantations of willow, Sida hermaphrodita and miscanthus.

In the layer 0-30 cm on all plantations, the increase of total nitrogen content in the soils, in average by about 4%, was observed. Detail analysis of mineral forms of this nutrient in the soils showed, that ammonium form of nitrogen ($N\text{-}NH_4$), on miscanthus and Sida hermaphrodita plantations, in upper layers of the soil 0-30 and 30-60 cm was reduced by over 50% compared with control surfaces (Table 7). But in deepest layer 60-90 cm the opposite relationship - more ammonium nitrogen in the soil from energy crops plantations - was recorded. Content of nitrate nitrogen (N-NO3) in the soil on miscanthus and Sida hermaphrodita plantations, on heavy soil (heavy silt loam) and on light soil defined as heavy loamy sand, decreased together with increase of depth of soil samples collection. Regardless of the depth, more of this nitrogen form was found on the plantations of energy crops than on the control surfaces (Table 8). It should be noted that the plantations of the species in SD Osiny were fertilized with relatively high doses of nitrogen.

Differences in nitrogen content of ammonium on plantations of willow and the control surfaces were much smaller. Only on the heaviest soil (heavy silty clay) in the layer 0-30 cm this difference was big (66% of $N\text{-}NH_4$ more in the soil from willow plantation). On the other willow plantations the differences in the amount of ammonium nitrogen in the topsoil and control surfaces were small - less than 5%. Amount of nitrate nitrogen in the soil on willow plantation depended on soil type (Table 9). Most ion of N-NO3 in 0-30 cm layer of soil was found on the heavy silt loam and heavy loamy sand, so on the most fertilized plantations. As far as increasing the depth, the content of this form of nitrogen had been declining markedly, although quite a lot of $N\text{-}NO_3$ was observed in the deeper layers. On control surfaces covered with grass or fallow there was significantly less of nitrate nitrogen, especially in deeper soil layers.

Table 7. The content of ammonia nitrogen in the soil on the plantations of miscanthus and Sida hermaphrodita, and the control surfaces covered with grass (Experimental Station Osiny - average of the years 2008-2009)

Soil type	Soil layer	Miscanthus		Fallow, grass		The amount of $N-NH_4$ on the plantations of miscanthus as percentage of control surfaces [in %]	Sida hermaphrodita		Fallow, grass		The amount of $N-NH_4$ on the plantations of Sida hermaphrodita as percentage of control surfaces [in %]
		$mg \cdot kg^{-1}$ soil	$kg \cdot ha^{-1}$	$mg \cdot kg^{-1}$ soil	$kg \cdot ha^{-1}$		$mg \cdot kg^{-1}$ soil	$kg \cdot ha^{-1}$	$mg \cdot kg^{-1}$ soil	$kg \cdot ha^{-1}$	
Heavy silt loam	0-30 cm	3.60	14.1	5.11	19.9	70.5	3.02	11.8	6.83	26.6	44.2
	30-60 cm	2.76	10.7	3.74	14.6	73.7	1.97	7.7	2.41	9.4	81.7
	60-90 cm	2.61	10.2	1.88	7.3	138.8	1.96	7.6	1.57	6.1	124.8
Heavy loamy sand	0-30 cm	2.35	10.6	2.76	12.4	85.1	2.57	11.6	3.02	13.6	85.1
	30-60 cm	1.51	6.8	1.54	6.9	98.1	1.52	6.8	1.90	8.6	80.0
	60-90 cm	1.23	5.5	1.22	5.5	100.8	1.39	6.3	1.16	5.2	119.8
Average for the layer of soil	0-30 cm	2.98	12.3	3.94	16.2	77.8	2.80	11.7	4.93	20.1	64.7
	30-60 cm	2.14	8.8	2.64	10.8	85.9	1.75	7.3	2.16	8.9	80.9
	60-90 cm	1.92	7.8	1.55	6.4	119.8	1.68	6.9	1.37	5.7	122.3

Source: own research

Table 8. The content of nitrate nitrogen in the soil in the plantations of miscanthus and Sida hermaphrodita, and the control surfaces covered with grass (Experimental Station Osiny - average of the years 2008-2009)

Soil type	Soil layer	Miscanthus		Fallow, grass		The amount of $N\text{-}NO_3$ on the plantations of miscanthus as percentage of control [in %]	Sida hermaphrodita		Fallow, grass		The amount of $N\text{-}NO_3$ on the plantations of Sida hermaphrodita as percentage of control surfaces [in %]
		$mg \cdot kg^{-1}$ soil	$kg \cdot ha^{-1}$	$mg \cdot kg^{-1}$ soil	$kg \cdot ha^{-1}$		$mg \cdot kg^{-1}$ soil	$kg \cdot ha^{-1}$	$mg \cdot kg^{-1}$ soil	$kg \cdot ha^{-1}$	
Heavy silt loam	0-30 cm	9.17	35.8	5.67	22.1	161.7	5.70	22.2	4.56	17.8	125.0
	30-60 cm	7.59	29.6	3.87	15.1	196.1	4.50	17.6	4.24	16.5	106.1
	60-90 cm	2.83	11.0	0.66	2.6	428.8	1.16	4.5	0.9	3.5	128.9
Heavy loamy sand	0-30 cm	3.39	15.3	2.53	11.4	133.9	4.73	21.3	2.94	13.2	160.9
	30-60 cm	1.32	5.9	1.15	5.2	114.8	2.56	11.5	1.78	8.0	143.8
	60-90 cm	0.56	2.5	0.45	2.0	124.4	2.15	9.7	1.13	5.1	190.3
Average for the layer of soil	0-30 cm	6.28	25.5	4.10	16.8	153.2	5.22	21.8	3.75	15.5	139.2
	30-60 cm	4.46	17.8	2.51	10.1	177.8	3.53	14.5	3.01	12.3	117.3
	60-90 cm	1.70	6.8	0.56	2.3	303.5	1.66	7.1	1.02	4.3	162.7

Source: own research

Table 9. The nitrate nitrogen content in the soil on the surfaces of control and expressed as a percentage of control on plantations of willow (average of the years 2007-2009)

Soil type	Soil layer	Willow plantation [mg·kg^{-1} soil]	Willow plantation [kg·ha^{-1}]	Control surface – grass, fallow [mg·kg^{-1} soil]	Control surface – grass, fallow [kg·ha^{-1}]	Content on willow plantation as percentage of control surface [%]
Heavy silt loam	0-30 cm	7.77	30.3	6.11	23.8	127
	30-60 cm	7.84	30.6	2.78	10.8	282
	60-90 cm	5.22	20.3	0.99	3.8	527
Silt clay	0-30 cm	3.40	13.3	2.74	10.7	124
	30-60 cm	1.66	6.5	1.73	6.7	95
	60-90 cm	0.46	1.8	0.48	1.9	96
Light loam	0-30 cm	2.76	12.4	4.09	18.4	67
	30-60 cm	1.04	4.7	2.47	11.1	42
	60-90 cm	0.92	4.1	1.94	8.7	47
Heavy loamy sand	0-30 cm	5.52	24.8	4.38	19.7	126
	30-60 cm	8.98	40.4	1.85	8.3	485
	60-90 cm	8.37	37.7	1.62	7.3	516
Slightly loamy sand	0-30 cm	1.09	5.0	1.17	5.4	93
	30-60 cm	0.40	1.8	0.51	2.3	78
	60-90 cm	0.29	1.3	0.36	1.7	81
The average content at different levels	0-30 cm	4.11	17.2	3.70	15.6	107.4
	30-60 cm	3.98	16.8	1.87	7.9	196.4
	60-90 cm	3.05	13.1	1.08	4.7	253.4

Source: own research

A particular object of research was established at the IBMER Centre at Kłudzienko: after two (year 2008) and three (year 2009) full growing seasons since the establishment of plantations. These studies conducted in the Centre showed that the content of ammonium nitrogen up to a depth of 60 cm of soil, on willow plantation, is higher by 15-30% than on the field with annual crops (Figure 5). In the case of nitrate nitrogen differences were much higher. On the willow plantation only small quantity of these ions was observed, but on the arable field - several times more (Figure 6).

Until now, fairly well recognized phenomenon of soil carbon accumulation was in forest areas. Research on these natural environments suggests that the carbon content increases with forest age. Only immediately after planting decreases of the organic carbon content, associated with intensive cultivation of the field preparing to set up plantation, can occur [Hansen 1993]. Dowydenko [2004] says that abandonment of deep cultivation prior to planting a forest could increase the possibility of accumulation of carbon in the soil on afforested land.

The youngest plantation in the IBMER Centre at Kłudzienko, where samples were taken in order to determine organic carbon content, was only two years old. Analyses carried out in soil samples taken from the plantation have shown that already in the initial period after the establishment of plantation fairly large changes in organic matter content occur in the soil. This is illustrated on the Figure 7, which shows that in the willow plantation after two years of establishment, content of organic carbon in the soil was significantly lower (by about 12%) than on arable field.

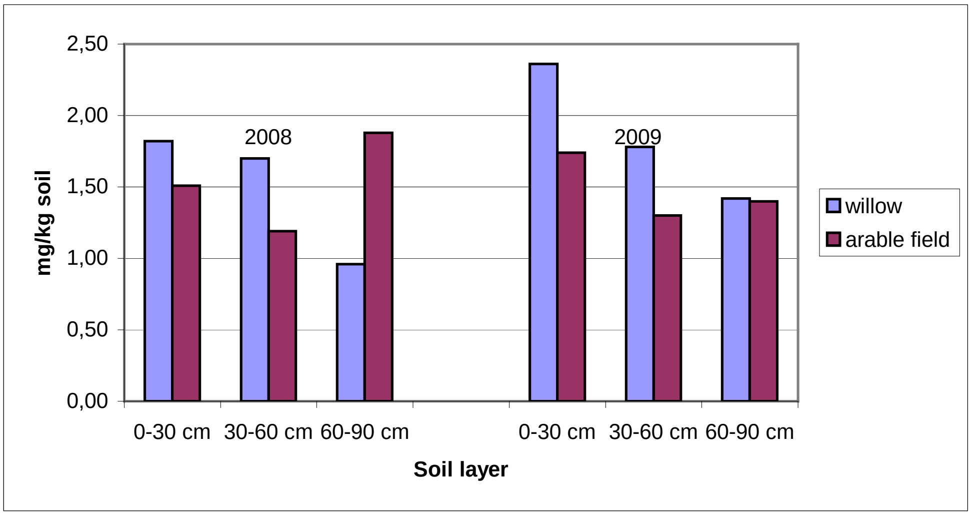


Figure 5. The content of ammonia nitrogen on the willow plantation and arable field (clay silt) (Kłudzienko 2008-2009)
Source: own research

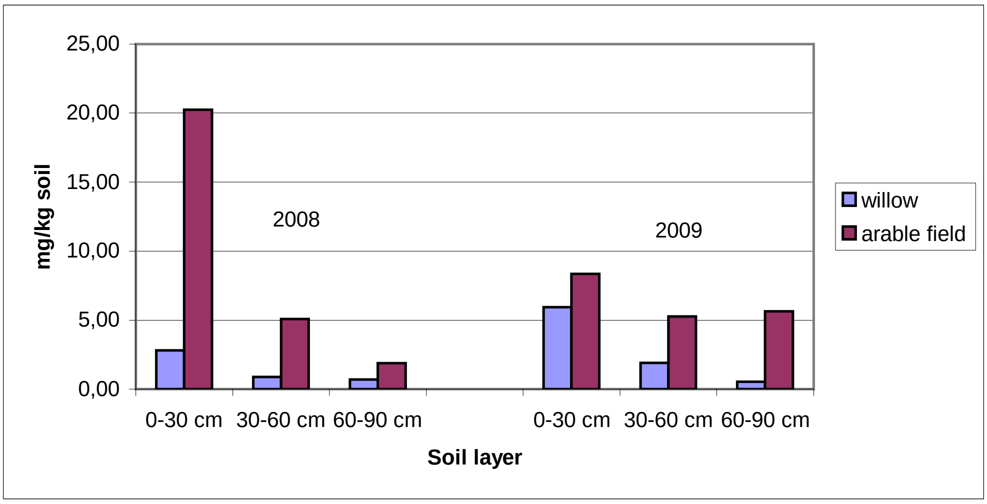


Figure 6. The content of nitrate nitrogen on the willow plantation and arable field (silt loam) (Kłudzienko 2008-2009)
Source: own research

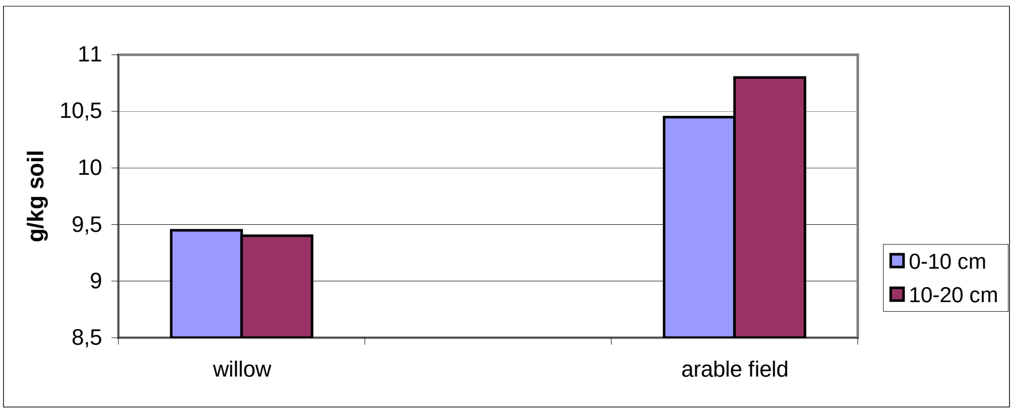


Figure 7. The content of organic carbon in the soil on the plantation of willow after two seasons since establishing (IBMER Kłudzienko-silt clay)
Source: own research

Generally, on older plantations, the phenomenon of accumulation of organic carbon was observed. For example, on the soil characterized as light loamy sand, after five seasons after plantation establishment, organic carbon content increased on the willow plantation, at 0-10 cm layer, by 3% compared to the control surface which was fallow, and by 6% compared to the arable field (Figure 8).

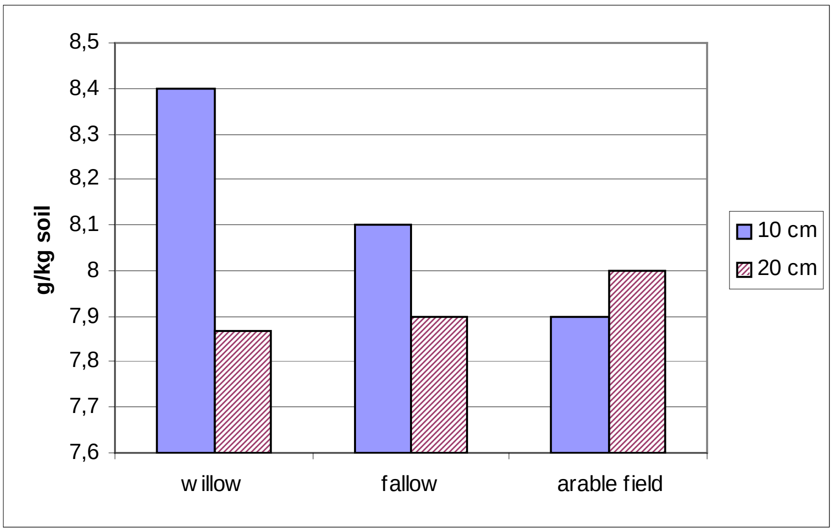


Figure 8. Organic carbon content in the soil at different levels in the willow plantation near Bydgoszcz (light loamy sand) after five seasons of plantation exploitation

Conclusions

The following chemical changes in the soil are occurred on energy crop plantations during the first decade of plantation exist:

1. The pH in the soil layer of 0-30 cm decreased, especially on strongly fertilized plantations.
2. Content of available phosphorus in the heavy soils, in the topsoil, has increased by within 8-13%.
3. Changes in content of available potassium were small. Only on the plantations of miscanthus reduction of this nutrient content was observed.
4. Changes in content of available magnesium in relation to the control surfaces did not generally exceed a few percent.
5. Changes in total nitrogen contents were relatively large, especially in the surface layer of 0-30 cm. Regardless of soil conditions, the average nitrogen content in this layer was higher by 4% than on control surfaces.
6. Very high levels of nitrate nitrogen in the soil before winter, causing a threat to the environment, occur only on plantations of energy crops harvested every three years (willow), which were fertilized "on reserve" after the harvest of biomass.
7. The risk of harm to the environment from the mineral forms of nitrogen in a case of not fertilized and fertilized with low doses energy crops (willow, miscanthus and Sida hermaphrodita) is negligible.
8. Cultivation of energy crops such as willow, miscanthus and Sida hermaphrodita affect changes in the content of organic carbon in the soil. The direction and magnitude of these

changes varies greatly and depends on the age of plantations and soil conditions. In the first 2-3 years after the establishment of plantation, the decrease in organic carbon content in the soil may occur. Generally after, 5-9 vegetation seasons organic carbon accumulation is observed, especially in the topsoil 0-10 cm. The magnitude of this accumulation is greater than on cultivated fields, overgrown with grass or surfaces that are fallow.

9. Relatively large changes in the soil during first years after establishment of the plantation of energy crops suggest the need for monitoring of this phenomenon until the liquidation of the plantations.

2.3 Photosynthetic productivity and efficiency of perennial energetic crops

Włodzimierz Majtkowski, Gabriela Majtkowska, Bartosz Tomaszewski

Summary

On the existing production fields in the period from 2007 to 2009 the growth of plants and the height of three perennial species yields planted for energetic purposes: *Salix viminalis*, *Miscanthus* x *giganteus* and *Sida hermaphrodita*, were examined. The highest biomass yield (23.7 t DM/ha) was obtained for *Miscanthus giganteus* on the plantation in Radzików, where it was planted on podzolic soil belonging to IV quality class. The smallest yield (8.3 t DM/ha) was observed on *Sida hermaphrodita* plantation in Gronowo Górne near Elbląg, on mineral soil belonging to class III. What had a negative impact on plants development was: damp deficit, weed infestation, low content of nutrients in the soil and low pH. The diversity of photosynthetic productivity depending on species and the impact of other factors having influence on biomass yield were also examined. The species of C3 photosynthesis had higher photosynthesis intensity when water management was not effective. *Salix* hybrids showed the highest intensity in full lighting (about 6.5 µmol $H_2O/m^2/s$), when the lowest intensity was examined for *Miscanthus giganteus* (about 4 µmol $H_2O/m^2/s$). The increase in photosynthesis intensity of these species was connected with the decrease in stomatal conductance. The rate of transpiration grew simultaneously, what indicated little effectiveness of water management.

Methods

Each species was examined on 3 production plantations (Table 10). The following factors were checked: plants overwintering, weed infestation of the plantations and pathogens occurrence. The plantations productivity and the plants biometric measurements were done after the end of the plants vegetation, i.e. in the period from October to March. Biomass was collected from 30 plants (3 replications). Humidity and the actual number of living plants compared to used plant density were included while converting yield to an area of 1 ha. Soil samples were collected from the examined areas, for which Nowosielski's horticultural method [2004] was used to determine:

- pH and salinity, in distilled H_2O,
- $N\text{-}NO_3$ – with the use of ion-selective electrode,
- P – colorimetric method (Spekol 11 Carl Zeiss Jena),
- Ca, K, Na – method of emission spectrometry,
- Mg – method of atomic absorption (atomic absorption spectrophotometer PU 9100X Philips).

The ranges of fertility, reaction and salinity for the examined soils were established on the basis of the obtained results. The analyses of chemical composition were done in the Chemical Laboratory of the Department of Root Crops Production Technology of Plant Breeding & Acclimatization Institute in Bydgoszcz.

In the period of growth and development the measurements of gas exchange, including for instance net photosynthesis intensity (Pn), transpiration (E) and stomatal conductance (Gs) were done. The measurements were performed with the use of LCi device (Li-COR Company). The same leaves were always used in the measurements, in their middle parts, under comparable environmental conditions, during the same hours, under constant-adjusted irradiation intensity PAR - 1200 μmol/m^2/s, under an average air temperature of 23 ^oC. The parameters were examined in full lighting and in shadow (inside the canopy); in the morning, noon and afternoon on experimental fields in Botanical Garden in Bydgoszcz; on podzolic soil belonging to class IV. On the basis of water utilization rate – WUE, that was calculated from the ratio of net photosynthesis intensity to transpiration intensity, efficiency of water utilization in photosynthesis was described [Pietkiewicz and others 2005].

Table 10. List of plantations under investigations

Species	**Location (voivodeship)**	**Year of planting**	**Area [ha]**
Salix viminalis	Marcelewo (kujawsko-pomorskie)	2004	50
	Przysiersk (kujawsko-pomorskie)	2005	7.5
	Suponin (kujawsko-pomorskie)	2004-2006	50
Miscanthus giganteus	Gronowo Górne (pomorskie)	2006	2
	Drewnowo (pomorskie)	2006	40
	Radzików (mazowieckie)	2006-2008	40
Sida hermaphrodita	Gronowo Górne (pomorskie)	2006	1.5
	Drewnowo (pomorskie)	2007	20
	Czciradz (lubuskie)	2003	10

The experiments results and discussion

The productivity of examined energetic plantations was diversified, depending on species and location (Table 11). The highest yields were obtained for *Miscanthus giganteus* in Radzików, which was grown on podzolic soil belonging to class IV (23.7 t DM/ha).

The sample yields of Miscanthus *giganteus* from chosen European experiments are shown in Table 12 [Lewandowski and others 2000]. In the cited work the authors demonstrate that *Miscanthus giganteus* yields were very differentiated and were included in the range from 4 to 44 tons of dry matter (DM) from 1 ha during the year, depending of soil and weather conditions, fertilization level, plantation age etc.

Sida hermaphrodita yields from plot experiments after Borkowska and Styk [2003] are shown in Table 13. They fluctuated from 9 to 18 tons of dry matter from 1 ha per year on the soil of good wheat complex.

The dry matter yield of willow wood from an area unit might be much diversified. It contains from several to tens tons of dry matter of wood from 1 hectare per year. The productivity of willow from selected countries is shown in Table 14.

Table 11. Results of yielding estimation of energetic crops from productive plantations

Species	Location of plantation, soil class/year of planting	Biomass humidity [%]	Plant density [%]	Yield DM [t/ha]
Miscanthus giganteus	Radzików, soil IV cl./2006	43.2	70.3	23.7
	Drewnowo, soil III cl./2006	32.8	73.7	17.5
	Gronowo Górne, soil III cl./2006	41.2	63.3	15.2
Sida hermaphrodita	Czciradz, soil IV cl./2003	24.1	68.2	14.4
	Drewnowo, soil III cl./2007	20.5	100	17.7
	Gronowo Górne, soil III cl./2006	28.6	83.3	8.3
Salix (2-year-old shoots)	Marcelewo, soil IV cl., variety TORA/2004	58.5	96.7	14.9
	Marcelewo, soil IV cl., variety TORDIS/2004	57.7	96.7	12.3
	Marcelewo, soil V cl./2004	56.1	96.7	10.8
	Suponin*****, soil IV cl./2004-2007	56.8	100	16.1
	Przysiersk*****, soil IV cl./2005	57.0	100	8.5

** - set of harvester*

Table 12. Examples of yields from selected European experience

Country	Average temperature and precipitation	Age of plantation [years]	Period of harvest	Yield [t DM/ha/year]	Comments
Denmark	7,3ºC, 693 mm	4-6	April	7-15	70-100 kg N/ha
Germany	6,3-9,0 ºC, 680-760 mm	3-4	December	4-20	80 kg N/ha
UK	500-700 mm	3	Spring	10-15	
Switzerland	7,5ºC, 944-1066 mm	1-2	January	13-19	0-80 kg N/ha
Austria	8,8ºC, 700 mm	3		22	
Italy	450 mm	2-3	Late spring	30-32	120 kg N/ha, irrigation
Spain	12-15 ºC, 1900 mm	4		14-34	0-120 kg N/ha,

Table 13. Dry matter yield of stems of Sida hermaphrodita depending on the substrate (average of 3 years)

Type of substrate	Dry matter yield [t/ha]	Ash content [%]	Precipitation [%]
Mineral soil (good wheat complex)	13.8-17.8	3.4-4.1	42.8 (harvest X)
Sewage sludge	9.3-11.3	3.7-4.2	28.2 (harvest XII)

Table 14. Yield of willow by various authors

Country	Dry matter [t/ha/year]	Author	Comments
Sweden	12-18	Gigler & others [1999]	good soil, 3-year cycle
Germany	6-14	Hoffmann & Weih [2005]	good soil, 3-year cycle
USA	13-23	Kopp & others [1997]	fertilization and irrigation, 3-year cycle
Canada	23	Labrecque & Teodorescu [2003]	loam soil, fertilization, 3-year cycle
Canada	9		sandy soil, without fertilization, 3-year cycle

One of the most important factors having an impact on plants development on the observed plantations was climatic conditions – precipitation and temperature. The temperature in the years 2008 and 2009 during the growing period exceeded considerably the average temperature in the period from 1951 to 1980, whereas the total precipitations were below the average. The periods of moisture deficit, caused by high temperatures during spring months, were especially unfavourable for the plants development, particularly for willow (the data from the weather station in Botanical Garden of Plant Breeding & Acclimatization Institute in Bydgoszcz - Figures 9, 10). Mild winters might also have a negative impact on the plants development, according to what was observed on *Miscanthus giganteus* plantations near Elbląg during the winter period 2007/2008. After the warm December and January the plants vegetation began, whereas after a typical winter the vegetation should start at the end of April and the beginning of May. The destruction of most young shoots appeared as a result of temperature drop to -8 ^{0}C in the North Poland terrain at night of April 21/22. The plantations valorisation done at the end of May 2008 showed that the plants had new shoots from the parts hidden below the ground and the buds that were not damaged by the frost, but the amount of culms was lower.

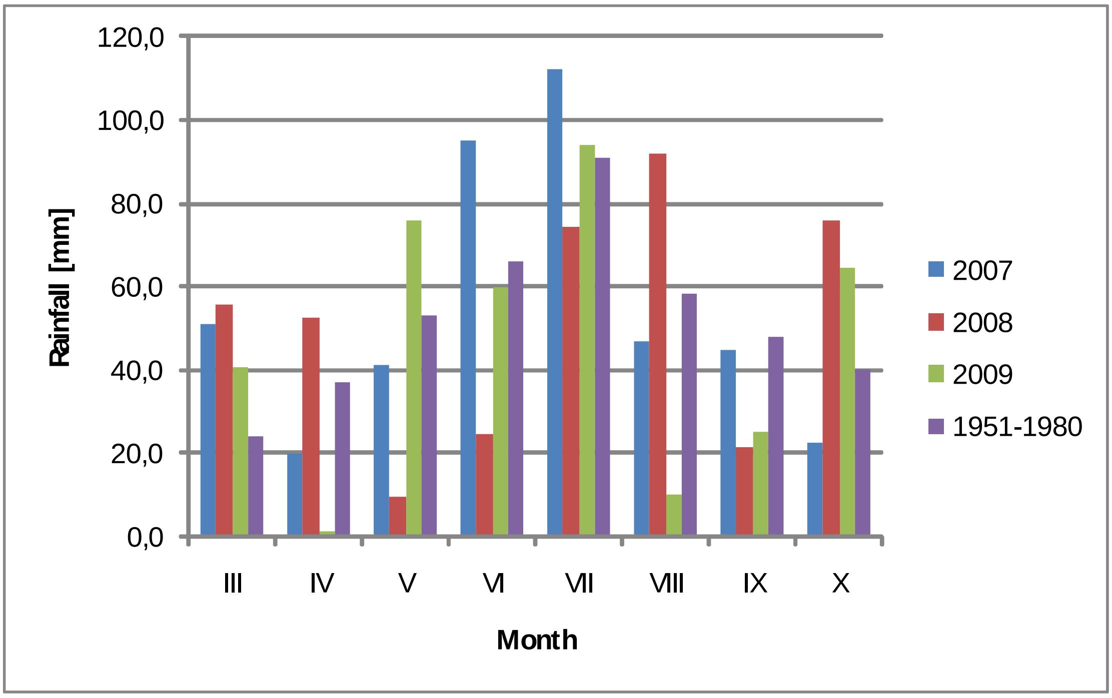


Figure 9. Weather data summary from 2007–2009 growing seasons – rainfall

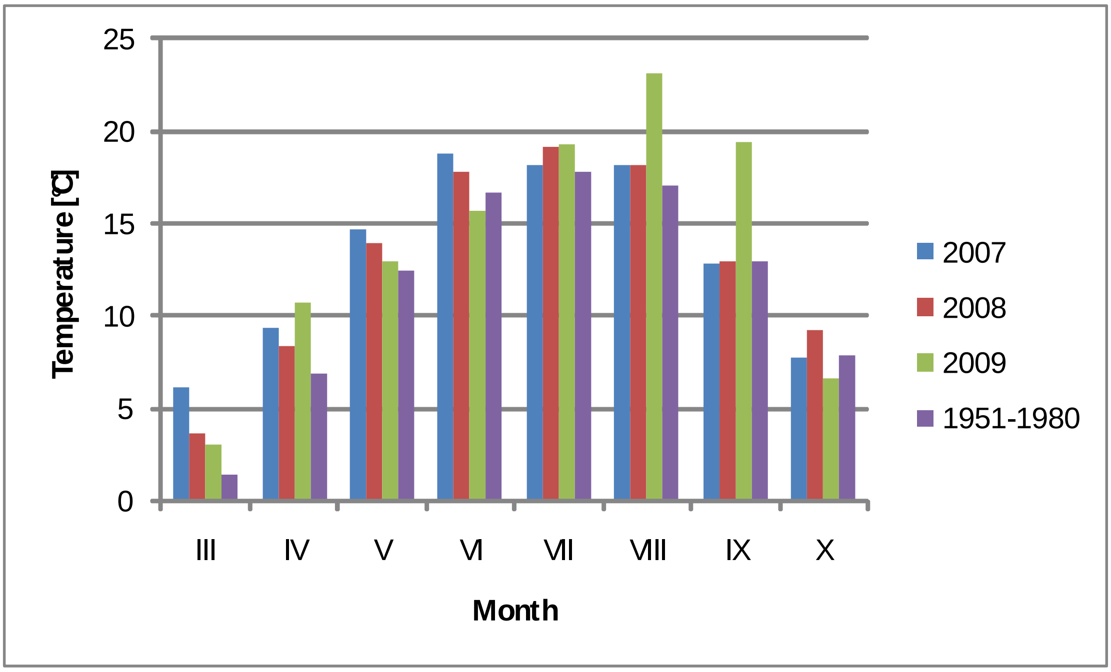


Figure 10. Weather data summary from 2007–2009 growing seasons – temperature

The weed infestation of a plantation is also very significant to obtain high yields. Weeds occurrence might increase the level of moisture deficit in soil caused by the periods of drought. The observations of weed infestation of *Miscanthus giganteus* plantations in Radzików showed the link with plants age (development degree). The differentiation of species causing weed infestation of particular fields with the crops planted in 2009 could have had the connection with forecrop (Table 15).

Table 15. Evaluation of weedy state of Miscanthus giganteus depending on the age of plantation and forecrop (Radzików, 10.09.2009)

No.	Year planting/field no.	Weed [%]	Dominant species	Forecrop
1	2006	1	*Artemisia vulgaris*	maize
2	2008	30	*Conyza canadensis* (20%), *Echinochloa crus-galli* (5%)	barley
3	2009 / I	90	*Agropyron repens* (60%), *Echinochloa crus-galli* (20%)	barley
4	2009 / IIA	90	*Solanum nigrum* (88%)	winter wheat
5	2009 / IIB	85	*Echinochloa crus-galli* (60%), *Solanum nigrum* (25%)	barley

The analyses of chemical composition of the soil samples that were collected from the areas of the examined plantations indicate nutrient exhaustion and low pH on all examined plantations (Table 16). Optimum pH for willow and Miscanthus *giganteus* is 5.5-7.0 [Stolarski 2004].

Table 16. Summary of results of the chemical of soil from the test plantation of energy crops (analysis 2009)

No.	Location	pH in KCl	Salinity	N-NO3	P	K	Na	Ca	Mg
			[g/dm³]	[mg/dm³ of soil]					
1	Radzików *Miscanthus* planted 2006	6.7	0.07	<10	18	53	17	287	53
2	Radzików *Miscanthus* planted 2008	7.9	0.05	<10	30	146	28	375	43
3	Marcelewo *Salix* soil IV cl.	7.4	0.03	<10	28	369	86	1604	98
4	Marcelewo *Salix* soil V cl.	6.5	0.04	<10	21	270	47	1086	64
5	Marcelewo *Salix* soil VI cl.	5.9	0.02	<10	50	137	21	960	35
6	Przysiersk *Salix* mineral soil	7.8	0.07	<10	24	357	32	1698	56
7	Przysiersk *Salix* peat soil	6.5	0.06	12	24	420	34	376	62
8	Gronowo G. *Sida*	5.9	0.31	100	54	75	40	140	70
9	Gronowo G. *Miscanthus*	5.3	0.11	26	50	100	45	86	62
10	Drewnowo *Sida*	6.2	0.14	20	88	180	40	252	45
11	Drewnowo *Miscanthus*	5.9	0.05	15	47	77	65	110	50
12	Suponin *Salix* planted 2004	4.8	0.11	<10	68	185	25	570	77
13	Suponin *Salix* planted 2005	4.5	0.13	<10	53	90	64	488	61
14	Suponin *Salix* planted 2006	3.6	0.05	<10	36	64	25	267	43
15	Suponin *Salix* planted 2007	2.7	0.24	16	36	37	25	187	17
16	Czciradz *Sida*	4.2	0.13	0,11	41	77	20	542	48

Photosynthesis is the most essential process that determines the creation of plants dry matter. The examined species differed in net photosynthesis intensity depending on light conditions. The highest photosynthesis intensity (about 15 µmol $CO_2/m^2/s$) in full lighting in the morning was observed for *Salix* hybrids. The value grew till the noon hours for *Salix* and Sida *hermaphrodita,* reaching 21 µmol $CO_2/m^2/s$ and 17 µmol $CO_2/m^2/s$, respectively. During the afternoon hours photosynthesis intensity of species that are mentioned above decreased, whereas it increased for *Miscanthus giganteus* till the level above 15 µmol $CO_2/m^2/s$. The highest photosynthesis intensity during the morning and afternoon hours was also observed for *Salix* hybrids in limited light conditions in shadow (inside the canopy) (Figure 11).

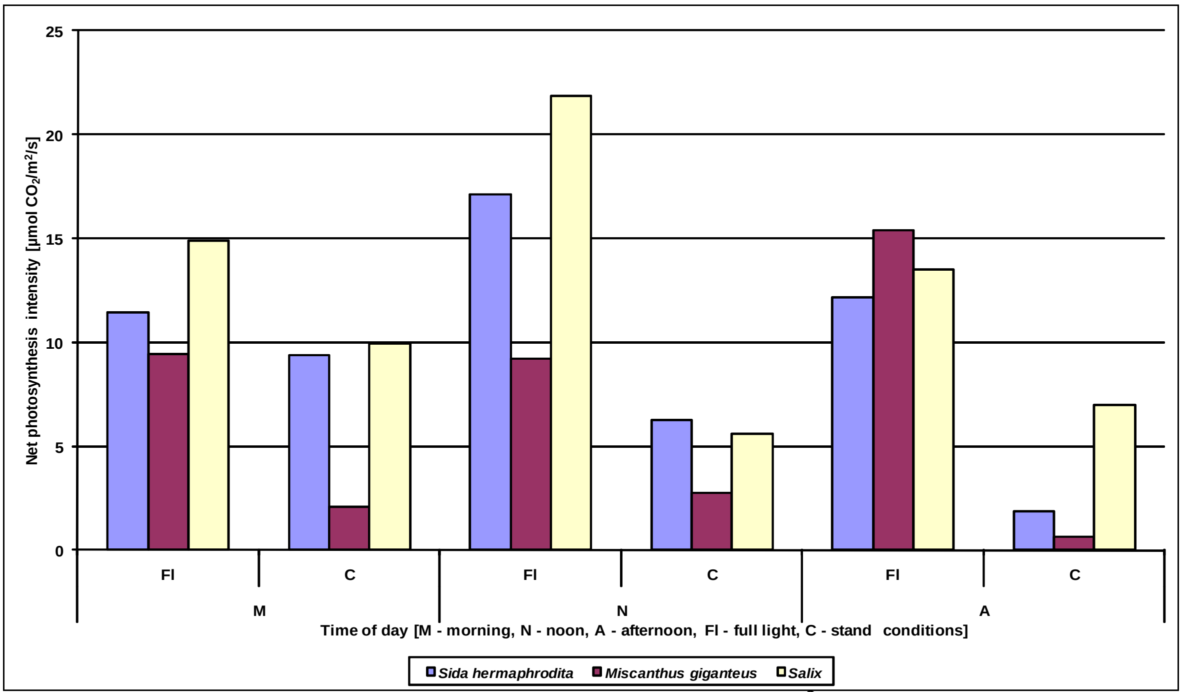


Figure 11. Process of net photosynthesis intensity [µmol $CO_2/m^2/s$] of the tested species in full light and in shadow (inside the canopy).

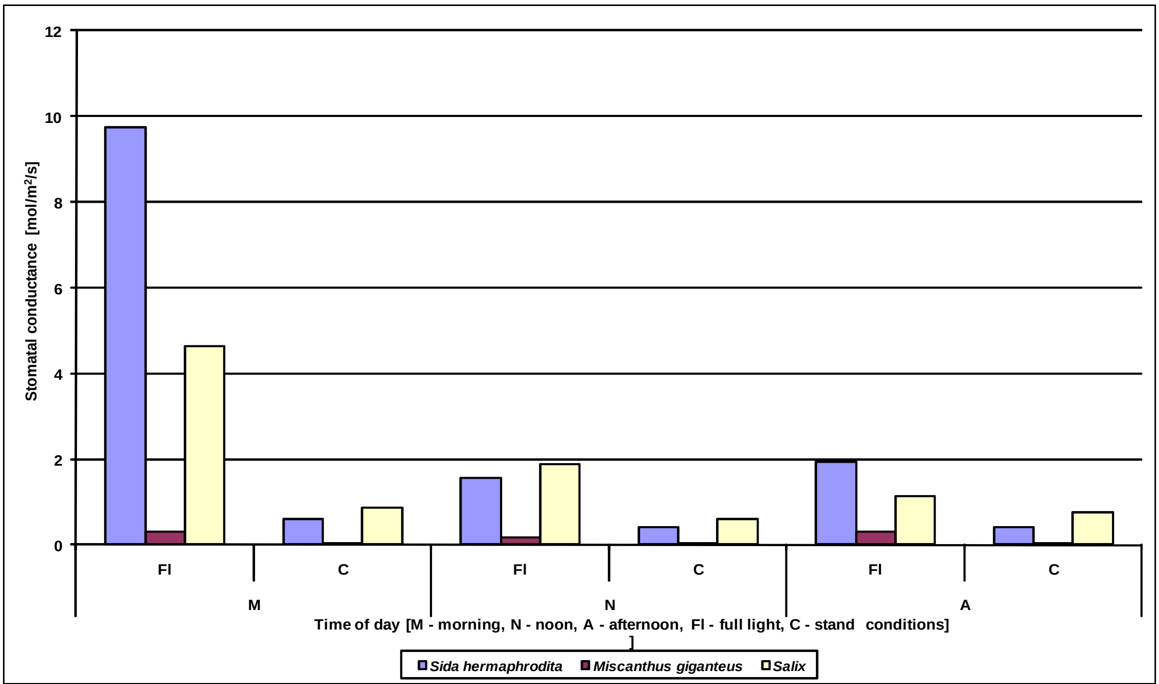


Figure 12. Stomatal conductance [$mol/m^2/s$] of the tested species in full light and in shadow (inside the canopy).

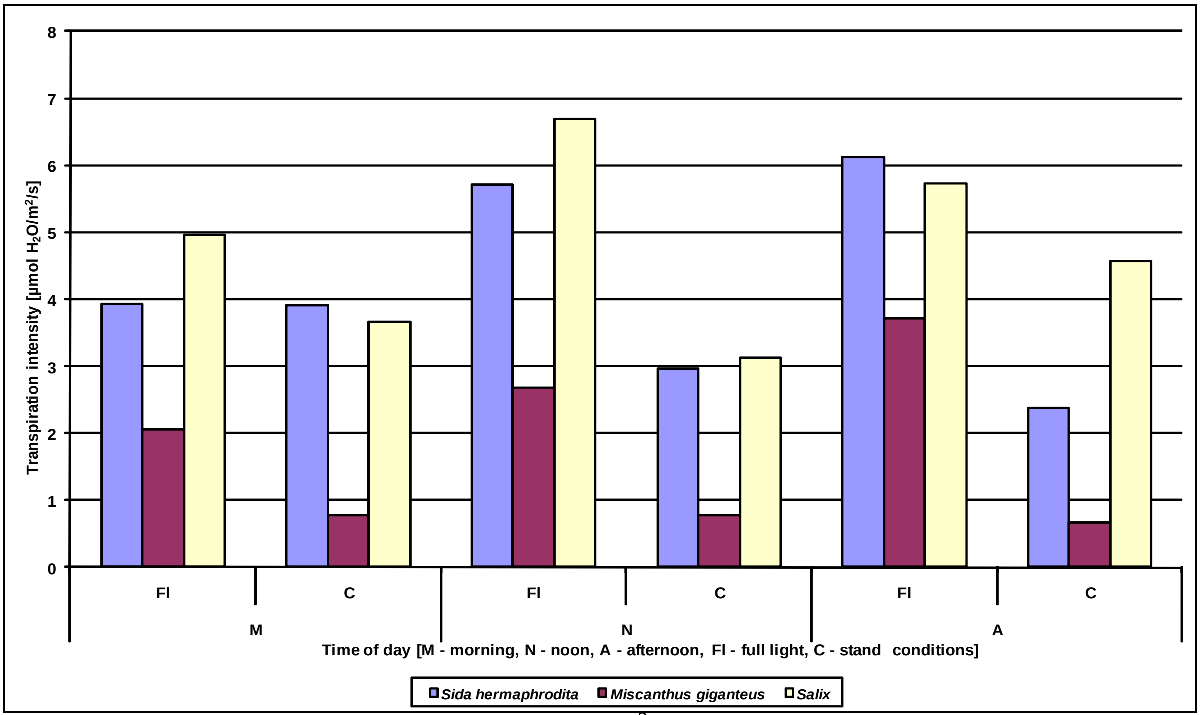


Figure 13. Transpiration intensity [µmol $H_2O/m^2/s$] of the tested species in full light and in shadow (inside the canopy).

The coefficients of water utilization in photosynthesis of *Salix* hybrids and *Sida hermaphrodita* were at the similar level. The highest water utilization coefficient (WUE) level and the lowest transpiration intensity of *Miscanthus giganteus* indicate effective water management in gas exchange process, what is connected with high biomass production (Figure 14).

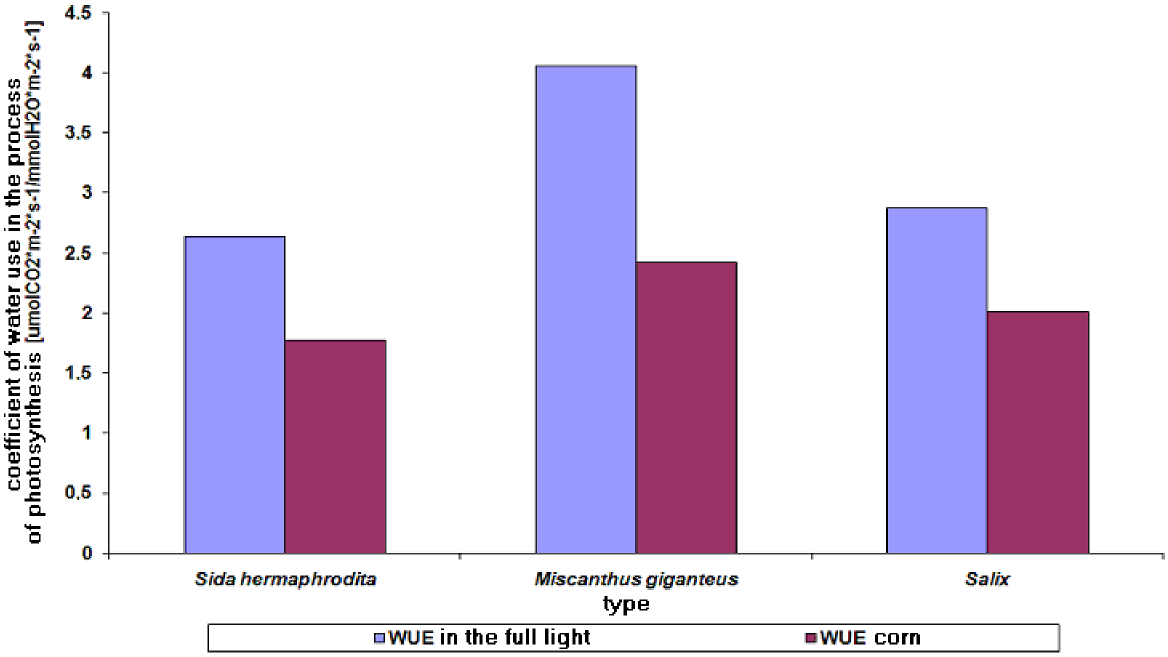


Figure 14. Water utilization coefficient [WUE = µmol $CO_2/m^2/s$: µmol $H_2O/m^2/s$] in shadow (inside the canopy) and in full light conditions.

Kalaji & Żebrowski [2004] and Starck [1995, 2002] demonstrated that photosynthesis intensity (temperatures to some degree) increases together with air temperature. The plants of C4 photosynthesis make better use of increasing photosynthetically active radiation (PAR) intensity in photosynthesis than the plants of C3 photosynthesis. Photosynthesis intensity of the species of C4 photosynthesis increases when the temperature is 22 ^{o}C, whereas a reverse phenomenon occurs for the species of C3 photosynthesis [Long 1983].

The examined plants species also differed in the rate of transpiration and stomatal conductance. *Salix* hybrids showed the highest transpiration intensity in full light conditions (~6.5 µmol $H_2O/m^2/s$), the lowest transpiration intensity was observed for *Miscanthus giganteus* (~4 µmol $H_2O/m^2/s$). The growth of photosynthesis intensity of these species was connected with the decrease of stomatal conductance. The rate of transpiration increased simultaneously, what suggested the low effectiveness of water management. *Salix* hybrids were characterized by the highest value of transpiration also in shadow (inside the canopy) whereas this process increased till the afternoon. The decrease of transpiration during a day was observed for *Miscanthus giganteus*, while a reverse process occurred in full light conditions (Figure 12, 13).

Conclusions

The height of biomass yield of grown energetic species is the resultant of many climatic- site and agrotechnical factors.
Biomass yields that were collected from the examined production plantations were lower than the experiment yields: from 38% to 67% lower (*Salix*), 15.7-60.5% (*Sida hermaphrodita*) and 23.3-50.8% (*Miscanthus giganteus*), depending on plantation location.
The examined species of energetic crops differed in net photosynthesis intensity. The species of C3 photosynthesis showed higher photosynthesis intensity when water management had low effectiveness.
The cultivation of species that have high level of water utilization (for instance Miscanthus *giganteus*) will allow using the terrain where moisture deficit occurs for biomass production.

2.4 Value of biomass energy, gas and chemical composition and ash content

Włodzimierz Majtkowski, Gabriela Majtkowska, Bartosz Tomaszewski

Summary

Biomass quality was estimated, considering especially chemical composition of plant material, the amount of obtained ash and humidity of biomass obtained from selected energy plant species: *Miscanthus giganteus*, *Sida hermaphrodita* and *Salix*. Biomass samples were collected after the end of plants vegetation in the period from November till April. The smallest content of water was observed in case of *Sida hermaphrodita* and *Miscanthus giganteus*, harvested in the middle of February 2009. They are as follow: 11.4% and 20.7% expressed in aerial dry matter (ADM). The humidity of collected fresh willow chips was about 46.4% ADM after 7 months of having been stored under an umbrella roof, on 2.5 metres high heap, the humidity fluctuated from 22.9 to 13.9% ADM and depended on the depth at which a sample was collected (value as follows: for 150 and 0 cm).

In research stove HDG EURO of 50 kW power, designed for burning of solid biomass, the quantity of produced "usable" energy (placed in buffers) and the amount of ash obtained after burning were examined. Research results proved the relation between thermal value and the humidity of energy material. Usable thermal energy of wooden pellets with 7.5% moisture content was 11.9 MJ/kg, for *Miscanthus giganteus* straw of humidity amounting 22.2% - 7.2 MJ/kg, and for willow chips with humidity amounting 50.1% - 1.6 MJ/kg. Ash quantity depended on plant species (for instance *Miscanthus giganteus* straw - 5.4%, wooden pellets - 0.5%). The measurement of combustion gas during the burning of biomass with humidity above 30%, with the use of TESTO 300 M analyser, showed the excess of limiting concentration for CO (> 5000 ppm) and NO (> 3750 ppm). As the result of protection of analyser against damage an automatic blackout of fumes pump occurred after the excess of limiting concentration.

Due to the fact that biomass of energetic crops differs from conventional energy sources in physico-chemical properties, the analysis of quality parameters connected with its burning is essential. The unfamiliarity with the specific biomass properties as well as improper apparatus and technological solutions connected with biomass applying in energetics might waste its beneficial ecological effect, stemming from wood biomass features. Biomass quality was assessed, considering especially the chemical composition of plant material, the amount of remaining ash and the humidity of biomass obtained from chosen species of energetic crops: *Salix, Miscanthus giganteus* and *Sida hermaphrodita*. The samples of biomass were collected after the end of the plants vegetation in the period from November to April. The lowest water content (up to 20% of aerial dry matter) was observed in *Sida hermaphrodita* and *Miscanthus giganteus* biomass, harvested in the middle of February 2009. The humidity of freshly collected willow chips was about 46.4% ADM After 7 months of having been stored under an umbrella roof, on 2.5 meters high heap, the humidity fluctuated from 22.9 to 13.9% ADM and depended on the depth at which a sample was collected (values for 150 and 0 cm respectively). The results of research done in HDG EURO 50 kW boiler proved calorific value relationship to the humidity of energetic raw material. "Usable" thermal energy of wood pellets that had humidity of 7.5% was 11.9 MJ/kg, for *Miscanthus giganteus* straw of humidity of 22.2% - 7.2 MJ/kg, and for willow chips with humidity of 50.1% - 1.6 MJ/kg. Ash quantity depended on plant species (for instance *Miscanthus giganteus* straw - 5.4%, wooden pellets - 0.5%).

Materials and methods

The aim of investigations was the assessment of biomass quality, considering especially the chemical composition of plant material, the amount of remaining ash and the humidity of biomass obtained from chosen species of energetic crops: *Salix, Miscanthus giganteus* and *Sida hermaphrodita*. The samples of biomass were collected after the end of the plants vegetation in the period from November to April. The plant material was dried at a temperature of approximately 60^{o}C in order to determine the content of air-dry matter. The impact of the length of the period of biomass conditioning on the decrease of humidity content was assessed. In HDG EURO 50 kW boiler, designed for solid biomass burning, the quantity of produced "usable" energy (placed in buffers) and the amount of ash remained after burning were examined. The efficiency of the combustion process on the basis of lambda coefficient and CO_2 content in combustion gases was investigated.

The analyses of the chemical composition of the plant material were done in the Chemical Laboratory of the Department of Root Crops Production Technology of Plant Breeding & Acclimatization Institute in Bydgoszcz. After milling and mineralization of the samples in sulphuric acid (in aluminium block) the following parameters were assessed:

- total nitrogen - Kjeldahl method (distilling apparatus Buechi B-324),
- total phosphorus - colorimetric method (Spekol 11 Carl Zeiss Jena),
- potassium, sodium, magnesium and calcium - method of atomic absorption (atomic absorption spectrophotometer PU 9100X Philips).

Results and discussion

The biomass humidity depending on the species and the harvest time.

The humidity of collected biomass depending on the species and the harvest time was examined. All of the examined species mature after the end of vegetation, what causes that biomass that is collected during this period is wet. The list of the results of biomass humidity assessment depending on the species and the harvest time is shown in Table 17.

The lowest water content was observed for the biomass of *Sida hermaphrodita* and *Miscanthus giganteus* collected in the middle of February 2009 (11.4% and 20.7% respectively, expressed in aerial dry matter). The humidity of freshly collected willow chips (the harvest was done during the leafless stage) was 46.4% ADM on average (Table 17). The high humidity of willow biomass causes serious difficulties with the storage of fresh chips. In wet piles as the result of happening microbiological processes the fast cellulose decomposition into CO_2 and water occurs, during which heat emission and the increase of temperature take place, causing the significant loss of calorific value. Janowicz and Hunder [2006] emphasize the occurrence of chimney effect in dump in which chips were in storage, leading to the differentiation of temperature, humidity and steam pressure between the external and internal layer (bottom). The decay of organic matter caused by the development of microorganisms, intensive especially in the dump interior, causes the increase of temperature and evaporation. The decrease of air temperature and the increase of vapour condensation and liquefaction of water in highest layer of the dump occur as convectional air and water vapour translocation to the top of the dump takes places. The consequence of these processes is the differentiation of biomass properties in different parts of this dump - partly dried material is inside, whereas the internal layer is the layer of the deposition of wet material. According to Danish data such a pile shouldn't be higher than 7-8 meters, because of the risk of sudden ignition [Serup et al. 2001].

Table 17. Biomass humidity depending on species and harvest time

Species		Harvest time	Humidity [% ADM]
Miscanthus giganteus		13.02.2008	45,8
		19.03.2008	34,0
		4.04.2008	22,2
		14.11.2008	39,1
		19.02.2009	20,7
		17.12.2009	28,9
		25.03.2010	26,0
Sida hermaphrodita		5.12.2007	21,6
		4.04.2008	20,1
		19.02.2009	11,4
Salix	annual shoots	2.03.2008	48,2
Salix	shoots 2-year		47,6
Salix	shoots 3-year		43,3

Source: own research.

There are good possibilities of adjustment of biomass harvest time to optimum (low) humidity on the plantations of *Sida hermaphrodita* and *Miscanthus giganteus*. Both species belong to C4 photosynthesis and compared with the species from native Polish flora, the type of C3 photosynthesis, they start the vegetation at the end of April and the beginning of May. Rescheduling of the harvest time of these species for the spring is a beneficial activity, in comparison with the winter period recommended in many previous publications [Huisman 1994, Roszewski 1996, Kościk and others 2004, Gumeniuk 2007]. Gostkowski [2006] reached a similar conclusion recommending the delay of *Miscanthus giganteus* harvest time till May. The observations of *Miscanthus giganteus* plantations near Elbląg (Gronowo Górne and Drewnowo) that were done in the period from 2007 to 2010 proved that the right conditions of biomass gathering occurred not until the spring. Mild winters during the years 2007/2008 and 2008/2009, without the periods of low temperatures, made it impossible to drive the machines and equipment on slimy ground. When the humidity of soil is high the wheels of the machines used for harvest might be the cause of the damage of underground rhizomes, leading to the decrease of yields even to 25% in the following year [Jonkonski 1994]. The winter 2009/2010 that was long with abundant snowfall also made biomass harvest impossible because of snow cover that was about 0.5 meter thick. However, the spring time of *Miscanthus giganteus* gathering is connected with the decrease of dry matter yield, what is emphasized by Roszewski [1996]. It is caused by leaf fall on the soil surface, under the influence of strong winds in the winter period. The decrease of yields resulting from leaf fall might reach even 30%. Fallen leaves are one of the causes of the limitation of weeds development and the increase of humus content in soil.

The humidity of willow shoots during the winter period remains at the same level and the delay of harvest time is not necessary. The decrease of water content of a few percents is observed for willow shoots collected in a three-year cycle.

Ecological aspects of biomass burning

In HDG EURO 50 boiler, the specialist boiler for wood, in which the studies were conducted, the process of biomass combustion was divided into 3 stages:

- drying (evaporation),
- gasification and burning,
- combustion complement of charcoal.

The humidity had the greatest impact on the course of burning process of different biomass types. It is proved that willow biomass that was freshly collected from the plantations is not fit to be burnt in the research boiler. The combustion of wood which humidity is higher than 30% might lead to the damage of a boiler caused by tarry substances pollution, formed during wet fuels burning. The measurements of combustion gas with the use of analyzer TESTO 300M showed exceeding of boundary value of CO concentration (> 5000 ppm) and NO concentration (> 3750 ppm). The automatic shutdown of fumes pomp occurred after the excess of limit in order to protect measurement cells CO and NO from damage. According to Zawistowski [2004], the humidity content in raw biomass that is above 45% has an impact on the decrease of the effectiveness of combustion process. The low calorific value per volume unit results in the necessity of the use of biomass amounts that have the volume several times bigger. Moreover, improper apparatus and technological solutions cause the great increase of harmful substances emission into the atmosphere, also carcinogenic, damaging the beneficial ecological effect stemming from wood biomass features. Wood biomass combustion in boilers that are not constructionally adapted to it, is the cause of excessive fume composition emission, because of the high content of humidity and volatile matter in this emission. Budny [2005] also pays attention to the ecological aspects of biomass combustion. He emphasizes that the emission of fume composition is dependent on biomass type and its physical properties.

Pisarek et al. [2000] as well as Niedziółka and Zuchniarz [2006] emphasize that the humidity of biomass of plant origin that is collected after the end of vegetation is included in the range from 15-60%. Calorific value of biomass that has the humidity 50-60% fluctuates from around 6-8 $MJ{\cdot}kg^{-1}$, partly dried to air-dry conditions, i.e. 10%-20% of humidity, increases to 14-16 $MJ{\cdot}kg^{-1}$ and around 19 $MJ{\cdot}kg^{-1}$ for completely dried biomass.

The results of the research performed in the Botanical Garden of Plant Breeding & Acclimatization Institute in Bydgoszcz proved the dependence of calorific value on the humidity of energetic raw material. Calorific value of pellets made from wood sawdust that had humidity 7.5% was 11.9 MJ/kg, 7.2 MJ/kg for *Miscanthus giganteus* of humidity 22.2%, 1.6 MJ/kg for willow chips of humidity 50.4% (Table 18). The storage of willow chips allowed the decrease of humidity to 28.2% (after 12 months) and 17.2% (after 18 months), what improved calorific value to 6.7 and 9.7 MJ/kg, respectively. Ash content depended on plant type (for instance *Miscanthus giganteus* straw – 5.4%, wood sawdust pellets – 0.5%).

Table 18. Calorific value of bio-fuels depending on the humidity (burning in the HDG EURO, 50 KW)

No.	**Fuel**	**Humidity [%]**	**Net calorific value* [MJ/kg]**	**Ash content [%]**
1	Beech wood chips	10.5	10.5	1.1
2	Fresh willow chips	50.4	1.6	2.6
3	Willow chips seasoned 12 months	28.2	6.7	3.0
4	Willow chips seasoned 18 months	17.2	9.7	7.0
5	Wood pellets from sawdust	7.5	11.9	0.5
6	Pellets from maize straw	8.2	11.9	5.3
7	*Miscanthus sacchariflorus* straw	34.3	5.1	10.3
8	*Miscanthus giganteus* straw	42.8	2.1	5.6
9	*Miscanthus giganteus* straw	22.2	7.2	5.4
10	*Miscanthus giganteus* straw	15.5	9.2	3.2
11	*Reynoutria japonica* straw	7.0	8.0	3.8

Source: own research

** - does not include chimney losses*

The results of the assess of biomass humidity as depending on the species, harvest time and the length of storage period (willow) are shown in Table 19. The analysis of the obtained results proved that the humidity of willow chips that were stored under the dump that was 2.5 meter high during the period of 7 months, fluctuated from 22.9% to 13.9% expressed in ADM and depended on the depth of water uptake (the values for 1.5 m and 0 cm, respectively).

Table 19. Results of moisture content of biomass

No.	**Species**	**Harvest time**	**Storage period**	**Moisture [% arid DM]**
1	*Miscanthus giganteus*	13.02.2008	-	39.3
2			5 days	36.3
3			14 days	32.3
4			8 months	9.0
5	Willow Salix	17.01.2008	-	57.4
6			17 weeks	23.8
7		4.02.2008	-	50.1
8			9 days	49.8
9			15 weeks	30.3
10			28 weeks 0* cm	13.9
11			28 weeks 50* cm	14.5
12			28 weeks 100* cm	25.1
13			28 weeks 150* cm	22.9
14			12 months	21.7
			18 months	10.7

Source: own research
**sampling depth of wood chips from the heap*

The humidity of energetic raw material has an impact on the efficiency of combustion process and the value of *Lambda* (excess air coefficient). λ coefficient defines the ratio of actual air quantity, in which fuel is burnt, to theoretical amount needed for complete fuel burning (stoichiometrical quantity). Too little air amount causes incomplete combustion of coal particles and the appearance of dangerous CO, and also the penetration of incompletely burnt hydrocarbons to fumes. Air excess causes the decrease of boiler temperature and the decrease of its efficiency leading to the appearance of harmful nitric oxides. The dependence between *Lambda* coefficient and the percentage content of oxygen and carbon dioxide in fumes during willow chips burning, that were in storage during the time of 12 months, is shown on the Figure 15 (the measurements were done every ten minutes).

Physico- chemical properties of biomass

Silvennoinen and Sadowski [2009] emphasize that the properties of biomass solid fuel among other things depend on: soil type, plant species, the part of used plant, the characteristic of yielding period (precipitation, temperature), fertilizing technology and harvest (pollution). Biofuels of agricultural origin might contain a lot of sulphur from used fertilizer or plant protective agents. The research of the chemical composition of plant material collected from energetic plantations proves the high diversity depending on the species and the localization of plantations (soil conditions) (Table 20).

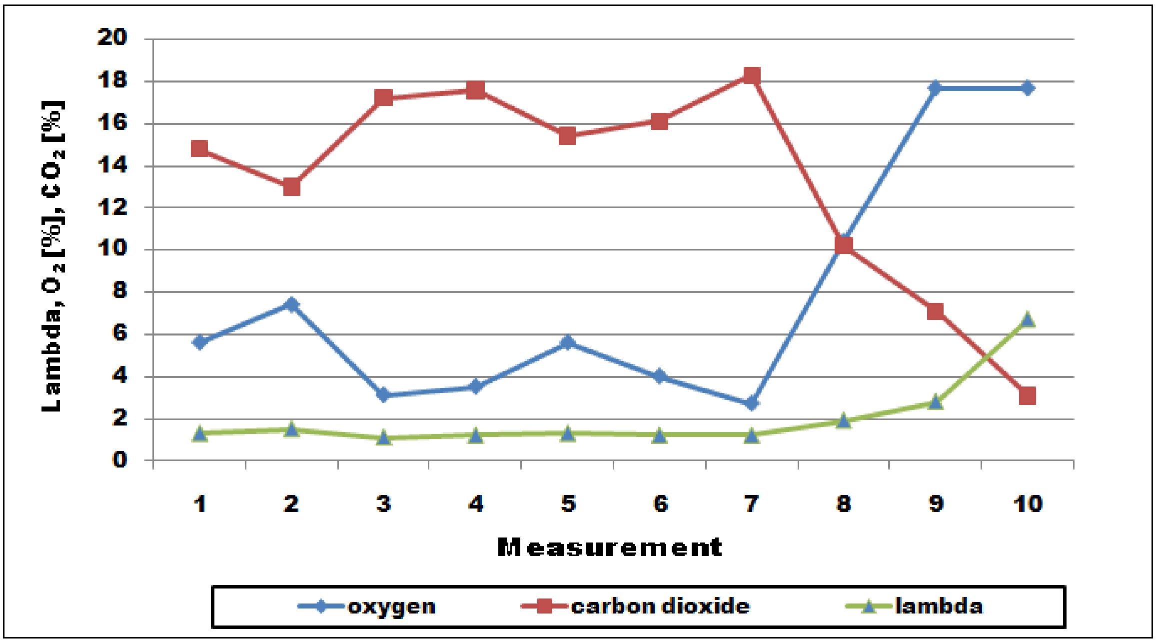


Figure 15. The relationship between Lambda factor and the percentage content of O_2 and CO_2 in the exhaust gas after combustion of willow chips, 12 months after harvest.

Table 20. Summary results of the chemical composition of biomass collected from selected plantations.

Species	**Location/year planting**	**Harvest time**	**N [%]**	**P [%]**	**Na [%]**	**K [%]**	**Ca [%]**	**Mg [%]**
Miscanthus giganteus	Radzików/2006	11.10.2007	0.54	0.026	0.059	0.896	0.923	0.09
	Gronowo G./2006	5.12.2007	0.99	0.058	0.030	1.361	0.206	0.102
	Gronowo G./2007		1.17	0.033	0.037	0.913	0.227	0.060
	Gronowo G./2007	18.02.2009	0.33	0.029	0.013	0.325	0.253	0.112
	Radzików/2006	17.12.2009	0.54	0.08	0.02	0.205	0.115	0.04
Sida hermaphrodita	Czciradz/2003	13.10.2007	0.47	0.028	0.048	0.876	0.554	0.096
	Gronowo G./2006	5.12.2007	0.43	0.007	0.044	0.315	0.660	0.054
		18.02.2009	0.19	0.012	0.023	0.223	0.247	0.107
Salix	Przysiersk/2005	25.01.2008	0.76	0.073	0.044	0.415	0.369	0.054
	Marcelewo/2004 - shoots annual	19.01.2009	0.78	0.119	0.014	0.228	0.436	0.123
	- shoots 2-year		0.64	0.095	0.010	0.211	0.390	0.114
	- shoots 3-year		0.57	0.098	0.011	0.203	0.372	0.110
	Marcelewo/2004 - shoots 2-year	25.02.2010	1.18	0.040	0.012	0.440	0.200	0.068
	Bydgoszcz/2004 - shoots annual		1.38	0.042	0.012	0.340	0.210	0.058
	- shoots 2-year		1.02	0.037	0.011	0.290	0.240	0.046
	- shoots 3-year		0.84	0.040	0.046	0.360	0.230	0.056

Source: own research

Gładki [2009] emphasize that energetic utilization of biomass is also made difficult by chlorine content and ash fusibility. The high content of alkaline compounds and chlorine (it might fluctuate from 0.02% to 1% in dry matter) might be the cause of boilers damage [Wisz and Matwiejew 2005]. Alkalies (sodium and potassium) have the greatest significance because of the tendency for reacting with chlorine, sulphur and silicon, depending on their content in fuel. The proportions of alkaline compounds (Fe_2O_3, CaO, MgO, Na_2O, K_2O, P_2O_5) to acid compounds (SiO_2, AlO_3, TiO_2) included in ash are especially important [Ściążko et al. 2006, Zamorowski 2006]. The more reactive alkalies included in fuel the higher the tendency to problems connected with ash and boiler operation (for instance agglomeration, deposits overgrowing, slag creation and corrosion).

Technological difficulties in using of plant raw materials for energetic purposes might also originate in the specific physico-chemical properties of biomass compared with fossil fuels, that are shown in Table 21 [Zawistowski 2007].

Table 21. Summary of relevant technological properties of coal and biomass

Parameters	Unit	Pit coal		Brown coal	Willow chips (3-year)	Straw (pressed)
		sort. nut	sort. culm			
Volatile fraction content in the dry state	%	31.2	30.9	46	80	70
Moisture content in working state	%	4	10	48	47	15
Bulk density in working state	kg/m^3	700	850	800	370	180
Calorific value in working state	GJ/Mg GJ/m^3	29.0 20.3	21.8 18.5	9.0 7.3	8.3 3.0	15.0 2.7

Source: Zawistowski [2007]

Conclusions

Humidity is the most important factor determining calorific value of biomass. It is the characteristic feature of species and connected with species time of agrotechnical maturity.
Biomass of different energetic crops species considerably differs in both ash content and its elemental composition. The content of alkaline oxides responsible for the decrease of temperature of ash fusibility is especially significant. This diversity must be taken into consideration while planning biomass utilization in combustion process or as the addition to fossil fuels.

3

Water management in growing crops for energy

3.1 The usefulness of spatial evaluation of arable lands for cultivation of energetic crops

Janusz Ostrowski, Agnieszka Gutkowska, Edmund Tusiński

Summary

This chapter presents methodical assumptions adopted in modelling the categorization and evaluation of land usefulness for cultivation of nine energetic plants and their cartographic presentation using computer technique. This proceeding is based on resources of a spatial data base for Polish marginal soils, elaborated and functioning in The Institute of Technology and Natural Sciences in Falenty (formerly IMUZ). Owing to this base is possible, not only cartographical visualization of location in region scale of soils, with various water conditions, useful for energetic plants cultivation, but also balancing their occurrence areas.

Abstract

The following assumptions and procedures were adopted to accomplish the task of spatial evaluation:

- evaluation and spatial delimitation of arable lands will be made with the computer technique using spatial information contained in the database on marginal soils [Ostrowski, 1999],

- general identification criteria take into account the habitat values of arable lands which may be allotted for energetic plant crops without detriment to food crops,

- built diagnostic models based on available parameters allow for constructing algorithms of spatial data processing,

- special software of these algorithms and qualification of arable lands realizes processing procedure that serves automatic generation of maps of the usefulness of these lands for growing energetic plants and calculating areas in valorisation groups.

Guided by resource criteria that determine the division of arable lands according to their crop values and by crop criteria that ensure the agreement of habitat conditions with the requirements of energetic plants (at allowable minimization of fulfilment of these requirements), we made general analysis of agricultural usefulness of soils for growing energetic plants. It was demonstrated that large part of grounds singled out after these criteria show crop limitations which, however, fall within the range of tolerance by energetic plants or are possible to correct with agro-technical measures (e.g. fertilization, plant selection, location of crop fields, irrigation).

Taking into account these limitations, arable lands were grouped into five categories of usefulness [Ostrowski 2008]:

1 (P) – arable lands preferred for growing energetic plants and fulfilling their habitat requirements,

2 (PW) – arable lands useful for growing energetic plants but limited by water factor resulting in the need of growing plants that tolerate water deficits or of using irrigation,

3 (PZ) – grounds preferred for growing energetic plants – restored or heavily polluted,

4 (PO) – arable lands useful for growing energetic plants with the preference for ecological and protective functions and a possibility of growing plants that are not spatially expansive,

5 (PR) – arable lands useful for growing energetic plants with the preference for agricultural use.

As seen from above definitions, grounds divided into different categories have different habitat conditions which differentiate their usefulness for growing particular energetic plants. This was reflected in the selection of criteria used in evaluation of the usefulness of these ground to cultivate energetic plants.

Two separate diagnostic models were constructed to categorise the grounds and to evaluate their usefulness for energetic plant crops. Both served for computer delimitation the grounds according to criteria adopted in these models.

Diagnostic structure of the first – the categorisation model – [Ostrowski, 2008] is composed of the relations of diagnostic systems parameterizing the following criteria:

soil productive potential,

hydro-climatic conditions,

agricultural usefulness of soils and grounds,

land use.

The second diagnostic model [Ostrowski, Gutkowska 2008] that serves for evaluating the usefulness of grounds for cultivation of nine energetic plants was constructed in a form of relational table and considered the following diagnostic criteria:

- soil - with the division into arable lands and grounds degraded or chemically polluted,

- water – understood as a need for or tolerance to a limited soil moisture during vegetative season,

- climatic – pertaining to the response of particular plants to rainfalls and thermal conditions,

- location – as an outcome of spatial expansion of energetic plants in view of a possibility of their growing in protected areas.

Based on comparative analysis of criteria of the presented diagnostic models and on water requirements of plants the relationships were estimated between these requirements and parameters characterising habitat conditions of soils with respect to water conditions.

Combining water requirements of energetic plants and their response to moisture conditions and fulfilment of these demands during vegetation period, the grounds useful for plant cultivation may be classified into three following groups:

I – grounds useful for growing plants that prefer good soil moisture and are sensitive to precipitation deficits: the common osier *Salix viminalis* L., the giant knotweed *Reynoutria sachalinensis* (F. Schmidt) Nakai, the reed canary grass *Phalaris arundinacea* L.;

II – grounds useful for growing plants that tolerate variable soil moisture and are less sensitive to precipitation deficits: the prairie cord grass *Spartina pectinata* Boscex Linl, the giant silver grass *Miscanthus sinensis gigantea* J.M.Greef & M.Deuter;

III – grounds useful for growing plants that tolerate limited soil moisture and are resistant to precipitation deficits: the Virginia mallow *Sida hermaphrodita* L. Rusby, the Jerusalem artichoke

Helianthus tuberosus L., the big bluestem *Andropogon gerardi* Vitman and the Amur silver grass *Miscanthus sacchariflorus* (Maxim.) Hackel.

Based on presented models and constructed algorithms the procedure was programmed for processing respective spatial data contained in the database on marginal soils. The data coded in a system of spatial reference fields [Podlacha, 1983] enable generation of the following raster maps in the scale 1:250 000 [Ostrowski, Gutkowska, Tusiński, 2008, 2009]:

map of arable lands categorisation,

maps of the soil usefulness for growing energetic plants (separately for each plant),

map of the evaluation of water conditions,

and appropriate tables with surface data.

Figure 16 shows an example of categorisation map and Figure 17 gives a legend to this map.

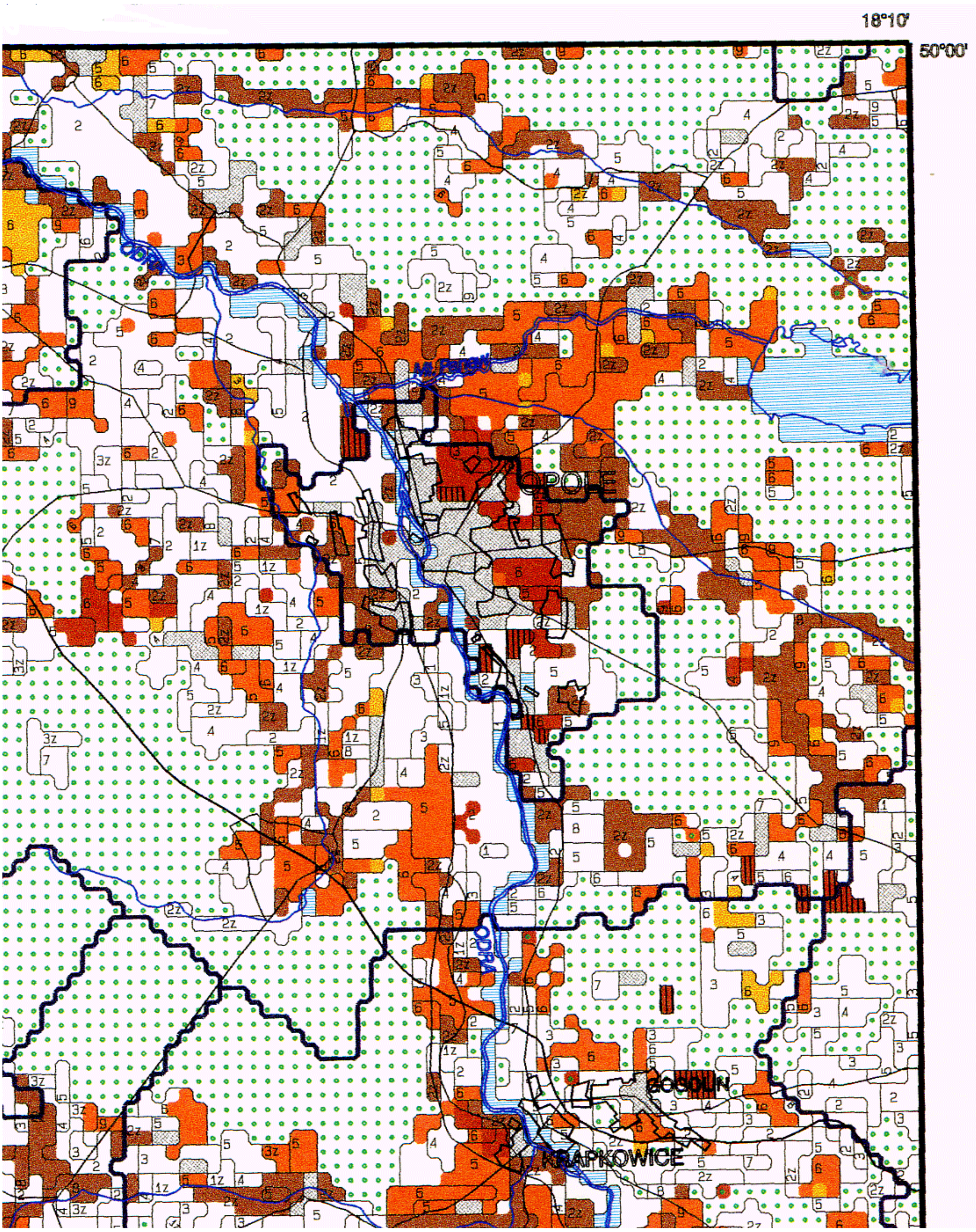


Figure 16. A map of categorisation of soils useful for growing energetic plants
(Opolskie voivodeship – fragment, scale 1:250 000 – slightly enlarged)

Source: own elaboration

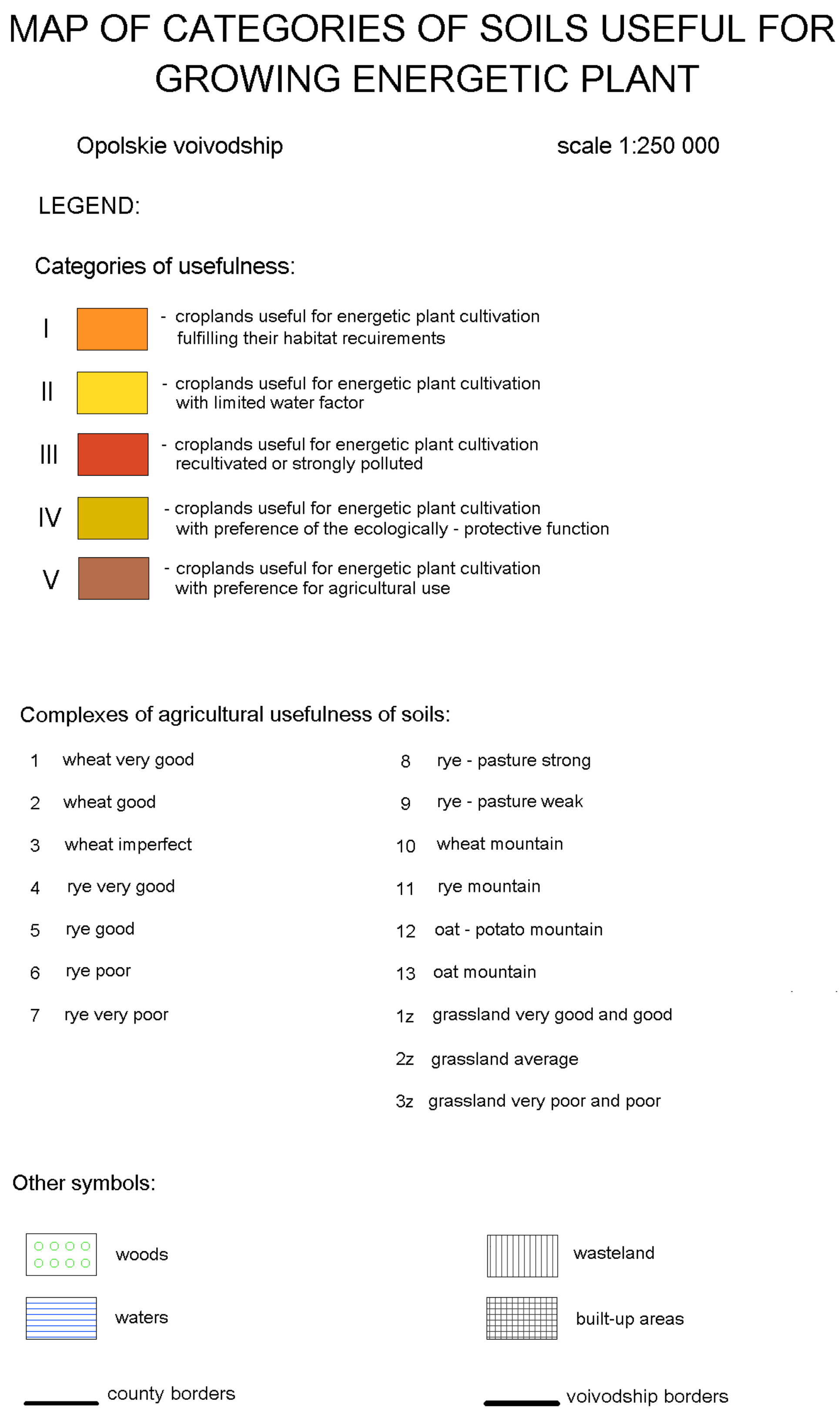


Figure 17. Legend to the map of categorisation of soils useful for growing energetic plants
Source own elaboration

3.2 Water use efficiency of energy crops

Agnieszka Trojanowska

Summary

The advantage of perennial energy crops is high yield of biomass. However, significant water demand and logistic problems related to harvest technique or storage of biomass with high water content are in contradiction.

On the other hand, comparing water use efficiency can be stated that perennial crops more effectively use water resources. Amount of water required to ensure growth of energy crops is significant. However, biomass yields are much higher than the ones of traditional annual cultivations. Nevertheless, demand for water of energy crops have to be taken into consideration while establishing plantation, particularly in a large scale. Perennial crops require more suitable water conditions than traditional agricultural crops, therefore they can negatively influence on the environment and water supplies [Kowalik and Scalenghe, 2009].

Abstract

Cultivation of energy crops in a large scale requires evaluation of availability of land and selection of appropriate locations for plantations. It is essential to take into account fertilization requirements of energy crops to optimize yields of biomass, as well as, soil and ground water contamination. Moreover, estimation of water demand for such crops is of high priority because of the limited water supply in Europe; in Poland as well.

In the paper, based on a literature analysis, selected energy crops have been described due to their water demand and water use efficiency. Water use efficiency (WUE) indicates on biomass growth per unit of water used. WUE is generally higher for crops with C_4 photosynthesis pathway [Berndes, 2002].

Willow

Undoubtedly, willow is a water-demanding crop. Willow is often located close to water supplies; the crop grows well in wet areas. Simultaneously, lack of appropriate amount of water limits biomass growth [Martin and Stephens, 2008].

Transpiration of willow is high. This results in a higher water demand during vegetation season [Linderson et al, 2007]. Transpiration index of willow is higher than of other crops [Hall et al., 1998]. Increased water requirement has not to be a negative characteristic of the crop. Willow is interesting species in term of possibilities to utilize huge amounts of wastewaters [Pistocchi et al, 2009]. Waste water contains significant amount of nitrogen and phosphorus that can positively affect biomass growth without necessity to use additional fertilization. The crop collects elements from waste what improves quality of applied waste water before leaching to the ground waters [Pistocchi et al, 2009]. Simultaneously, waste water is an additional resource of water for crops, beside the precipitation. However, to optimize waste water use on willow plantation taking into account environment protection (minimize nutrient leaching to ground water) it is essential to evaluate precisely water demand for such crop [Pistocchi et al, 2009].

According to research carried out by Pistocci et al. [2009], total evapotranspiration of willow *Salix alba* equals from 607mm (low fertilization rate) to 919mm (high fertilization rate) during a vegetation season. Observation was made in the first year of a second rotation. Willow grows in 2 year harvest cycles, with harvesting after first growing season. The same species of willow was analyzed also during two following years of a first cycle of cultivation. Results achieved by

Guidi et al. [2008] are as follows: evapotranspiration in a vegetation season with no fertilization equalled from 620-890 mm to 1190-1790 mm on a fertilized plot. That indicates on fertilization influence on a demand for water. Maximal evapotranspiration was observed during summer what is most likely a result of high force of atmospheric evaporation in that time, as well as, higher leaf area index and crop size. In autumn, evapotranspiration decreases due to not sufficient amount of light and lower temperature.

Martin and Stephens [2006, 2008] indicate on changes in evapotranspiration of willow depending on crop's age. Changes on sandy loam were determined at level of 359, 868 and 1192l in following growing seasons. The first value was estimated for the year of plantation establishment. The intensification of evapotranspiration in summer months was observed (half of June – September). That consists of 67-78% in relation to the whole vegetation season. In the half of July, depending on soil condition evapotranspiration equalled 1.4-13.6 l per day.

Quite low transpiration of willow present Linderson et al. [2007]. Authors determined transpiration of willow at level of 100-325mm. Persson [1997] estimated transpiration of willow on a similar level, 255-375mm in a growing season (April – October). Evaporation on a willow plantation equalled 2,3mm per day. In other paper however, Persson [1995] assessed that willow's demand for water is higher, approximately 480mm.

Daily water usage of willow was estimated by many researchers, also by Guidi et al. [2005]. Average evapotranspiration of willow was evaluated as 3.2-7.6 mm per day. That was confirmed by Elowson [1999]. Author estimated daily usage of water at level of 5mm. Slightly higher values of evapotranspiration present Persson and Lindorth [1994]. The daily water demand equals 8-9mm.

Białowiec et al. [2007] carried out research in relation to evapotranspiration of willow *Salix amygdalina*. Evapotranspiration was oscillating between 150 and 545 mm (sandy soil fertilized with sewage sludge) and between 183 and 411mm (sandy soil). Correlation between biomass growth and transpiration rate was estimated. It was assessed that 1 kg d.m/m^2 biomass growth causes transpiration increase by 310 mm in the first year and by 388 mm during the second year of cultivation. Authors quote results of Agopsowicz [1994] who estimated evapotranspiration of 3-month-old willow at level of 960-1080 mm.

Irrigated and fertilized willow growing on a loamy soil has evapotranspiration in range of 360 and 404 mm [Dimitriou et al, 2009 after Person and Lindorth, 1994]. However, Hall [2003a, b] estimated evapotranspiration at level of 600 mm.

Different locations and conditions, under which willow is cultivated, cause divergence of particular research results. Above information were gathered in Table 22.

Estimated evapotranspiration of willow is high comparing to annual crops [Hall, 1998]. However, it is significantly connected with local climate-soil conditions and with i.e. age of plants or cultivated species [Dimitriou, 2009]. Evapotranspiration rates differ between locations and over time [Persson, 1995]. Willow as a new crop requires further research and observations related to demand for water in small and big scale cultivations.

Authoritative information about water requirements of willow assures value of water use efficiency factor. According to Weih and Nordh [2002] water use efficiency (WUE) depends on level of CO_2 assimilation per unit of water. Ability to keep water during drought also determines WUE value. Martin and Stephens [2006] estimated WUE rate for willow. Value of this factor was estimated on a basis of several-year research. WUE equalled 1.36-5.05 g kg^{-1}. The biggest differences were observed between particular years and due to soil condition. Linderson et al. (2007) estimated WUE at level of app. 5.3 g kg^{-1}. Lindroth and Ciencala [1996] estimated the factor for whole crop, with underground parts. Authors evaluated WUE at level of 6.3 g kg^{-1}.

Table 22. Water demand (evapotranspiration) of willow according to different researchers

	Author	During vegetation season	Per day
1	Pistocchi et al.	607 mm- no fertilization 919 mm	
2	Guidi et al.	620-890 mm- no fertilization 1190-1790 mm	
3	Guidi et al.		3.2-7.6 mm
4	Martin and Stephens	359 l, 868 l, 1192 l in following years	1.4-13.6 l
5	Person	255-375 mm transpiration	
6	Persson and Lindorth		8-9 mm
7	Elowson		5 mm
8	Białowiec et al.	150-545 mm sandy soil fertilized with sewage sludge 183-411 mm sandy soil	
9	Agopsowicz	960-1080 mm	
10	Hall	600 mm	
11	Linderson et al.	100-325 mm	

Source: Own elaboration

Miscanthus

Miscanthus, like willow, is a perennial crop. The crop has C_4 photosynthesis pathway what enables to produce significant yields of biomass in vegetation season. Biomass yields depend on location of the plantation, fertilization level and harvesting time.

In Germany, yields of biomass, due to location and year equal from 6.2 to 19.8 t DM ha^{-1} [Kahle et al., 2001]. In Italy observed yields of biomass were much higher – in average 28.7 t DM ha^{-1} [Angelini et al. 2009].

Demand for water of Miscanthus was estimated by Cosentino et al. [2007]. Crops were cultivated in non-stress conditions. Evaporated water was supplied. Crops were cultivated in three different systems (with supply of evaporated water in 25%, 50% and 100%). In the most favourable water conditions, during the second rotation of cultivation, demand for water was 391.7; 557.6 and 932.9 mm. During the next vegetation season water demand was lower and equalled 347.9; 368.3 and 491 mm, in the described cultivation systems. Increasing of the water supply resulted in decreasing effectiveness of water use by crops. WUE factor during 2 observed years, oscillated between 2.56-4.83 and 3.49-4.51g kg^{-1}, respectively. The low rate of WUE, connected with high water availability, the authors explain with higher water use than necessary for crops to grow.

Water use efficiency was also estimated by Clifton-Brown and Lewandowski [2000]. WUE for whole crop was assessed at level of 11.5-14.2 g DM kg^{-1}. The factor rate did not differ significantly between particular experiences (plots) with different irrigation. According to biomass yields (the upper parts of crop) WUE equalled 2.2-4.1 g kg^{-1} with relation to the species.

Beale et al. [1999] showed relation between water supply and effectiveness of its use. WUE factor calculated for crops growing only with precipitation water supply equalled 9.2 - 9.5 g kg^{-1}. However, crops additionally irrigated were characterized by WUE 7.8-9.1 g kg^{-1}. Authors estimated also the crop index K_c for Miscanthus. The index was 0.85 for crops not irrigated, in April-August. Irrigated crops had the crop index at level of 1.29.

In Table 23 data on effectiveness in water use are presented. Data are gathered for willow and Miscanthus.

Table 23. Water Use Efficiency factor – Willow and Miscanthus

	Author	WUE
	Willow	
1	Martin and Stephens	1.36-5.05 g kg^{-1}
2	Linderson et al.	5.3 g kg^{-1}
3	Lindroth and Ciencala	6.3 g kg^{-1} (whole crop)
	Miscanthus	
4	Cosentino et al.	2.56-4.83 and 3.49-4.51g kg^{-1}
5	Clifton-Brown and Lewandowski	2.2-4.1 g kg^{-1} 11.5-14.2 g DM kg^{-1} (whole crop)
6	Beale et al.	9.2-9.5 g kg^{-1}

Source: Own elaboration

On a basis of above data can be stated that efficiency of water use of Miscanthus is higher than willows'. However, the water requirements during vegetation season for both crops are similar.

Traditional crops (wheat)

Demand for water of energy crops is high and during vegetation season equals in average 600-1000 mm. The comparison of water demand of annual and perennial crops was done. Water use of wheat was analyzed. On a basis of research carried out by Qiu et al. [2008] it was estimated that wheat requires 257-467 mm of water in vegetation season. Research was carried out in 2002-2003; level of irrigation of plots was different. Water use efficiency factor was 1.15-2.13 g grain kg^{-1} water. Observations were done also in following growing seasons. WUE factor was lower and equalled 1.29-1.52 g grain kg^{-1} water. Evapotranspiration of wheat was observed over several years. It was estimated that wheat uses app. 308 mm of water during year [Pala et al., 2007]. Authors assessed a WUE factor at level of 2.7 g grain ha^{-1} mm^{-1} (0.27 g kg^{-1}). Wheat is a traditional agricultural crop. Its basic product is grain, therefore most analysis compare water use efficiency with grain yield. However, for energy production purposes the by-product (straw) can be used. According to Corbeels et al. [1998] water use efficiency factor for wheat straw equals app. 2.8-3.1 kg DM ha^{-1} mm^{-1} (0.28-0.31 g kg^{-1}).

3.2 Water consumption and utilisation by the common osier and giant silver grass measured in lysimetric and field studies

Sergiusz Jurczuk, Mariusz Rydałowski, Anna Łempicka

Summary

Studies on water consumption by the common osier *Salix viminalis* L. performed in the lysimetric station in Falenty on black degraded earth showed that appropriate water conditions markedly affected plant yield but resulted in a large water consumption. Comparison of the crops grown under productive conditions without irrigation showed that water consumption by the giant silver grass was 400 mm per the vegetation season while that by the common osier was by 85 mm larger. The efficiency of water use by the grass was much better than by the osier and dry matter yield was two times bigger. Plant coefficient k_c at assumedly high osier yields of 20 t ha^{-1} was also high and ranged between 0.97 and 1.33. At yields of c. 10 t ha^{-1} the coefficient was 0.78. In the giant silver grass yielding 20 t ha^{-1} the coefficient amounted only 0.66.

Introduction

The cultivation of plants for energetic purposes may improve economic situation of Polish farmers, create new jobs and facilitate regional development. The development of fast growing crops of energetic plants may, however, cause unpredictable environmental consequences.

The problem of water management of fast growing crops is important when considering issues associated with the cultivation of plants for energetic purposes and conditions required for their proper growth. Water in the natural environment is a means of biomass production and a factor affecting ecological equilibrium. It is thus very important to estimate water consumption and its effectiveness in Poland. Climatic changes already present in Poland manifest themselves by extreme meteorological phenomena like alternating long term droughts and excessive rainfalls and may interfere in the quality and amount of biomass production in many regions of the country. It is also important to estimate the effect of fields on soil water resources. Fields of perennial energetic plants set up now may have soil and water requirements markedly different from those established before. This may unfavourably affect water relations near fields and disturb environmental water equilibrium.

The number of publications devoted to the crops of energetic plants is increasing in the world literature due to increasing demand for biomass for energy production. Literature on water demands is, however, insufficient. One may find only general information on water and habitat requirements of energetic plants in Polish literature.

It is assumed that the long term crops of energetic plants have higher demands for water than traditional crops since the former produce, as a rule, larger biomass. It is estimated that water demands of the common osier are higher by 150 – 200 mm as compared with traditional crops [Hall 2003, Faber 2008]. There is a need of more accurate estimation of water consumption by osier and of searching for energetic plants of smaller demands for water but of comparable yields. Water needs of other perennial energetic plants are known still less than those of osier.

The aim of undertaken studies was to estimate the consumption and utilisation of water and to assess the effect of energetic plants on water resources. Lysimetric studies on the crop of the common osier (*Salix viminalis* L.) and field studies on the common osier (*Salix viminalis* L.) and the giant silver grass (*Miscanthus sinensis giganteus*) were performed. The study involved:

- estimation of optimum ground water levels in soils intended for fields of fast growing plants,
- estimation of water consumption and utilisation by energetic plants and (based on these estimates) an evaluation of the need of their irrigation,

- an assessment of the effect of biomass production on the amount and temporal variability of water resources.

Methods

To solve the problem of water management the study was performed under experimental conditions in lysimeters and under productive conditions. The lysimetric experiment was carried out in the study plot in Falenty [Jurczuk, Rydałowski 2009]. Soil in lysimetric station was black degraded earth of the class IVb built of weakly loamy sand to a depth of 60 cm overlying a thick layer of loose sand. Ground water table was situated at a depth of 100 – 150 cm beneath the ground surface. Nine lysimeters with three variants of ground water table depth (0.3, 1.0 and 1.7 m) in three repetitions were set up in a field cropped with the common osier (*Salix viminalis* L.) var. Turbo. Piesometers were installed in lysimeters to control ground water level and sensors to measure soil moisture. Ground water table depths were kept constant and measurements involved: soil moisture, plant height and annual yield biomass. Meteorological data were taken from the station situated near lysimeters.

Water budget of energetic plant crops was calculated for ten-day periods according to equation:

$$ETr = W_p + \Delta_r + P - W_k$$

where:
ETr – actual evapotranspiration, mm,
W_p – soil water reserve at the beginning of the period, mm,
W_k – soil water reserve at the end of the period, mm,
P – atmospheric precipitation, mm,
Δ_r – difference between poured and poured out water layer to maintain constant water table, mm.

Evapotranspiration in lysimeters was compared with the index of evapotranspiration calculated for a standard plant (frequently mown grass) with the method of Penman-Monteith [Allen et al. 1998] based on meteorological data to calculate plant coefficient k_c that served for estimating water demands and deficits. From water consumption and yielding an index of water use efficiency (WUE) i.e. the ratio of dry matter yield to the amount of used water was calculated.

Field studies were carried out in three fields of the common osier and of giant silver grass. In several points of each field soil moisture and ground water table were monitored and biomass yield was measured every year.

The following fields were studied in Masovian Province:

A – field of the common osier in Plecewice (Brochów commune) of an area of 1.5 ha situated on mineral brown soil class IVb built of sand and loamy sand to a depth of 1.0 m and of dusty silt and silt deeper. The common osier var. 1054 was planted in spring 2006 at a spanning of 70x38 cm.

B – field of the common osier around lysimetric station of the Institute of Life Sciences and Technology in Falenty (Raszyn commune) situated on black degraded earth class IVb. The common osier var. Turbo was planted in spring 2008 at a spanning of 50x50 cm.

C – field of the giant silver grass of the Institute of Plant Breeding and Acclimatization in Radzików (Błonie commune) of an area of 6.0 ha situated on podzolic soil class IV b built of loamy sand, light loam and sandy dust to a depth of 1.3 m and of loam deeper. The giant silver grass was planted in spring 2006 at a spanning of 100x100 cm.

Piesometers to measure ground water level, 1.0 m long thin-walled pipes to measure soil moisture with Delta-T Profile Probe and automatic pluviographs were installed in these fields. Measurements of energetic plant yielding included: cutting of plants, determination of fresh and dry matter yield and of plant neatness. Ten plants were cut in each stand.

Soil water resources were estimated based on measurements of soil moisture and ground water table depth. Field water consumption was calculated as a sum of precipitation and water depletion from soil during vegetation season and plant coefficient k_c and the WUE index - as for lysimeters. Vegetation period for all crops was assumed to be April till October.

Results and discussion

Precipitation in the vegetation period of 2008 was close to long term average as seen from long term measurements of meteorological conditions in the station Falenty. Mean precipitation from 3 fields in 2009 was by 128 mm higher than that in 2008. The whole vegetation period of 2009 was characterized by abundant rainfalls close to the extreme measured in the station Falenty (Table 24).

Table 24. Precipitation sums in the vegetation periods (April – October) [mm]

Year	Lysimetric station osier	Field – plant		
		A – osier	B – osier	C – giant silver grass
2008	411.8	287.7	411.8	332.9
2009	524.8	390.6	524.8	501.9
1966 – 2009	390.7	n.d.[1)]	390.7	n.d.[1)]

[1)] *No data*
Source: own calculations

Studies in the lysimetric station showed a strong relationship between the yield of common osier and water conditions. In the average year 2008 the optimum water level was c. 100 cm and dry matter plant yield obtained under these conditions was 21.2 t ha^{-1} (Table 25). At a shallow ground water table (30 cm) substantial soil moisture limited plant mass increments while at a deeper one (170 cm) the plant yield markedly declined to 12.0 t ha^{-1} due to the depletion of easily available water. In the very wet year 2009 the largest yield was obtained at the lowest ground water table depth of 170 cm (18.6 t ha^{-1}) and the smallest – at a level of 30 cm (12.7 t ha^{-1}). Yields at the optimum water level may be considered potential.

Table 25. Ground water table depths and dry matter yields of the common osier and giant silver grass in the vegetation period April – October [t·ha^{-1}]

Year	Lysimeter - osier, ground water table depth in cm			Field – plant					
				A – osier		B – osier		C – giant silver grass	
	30	100	170	Gwd[1)] [cm]	Yield	Gwd[1)] [cm]	Yield	Gwd[1)] [cm]	Yield
2008	16.66	21.16	12.01	192	9.50	141	7.80	202	19.00
2009	12.72	13.52	18.60	148	11.40	133	11.70	182	21.20
Mean	14.69	17.34	15.30	170	10.45	137	9.75	192	20.10

[1)] *Mean ground water table depth*
Source: own calculations

The dry matter yields of the common osier from field A were 9.5 t ha^{-1} in 2008 (Table 25) at a mean ground water table depth of 192 cm and 11.4 t ha^{-1} in 2009 at a mean ground water table depth of 148 cm. Mean annual yield was 10.4 t ha^{-1}. In field B mean ground water table depths in the years 2008 and 2009 were 141 and 133 cm, respectively, and annual yields were similar to those from field A. Annual dry matter yields obtained from various soils in field experiments in Poland vary from 5.4 and 21.7 t ha^{-1}, those from light soils range between 5.4 and 14.6 t ha^{-1} [Faber et al. 2007]. Therefore, yields obtained from studied fields are similar to the country mean yields from light soils.

The yields of the giant silver grass from field C in the third and fourth year of growth were c. 20 t ha^{-1} (Table 25). Yields obtained from other fields were 10.6 – 14.1 t ha^{-1} [Podlaski et al. 2009], 17.9 – 18.9 t ha^{-1} [Kuś, Matyka 2009], or 13.8 – 26.8 t ha^{-1} [Faber et al. 2007]. The yields from field C are thus similar to the average results in Poland.

The common osier grown in lysimeters showed a large water consumption of 660 to 887 mm during the vegetation season of 2008 and 809 – 905 mm in the vegetation season of 2009 (Table 26). In the year 2008 at ground water levels of 30 cm and 100 cm water consumption was the same and amounted 887 mm while at the ground water depth of 170 cm it was slightly lower – 660 mm. The largest water consumption in 2009 was noted at the deepest ground water level and the smallest – at the medium one.

Table 26. Water consumption by the common osier and giant silver grass in the vegetation period April – October [mm]

Year	Lysimeter – osier, ground water depth in cm			Field – plant		
	30	100	170	A – osier	B – osier	C – giant silver grass
2008	886.9	887.2	660.5	470.9	480.5	355.2
2009	864.2	808.6	905.1	419.3	559.8	439.2
Mean	875.6	847.9	782.8	445.1	520.2	397.2

Source: own elaboration

Mean water consumption by the common osier in the vegetation periods of the years 2008 and 2009 was 445 mm in field A and 520 mm in field B (Table 26). Larger water consumption in B than in A at a similar plant yield may be explained by higher level of ground water table. Water consumption by the giant silver grass in field C was smaller and amounted 397 mm as a mean value of two seasons. Hence, field studies demonstrated that water consumption by osier was by 85 mm larger than that by the giant silver grass while the yield of the former was two times smaller than the yield of the latter.

Evapotranspiration by willow was estimated in Sweden at 365 – 495 mm [Persson 1995], in England – at 550 – 650 mm [Hall 2003]. In Italy the evapotranspiration of *Salix alba* in the first vegetation season was estimated at 620 mm in a non-fertilised lysimeter and at 1190 in a lysimeter fertilised with nitrogen and phosphorus. In the second vegetation season the respective values were 890 and 1790 mm [Guidi 2007]. Results obtained in lysimeters in Poland show that evaporation values fall within the range determined in other European countries and are typical for our geographic location.

Results obtained by Marcilonek [1979] for the period April - September may be used to compare water consumption by energetic plants under productive conditions with that by traditional plants in fields of natural water budget. For a crop rotation composed of 4 – 8 plants, mean water consumption was 408 mm in light soil, 431 mm in medium soil and up to 494 in heavy soil.

Other data indicate that water consumption by non-irrigated crop plants in Poland was: for potatoes – 420 mm [Trybała 1996]. winter wheat – 396 mm, sugar beets (April – October) – 401 mm [Łabędzki 2006]. Having in mind these data one may conclude that water consumption by the giant silver grass was similar to water consumption by traditional field crops while that by the common osier was by c. 85 mm larger.

Plant coefficient k_c for the common osier in lysimeters was 0.97 – 1.30 in the vegetation period 2008 and 1.23 – 1.38 in the vegetation period 2009 (Table 27). Sometimes in the literature coefficient k_c for energetic plants is given for the period April – September. Considering this, the coefficient for studied crops was slightly smaller and amounted 0.86 – 1.22 in 2008 and 1.16 – 1.32 in 2009. In Italy the coefficient for the period April – September was 1.25 – 2.84 in the first year and 1.97 – 5.3 in the second year of plant growth [Guidi 2007]. Under field conditions without irrigation at nearly twice lower yield of the common osier the coefficient was also smaller and equal to 0.78 on average. The coefficient for the giant silver grass was only 0.66.

Table 27. Plant coefficient k_c for the common osier and giant silver grass in the vegetation period (April – October)

Year	Lysimeter –osier, ground water depth in cm			Field – plant		
	30	100	170	A – osier	B – osier	C – giant silver grass
2008	1.30	1.30	0.97	0.76	0.69	0.57
2009	1.32	1.23	1.38	0.80	0.85	0.75
Mean	1.31	1.26	1.18	0.78	0.77	0.66

Source: own elaboration

The index of water use efficiency in lysimeters varied from 1.82 to 2.39 g dry matter per kilogram of used water in 2008 and from 1.48 to 2.06 g kg^{-1} in 2009 (Table 28). In both years the index was highest at the optimum ground water table depth. Jørgensen and Schelde [2001] for evapotranspiration of willow without leaves, based on Lindroth's data for leaved plant, estimated the WUE index at 2.2 – 2.9 g kg^{-1}. Based on Mortensen's data the index varied between 0.3 and 1.7 while their own data gave the values from 1.7 to 1.9 g kg^{-1}. Values of the WUE obtained in lysimetric station in Falenty fall within the limits given by the above authors. For osier in field A mean value of the index from two years was 2.37 and in field B – 1.85 g kg^{-1}. For the giant silver grass the index was much higher with the mean of 5.09 g kg^{-1}.

Table 28. The index of water use efficiency by the common osier and giant silver grass in the vegetation period (April – October) [$g \cdot kg^{-1}$]

Year	Lysimeter – osier, ground water table depth in cm			Field – plant		
	30	100	170	A – osier	B – osier	C – giant silver grass
2008	1.88	2.39	1.82	2.02	1.62	5.35
2009	1.48	1.67	2.06	2.72	2.09	4.83
Mean	1.68	2.03	1.94	2.37	1.85	5.09

Source: own elaboration

Summary

Studies in lysimetric station in Falenty on the common osier *Salix viminalis* L. yielding carried out at constant but differentiated ground water table depths (30, 100 and 170 cm) showed that in a vegetation period of average precipitation the highest dry matter yield (21.2 $t \cdot ha^{-1}$) was obtained at the ground water level of 100 cm. In the next wet year the highest dry matter yield (18.6 $t \cdot ha^{-1}$) was obtained at the ground water level of 170 cm. Yields were large and may be seen as potential.

In productive fields of the osier cut every year and grown on soils of the class IVb without irrigation and moderate ground water depths (137 – 170 cm on average) and under meteorological conditions of dry and wet year the dry matter yields amounted c. 10 t ha^{-1}. Dry matter yields of the giant silver grass grown on soil of the same class at a mean ground water depth of 192 cm were much larger amounting c. 20 t ha^{-1}. Obtained yields of both plants were similar to the means from other fields in Poland.

Lysimetric studies showed that providing appropriate water conditions markedly affected yielding of the common osier but resulted in a large water consumption. Water use by the common osier in lysimeters was 660 – 887 mm in the first and 809 – 905 mm in the second year of plant growth.

Under productive conditions without irrigation the water consumption by the common osier was smaller. Comparison of both crops during two years long study showed that field water consumption by the giant silver grass was c. 400 mm per vegetation season while that by the common osier was by 85 mm larger.

Plant coefficient k_c calculated to estimate water needs and deficits with the Penman-Montheit method was high (0.97 – 1.33) at large yields of the common osier (c. 20 t ha^{-1}). At a yield of 10 t ha^{-1} the coefficient equalled 0.78. For the giant silver grass of a yield of 20 t ha^{-1} it was only 0.66.

The index of water use efficiency calculated for lysimetric data from the year 2008 was 1.82 – 2.39 dry matter per kilogram water being most favourable at a mean ground water table depth. In 2009 it was 1.48 – 2.06 and the highest values were obtained at the deepest ground water level (1.7 m). The WUE index for osier fields without irrigation ranged between 1.85 and 2.40 g kg^{-1}. The giant silver grass used water more economically and its index was 5.1 g kg^{-1}.

To increase yielding of the common osier one should apply irrigation. As shown in studies in lysimetric station in Falenty the fulfilment of all water demands would allow for obtaining a potential yield of over 20 t ha^{-1} instead of 10 t ha^{-1} obtained without irrigation. The need for irrigation of the giant silver grass is less important. At a natural water budget one may obtain yields of c. 20 t ha^{-1}. Due to limited water resources in Poland the implementation of large-scale production of the common osier may lead to the deepening of water deficit.

3.3 Water requirements and deficits in energetic willow on mineral soils in view of the model studies

Leszek Łabędzki, Ewa Kanecka-Geszke

Summary

Mean water requirements of energetic willow yielding 13 – 15 t ha^{-1} in central Poland are 420 mm as shown in model studies. Mean water deficits of energetic willow grown in this region on mineral soils with deep ground water table range from 25 mm in soils of the largest available water reserves (300 mm) to 105 mm in soils of the least reserves (100 mm). Water deficits indicate a need of irrigation in the crops of energetic willow in July, August and September.

Crops of energetic willow in sandy-loamy soils with deep ground water table not fed with this water in the region of central Poland are threatened with periodical water deficits and need irrigation to obtain high yields.

Introduction

Energetic willow is considered a water demanding plant. Its crop needs soils of large resources of plant available water [Halldin, Lindroth, 1989; Liziński, Augustyniak, 2005; Pistocchi et al., 2009]. Water requirements by highly productive willow are by 150 – 200 mm higher as compared with traditional crops [Hall, 2003; Faber, 2008]. Demands for water in willow plantations during the vegetation season are estimated at 550 – 650 mm while water consumption may reach 5 - 11 mm·d^{-1} [Hall, 2003]. Kowalik and Scalenghe [2009] estimated water requirements of energetic willow as a product of yield and transpiration coefficient adopted from spruce. At reference yields of 8 t ha^{-1} water demands amounted 194 mm during the vegetation season. Under productive conditions, however, yields may reach 16 – 20 t ha^{-1}. Then water demands of plants may increase to 400 – 500 mm.

In reference to the unit yield, a willow field is assumed to use 300 – 500 dm^3 of water per kg dry matter [Roszewski, 1996]. Hall [2003] noticed that plants may contribute to water deficits in areas where summer rainfalls are smaller than 550 mm. Chołuj et al. [2008] reported that willow needs more than 500 mm of precipitation annually to achieve abundant growth and drought may decrease its yielding even by 50%.

According to Ostrowski et al. [2009] energetic willow is a plant that prefers high soil moisture and is sensitive to low precipitations. Its cultivation is recommended on moist but not long flooded soils with optimum ground water table depth of 100 – 130 cm in sandy soils and 160 – 190 cm in loamy soils. Assuming the efficiency of water use equal 3.35 g dry matter kg^{-1} of water the authors estimated that 360 mm of water is needed in the vegetation period to obtain 12 t ha^{-1} yield.

Jurczuk and Rydałowski [2009] based on lysimetric studies found that energetic willow used 887 mm of water in the vegetation period when ground water table was maintained at depths of 30 and 100 cm. When the depth was maintained at 170 cm the consumption of water decreased to 660 mm.

According to Jørgensen and Schelde [2001] the selection of appropriate energetic plants for a given region must be based on the evaluation of water requirements in relation to local water conditions since water is often a yield-limiting factor.

Water requirements of crop plants depend on the rate and amount of biomass increments which determine the obtained yield. The higher is the yield the more water is used by plants for its production. Rational water management requires recognising water demands of plants which show a simple relation to yields under given habitat conditions. Water requirements not fulfilled by natural inputs cause water deficit which must be determined to predict yields or to stabilise them through irrigation.

Water requirements of agricultural crops are understood as the amount of water needed to achieve a definite productive effect (final yield). Water deficits are the water requirements minus atmospheric precipitation and soil water resources available for plants. Water deficits point to the need of water delivery from outside and to water demands for irrigation purposes.

Results of presented studies pertain to the demands and water deficits of energetic willow grown on mineral soils of precipitation-retention water budget with a deep ground water table without ground recharge of the moisture in the root zone.

Method of calculating water requirements and deficits

Water requirements and deficits for various probabilities of exceeding were calculated for meteorological station of the Institute of Technology and Life Sciences, Bydgoszcz with the use of long-term databases (from the years 1970 – 2009). The station represents climatic conditions of central Poland. Water balance of the root zone was based on methods elaborated by Allen et al. [1998], Doorenbos and Pruitt [1977], Łabędzki [1997, 2006], Roguski, Sarnacka and Drupka [1988] and by Smith [1992] with the use of the CROPDEF model [Łabędzki 1997, 2006]. Balance in each year was initiated with the assumption of full soil useful retention in spring (at field water capacity). Calculations were made for calendar decades (ten-days periods). Monthly sums and sums for the whole vegetation period of potential evapotranspiration and water deficit were calculated for definite probabilities of exceeding using Pearson type III probability distribution to describe their random character.

Available water reserves (*ZWD)* understood as a sum of useful water (the difference between the state of field water capacity and the state of permanent wilting) in the soil profile of a given depth and the amount of water delivered through capillary rising from deeper soil layers to root zone were balanced. Calculations were made for *ZWD* from 100 to 300 mm every 10 mm.

Changes of available water reserves in soil were calculated for the vegetation period from April 1. till the end of September in decade periods acc. to equation:

$$ZWD_{pt} = ZWD_{k(t-1)} = ZWD_{p(t-1)} + P_{t-1} - ETp_{t-1}$$

where:

ZWD_{pt} − the reserve of useful water at the beginning of the decade *t* in root zone (mm),

$ZWD_{k(t-1)}, ZWD_{p(t-1)}$ – the reserve of useful water in the end and at the beginning of the decade *t-1* in root zone (mm),

P_{t-1} − precipitation in the decade *t-1* (mm),

ETp_{t-1} − potential evapotranspiration in the decade *t-1* (mm).

Potential evapotranspiration (*ETp)* in a decade (mm) being the actual plant evapotranspiration at sufficient soil moisture was calculated as:

$$ETp = k_c\, ET_o$$

where:

ET_o − index evapotranspiration acc. to Penman-Monteith (mm),
k_c – plant coefficient dependent on the plant growth phase and yield.

The exhaustion of easily available water at which plant growth is not inhibited was adopted as a criterion of water deficit in the decade *t-1* of the vegetation period. In the period when easily available water was exhausted, water deficit N_{t-1} in the decade *t-1* was calculated from equation:

$$N_{t-1} = ZWTD - ZWD_{k(t-1)}$$

where:

$ZWTD$ – reserve of hardly available water (mm).

The reserve of hardly available water was calculated using a coefficient of water availability *p* which determines the contribution of easily available to total available water:

$$ZWŁD = p \cdot ZWD$$

$$ZWTD = (1 - p) \cdot ZWD$$

where:

ZWŁD – reserve of easily available water (mm),
p – coefficient of water availability,
ZWD – reserve of available water (mm).

Coefficient of water availability *p* determines which part of available water is easily available to plants. It depends on plant growth phase and on the depth of roots.

Now, there are no detailed data on coefficients k_c and *p* for energetic willow. Therefore, they were adopted based on scarce literature data. Plant coefficient k_c was estimated based on values given by Allen et al. [1998], Allen [2009] and Persson [1995] (Table 29). Coefficient of water availability adopted in the model was $p = 0.5$ as in most field and garden crops [Allen et al., 1998; Doorenbos, Pruitt, 1977].

Table 29. Plant coefficient k_c from Penman-Monteith equation

Month	Decade	k_c
April	1	0.3
	2	0.3
	3	0.3
May	1	0.4
	2	0.4
	3	0.4
June	1	0.6
	2	0.6
	3	0.6
July	1	1.0
	2	1.0
	3	1.0
August	1	1.2
	2	1.2
	3	1.2
September	1	1.2
	2	1.2
	3	1.2

Water deficits calculated with eq. (3) should be dealt with as reference (index) deficits pertaining to soil profile not deeper than 200 cm. Reserves of useful water in such a profile are 100 – 250 mm in light and medium soils. Together with the input of water from deeper soil layers they form reserves of water available for plants which may be balanced. The deficits pertain to habitats with mineral soils not fed with ground water and with a deep ground water table which does not affect soil moisture in the layer being balanced (0 – 2 m).

Coefficient k_c determining the value of potential evapotranspiration should be related to biomass or final yield. Potential evapotranspiration may be equated with water demands of plants giving a definite yield. There are no results of studies that would allow for estimating the relationship between k_c and yield. For the needs of this study one may assume that calculated requirements and deficits of water refer to willow yields of 13 – 15 t ha^{-1} as indicated in calculations by Kowalik and Scalenghe [2009]. Adopted values of plant coefficients k_c pertain to willow in the second and third year of its growth.

Water deficits are calculated for fixed probabilities of exceeding which determine the frequency of appearance of water deficits of a given value or higher (e.g. 50% probability means that a given water deficit or larger deficits would appear every second year; 20% probability means its appearance every five years). So calculated water deficits may be identified with net water requirements for irrigation.

Water requirements of energetic willow crops

Water requirements of highly yielding energetic willow (measured as potential evapotranspiration) in the periods April – September of the years 1970 – 2009 in central Poland varied from 352 mm in 1987 to 502 mm in 1975 (Table 30). Mean water requirements for the long period were estimated at 420 mm with standard deviation equal 34 mm which indicated small variability of the needs for irrigation in the analysed period (variability coefficient = 8%). Water requirements of a probability of exceeding of 0.5 compared with the mean value showed a slight asymmetry of their distribution.

Table 30. Statistical parameters of water requirements of energetic willow (ET_p) and precipitation P in vegetation periods of the years 1970-2009

Parameter	ET_p (mm)	P (mm)
Mean	420	325
Standard deviation	34	96
Minimum (year)	352 (1987)	113 (1989)
Maximum (year)	502 (1975)	651 (1980)
Value for p = 0.5	417	311

p – probability of exceeding

When comparing mean water demands with mean atmospheric precipitations one may come to the conclusion on expected deficit of rainfall needed to fulfil water demands of energetic willow grown in such climatic conditions. In particular years this balance might not be negative. The highest and the lowest water demands occurred in the years other than the lowest and the highest precipitation (Table 30). Water requirements and water consumption depend also on other meteorological factors like temperature, air humidity and solar radiation.

Water deficits of energetic willow crops

Water deficits calculated in decades depend on precipitation, potential evapotranspiration i.e. on plant demands for water and on soil water reserves.

In the whole vegetation period (April – September) mean water deficits for energetic willow ranged in the years 1970 – 2009 from 25 mm in the soil of the largest reserves of available water (*ZWD* = 300 mm) to 105 mm in the soil of the smallest reserves (*ZWD* = 100 mm) (Table 31). The smallest water deficits were noted in 1985; in fact they did not occur in any soil. The largest deficits were recorded in the year 1992 which was characterised by an extreme drought. In the vegetation period they amounted from 160 mm in soil of the largest *ZWD* to 265 mm in soil of the smallest *ZWD*.

Table 31. Statistical parameters of water deficits for energetic willow *N* in vegetation periods of the years 1970-2009 in soils of available water reserves = *ZWD*

ZWD (mm)	*N* (mm)			
	mean	standard deviation	minimum (1985)	maximum (1992)
100	105	70	4	265
150	79	66	0	234
200	56	61	0	220
250	38	53	0	190
300	25	42	0	160

Based on deficits of a definite probability of exceeding (Table 32) during the vegetation period in central Poland one may expect every second year the water deficits in crops of energetic willow from 10 mm in soils of *ZWD* = 300 mm to 100 mm in soils of *ZWD* = 100 mm. Every five years the deficits might amount from 50 to 160 mm, respectively.

Table 32. Water deficits *N* in energetic willow crops of a definite probability of exceeding *p* in the vegetation period in soils of available water reserves = *ZWD*

ZWD (mm)	*N* (mm) for *p*								
	0.01	0.05	0.10	0.20	0.50	0.80	0.90	0.95	0.99
100	295	229	197	160	98	46	22	5	0
150	264	198	166	131	71	23	2	0	0
200	239	170	137	102	46	4	0	0	0
250	208	139	108	75	27	0	0	0	0
300	173	108	79	51	13	0	0	0	0

The relationship between water deficits of a probability of exceeding of p = 0.5 and available water reserves in soil *ZWD* had nearly linear character (Figure 18). Hence, the relationship may be described with linear regression with the correlation coefficient r = - 0.99. Based on linear regression one may find that the crops of energetic willow in central Poland will not be exposed to water deficit in an average year (p = 0,5) if they have at their disposal at least 310 mm of water in soil in a form of easily available water and water from the capillary rising.

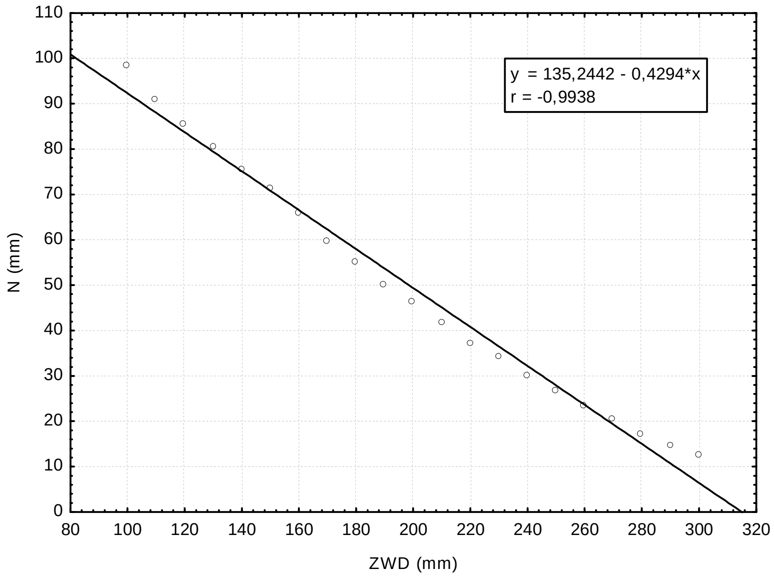


Figure 18. Linear regression of water deficits N in energetic willow of 50% probability of exceeding in the vegetation period on available water reserves in soil ZWD

Water deficits for energetic willow appear not earlier than in July. Even in soils of the least water reserves (*ZWD* = 100 mm), after-winter reserves are sufficient to cover water demands till the end of May. In July in middle Poland one may expect water deficits in energetic willow crops every second year ranging from 0 mm in soils of *ZWD* = 300 mm to 26 mm in soils of *ZWD* = 100 mm (Table 33). Every fifth year the deficits may reach 10 mm and 62 mm, respectively.

Table 33. Water deficits *N* in energetic willow of a given probability of exceeding *p* in July in soils of available water resources = *ZWD*

ZWD (mm)	*N* (mm) for *p*								
	0.01	0.05	0.10	0.20	0.50	0.80	0.90	0.95	0.99
100	155	107	86	62	26	0	0	0	0
150	139	92	71	48	15	0	0	0	0
200	114	70	51	32	6	0	0	0	0
250	84	49	33	19	1	0	0	0	0
300	54	30	19	10	0	0	0	0	0

The relationship between water deficits of a probability of exceeding $p = 0.5$ in July and available water reserves in soil *ZWD* also showed linear character (Figure 19). When approximating this relationship with linear regression one obtains correlation coefficient $r = -0.98$. Based on this regression one may find that the crops of energetic willow from middle Poland in July will not be exposed to water deficit in an average year ($p = 0.5$) if they have at least 250 mm of water in soil at their disposal.

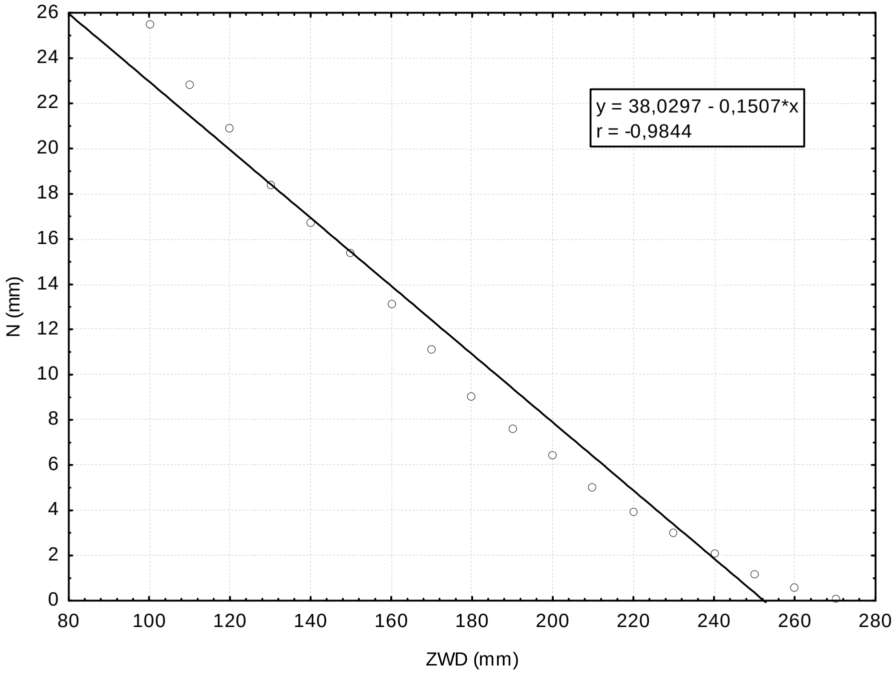


Figure 19. Linear regression of water deficits N of 50% probability of exceeding in energetic willow in July on available water reserves ZWD in soil

In August, in middle Poland water deficits in the crops of energetic willow may occur every second year and amount from 7 mm in soils of *ZWD* = 300 mm to 50 mm in soils of *ZWD* = 100 mm (Table 34). Every fifth year the deficits may reach 30 mm and 80 mm, respectively. The relationship between water deficits of a probability of exceeding $p = 0.5$ in August and available soil water reserves *ZWD* (Figure 20) approximated with linear regression gave a high correlation coefficient of $r = -0.997$. Based on this regression one may assume that in August the crops of energetic willow from central Poland will not be exposed to water deficits in an average year ($p = 0.5$) if they have at least 320 mm of water in soil at their disposal.

Table 34. Water deficits *N* in energetic willow of a given probability of exceeding *p* in August in soils of available water reserves = *ZWD*

ZWD (mm)	*N* (mm) for *p*								
	0.01	0.05	0.10	0.20	0.50	0.80	0.90	0.95	0.99
100	130	106	93	78	50	23	9	0	0
150	123	97	84	68	40	13	0	0	0
200	118	87	71	55	26	4	0	0	0
250	109	75	59	42	15	0	0	0	0
300	99	63	47	30	7	0	0	0	0

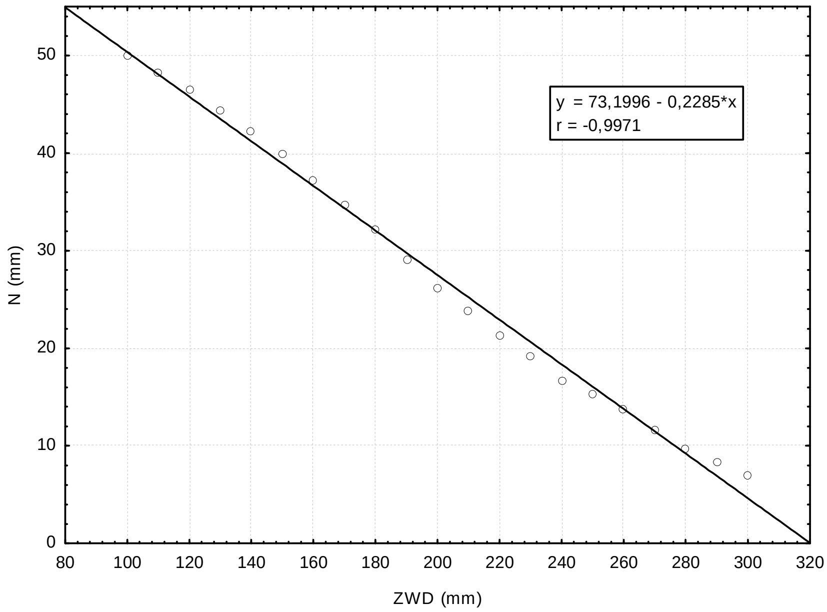


Figure 20. Linear regression of water deficits N in energetic willow of 50% probability of exceeding in August on available water reserves ZWD

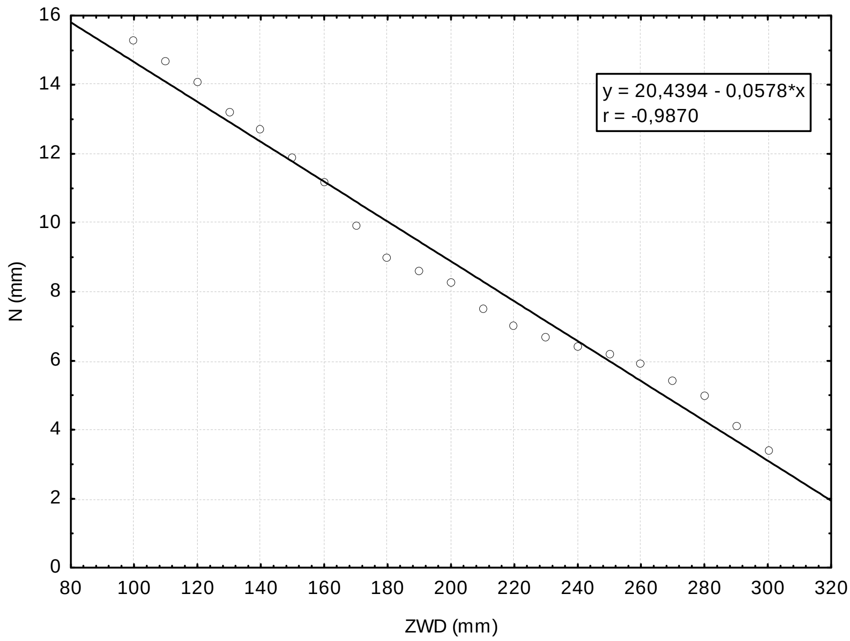


Figure 21. Linear regression of water deficits N in energetic willow of 50% probability of exceeding in September on available water reserves in soil ZWD

In September water deficits in central Poland are the least out of the three months of occurrence. Every second year they may reach from 3 mm in soils of *ZWD* = 300 mm to 15 mm in soils of *ZWD* = 100 mm (Table 35). Every fifth year the deficits may amount from 15 mm to 35 mm, respectively. The relationship between water deficits of a probability of exceeding $p = 0.5$ and available water reserves in soil *ZWD* (Figure 21) approximated with linear regression showed a high coefficient of linear correlation $r = -0.987$. Based on this regression one may assume that in

September the crops of energetic willow in central Poland will not be exposed to water deficits in an average year (p = 0.5) if they have at least 350 mm of soil water at their disposal.

Table 35. Water deficits in energetic willow of a given probability of exceeding p in September in soils of available water reserves = *ZWD*

ZWD (mm)	*N* (mm) for *p*								
	0.01	0.05	0.10	0.20	0.50	0.80	0.90	0.95	0.99
100	76	55	45	34	15	1	0	0	0
150	71	50	40	29	12	0	0	0	0
200	66	45	35	24	8	0	0	0	0
250	60	40	30	21	6	0	0	0	0
300	49	31	23	15	3	0	0	0	0

4

Material-energy inputs

4.1 Comparison of unitary cumulative energy consumption for crops of: willow, miscanthus and Pennsylvanian mallow

Marek Hryniewicz, Anna Grzybek

Summary

A method of calculation of material-energy expenses has been presented for crops of: willow, miscanthus and Pennsylvanian mallow. The cumulative energy method for crops estimation has been applied in calculations. The method affords possibilities for a comparison of different production technologies in complete independence from changes of market prices. Detailed technological charts were presented for energy crop plantations. Calculations were related to one hectare of crop. It enables comparison of calculations results for plantations of any size. The sum of unitary cumulative energy consumption per one hectare of particular crops amounted as follows: willow 100,944 MJ/ha, miscanthus 207,389 MJ/ha, Pennsylvanian mallow 198,469 MJ/ha. Willow crop in whole life cycle of production was about 50% less energy-consuming in comparison with crops of miscanthus and Pennsylvanian mallow. Moreover, crop of Pennsylvanian mallow was slightly less energy-consuming than miscanthus.

Introduction

Each energy crop (as willow, miscanthus or Pennsylvanian mallow) has its own specific production technology. It would be interesting to compare these technologies independently from plantation size with assumption of using maximum unified equipment. It would allow making conclusions about material-energy inputs required for each crop. It could give to planters an advice when making their decision about choice of appropriate energy plant.

The method

Cumulative energy consumption method has been described in details in works of Grzybek [2003], Roszkowski [1980] and Wójcicki [2000]. The method is based on calculation, in energy units, of material-energy streams which are required for given kind of energy biomass production with use of given technology. Material-energy inputs can be related to one hectare of crop or to one GJ of energy included in biomass. An advantage of unitary energy inputs per one hectare is independence from crop area. Investigations were done on the basis of technological charts where types of used tractors and machines, tools, time of work for machines and tractors, tools, fuel consumption, type and quantity of used chemicals and sowing material were given for all operations. Also human labour inputs were taken into account during the investigations. When selection of machines for technologies, the principle of using the best part of the same type machines in all technologies was kept. It prevented discrepancies connected with utilization of different power tractors (what could make results interpretation difficult). Technological charts for willow, miscanthus and Pennsylvanian mallow crops are presented, respectively, in tables 36, 37 and 38. Unitary quantities of energy cumulated in different kinds of machines, energy carriers, chemicals and sowing material are presented in Table 39. Table 40 presents unitary quantities of energy cumulated in specific machines and tools. They include sum of primary energy input for production of machine or tool and primary energy demand for disposal.

Table 36. Technological chart for willow crop

Operation	Tractor or self-propelled harvester	Fuel cons. [l/h]	Machine	Labour inputs per 1 ha		Consumed materials, harvests	
				motor-hours	labour-hours	Kind	Q-ty
Plantation establishment				**8.51**	**15.79**		
Spraying	Trac. 60 kW	8	Sprayer 12 m. 800 l	0.48	0.56	Roundap (l/ha)	5
Deep ploughing	Trac. 118 kW	15.6	Plough 5- fur. rotated	1.09	1.16		
Fertilizing NPK	Trac. 60 kW	8	Fertilizer distributor MX1200 18 m	0.69	0.69	NPK 8-24-24 (kg/ha)	160
Fertilizing N	Trac. 60 kW	8	Fertilizer distributor MX1200 18 m	0.69	0.76	Ammon. nitrate (kg/ha)	140
Tillage	Trac. 118 kW	15.6	Cultivator aggregate QUICK (3 m)	0.84	0.91		
Planting	Trac. 60 kW	8	Planter 2-rows STEP	4.2	11.11	Cuttings (thou. pcs./ha)	18
Spraying	Trac. 60 kW	8	Sprayer 12 m. 800 l	0.52	0.6	Lontrel 300SL (l/ha)	0.5
1st 3-years cycle				**6.36**	**6.47**		
Harvesting	Claas J. 860	39.73	Attachment HS2	0.83	0.94	Chips (t/ha)	16.9
Chips transporting	Trac. 60 kW	8	Trailer 4.5 t	2.2	2.2	Chips (m^3/ha)	22.5
Chips transporting	Trac. 60 kW	8	Trailer 4.5 t	2.2	2.2	Chips (m^3/ha)	22.5
Heap forming and chips poking	Trac. 60 kW	8	Loader TUR 1.5 t	1.13	1.13	Chips (m^3/ha)	45
The next 3-years cycles– 5 cycles				**10.12**	**10.43**		
Fertilizing NPK	Trac. 60 kW	8	Fert. distributor MX1200 18m	0.74	0.81	NPK 8-24-24 (kg/ha)	140
Fertilizing N	Trac. 60 kW	8	Attachment HS2	0.65	0.72	Ammon. nitrate (kg/ha)	120
Interrows scarification	Trac. 60 kW	8	Cultivator 3 m	0.76	0.82		
Harvesting	Claas J. 860	39.89	Attachment HS2	0.89	1	Chips (t/ha)	23.3
Chips transporting	Trac. 60 kW	8	Trailer 4.5 t	2.36	2.36	Chips (m^3/ha)	22.1
Chips transporting	Trac. 60 kW	8	Trailer 4.5 t	2.36	2.36	Chips (m^3/ha)	22.1
Chips transporting	Trac. 60 kW	8	Trailer 4.5 t	2.36	2.36	Chips (m^3/ha)	22.1
Heap forming and chips poking	Trac. 60 kW	8	Loader TUR 1.5 t	1.41	1.41	Chips (m^3/ha)	66.4
Plantation liquidation (forecast)				**7.7**	**74.77**		
Spraying	Trac. 60 kW	8	Sprayer 12 m. 800 l	0.45	0.52	Roundap (l/ha)	6
Roots removing	Trac. 60 kW	8	2-furrow plough	4.01	4.01		
Manual labour	4 persons	0	Manual tools	0	67		
Roots transport	Trac. 35 kW	4.6	Trailer 4.5 t	0.23	0.23		
Harrowing*2	Trac. 60 kW	8	Heavy harrow 3.2 m	3	3		

Source: Muzalewski (2009a)

Table 37. Technological chart for miscanthus crop

Operation	Tractor or self-propelled harvester	Fuel cons. [l/h]	Machine	Labour expenses per 1 ha		Consumed materials, harvests	
				mo-tor-hours	labour-hours	Kind	Q-ty
Plantation establishment							
Spraying	Tract. 60 kW	8	Sprayer 2000, 18m	0.21	0.21	Roundap (l/ha)	3
Disc harrowing	Tract. 118 kW	15.6	Disc harrow 3m	0.39	0.39		
Deep ploughing	Tract. 118 kW	15.6	Plough 5-fur. rotated	1.17	1.17		
Harrowing	Tract. 60 kW	8	Harrow 6-p. heavy	0.58	0.58		
Fertilizing NPK	Tract. 60 kW	8	Fert. distr.1000 kg, 18m	0.29	0.29	NPK 5-20-30 (kg/ha)	250
Fertilizer loading	Tract. 60 kW	8	Loader Big-bag	0.06	0.06		
Fertilizer transporting	Tract. 60 kW	8	Trailer 6 t	0.1	0.1		
Tillage before sowing	Tract. 118 kW	15.6	Rotated harrow,3 m	1.33	1.33		
Cuttings transporting	Tract. 35 kW	4.6	Trailer 4 t	0.25	0.25		
Planting	Tract. 60 kW	8	Planter 4 rows	2.2	2.2	Root cuttings (kg/ha)	10
Spraying	Tract. 60 kW	8	Sprayer 2000, 18m	0.21	0.21	Herbicide (l/ha)	0.63
Rolling	Tract. 60 kW	8	Roller Cambridge 6 m	0.27	0.27		
1st production cycle (4.0 t/ha)							
Spraying	Tract. 60 kW	8	Sprayer 2000, 18m	0.21	0.21	Herbicide (l/ha)	0.63
Fertilizing N	Tract. 60 kW	8	Fert. distr.1000 kg, 18m	0.23	0.23	Amm. nitrate (kg/ha)	70
Fertilizer loading	Tract. 60 kW	8	Loader Big-bag	0.06	0.11		
Fertilizer transport	Tract. 60 kW	8	Trailer 6 t	0.05	0.1		
Mowing	Tract. 118 kW	15.6	Disc mower+cond. 3m	0.67	0.67	Yield (t)	4
Harvesting and baling	Tract. 118 kW	15.6	Baler Vicon LB12200	0.62	0.62	String (kg/ha)	3.6
Stacking and bales loading	Tract. 60 kW	8	Loader TUR 1.5 t	0.33	0.33		
Bales transporting	Tract. 60 kW	8	Trailer T023	0.21	0.21		
Bales transporting	Tract. 60 kW	8	Trailer T023	0.18	0.18		
Bales unloading and stacking	Tract. 60 kW	8	Loader TUR 1.5 t	0.29	0.29		
2nd production cycle (12.5 t/ha)							
Fertilizing NPK	Tract. 60 kW	8	Fert. distr.1000 kg, 18m	0.29	0.29	NPK 5-20-30	200
Fertilizing N	Tract. 60 kW	8	Fert. distr.1000 kg, 18m	0.23	0.23	Amm. nitrate (kg/ha)	70
Fertilizer loading	Tract. 60 kW	8	Loader Big-bag	0.18	0.23		
Fertilizer transporting	Tract. 60 kW	8	Trailer 6 t	0.2	0.25		
Spraying	Tract. 60 kW	8	Sprayer 2000, 18m	0.23	0.23	Herbicide	0.63
Mowing	Tract. 118 kW	15.6	Disc mower+cond. 3m	0.67	0.67	Yield (t)	12.5
Harvesting and pressing	Tract. 118 kW	15.6	Baler Vicon LB12200	0.82	0.82	String (kg/ha)	11.1
Stacking and bales loading	Tract. 60 kW	8	Loader TUR 1.5 t	0.74	0.74		
Bales transporting	Tract. 60 kW	8	Trailer T023	0.15	0.15		
Bales transporting	Tract. 60 kW	8	Trailer T023	0.15	0.15		
Bales transporting	Tract. 60 kW	8	Trailer T023	0.15	0.15		
Bales unloading and stacking	Tract. 60 kW	8	Loader TUR 1.5 t	0.65	0.65		
The next production cycles (13*19.4 t/ha)							
Fertilizing NPK	Tract. 60 kW	8	Fert. distr.1000 kg, 18m	0.29	0.29	NPK 5-20-30 (kg/ha)	200
Fertilizing N	Tract. 60 kW	8	Fert. distr.1000 kg, 18m	0.23	0.23	Amm. nitrate (kg/ha)	70
Fertilizer loading	Tract. 60 kW	8	Loader Big-bag	0.18	0.23		
Fertilizer transporting	Tract. 60 kW	8	Trailer 6 t	0.2	0.25		
Mowing	Tract. 118 kW	15.6	Disc mower+cond. 3m	0.83	0.83	Yield (t)	19.4
Harvesting and pressing	Tract. 118 kW	15.6	Baler Vicon LB12200	1.14	1.14	String (kg/ha)	17.1
Stacking and bales loading	Tract. 60 kW	8	Loader TUR 1.5 t	1.06	1.06		
Bales transporting	Tract. 60 kW	8	Trailer T023	0.2	0.2		
Bales transporting	Tract. 60 kW	8	Trailer T023	0.2	0.2		
Bales transporting	Tract. 60 kW	8	Trailer T023	0.23	0.23		
Bales unloading and stacking	Tract. 60 kW	8	Loader TUR 1.5 t	0.98	0.98		
Plantation liquidation							
Spraying	Tract. 60 kW	8	Sprayer 2000, 18m	0.23	0.23	Roundap (l/ha)	5
Grinding	Tract. 118 kW	15.6	Disc harrow 3m	1.59	1.59		
Harrowing *2	Tract. 60 kW	8	Harrow 6-p. heavy	1.17	1.17		

Source: Muzalewski (2009b)

Table 38. Technological chart for Pennsylvanian mallow crop

Operation	Tractor or self-propelled harvester	Fuel cons. [l/h]	Machine	Labour expenses per 1 ha		Consumed materials. Harvests	
				mo-tor-hours	labour-hours	Kind	Q-ty
Plantation establishment							
Spraying	Tract. 60 kW	8	Sprayer 2000, 18m	0.27	0.27	Roundap (l/ha)	3
Disc harrowing	Tract. 118 kW	15.6	Disc harrow 3m	0.39	0.39		
Deep ploughing	Tract. 118 kW	15.6	Plough 5-fur. rotated	1.16	1.16		
Harrowing	Tract. 60 kW	8	Harrow 6-p. heavy	0.58	0.58		
Tillage before sowing	Tract. 118 kW	15.6	Aggregate U 749 3.7m	0.51	0.51		
Sowing	Tract. 60 kW	8	Cereal drill 3m	0.88	0.88	Seeds (kg/ha)	3
Spraying	Tract. 60 kW	8	Sprayer 2000, 18m	0.27	0.27	Herbicide (l/ha)	2.5
1st production cycle (6.0 t/ha)							
Spraying	Tract. 60 kW	8	Sprayer 2000, 18m	0.27	0.27	Herbicide (l/ha)	2.5
Hoeing	Tract. 35 kW	4.6	Hoe 5-rows	3.21	3.21		
Hoeing	Tract. 35 kW	4.6	Hoe 5-rows	3.21	3.21		
Mowing	Tract. 118 kW	15.6	Disc mower+cond. 3 m	0.62	0.62		
Harvesting and baling	Tract. 118 kW	15.6	Baler Vicon LB12200	0.77	0.77	String (kg/ha)	6.15
Stacking and bales loading	Tract. 60 kW	8	Loader TUR 1.5 t	0.57	0.57		
Bales transporting	Tract. 60 kW	8	Trailer T023	0.38	0.38		
Bales transporting	Tract. 60 kW	8	Trailer T023	0.43	0.43		
Bales unloading and stacking	Tract. 60 kW	8	Loader TUR 1.5 t	0.45	0.45		
The next production cycles (14*average 12.0 t/ha)							
Fertilizing NPK	Tract. 60 kW	8	Fert. distr.1000 kg, 18m	0.35	0.35	NPK 5-20-30 (kg/ha)	300
Fertilizing N	Tract. 60 kW	8	Fert. distr.1000 kg, 18m	0.29	0.29	Amm. nitrate (kg/ha)	100
Fertilizer transporting	Tract. 60 kW	8	Trailer 4 t	0.25	0.25		
Mowing	Tract. 118 kW	15.6	Disc mower+cond. 3m	0.7	0.7		
Harvesting and baling	Tract. 118 kW	15.6	Baler Vicon LB12200	0.89	0.89	String (kg/ha)	10.7
Stacking and bales loading	Tract. 60 kW	8	Loader TUR 1.5 t	0.95	0.95		
Bales transporting	Tract. 60 kW	8	Trailer T023	0.63	0.63		
Bales transporting	Tract. 60 kW	8	Trailer T023	0.5	0.5		
Bales unloading and stacking	Tract. 60 kW	8	Loader TUR 1.5 t	0.95	0.95		
Plantation liquidation							
Spraying	Tract. 60 kW	8	Sprayer 2000. 18 m	0.29	0.29	Roundap (l/ha)	5
Grinding	Tract. 118 kW	15.6	Rotated harrow, 3 m	1.54	1.54		
Harrowing *2	Tract. 60 kW	8	Harrow 6-p. heavy	1.17	1.17		

Source: Muzalewski (2009c)

Table 39. Unitary quantities of energy cumulated in particular kinds of production inputs

Kind of input	Value	Unit
Diesel oil	58.3	MJ/l
Labour	80	MJ/lbh
Willow cutting[1)]	0.0204	MJ/pcs
Herbicides	351.6	MJ/l
NPK	12.16	MJ/kg
Ammonium nitrate	26.18	MJ/kg
Tractors	125	MJ/kg
Tractor tools	100	MJ/kg
Agricultural land	10 000	MJ/ha/year
Manual tools	100	MJ/kg
Root cutting	100	MJ/kg
String	50	MJ/kg
Seeds	100	MJ/kg

Source: Wójcicki (2000),[1)] estimation

Table 40. Unitary quantities of energy cumulated in specific machines and tools

Machine or tool	Mass	Energ.
[name]	[kg]	[MJ]
Tractor 35 kW	2 500	312 500
Tractor 60 kW	3 905	488 125
Tractor 118 kW	5 920	740 000
Sprayer 2000, 18m	1 685	168 500
Disc harrow, 3m	690	69 000
5-furrow, rotated plough	500	50 000
Harrow, 6-p. heavy	1 205	120 500
Fertilizer distributor, 1000 kg, 18m	265	26 500
Loader Big-bag	300	30 000
Trailer 6 t	2 120	212 000
Rotated harrow, 3m	1 180	118 000
Trailer 4.5 t	1 950	195 000
4-row planter	310	31 000
Roller Cambridge 6 m	2 340	234 000
Disc mower-conditioner 3m	475	47 500
Baler Vicon LB12200	8 500	850 000
Loader TUR 1.5 t	400	40 000
Trailer T023	3 700	370 000
Forage harvester Claas J. 860	10 800	1 350 000
Attachment HS2	500	50 000
Manual tools	10	1 000
Cultivator aggregate QUICK (3 m)	500	50 000
Planter 2-rows STEP	180	18 000
2-furrow plough,	250	25 000
Cultivator	795	79 500
Aggregate U 749, 3.7m	500	50 000
Cereal drill, 3m	490	49 000
5-row hoe, VCO-5-430	470	47 000

Source: own calculations

Results

Unitary inputs of cumulative energy for willow crop are presented in table 41. Figure 22 presents the graphical visualization of values of specific streams of cumulative energy inputs per hectare for willow crop. The per-cent structure (distribution) of cumulative energy inputs per each cycle of willow production is visualized on Figure 23.

Table 41. Unitary inputs of cumulative energy for willow crop

Cycle	Year	Cumulative energy of machines assembly[1)]	Cumulative energy of Diesel oil	Cumulative energy of labour	Cumulative energy of chemicals	Cumulative energy of cuttings	Sum of cumulative energies	Structure
		[MJ/ha]	[MJ/ha]	[MJ/ha]	[MJ/ha]	[MJ/ha]	[MJ/ha]	[%]
0	0	595	4 823	1 263	7 545	367	14 593	14.46%
I	1	0	0	0	0	0	0	0.00%
	2	0	0	0	0	0	0	0.00%
	3	544	4 501	518	0	0	5 563	5.51%
II	4	0	0	0	0	0	0	0.00%
	5	0	0	0	0	0	0	0.00%
	6	910	7 031	947	4 844	0	13 732	13.60%
III	7	0	0	0	0	0	0	0.00%
	8	0	0	0	0	0	0	0.00%
	9	910	7 031	947	4 844	0	13 732	13.60%
IV	10	0	0	0	0	0	0	0.00%
	11	0	0	0	0	0	0	0.00%
	12	910	7 031	947	4 844	0	13 732	13.60%
V	13	0	0	0	0	0	0	0.00%
	14	0	0	0	0	0	0	0.00%
	15	910	7 031	947	4 844	0	13 732	13.60%
VI	16	0	0	0	0	0	0	0.00%
	17	0	0	0	0	0	0	0.00%
	18	910	7 031	947	4 844	0	13 732	13.60%
VII	19	497	3 543	5 981	2 110	0	12 131	12.02%
Sum		6 186	48 020	12 497	33 874	367	100 944	100.00%

Source: own calculations, [1)]sum of cumulative energies of tractors and tools

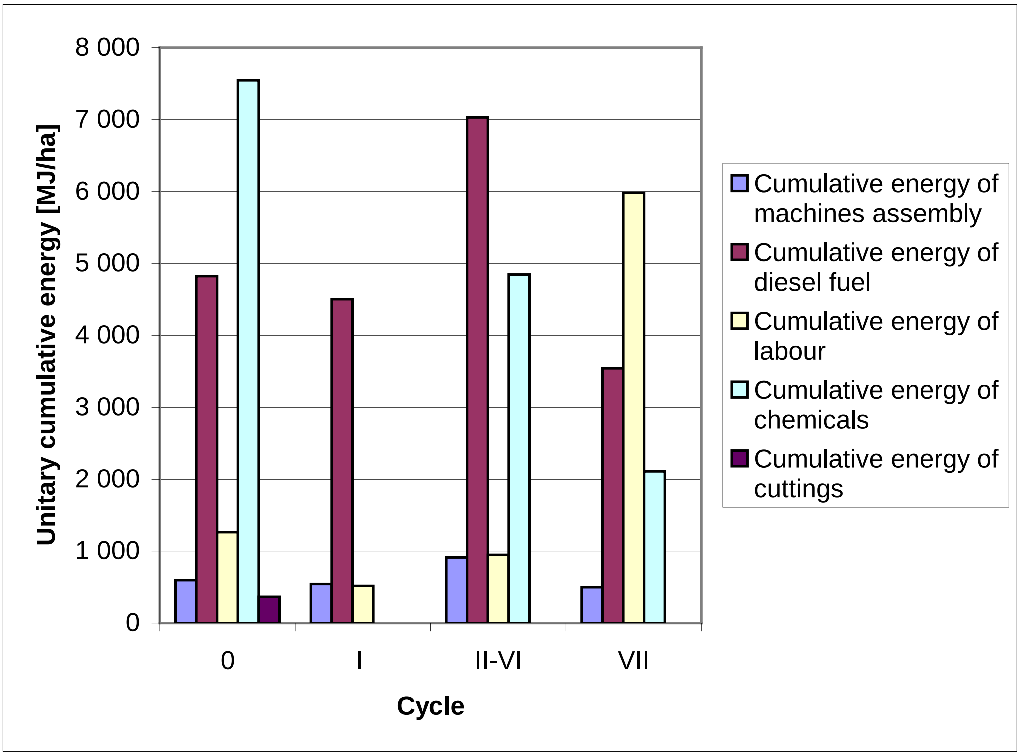


Figure 22. Graphical visualization of values of specific categories of cumulative energy per hectare for willow crop

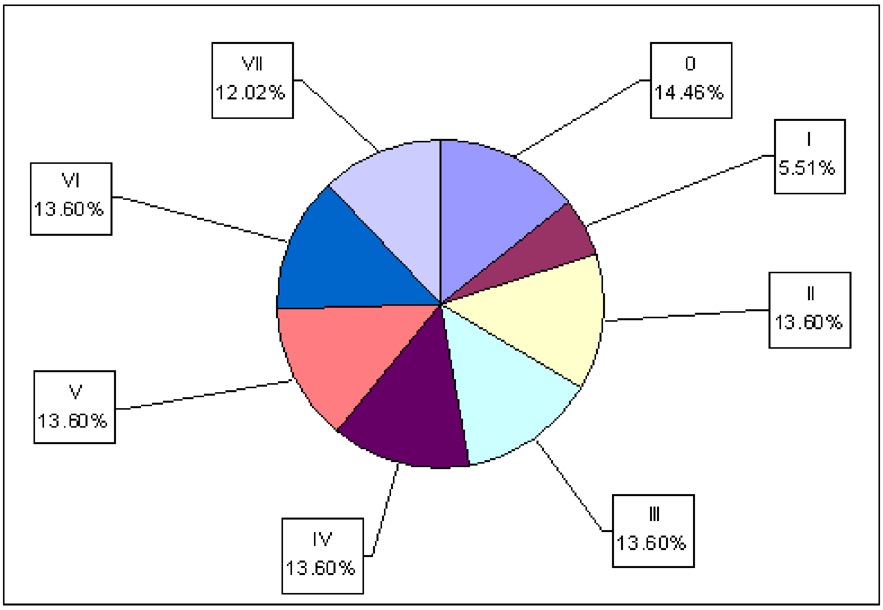


Figure 23. The per-cent structure (distribution) of cumulative energy inputs per particular cycles of willow production

Table 42 presents unitary inputs of cumulative energy for miscanthus crop.

Table 42. Unitary inputs of cumulative energy for miscanthus crop

Cycle	Year	Cumulative energy of tractor	Cumulative energy of tool	Cumulative energy of machines assembly[1)]	Cumulative energy of labour	Cumulative energy of Diesel oil	Cumulative energy of cuttings	Cumulative energy of chemicals	Sum of cumulative energies	Structure
		[MJ/ha]	[MJ/ha]	[MJ/ha]	[MJ/ha]	[MJ/ha]	[MJ/ha]	[MJ/ha]	[MJ/ha]	[%]
0	0	471	68	538	564	6 728	1 000	4 316	13 147	6.34%
I	1	196	90	286	236	5 550	0	2 234	8 307	4.01%
II	2	291	120	411	365	6 483	0	5 041	12 300	5.93%
III-XVI	3	365	158	523	451	6 017	0	5 120	12 109	5.84%
XVII	17	213	42	254	239	1 842	0	1 758	4 094	1.97%
	Sum	6 279	2 526	8 805	7 716	104 835	1 000	85 024	207 380	100.00%

Source: own calculations, [1)]sum of cumulative energies of tractors and tools

Graphical visualization of values of specific categories of cumulative energy per hectare for miscanthus crop is on Figure 24. The per-cent structure (distribution) of cumulative energy inputs per each cycle of miscanthus production is visualized on Figure 25. Table 43 presents unitary inputs of cumulative energy for Pennsylvanian mallow crop. Graphical visualization of values of specific categories of cumulative energy per hectare for Pennsylvanian mallow crop is shown on Figure 26. The per-cent structure (distribution) of cumulative energy inputs per each cycle of Pennsylvanian mallow production is visualized on Figure 27.

Table 43. Unitary inputs of cumulative energy for Pennsylvanian mallow crop

Cycle	Year	Cumulative energy of tractor	Cumulative energy of tool	Cumulative energy of machines assembly[1)]	Cumulative energy of labour	Cumulative energy of Diesel oil	Cumulative energy of cuttings	Cumulative energy of chemicals	Sum of cumulative energies	Structure
		[MJ/ha]	[MJ/ha]	[MJ/ha]	[MJ/ha]	[MJ/ha]	[MJ/ha]	[MJ/ha]	[MJ/ha]	
0	0	285	36	321	325	4 594	300	1 934	7 474	3.77%
I	1	463	157	620	793	4 687	0	1 187	7 287	3.67%
II-XV	2	352	154	505	440	5 084	0	6 801	12 830	6.46%
XVI	16	211	42	254	240	1 842	0	1 758	4 094	2.06%
	Sum	5 884	2 385	8 269	7 512	82 296	300	100 092	198 469	100.00%

Source: own calculations, [1)]sum of cumulative energies of tractors and tools

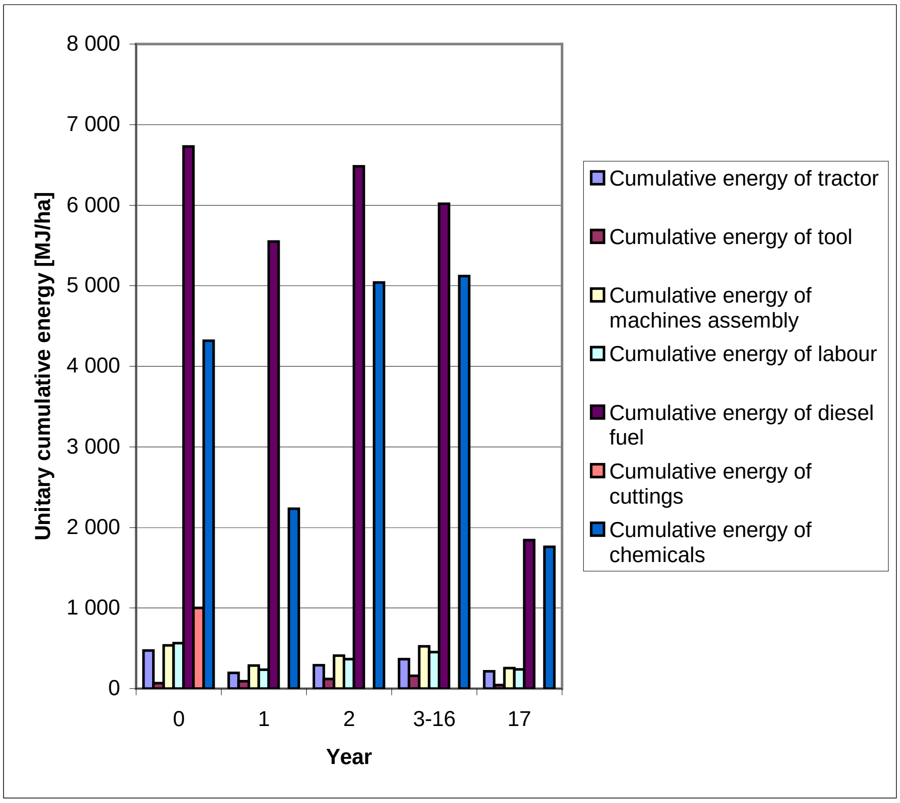


Figure 24. Graphical visualization of values of specific categories of cumulative energy inputs per hectare for miscanthus crop

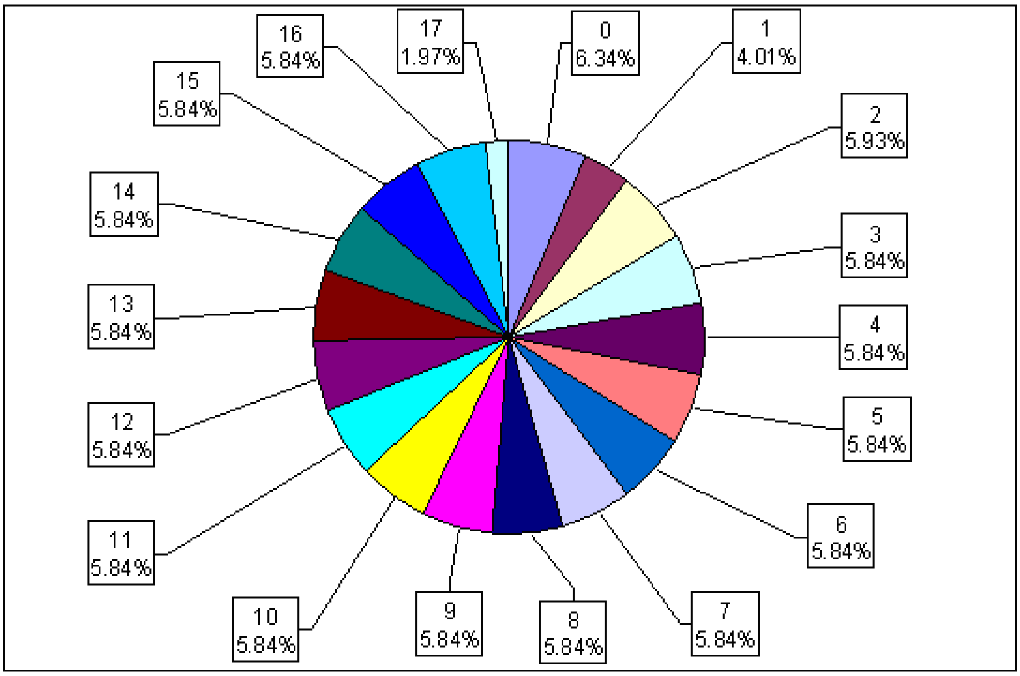


Figure 25. The per-cent structure (distribution) of cumulative energy inputs per particular cycles of miscanthus production

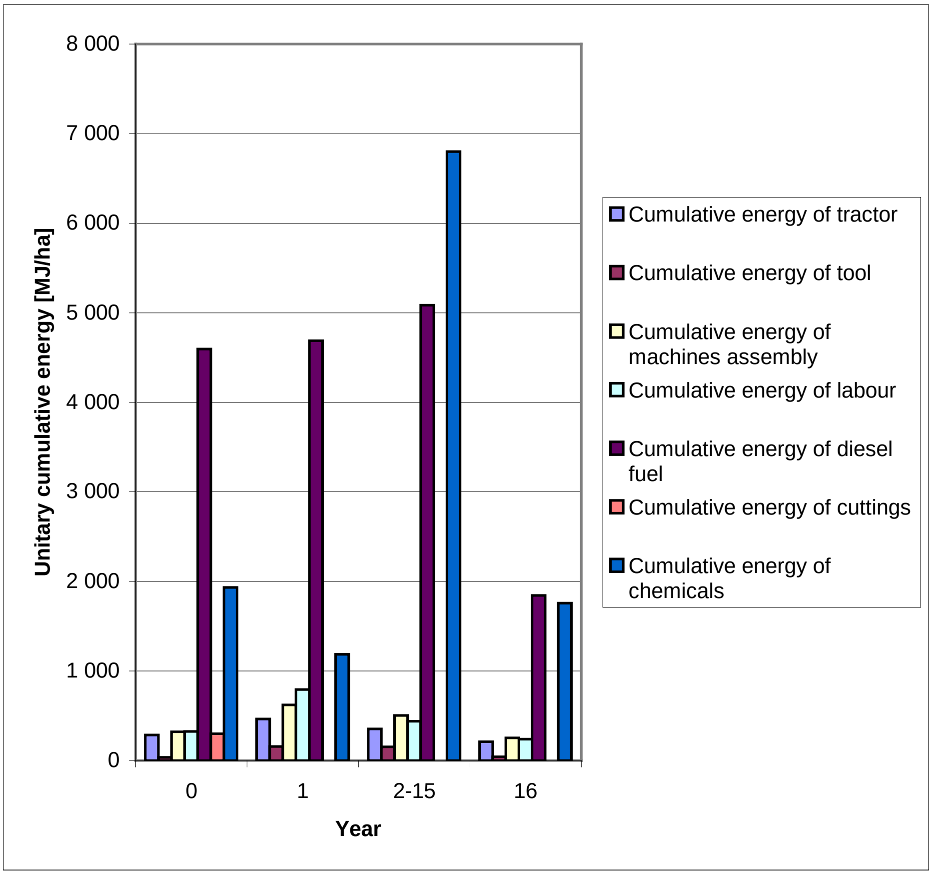


Figure 26. Graphical visualization of values of specific categories of cumulative energy inputs per hectare for Pennsylvanian mallow crop

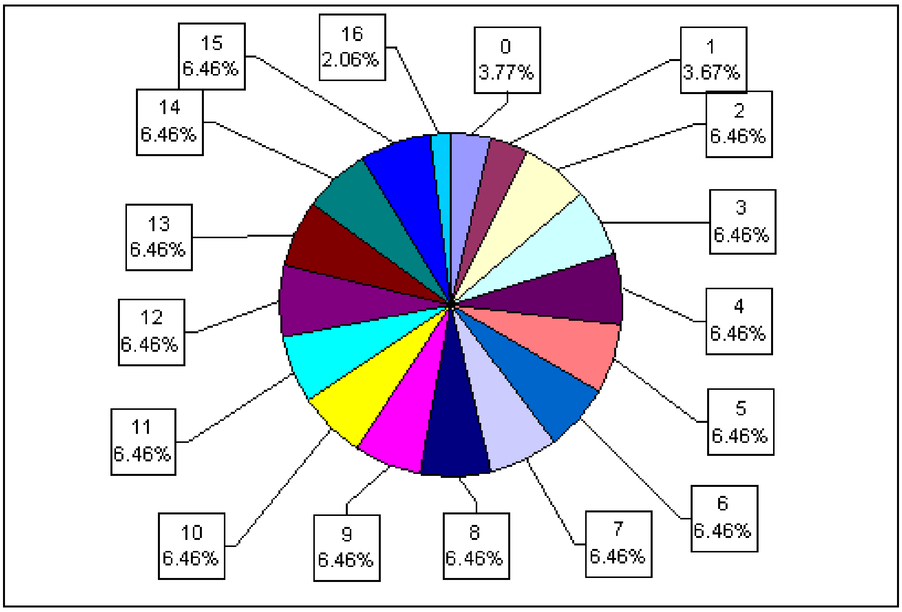


Figure 27. The per-cent structure (distribution) of cumulative energy inputs per particular cycles of Pennsylvanian mallow production

Conclusions

The sum of unitary cumulated energy inputs per one hectare of crop are: willow 100.944 MJ/ha, miscanthus 207.389 MJ/ha, Pennsylvanian mallow 198.469 MJ/ha. Willow crop in whole life cycle of plantation is about 50% less energy-consuming in comparison with crops of miscanthus and Pennsylvanian mallow. Moreover, crop of Pennsylvanian mallow is slightly less energy-consuming than miscanthus. Much lower cumulated energy inputs for willow crop in comparison with miscanthus and Pennsylvanian mallow crops can be explained by fact that willow is harvested every three years. Miscanthus and Pennsylvanian mallow are harvested every year. It is the reason of bigger utilization of machines, consumption of Diesel oil and human work in whole life cycle of plantation.

5

Economic Evaluation

5.1 Economic profitability of willow biomass production for energy purpose

Jan Pawlak

Summary

The per cent share of labour in total operation cost structure growth as the man-hour cost increases, and drops along the increase of mechanization level. The purposefulness of application of the high level mechanization technology variant is the higher, the larger is the willow plantation, and the more expensive is the labour.

In 2008, prices of Diesel oil and electricity in Poland were, in general, lower than in West European countries, but higher than in South Korea, Japan and USA. During 2000-2008 growth of Diesel oil prices ranged from 28.5% (Czech Republic) to 163.5% (S. Korea), and of electricity from 3% (S. Korea) to 109.7% (Hungary).

Introduction

Concern over national energy security and the necessity to overcome burdens associated with fossil energy sources has prompted interest in expanding domestic renewable energy markets. Biomass, and in particular dedicated energy crops, has received growing attention as a promising means to develop local, sustainable energy sources [Heller et Al. 2003]. The biomass is closely connected with agriculture and in Poland it is now the main renewable energy source.

The use of renewable energy source is justifiable under two conditions: 1) positive net energy output-input ratio, meaning that the calorific value of received renewable energy carrier is higher than direct and indirect energy inputs for its production, 2) price of energy unit in the renewable source is not higher than in currently used fossil fuels. Results of American research, using life cycle assessment, show that with current practices in New York State one can receive 55 units of energy produced in biomass from short rotation woody crop per unit of fossil energy [Heller et Al. 2003].

There are many ways to improve the efficiency of willow biomass production, both in energy and economic aspects. In a case of willow biomass for energy there are two pathways to make its use economically viable. One is to improve the efficiency of production by reducing operating costs and increasing yields. The other is to value the environmental and rural benefits associated with the system [Keoleian, Volk 2005]. To lower the costs and improve the production efficiency of biomass, the knowledge of influence of different factors, such as production process technology, scale of production, kind of site for plantation, labour costs, price of biomass produced, as well as interrelations between them, is necessary.

The knowledge of the production cost per unit of the calorific value of the energy crop makes it possible to compare different renewable energy sources and different technologies of their production. It can also serve as a meter to evaluate a purposefulness of the use of renewable energy source instead of a fossil energy carrier. It will also help to make a choice of the most convenient energy crop with regard to economic and environment criteria.

The purpose of this chapter is to present results of research and studies of economic profitability of energy crop cultivation, carried out within the project "Modelling of biomass utilization for energy purpose".

The range of present analysis is limited to the presentation of model based simulation studies of willow biomass production costs. The effect of some factors on economic efficiency of the use of willow biomass for energy purposes is shown. Since the competitiveness of biomass for energy depends, among others, on prices of currently used fossil fuels and electric energy, results of studies of prices of selected conventional energy carriers in Poland and in some other countries are also presented.

Material and methods

Model method has been applied to study effects of different factors on costs and efficiency of willow biomass production for energy. Materials from earlier publications [Dubas et al. 2004, Dubas, Tomczyk 2005, Pasyniuk 2007, Stolarski 2005, Stolarski et al. 2008, Szczukowski, Budny 2003, Szczukowski et al. 2004] were used as an input data to elaborate models of two variants of technology processes [Pawlak 2010]. Variant I is labour intensive, especially regarding planting and harvest operations. Harvested material is transported to storage place in not chipped form. In variant II majority of operations is mechanized, and harvested material is chipped on fields with direct loading on transport means and carried to storage place in a form of woodchips.

The model base-case scenario assumes six 3-year rotations and includes site preparation, coppicing after the first year of growth, and the removal of willow stools at the end of the useful life of plantation. Harvesting is executed on 3-year cycles.

Production cost of willow for energy includes labour, machinery operation costs and costs of materials. Cost of labour is calculated by multiplication of number of workers, time of work and salary (including all taxes and allowances) per unit of time. Operation cost of power (tractors, engines and so on) and machinery includes here depreciation, storage and conservation, insurance, repair, maintenance and energy. Material inputs (cutting units, fertilizers, pesticides, etc.) in relevant units of measure are multiplied by price per unit of measure.

Total amounts of production costs together with market value of produced energy crop and its calorific value create the base of model for evaluation of the economic efficiency of the bioenergy production. The economic efficiency of production of i-th energy crop can be calculated using the following formula:

$$E_{ci} = \frac{P_{ci}}{N_{ci}}$$

Where:

E_{ci} - efficiency of production of i-th energy crop
P_{ci} - market value of produced i-th energy crop, PLN*ha^{-1}
N_{ci} - costs of production of i-th energy crop, PLN*ha^{-1}

For comparative purposes, the cost of production per unit of the calorific value of i-th energy crop should be determined:

$$C_{ci} = \frac{N_{ci}}{Q_{ci}} \qquad (PLN*MJ^{-1})$$

Where:

C_{ci} - the cost of production of the unit of the calorific value of i-th energy crop, PLN*MJ^{-1}
Q_{ci} - calorific value of produced energy crop, MJ*ha^{-1}.

When analyzing prices of energy, data of Central Statistical Office (GUS) as well as of international organizations, engaged in research concerning energy, like International Energy Agency [IEA 2009, IEA 2009a] and Energy Information and Administration [2010] were used. Lack of 2008 data on electric energy prices for Germany and Japan in publications of International Energy Agency caused, that in these cases estimations were necessary.

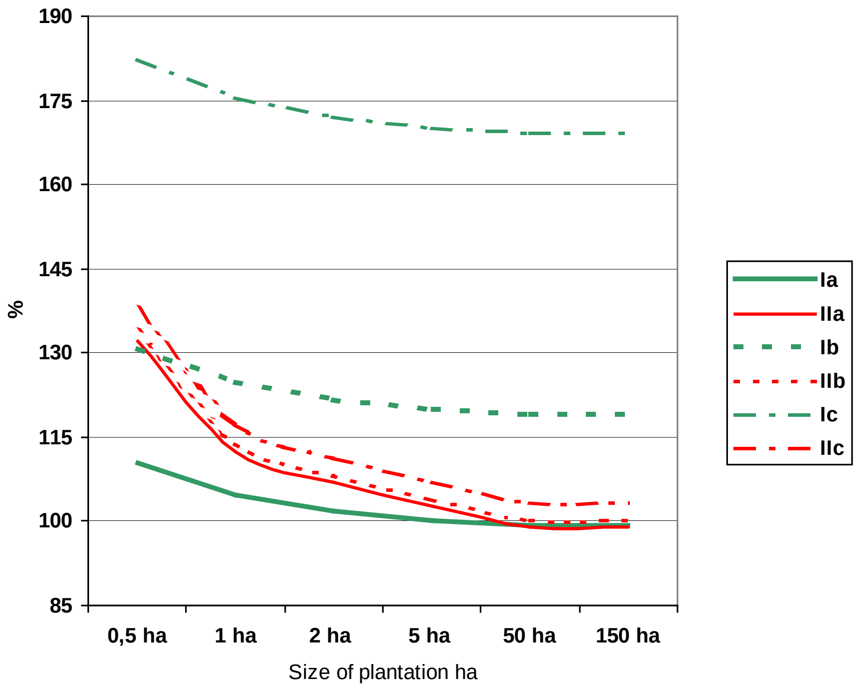
Results of model-based simulation studies

Biomass production costs on willow plantations decrease, and the efficiency of production increases as the size of plantation grows. Kind of the technology variant applied for a willow bioenergy production has an effect both on level and structure of operation costs.

With equal price of biomass and prices of machinery, the purposefulness of application of the high level mechanization technology variant is the higher, the larger is the willow plantation, and the more expensive is the labour. With the labour costs of 8 and 10 PLN*h^{-1}, on 0.5 hectare plantation application of such technology variant is not advisable. Under such conditions technology variant II generates operation costs by 19.6% higher when the labour costs amount to 8 PLN*h^{-1} and by 2.1% higher when the labour costs amount to 10 PLN*h^{-1}. Therefore, on 0.5 hectare plantation more convenient, from economic point of view, is adoption of the variant I, if the labour cost amounts to 8 and 10 PLN*h^{-1}. When the cost of labour amounts to 8 PLN*h^{-1}, adoption of the highly mechanized technology variant II is justifiable only on plantations of 5 hectare and more. However, when the labour cost amounts to 15 PLN*h^{-1}, technology variant II is more convenient even in a case of 0.5 hectare plantation (Figure 28).

If the technology variant I is applied, labour dominates in the operation cost structure. Its share ranges from 78 to 84% when the unitary cost of labour amounts to 10 PLN*h^{-1}. The share of labour in total operation cost structure depends on man-hour cost. It ranges from 84 to 89% in a case with price of man-hour of 15 PLN*h^{-1}. The per cent share of labour in total operation cost structure grows as the size of plantation increases. It is a result of increasing operation capacities during machinery works when size of fields grows. Application of highly mechanized technology variant II brings about drop of per cent share of labour in total operation cost structure to 6% with labour unitary cost 10 PLN*h^{-1} and to 9% with labour unitary cost 15 PLN*h^{-1}.

As a result of an increase of operation capacities when field works executed with machines, along with grows of size of fields, the reduction of operation costs is observed. When the labour intensive technology variant I is applied, this reduction is of relatively little importance. On plantations of 50 and more hectares operation cost with labour unitary cost of 10 PLN*h^{-1} is by 8.9% lower than on 0.5 hectare plantation. However, adoption of the highly mechanized technology variant II brings about more important cost reduction - by 25% (Figure 28).



Source: author's calculations

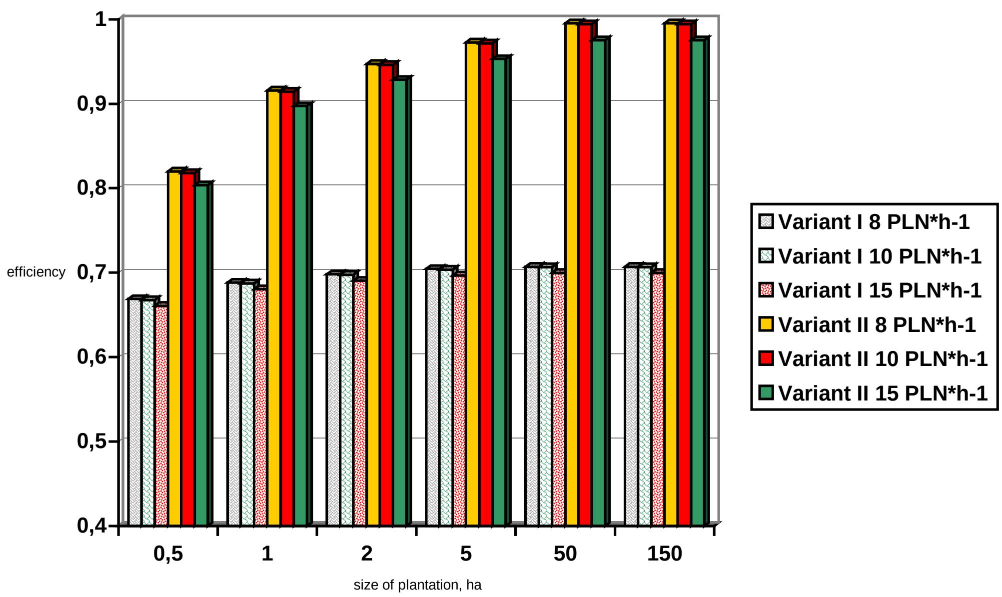


Figure 29. Efficiency of inputs for willow biomass production when price of GJ produced energy is equal with price of GJ in coal-dust
Source: author's calculations

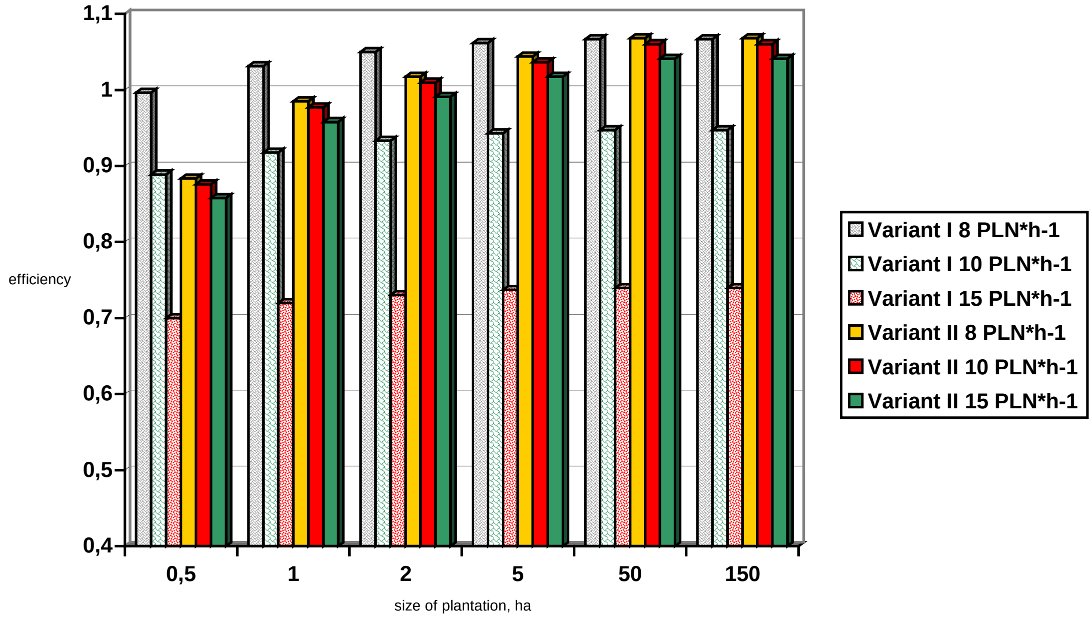


Figure 30. Efficiency of inputs for willow biomass production when price of GJ produced energy amounts to 21.4 PLN
Source: author's calculations

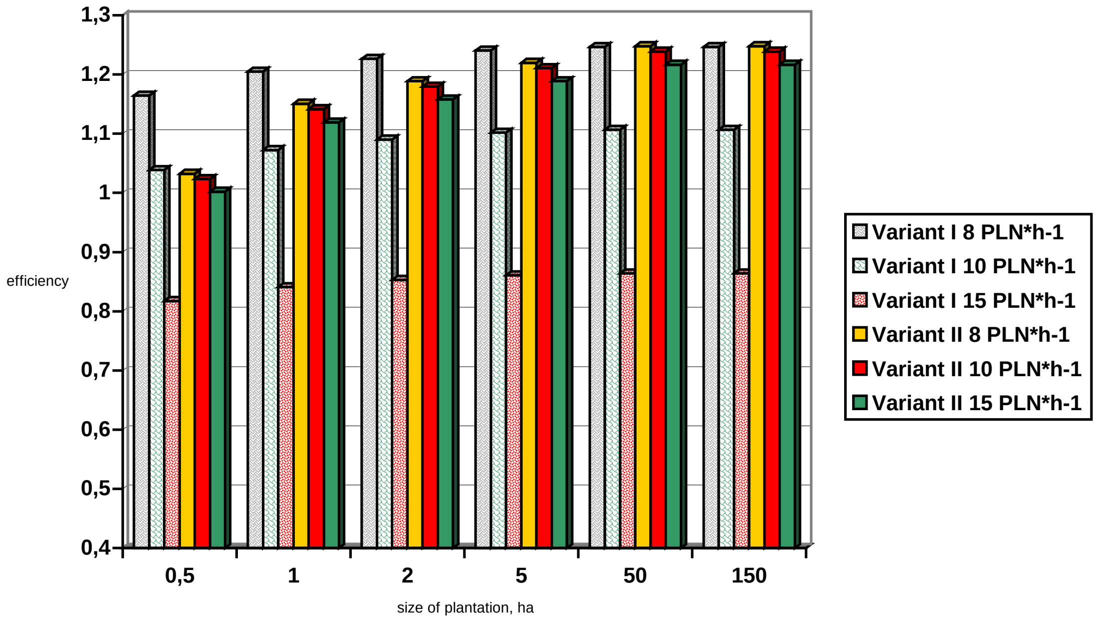


Figure 31. Efficiency of inputs for willow biomass production when price of GJ produced energy amounts to 25 PLN
Source: author's calculations

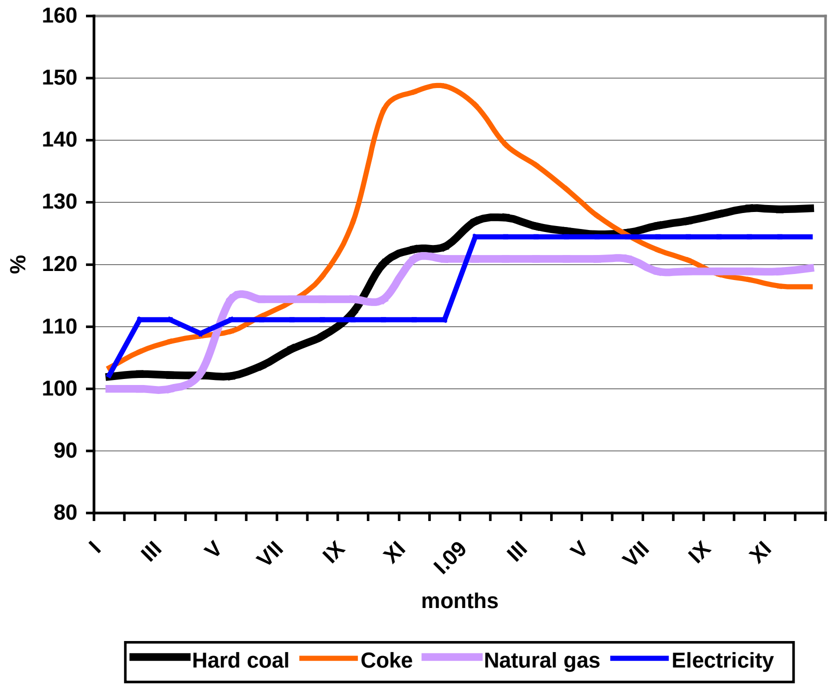


Figure 32. Price indices of selected energy carriers in Poland December 2007 =100
Source: author's calculations basing on GUS data

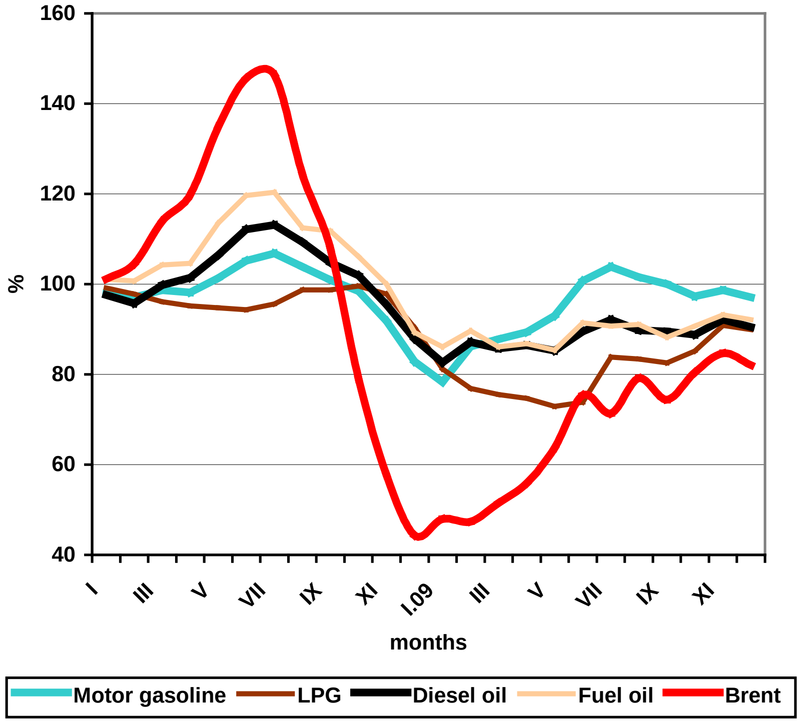


Figure 33. Price indices of selected energy carriers in Poland December 2007 =100.
Source: author's calculations basing on GUS and EIA 2010 data

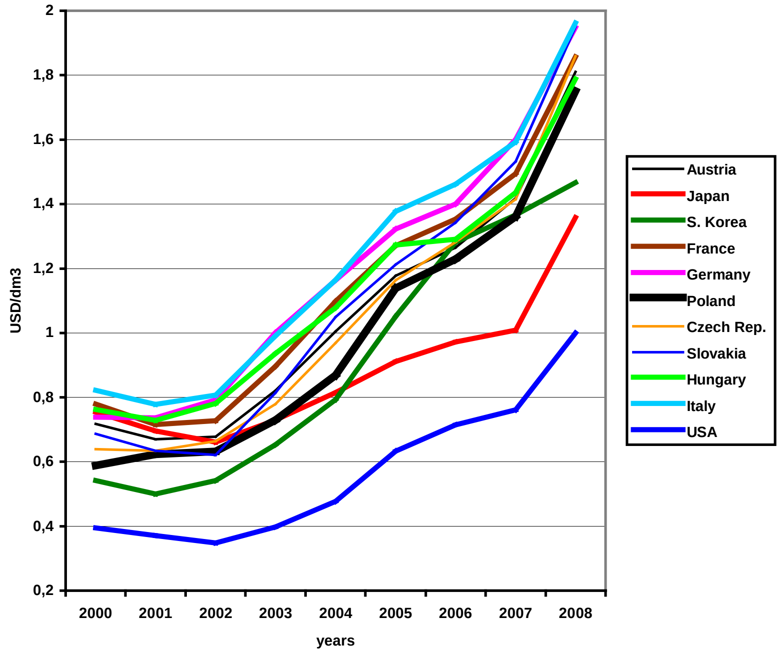


Figure 34. Prices of Diesel oil in selected countries in USD per dm^3
Source: (IEA 2009, IEA 2009a)

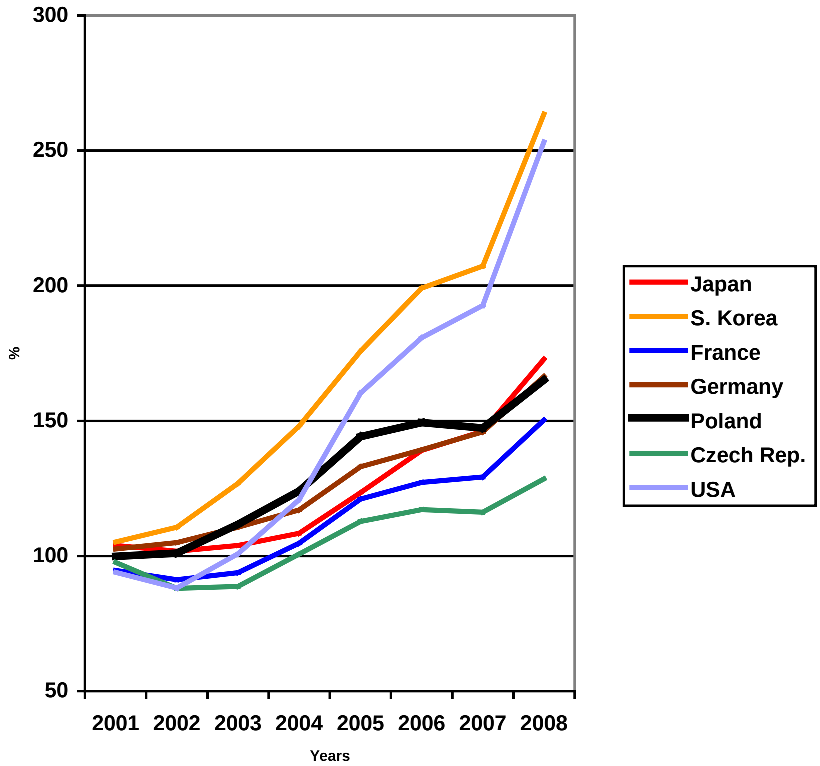


Figure 35. Price indices (in national currencies) of Diesel oil in selected countries. 2000 = 100.
Source: Author's calculations basing on (IEA 2009 and IEA 2009a)

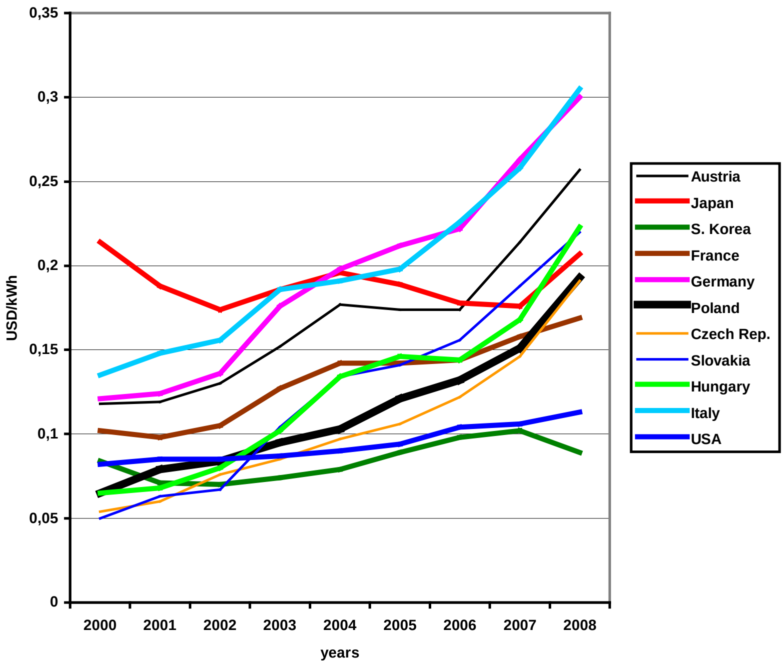


*Figure 36. Prices of electricity in selected countries in USD*kWh^{-1}*
Source: (IEA 2009, IEA 2009a)

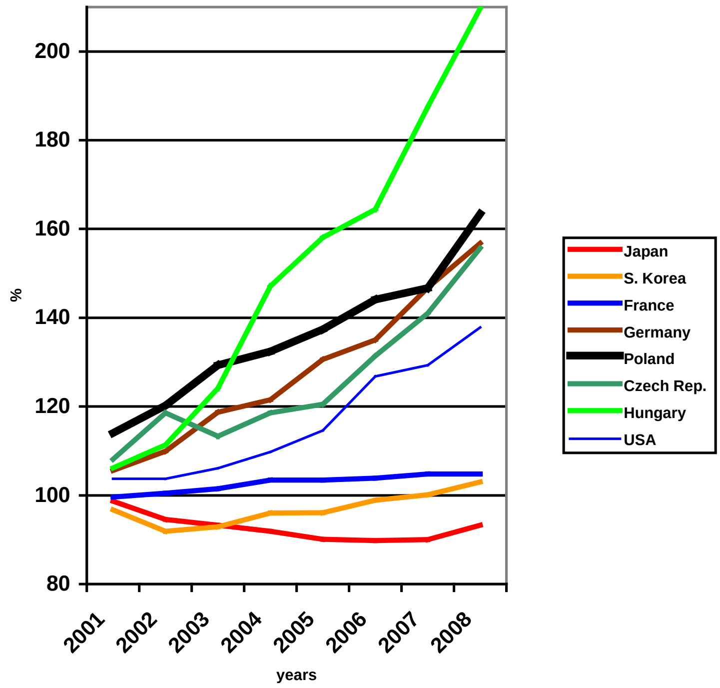


Figure 37. Price indices (in national currencies) of electricity in selected countries 2000 = 100
Source: Author's calculations basing on (IEA 2009 and IEA 2009a)

Values of unitary labour and machinery inputs when preparing of site and planting the willow for energy, received as a result of calculations using model method, are lower than the ones from research in practice [Kwaśniewski 2007, 2007a, 2008]. It has also an effect on operation costs. When building the model, optimal work organization, convenient location of plantation and a good technical shape and choice of equipment were assumed. In practice, there is difficult to fulfil all these conditions. Therefore, results received in practice are usually les favourable than the ones from model studies.

Operation costs together with material ones have an effect on efficiency of willow biomass production for energy. If the price of GJ of produced willow biomass would be equal to the price of GJ in coal-dust, even with unitary man-hour cost of 8 PLN*h^{-1} efficiency index over 1, in a case of adoption of highly mechanized technology variant II, would be available only on plantations of 50 hectares and more. Application of labour intensive variant I would assure minimal efficiency even on plantations of 2 hectares, under condition that the willow was not planted on waste land, where inputs for preparation of site are higher than on arable land or on meadows and pastures. If the price of GJ of produced willow biomass would be equal to the price of GJ in coal-dust and unitary man-hour cost of 10 PLN*h^{-1} efficiency index slightly higher than 1, in a case of adoption of highly mechanized technology variant II, would also be available only on plantations of 50 hectares and more, but under condition that the plantation was not planted on waste land. With unitary man-hour cost of 15 PLN*h^{-1}, even on plantations of 50 hectares and more, achievement of efficiency index at least 1, would not be possible irrespective of a variant of technology adopted (Figure 29).

If the price of GJ of produced willow biomass would amount to 21.4 PLN*GJ^{-1}, and unitary man-hour cost 8 PLN*h^{-1} efficiency index over 1, in a case of adoption of highly mechanized technology variant II, would be available on plantations of 2 hectares and more, but under condition that the plantation was not planted on waste land. Adoption of technology variant I would be minimally efficient even on 1 hectare plantations. With the price of GJ of produced willow biomass of 21.4 PLN*GJ^{-1}, and unitary man-hour cost of 10 PLN*h^{-1} efficiency index over 1, in a case of adoption of highly mechanized technology variant II, would be available on plantations of 2 hectares and more, but under condition that the plantation was not planted on waste land. With the price of GJ of produced willow biomass of 21.4 PLN*GJ^{-1}, and unitary man-hour cost of 15 PLN*h^{-1} efficiency index above 1, in a case of adoption of highly mechanized technology variant II, would be available on plantations of 5 hectares and more, but under condition that the plantation was not planted on waste land (Figure 30).

Above examples show that efficiency of inputs for production of willow biomass for energy purpose depends not only on size of plantation and level of mechanization, but also on kind of the site for planting.

More significant, than kind of the site for planting, is the price of produced biomass. The effect of this factor on production efficiency of the willow biomass for energy will be shown on the following examples, with assumption that the price of unit of energy in willow biomass would amount to 25 PLN*GJ^{-1}. However, we have to remember that increase of price of energy in willow biomass with constant price of fossil fuel would cause the competitiveness of biomass energy to decrease.

Price of 25 PLN*GJ^{-1} with unitary man-hour cost of 8 and 10 PLN*h^{-1} would assure efficiency index over 1, in a case of both technology variants, even on plantations of 0.5 hectare. With the price of GJ of produced willow biomass of 25 PLN*GJ^{-1}, and unitary man-hour cost of 15 PLN*h^{-1}, efficiency index over 1 would be achievable only in a case of adoption of highly mechanized technology variant II on plantations of 2 hectares and more (Figure 31).

Above examples show that by rational choice of production technology, taking into account local conditions, such as size of plantations, price of produced biomass, labour cost and kind of site for plantation, one can to have an effect on operation costs and efficiency of inputs for willow biomass production for energy.

Results of model simulation studies for Poland are more optimistic as compared to American example. Current cost to produce and deliver short rotation woody crops in the USA are 2.60-3.00 USD*GJ^{-1} [Tharakan et al 2005b]. This prices are greater than commonly used coal, which for large-scale power producers in the Northeast USA ranged from 1.40 to 1.9 USD*GJ^{-1} [Keoleian, Volk 2005]. A reason of the divergence is probably significantly higher cost of man-hour and lower price of fossil energy carriers in the USA, as compared to Poland. Next section of this chapter will show comparison of fossil fuel (Diesel oil) and electric energy prices in selected countries, including Poland and the USA.

Prices of selected conventional energy carriers

In 2009 average prices of hard coal, coke, natural gas and electricity in Poland were by 4.9 to 16.6% higher than in 2008 (Fig 32).

Instead liquid fuels derived from crude oil and LPG were by 4.1 to 16.1% cheaper (Figure 33). Both increase, and drop in prices of energy carriers originated from crude oil had clearly lower dynamics than price of raw material (crude oil – Brent).

In 2008 r. average yearly price of Diesel oil in Poland was a little lower than in West European countries as well as in Czech Republic, Slovakia and Hungary, but higher than in South Korea, Japan and much higher than in USA (Figure 34).

Diminution in value of US dollar as related to country values caused that dynamics of changes in prices in this currency was stronger then the one in national currency. Increase in prices of Diesel oil in national currencies during 2000-2008 ranged from 28.5% in Czech Republic to 163.5% in South Korea. In Poland it achieved 65.1% (Figure 35).

As compared to Western Europe also price of electricity in Poland was generally lower. However, after increases during last years it was in 2008 by 14.2% higher than in France. Lower than in Poland were in 2008 prices of electricity in South Korea, USA and Czech Republic (Figure 36).

During 2000-2008 prices of electricity in national currencies of countries being subject of the analysis increased by 3.0% in South Korea to 109.7% in Hungary. In Poland the increase by 63.4% was observed. Only in Japan decrease in price by 6.6% was noted (Figure 37).

Changes in prices of conventional energy prices have the influence on competitiveness of energy originated from renewable source including biomass.

Conclusion

Biomass production costs on willow plantations decrease, and the efficiency of production increases as the size of plantation grows.

With equal price of biomass and prices of machinery, the purposefulness of application of the high level mechanization technology variant is the higher, the larger is the willow plantation, and the more expensive is the labour.

On small-size plantations application of highly mechanized technology variant II generates higher costs as compared to labour intensive technology variant I, if the labour costs amount to 8 and 10 PLN*h^{-1}. Under such conditions, on 0.5 hectare plantation application of such technology variant is not advisable. However, increase of labour cost to 15 PLN*h^{-1} would cause the viability of the technology variant II even on 0.5 hectare plantation.

The kind of a site for planting also has an effect on the efficiency. In a case as it is planted on waste land, the inputs are higher than when it is planted on arable land or on permanent meadows or pastures.

Average prices of hard coal, coke, natural gas and electricity in Poland in 2009 were by 4.9 to 16.6% higher than in 2008, and liquid fuels derived from crude oil and LPG were by 4.1 to 16.1% cheaper.

In 2008, average yearly prices of Diesel oil and electricity in Poland were, in general, a little lower than in West European countries, but higher than in South Korea, Japan and the USA.

Research undertaken within the interdisciplinary project "Modelling of biomass utilization for energy purpose” provides data enabling the choice of technology of production of energy crop the most convenient from economic point of view. The choice has to include in reckoning local conditions, effecting both the yield and quality of product. That is why results from different habitats are needed.

The analysis shows the usability of the method adopted in this work to evaluate the efficiency of biomass production for energy. Received results prove that the choice of suitable technology can improve the efficiency of willow for energy production.

The diversity of both natural conditions and other factors having an effect on economic efficiency of production of energy crop cause that continuation of research in this field is necessary. Use of biomass for energy, as the renewable energy source is to be a way to protect the environment. Therefore, economic analyses have to take into consideration also environment costs.

5.2 Costs and profitability of production of energy crops

Aleksander Muzalewski

Summary

The research of cost and profitability was carried out in the six plantations of willow, miscanthus and Sida hermaphrodita. Cost of production of energy crops in the entire lifetime of the plantation ranges from 1546 to 2640 PLN/ha/year and in terms of calorific value of biomass - from 13.2 to 32.7 PLN/GJ. In the structure of production costs operating costs of mechanization dominate. Their share is in the range from 31.1% to 47.6%. The results indicate a relatively high profitability of energy crops on most of the studied plantations. A proof of this is profit from 344 to 900 PLN/ha/year achieved on five plantations. However, on 1.6 hectares of willow plantations a negative financial result was received.

Introduction

Profitability of production of energy crops is conditioned by the prices charged by energy sector for agricultural biomass and its production cost [Ericsson et al. 2009]. For the development of this kind of production, the implementation of effective cultivation technology is also important [Chołuj et al. 2008], including the specialized machinery, especially to harvest willow [Muzalewski 2009]. These factors influence on the risk associated with investing in long-term energy plantations and decide on the profitability of this kind of production.

Purpose and scope of research

The aim of the study is to analyze and evaluate costs and profitability of production of selected energy crops. The study included plantations established in 2004-2008:

- Willow (Salix viminalis) with areas of 1.6 and 71 ha,
- Miscanthus (Miscanthus sinensis x giganteus) with areas of 5 and 20 ha,
- Sida hermaphrodita with area of 1 and 4 ha.

Selected elements of the surveyed plantations are presented in Table 44

The method of research

Production inputs and their costs were analyzed throughout the lifetime of plantations, which include: the establishment, operation and liquidation of plantations, including the cost of handling (from field to farm). Data for analysis were collected during the visits of plantations in the first half of 2009. Above-mentioned data concern the process of production and costs incurred in the first years of energy crops production. As a result of combination with literature data ([Dubas 2006], [Faber et al. 2009], [Gostkowski 2006], [Kowalczyk-Juśko and Gradziuk 2006]), the determination of the further course of production process was possible, including assessment of costs and benefits of throughout the lifetime of the plantation also including the costs of liquidation [Stolarski 2008].

Costs of production of energy crops in the entire lifetime of the plantation were calculated according to the level of net prices (excluding VAT) at the end of 2009. These costs include both the costs of any material inputs, including depreciation of capital assets and costs of labour and money considerations (insurance, taxes).

Costs of machinery on the plantations were determined by calculation method [Muzalewski 2009], also using indicators for selected machines according to German sources [KTBL 2006].

The costs of machinery services were accounted according to market prices or estimated using calculation method.

The cost of human labour inputs was calculated at parity rate of salary, equal to 15 PLN/hour.

For the analysis of the profitability of production of energy crops the term of profit was used as the difference between incomes and production costs.

The revenues associated with the production of energy crops consist of the value of harvested yield and potential revenues in the form: Single Area Payment Scheme (SAPS), payments to favoured areas (LFA), payments for energy crops (RE) and a grant to establish perennial energy crops (TRE). It should be noted that since the beginning of 2010 the support for the production of energy crops in the form of payments RE and grants TRE are no longer used.

To estimate the value of the harvested yield of energy crops a purchase price was assumed in the amount of 18 PLN/GJ of calorific value.

Characteristics of surveyed plantations

The characteristics of surveyed plantations are given in Table 44. The lifetime of the plantation adopted to analyze, covering the years of direct energy crop production in the subsequent cycles (1 - or 3-year), as well as one year necessary to prepare the field to establish and liquidation of the plantation, amounts from 16 to 20 years, depending on the kind of plantation. The average dry matter yield of harvested crops, estimated on the basis of empirical data and the forecasts of further use of plantations, was in the case of willows 6.88 and 8.00 t/ha/year, miscanthus 10.45 and 11.08 t/ha/year, and Sida hermaphrodita 9.28 and 10.82 t/ha/year throughout the lifetime of plantations. The humidity of harvested willow chips was 55%, bales of miscanthus 30% and Sida hermaphrodita (bales or chaff) 18-20%.

Table 44. Characteristics of tested plantations of energy crops

Items	Willow		Miscanthus		Sida hermaphrodita	
Symbol of plantation	W1	W2	M1	M2	S1	S2
Plantation area, ha	1.6	70.9	5.0	20.0	1.0	4.0
Useful life, years	20	19	16	16	16	16
Transport distance, km	1.5	2.0	1.25	4.0	0.3	2.0
Date of planting (sowing)	IV.2005	XI.2005	IV.2006	IV.2006	IV.2008	IV.2004
Density of plant., 1000 pcs./ha	29	18	10	10	28	29.6
Number of harvesting cycles	1+6	6	15	15	15	15
Form of harvested biomass*	S. C	C	B	B	CH	B
Yield of fresh mass, t/ha/year	15.30	17.78	14.93	15.83	13.20	11.6
Humidity of biomass, %	0.55	0.55	0.30	0.30	0.18	0.20
Dry matter yield, t/ha/year	6.88	8.00	10.45	11.08	10.82	9.28
Calorific value, GJ/t f.m.	6.63	6.63	12.38	12.38	13.66	13.25

Source: Own research in the project EN 0073
** S - long shoots, C - willow wood chips, B – bales of pressed plants, CH - chaff.*

Production technology and level of expenditures

On the plantation W1 (1.6 ha) willow cuttings were planted by hand. The harvest of willow stems were made by tractor mower with a cutting disc. The cut stems were stacked near the field, and then they were brought to the farm and after seasoning were chipped by stationary chipper.

The first harvest was performed in the year after the planting and further six production harvests were performed in the three-year cycles.

On the plantation W2 (70.9 ha) the planting of willow was carried out by planter in quantities of 18.000 pcs/ha. The harvest was done by a self-propelled forage harvester (317 kW) with extra shearing unit HS-2 (see Phot. 6) [Muzalewski 2009]. Willow chips were brought to the farm by volume trailers. Willow harvests were realized in three-year cycles.

Plantations M1 (5 ha) and M2 (20 ha) were planted by planters in an amount of about 10.000 pieces of Miscanthus rhizome per hectare.

On the plantation S2 (4 ha) seeds of Sida hermaphrodita were sown by drilling machine. Disc mowers with conditioner were used for annual cutting of miscanthus and Sida hermaphrodita on each of the above three plantations. Cut-off straw was collected by big balers forming rectangular bales with a volume of about 2.0-2.1 m^3 and a weight of 300-360 kg (Phot. 7).

Phot. 6. Harvesting of willow with self-propelled forage harvester with a unit HS-2 (Photo by W. Markiewicz IBMER)

Phot. 7. Harvesting of Miscanthus with baler (Photo: L. Hak Agro-Energy)

Telescopic handlers were used for loading bales on the trailers, as well as for unloading and stacking them on the farm. Bales of pressed energy plants were brought to a farm with specialized platforms for straw bales, and on the plantation M1 (5 hectares) with the usual tractor trailers. On a small plantation S1 (1 ha) planting of Sida hermaphrodita was made by hand from prepared on the farm seedlings. One row tractor harvester-chipper was applied for Sida hermaphrodita harvesting.

The studied plantations differ in the energy inputs, and in particular in the level of mechanization of work (Table 45).

Table 45. Production inputs on particular plantations

Items		Willow		Miscanthus		Sida hermaphrodita	
Symbol of plantation		W1	W2	M1	M2	S1	S2
Plantation area, ha		1.60	70.9	5.0	20.0	1.0	4.0
Fertilizers NPK, kg/ha/year		76.8	90.4	61.9	111.9	116.8	125.1
Labour, h/ha/year		70.1	9.9	9.5	6.0	36.4	7.1
Energetic means	h/ha/year	16.7	5.7	7.5	5.2	16.6	5,7
	kWh/ha/year	610	512	651	469	704	486
Diesel oil, l/ha/year		87.8	66.4	87.8	62.8	95.5	65.3

Source: Own research in the project EN 0073

On plantations W1 and S1, located in small farms, labour-intensive production technologies dominate, using tractors of low power and low-capacity machines. Much work is done by hand with the result that unit labour inputs are very high and are respectively 70.1 and 36.4 h/ha/year. Plantations W2, M1, M2 and S2 are run by large agricultural enterprises, which possess powerful tractor-machine sets and self-propelled machinery. Production technologies used in these enterprises for energy crops are characterized by very low unitary labour inputs - from 6.0 to 9.9 h/ha/year.

The average consumption of fertilizers throughout the lifetime of the studied plantations amounts (in a pure component) from 61.9 to 125.1 kg/ha/year, and Diesel oil from 62.8 to 95.5 l/ha/year (Table 45). The inputs of energy means (tractors, mobile machinery, motor equipment) ranges from 5.2 to 16.7 h/ha/year and in units of energy from 469 to 704 kWh/ha/year.

Production costs

The highest cost of production of energy crops was found on a willow plantation of 1.6 hectares (2640 PLN/ha/year), and lowest on the willow plantation of 70.9 ha (1546 PLN/ha/year) (Table 46). The production costs of miscanthus and Sida hermaphrodita on all four tested plantations ware similar and ranged from 2192 to 2499 PLN/ha/year.

Operating costs of the means of mechanization dominate in the cost structure of energy crops production. Their share is in the range of 31.1% (plantation S1) to 47.6% (W2) (see Figures 38-40). In the case of poorly mechanized production technologies on small plantations of willow (1.6 ha) and Sida hermaphrodita (1 ha) high proportion of labour costs was found, respectively 39.8 and 21.8%.

Table 46. Costs of production of energy crops

Items		Willow		Miscanthus		Sida hermaphrodita	
Symbol of plantation		W1	W2	M1	M2	S1	S2
Plantation area, ha		1.60	70.9	5.0	20.0	1.0	4.0
Total cost	(PLN/ha/year)	2640	1546	2377	2426	2499	2192
	(PLN/t f. mass	216.6	91.8	169.8	163.5	216.1	201.5
	(PLN/GJ)	32.7	13.8	13.7	13.2	15.8	15.2

Source: Own research in the project EN 0073

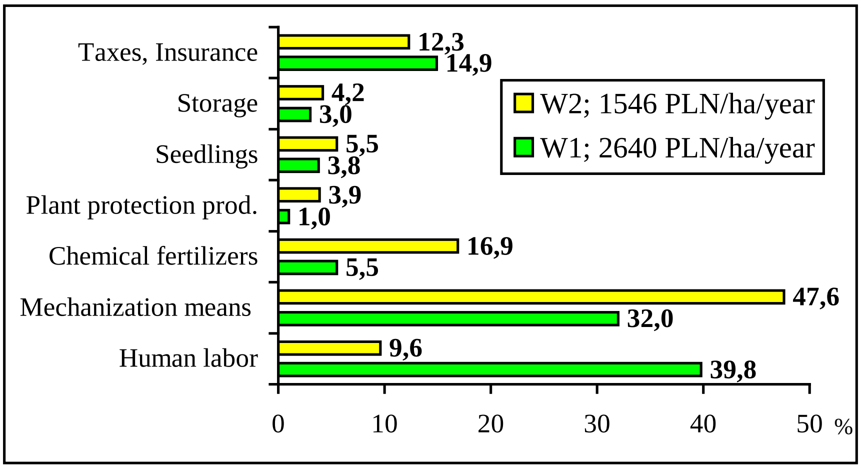


Figure 38. Structure (%) of production costs for willow plantations W1 and W2 according to the type of inputs.

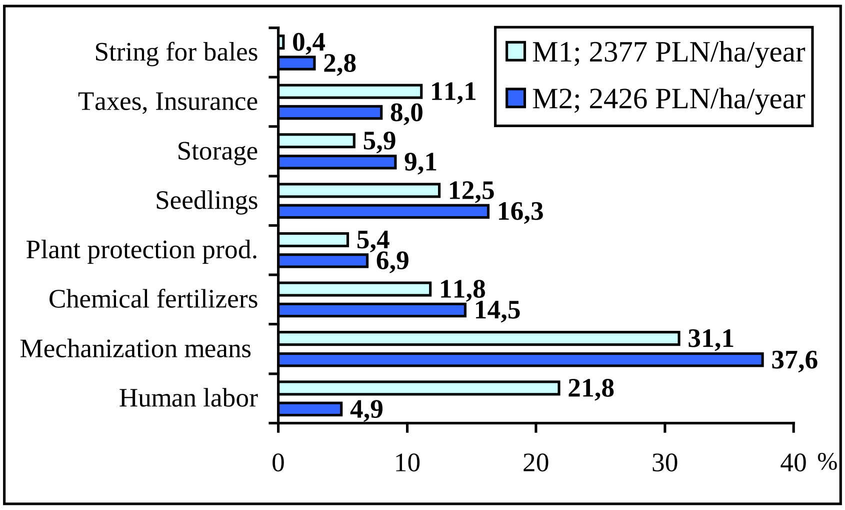


Figure 39. Structure (%) of production costs for Miscanthus plantations M1 and M2 according to the type of inputs.

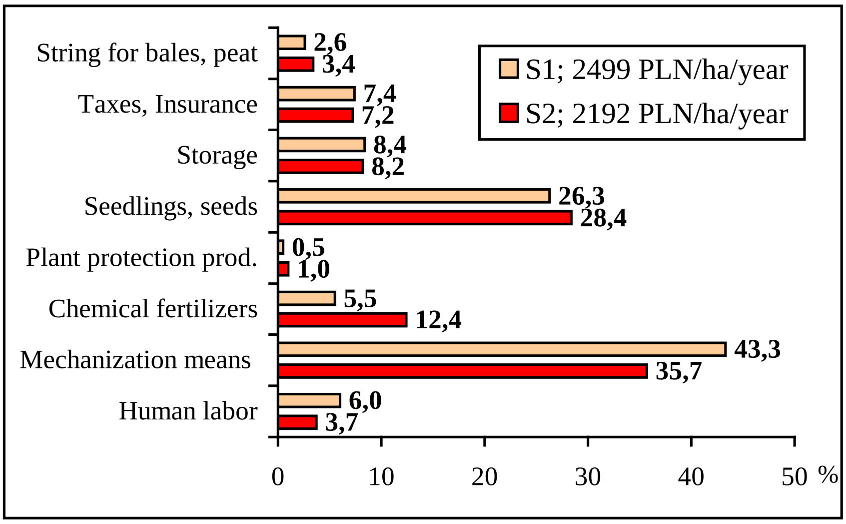


Figure 40. Structure (%) of production costs for Sida hermaphrodita plantations S1 and S2 according to the type of inputs.

On the plantations of miscanthus (M1 and M2) the costs of purchase of planting material (rhizomes) had a significant share in production costs, respectively 26.3 and 28.4%. The share of the cost of consumed fertilizer in the cost of production of energy crops varies from 5.5 to 16.9% and the share of used chemical plant protection means - from 0.5 to 6.9%, depending on the plant or technology.

In the cost structure of energy crops production by type of operation (Table 47), the highest average share have activities directly related to the harvest (19,2-34,5%), followed by mechanical planting of miscanthus rhizomes (27.9 and 29, 4%) and manual planting of Sida hermaphrodita seedlings (19.4%).

Table 47. The level and structure of production cost of energy crops on the plantations examined by type of production operations

Items	Willow		Miscanthus		Sida hermaphrodita	
Symbol of plantation	W1	W2	M1	M2	S1	S2
Plantation area, ha	1.60	70.9	5.0	20.0	1.0	4.0
Total cost (PLN/ha/year), including (%):	2640	1546	2377	2426	2499	2192
Soil cultivation	0.5	1.7	1.4	1.1	1.2	1.0
Fertilization	6.8	21.1	6.4	14.4	13.8	19.7
Plant protection/care	10.2	4.1	0.2	0.9	12.0	9.4
Planting (seeding)	6.5	7.3	27.9	29.4	19.4	16.5
Harvesting	26.5	26.6	34.5	28.4	19.2	25.9
Handling, stacking bales, shaping prism	5.9	14.4	12.7	9.4	16.3	9.4
Chipping	22.5	-	-	-	-	-
Liquidation of plantation	3.2	8.2	1.1	1.1	1.2	1.0
Overheads and Inventory	3.0	4.2	8.4	8.2	5.9	9.1
Taxes and insurance	14.9	12.3	7.4	7.2	11.1	8.0

Source: Own research in the project EN 0073

These costs include operating costs of used tractors and machinery, the people involved and consumable materials and other inputs (seedlings, rhizomes, string for balers etc.). In the case of plantation W1 a significant share (22.5% of production costs) also has the costs of chipping the willow shoots with stationary chipper.

Profitability of energy crops

The category of profit (P) was used to assess the profitability of production of energy crops. The profit P1 from the production of energy crops, determined as the difference between value and costs of production, on the plantations W2, M1, M2, S1 and S2 was from 344 to 880 PLN/ha/year (Table 48). Only on a willow plantation W1 (1.6 ha) a distinct loss of -1186 PLN/ha/year, on average throughout the lifetime of the plantation, has been observed. Among the surveyed crops miscanthus had the highest profitability of production (profit P1 = 743 and 880 PLN/ha/year). Profit from the production of Sida hermaphrodita was over twice lower (P1 = 344 and 402 PLN/ha/year).

Table 48. Calculation of profit (in PLN/ha/year) from the production of energy crops

Items	Willow		Miscanthus		Sida hermaphrodita	
Symbol of plantation	W1	W2	M1	M2	S1	S2
Plantation area, ha	1.6	70.9	5.0	20.0	1.0	4.0
Production value	1454	2011	3120	3306	2843	2594
- Production costs	2640	1546	2377	2426	2499	2192
= Profit P1	**-1186**	**464**	**743**	**880**	**344**	**402**
+ SAPS	507	507	507	507	507	507
= Profit P2	**-679**	**971**	**1250**	**1387**	**851**	**909**
+ LAF	179	179	179	179	179	179
= Profit P3	**-500**	**1150**	**1429**	**1566**	**1030**	**1088**
+ RE	181	180	178	178	178	178
+ TRE	215	226	338	338	191	191
= Profit P4	**-104**	**1557**	**1945**	**2082**	**1400**	**1457**

Source: Own research in the project EN 0073

The level of profit is significantly increased by the payments and subsidies for energy crops (SAPS, LFA, RE, TRE). In 2009, the total amount of these potential revenues on surveyed plantations of willow amounted from 1012 to 1092 PLN/ha/year, miscanthus - 1202 PLN/ha/year and Sida hermaphrodita – 1055 PLN/ha/year. On the willow plantation W1 total of these payments limited potential loss for P4 to -104 PLN/ha/year, and on the remaining five plantations increased value of the profit P4 from 1400 PLN/ha/year (plantation S1) to 2082 PLN/ha/year (plantation M2).

For the market price of the biomass of 18 PLN/GJ, calculated purchase price of fresh biomass ranges on the tested plantations from 119.3 PLN/t to 245.9 PLN/t, depending on the species and the calorific value of plants (Tables 44 and 49).

In order to ensure the profitability of willow production on plantation W1, the equilibrium price EP1, i.e. the price paid for the willow chips which balances the production costs (profit P1 = 0), should be 216.6 PLN per 1 tonne of fresh chips (Table 49).

After taking into account all of the potential payments to the willow plantation the equilibrium price EP4 (for profit P4 = 0) decreases up to 127.9 PLN/t. On the other five profitable plantations market prices of energy crops are higher than the calculated equilibrium prices.

Table 49. Purchase and equilibrium prices of energy crops

Items		Willow		Miscanthus		Sida hermaphrodita	
Plantation area, ha		1.6	70.9	5.0	20.0	1.0	4.0
Purchase price	PLN/GJ	18.0					
	PLN/t fresh m.	119.3	119.3	222.8	222.8	245.9	238,5
Equilibrium price (PLN/t fresh m.):							
EP1 for P1 = 0		216.6	91.8	169.8	163.5	216.1	201.5
EP4 for P4 = 0		127.9	26.9	83.9	82.5	124.8	104.5

Source: Own research in the project EN 0073

Summary

The production costs on six surveyed plantations of energy crops range from 1546 PLN/ha/year (plantation W2) to 2640 PLN/ha/year (W1), and in terms of calorific value of the harvested biomass - from 13.2 PLN/GJ (M2) to 32.7 PLN/GJ (W1). In the structure of production costs operating costs of mechanization dominate; their share is in the range of 31.1% (plantation S1) to

47.6% (W2). Similarly, in the structure of production costs by type of operations the highest average share has the harvesting of energy crops (19.2-34.5%).

The results of field research, including analysis of inputs, production costs and effects, indicate a relatively high profitability of energy crops on most of the studied plantations. A proof of this is achieved in five plantations profit (Z1) in height from 344 to 880 PLN/ha/year. The scale of this gain can be significantly enlarged by the potential payments for energy crops (SAPS, LFA, RE, TRE). A loss of 1180 PLN/ha/year was recorded only on a willow plantation of 1.6 hectares. This loss was primarily caused by too labour-consuming production technology, in relation to the effects achieved.

It should be noted that the results of the analysis are based on data from the first years of use of plantations (plantations were established in 2004-2008), assuming a model production processes in the subsequent years of use of the plantation. High profitability of production of energy crops, found in this study, is due to the effect of relatively high yields, in relation to the average mineral fertilizer inputs (62 ÷ 125 kg of NPK/ha/year), and chemical plant protection means.

The final cost-effectiveness of production and marketing of energy crops will be determined by the management of harvested biomass, including transport costs to power plants, as well as any additional costs of converting biomass (drying, briquetting, pelleting).

6

Monitoring methods of remote sensing elaborations energy crops

6.1 Application of remote sensing based information for monitoring development of plants used for energy production

Katarzyna Dąbrowska–Zielińska, Zbigniew Bochenek, Maria Budzyńska

Summary

The aim of the Project is to develop the methodology for monitoring development of plants for energy production in order to estimate their biomass. It is made by analysis of plant growth conditions and increase of biomass based on satellite images with low- (AVHRR, TERRA MODIS) and high spatial resolutions (Landsat ETM). Firstly, terrain works were made, which were focused on locating and describing growth conditions and the area for fourteen plantations of energetic willow. At the second stage, the analysis of satellite images has been made, from which NDVI index was estimated, for the 2005 –2008 growing seasons. Additionally, radiation temperature of vegetation was estimated from MODIS data. Those studies allow us to state that remote sensing gives us the possibility of monitoring the plantations of plants for energy production, and finding out in which season they should be irrigated. The remote sensing approach allows also to choose less-favoured agricultural areas, which can be used for setting plantations mentioned above.

Theoretical Background

Remote sensing based information can be an effective tool for determining areas of plants for energy production and for biomass monitoring. In particular, various types of satellite data, including high-resolution images, acquired by Landsat, SPOT and ASTER satellites, and medium resolution images of MODIS type, are predestined for this kind of work. In the presented work it was assumed, that several types of satellite images, characterized by different spatial and spectral resolutions, will be used, in order to precisely characterize development of plants for energy production and infer on their biomass amount.

Possibilities of monitoring plant development with the use of remote sensing technique is closely related to behaviour of radiation, while interacting with vegetation. Reflection and absorption of radiation by plants is dependent on leaf pigments, water content and cellulose. These substances react differently to radiation, depending on wavelength. In visible range, covering 400 – 700 nm wavelengths, reflection is controlled by pigments contained in leaves. Part of visible radiation is absorbed and used in photosynthesis process. Chlorophyll a and b are the main assimilation pigments taking part in this process. They have maximum of absorption in blue (ca. 450 nm) and red (ca. 680 nm) part of spectrum, while reflection of radiation by vegetation is located in green (ca. 550 nm) radiation range. In near infrared range (700 – 900 nm) high increase of reflection is observed. Magnitude of near infrared reflection is highly dependent on type of plants, creating possibilities of their distinguishing.

In a case of longer infrared wavelengths changes in reflection depend mainly on water content in plant cells, as well as on content of lignin and cellulose. High content of water in plant cells causes decrease of reflection of infrared radiation, while in drought conditions, for plants under water stress, reflection in this spectral range significantly increases.

Knowledge on reflection of radiation by vegetation in visible and near infrared bands and emission of radiation in far infrared band was a basis for construction of instruments recording these wavelengths of spectrum. These instruments, called multispectral scanners are installed on boards of numerous environmental satellites. Two radiation bands – red and near infrared - proved to be especially important for studying vegetation, hence they were used most frequently for constructing vegetation indices, characterizing plant development.

In order to examine usefulness of remote sensing data for monitoring plants used for energy production two types of satellite images were used - images with high temporal frequency (NOAA AVHRR, TERRA MODIS), characterized by relatively low ground resolution (250 – 1000 m), as well as archival and recent high-resolution images of Landsat ETM type. The aim of the analyses was to prepare methodology of monitoring development of plants for energy production in order to estimate their biomass. This type of work has been already carried out at the Institute of Geodesy and Cartography in relation to the main crops and grasslands (Dabrowska-Zielinska K., 1995). As a result of these works the system for monitoring crop/grassland conditions with the use of low-resolution satellite images has been elaborated, as well as method for forecasting yield of the main crops has been prepared. Experience gained in the course of these activities was used for conducting tasks within the presented work.

Vegetation indices used for environmental studies

Among several remote sensing based indices used for monitoring vegetation the most commonly are: simple Vegetation Index (VI) and more modified Normalized Difference Vegetation Index (NDVI). These indices serve first of all for locating vegetation, but also for determining biophysical parameters of plants (Running et al., 1994).

Vegetation Index VI is defined as ratio of radiation reflected in near infrared and red band. It is described by a formula:

$$VI = \frac{\rho_{NIR}}{\rho_{RED}}$$

where:

ρ_{NIR} - reflectance in near infrared band;

ρ_{RED} - reflectance in red band.

This index emphasizes vegetation on the satellite image through its distinguishing from other land cover categories existing on Earth surface.

Normalized Difference Vegetation Index (NDVI) is the most frequently used index for vegetation studies. It is described by a formula:

$$NDVI = \frac{(\rho_{NIR} - \rho_{RED})}{(\rho_{NIR} + \rho_{RED})}$$

This index can vary from -1 to +1. Positive values appear for areas, where near infrared reflectance is higher than that in red band. Negative values are characteristic for areas not covered with vegetation. In a case of positive NDVI values its magnitude is determined by density of vegetation canopy (biomass) and its vigour.

If vegetation cover is sparse, VI and NDVI indices are influenced by reflection of radiation from soil. Depending on soil colour magnitude of both indices can be higher or lower; dark soils cause their increase, while bright soils decrease. Soil moisture also has impact on both indices; wet soil has similar reflectance as dark soil, so it increases magnitude of VI and NDVI indices.

NDVI index is a basis for deriving new index, especially used for monitoring vegetation, while having long series of satellite observations. It is called Vegetation Condition Index (VCI) and is constructed, taking into account minimum and maximum NDVI value from multiyear NDVI data, The following formula is applied for this index:

$$VCI = 100\frac{NDVI - NDVI_{\min}}{NDVI_{\max} - NDVI_{\min}}$$

Beside these commonly used indices also other vegetation indices are worth mentioning, especially those, which consider impact of aerosols in the atmosphere on amount of reflected radiation. Many of them were recently tested – Atmospherically Resistant Vegetation Index (ARVI), Soil Adjusted Vegetation Index (SAVI), Global Environment Vegetation Index (GEMI). Studies on these indices led to elaborating Environment Vegetation Index (EVI), which became one of vegetation products offered from TERRA MODIS data. This index is based on red, infrared and blue band, which is highly absorbed by plants and scattered by atmospheric aerosols. The index compensates the effect of radiation scattering, being calculated according to formula:

$$EVI = 2{,}0\times\left(\frac{\rho_{NIR} - \rho_{RED}}{1 + \rho_{NIR} + 6\rho_{RED} - 7{,}5\rho_{BLUE}}\right)$$

Apart from indices based on reflected radiation, also some indices which use long wave, far infrared radiation are applied. Among them the most known is Temperature Condition Index – TCI, which takes into account minimum and maximum temperature within time series temperature data. It is determined according to formula:

$$TCI = 100\frac{Ts_{\max} - T}{Ts_{\max} - Ts_{\min}}$$

TCI index characterizes water availability for vegetation development. It is changeable throughout vegetation period – its low values in early spring confirm good conditions of plant development, while in later phases of vegetation period they can be an indicator of stress conditions, leading to drought situation.

Preparatory Field Campaign

At first stage of research works plantations of plants for energy production, to be used for remote sensing based analyses, were selected. They were indicated by the Institute for Building, Mechanization and Electrification of Agriculture (IBMER) within podkarpackie, lubelskie and kujawsko-pomorskie voivodeships. 16 plantations of willow used for energy production were located and described on the area of the following counties and communes:

- Ropczycko-sedziszowski county – Ostrow and Ropczyce communes
- Stalowowolski county – Stalowa Wola commune
- Tarnobrzeski county – Nowa Deba commune
- Lubaczowski county – Lubaczow and Oleszyce communes
- Przemyski county – Fredropol commune
- Bydgoszcz county – Dobrcz commune

Location of each plantation was done on the basis of its general description, applying for precise location GPS measurements. After finding plantation in the field, its accurate boundaries were drawn on the 1:100 000 map and on the Landsat Thematic Mapper satellite image. Exemplary image of Stalowa Wola plantation is presented in Figure 41. Next development stage and size of each plantation was described. The selected plantations were characterized by various development stages – from recently harvested to dense vegetation cover up to 4 meters high. Also size of plantations varied – from 7 ha at Nowa Deba commune to 80 ha at reclamation dump close to Stalowa Wola.

As a result of field work the technical report has been prepared; it contained the detailed information on location and development stage of the selected plantations. This information was indispensable for next phases of the work, when different types of satellite data were applied.

Analysis of high-resolution satellite images for the selected plantations

At first stage of the works application of high-resolution satellite images for monitoring biomass of plants used for energy production was studied. Landsat Thematic Mapper images were used for this purpose; they were collected from archival resources for 8 plantations, located in 4 voivodeships (podkarpackie, lubelskie, swietokrzyskie, and kujawsko-pomorskie), namely for:

- Stalowa Wola plantation – ca. 80 ha
- Lubaczow plantation – ca. 40 ha
- Chmielow plantation – ca 38 ha
- Tarnowska Wola plantation – ca 24 ha
- Rozwienica plantation – ca. 10 ha
- Chotelek plantation – ca. 20 ha
- Marcelewo plantation – ca. 50 ha
- Suponin plantation – ca. 41 ha.

Landsat Thematic Mapper images were collected for 2006 – 2007 period, for different vegetation phases (from May till September). Changes of NDVI index in this period for 6 plantations located in southern Poland were presented in Figure 42. Changes of NDVI values illustrate fluctuations of this index, depending on vegetation phase and environmental conditions. At middle phase of 2006 vegetation period (June – July) for all analyzed plantations high NDVI values were observed, manifested due to dense plant canopy and good growth conditions (no water deficit). In September 2006 decrease of NDVI index appeared for majority of plantations, related to development cycle of plants and management practices conducted on plantations. Similar situation could be observed on the basis of available 2007 Landsat TM images.

Special emphasis was put to two plantations – Marcelewo and Suponin - monitored by the Institute for Land Reclamation and Grassland Farming (IMUZ) and the Plant Breeding and Acclimatisation Institute (IHAR). They are located in kujawsko-pomorskie voivodeship (Bydgoszcz district). Both institutes make on these plantations regular measurements of agro meteorological parameters: air temperature, soil moisture, amount of precipitation and sunshine.

In the course of field work information concerning development cycle and agronomic practices for both plantations was collected. Also air temperature, monitored by IHAR, was obtained. All types of information were used in the course of analysis of 2006 – 2007 Landsat Thematic Mapper images, acquired for Marcelewo and Suponin plantations.

Analysis of low-resolution satellite images for the selected plantations

Due to needs of long-term, regular monitoring of the selected plantations analysis of application of low-resolution satellite images was done at the next stage of the works. The data were acquired by AVHRR scanner installed on the boards of NOAA satellites. This scanner enables to collect radiation information in 5 spectral bands, covering visible, near infrared and far infrared ranges. Ground resolution of these images is 1000 m. NOAA AVHRR images are daily captured at the Institute of Geodesy and Cartography with the use of NOAA receiving station. They are next processed in order to derive vegetation index – NDVI, characterizing development stage of plants. Acquisition of images in a daily sequence and their analysis in ten-day's cycle enables to monitor vegetation growth and to infer information on amount of biomass.

Database of NOAA AVHRR satellite images, existing at the Institute of Geodesy and Cartography, beside original data, contains their various transformations, including ten-day composites of Normalized Difference Vegetation Index – NDVI, covering 1997 – 2010 period. For the presented work NDVI images covering 2005 – 2008 period, i.e. period of development of plantations of willow used for energy production, were applied. Three the largest plantations were selected, namely:

- Plantation close to Chmielow - ca. 38 ha
- Plantation close to Lubaczow - ca.40 ha
- Plantation close to Stalowa Wola - ca. 80 ha

For each plantation, located on the satellite images with the use of coordinates, measured in the course of field work, values of NDVI index were determined in the succeeding decades of vegetation period, i.e. from April till September.

On the basis of NDVI index determined for the selected plantations in 2005 – 2008 period graphs representing variability of this index were prepared. They were presented in Figures from 43 to 46.

Analysis of changes of NDVI index through vegetation periods reveals high differentiation resulting from vegetation conditions and development phase of plants. In 2005 at the beginning increase of NDVI was blocked for all 3 plantations, while later up to July quite even increase was observed; afterwards lower NDVI values appeared due to unfavourable weather conditions. Similar situation was observed in 2006, when at first two decades values of NDVI did not grow much, while in the succeeding period, up to beginning of July increase of this index was observed, followed by gradual decrease for all plantations (and for reference podkarpackie voivodeship) up to end of August.

Different situation, expressed by NDVI changes, appeared in 2007. At first part of vegetation period (April – May) fluctuations of NDVI were observed for all plantations, with increase up to mid-June, decrease with minimum at the end of July / beginning of August and gradual increase up to end of August. Slightly similar shape of NDVI curves was observed in 2008. Fluctuations of NDVI appeared in April, next maximum values were reached in June / beginning of July, followed by decrease up to mid-August and slight increase at the end of August.

Values of NDVI index were also studied in time profile 2005 -2008. Its comparison reveals, that depending on agrometeorological conditions NDVI values at the same decade in various years can differ, indicating shift of start of vegetation period or drought conditions. Comparative analysis of this type was presented on the example of Stalowa Wola plantation in Figure 47.

Analysis of TERRA MODIS satellite images in 2006 – 2008 time profile

MODIS instrument (Moderate Resolution Imaging Spectroradiometer) installed on the board of TERRA satellite records radiation in 36 narrow spectral bands from 400 till 14400 nm. First two spectral bands 620 – 670 nm and 841 - 876 nm are characterized by the highest ground resolution – 250 meters; they are applied for calculating Normalized Difference Vegetation Index – NDVI. The remaining bands have ground resolution of 500 m (for visible spectrum) and 1000 m (for middle and far infrared). Path width for MODIS instrument is 2330 km, which allows for collecting data for the same area with daily frequency. On the basis of daily images various products are generated, for instance 8-day composites of NDVI index and radiation temperature. These products are stored at the database of the Institute of Geodesy and Cartography; they were used for conducting next stage of the works.

In this stage TERRA MODIS data collected in 2006 – 2008 vegetation periods (April – September), were analyzed. Two parameters were taken into consideration: NDVI index and radiation temperature of plants. The analysis was done for Marcelewo plantation, which is monitored by 2 agricultural institutes – ITP (former IMUZ) and IHAR.

Changes of NDVI MODIS for Marcelewo plantation in three vegetation periods – 2006, 2007 and 2008 – are presented in Figure 48. Analysis of these graphs generally confirms characteristics of NDVI changes obtained on the basis of NOAA AVHRR images. Development of plantation starts at the beginning of April 2006 from low NDVI values; next gradual increase is observed up to maximum value at the end of June. At the second part of 2006 vegetation period fluctuations of NDVI index, related to meteorological conditions, appear. Changes of NDVI in 2007 reveal differentiated development conditions at first stage of vegetation period, expressed by relatively slow increase of the index. In the middle of vegetation period (June) significant increase of index was observed and its stabilization on the high level for a quite long time. In 2008 relatively slow increase of NDVI index appeared till beginning of July, followed by its quite high values till the end of vegetation period.

Similar graphs were prepared for changes of radiation temperature, determined on the basis of thermal channels of MODIS instrument. They are presented in Figure 49. Graphs reveal quite high fluctuations of temperature, in particular at middle and second part of vegetation period, with amplitude, which is different for 3 years under study (2006, 2007 and 2008). In order to analyze, if these fluctuations had impact on plant development, it was decided to compare values of radiation temperature, derived from satellite data with air temperature, measured at the same time in the field. So, first graphs illustrating changes of air temperature in three vegetation periods – 2006, 2007 and 2008 - were prepared; they were presented in Figure 50. Next for succeeding 8-day periods differences between radiation and air temperature were calculated. Magnitude of these differences can be an evidence of stress conditions in plant development. Changes of temperature differences within vegetation periods (2006, 2007 and 2008) were presented in Figure 51.

In order to examine, how described above conditions of plant development can affect amount of biomass, expressed by cumulated NDVI index, graphs representing this index were prepared for three vegetation periods. They were presented in Figure 52. It results from their analysis, that at first two years of plantation development increase of biomass was similar, while in third year (2008) distinct increase of biomass, expressed by cumulated NDVI index, was observed, especially in the second part of vegetation period. It proves, that high amount of biomass was formed at the plantation, regardless of temperature fluctuations, which appeared in 2008.

The following conclusions can be drawn from analysis of the prepared graphs:

- In 2006 stress conditions of development, expressed by high difference between air and radiation temperature, appeared in May and at the beginning of June. To a lesser extent this phenomenon could be observed between July / August and between August / September;
- In 2007 conditions of plant development were good till end of June / beginning of July, when the highest differences between temperatures appeared. At the second part of vegetation period situation was fairly stabilized (excluding second part of August);
- In 2008 relatively the highest fluctuations of differences between air and radiation temperature appeared, with maximum values observed in mid-June, mid-August and in September.

Conclusions

Monitoring of areas covered by plants used for energy production applying remote sensing techniques gives possibilities of yield estimation and determination, at which phase of vegetation period irrigation should be applied. Both types of satellite images proved to be useful for monitoring vegetation conditions – medium-resolution data of MODIS type, which allow for monitoring with high temporal frequency, using both vegetation indices and temperature information, as well as high-resolution data of Landsat TM type, which deliver more precise spatial information on development phase of plantations. Further works are conducted on determining amount of evaporation and on applying moisture indices, derived from ratio of current to potential evapotranspiration. Remote sensing images and techniques can also support selection of less-favoured agricultural areas, which can be suitable for developing plantations with plants used for energy production.

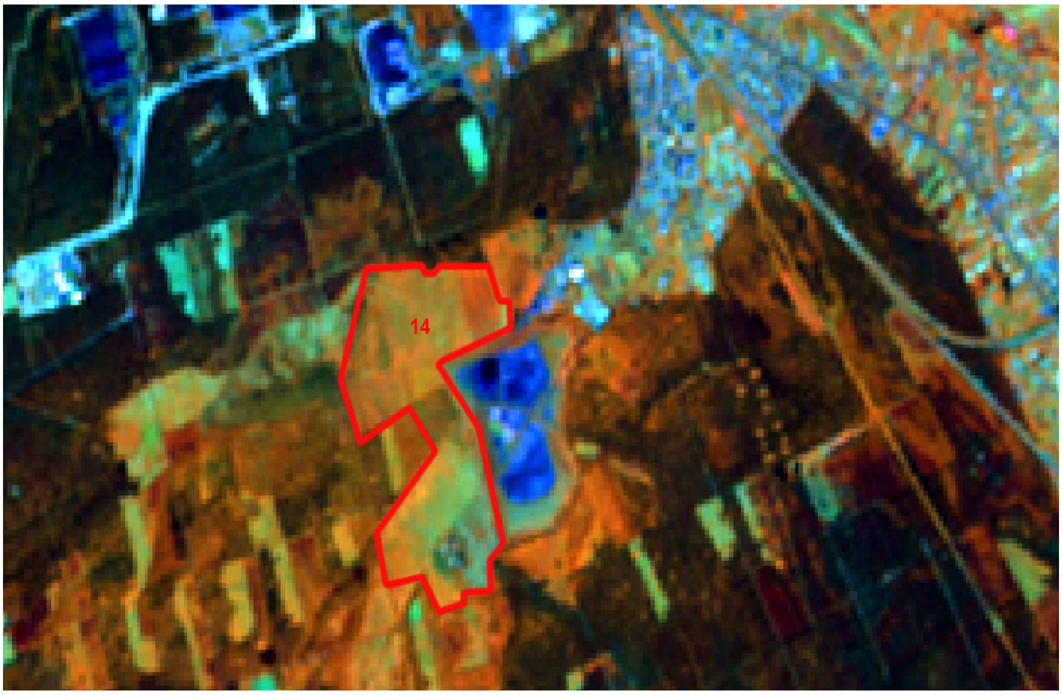


Figure 41. Location of Stalowa Wola plantation on Landsat Thematic Mapper image
Source: in-house preparation

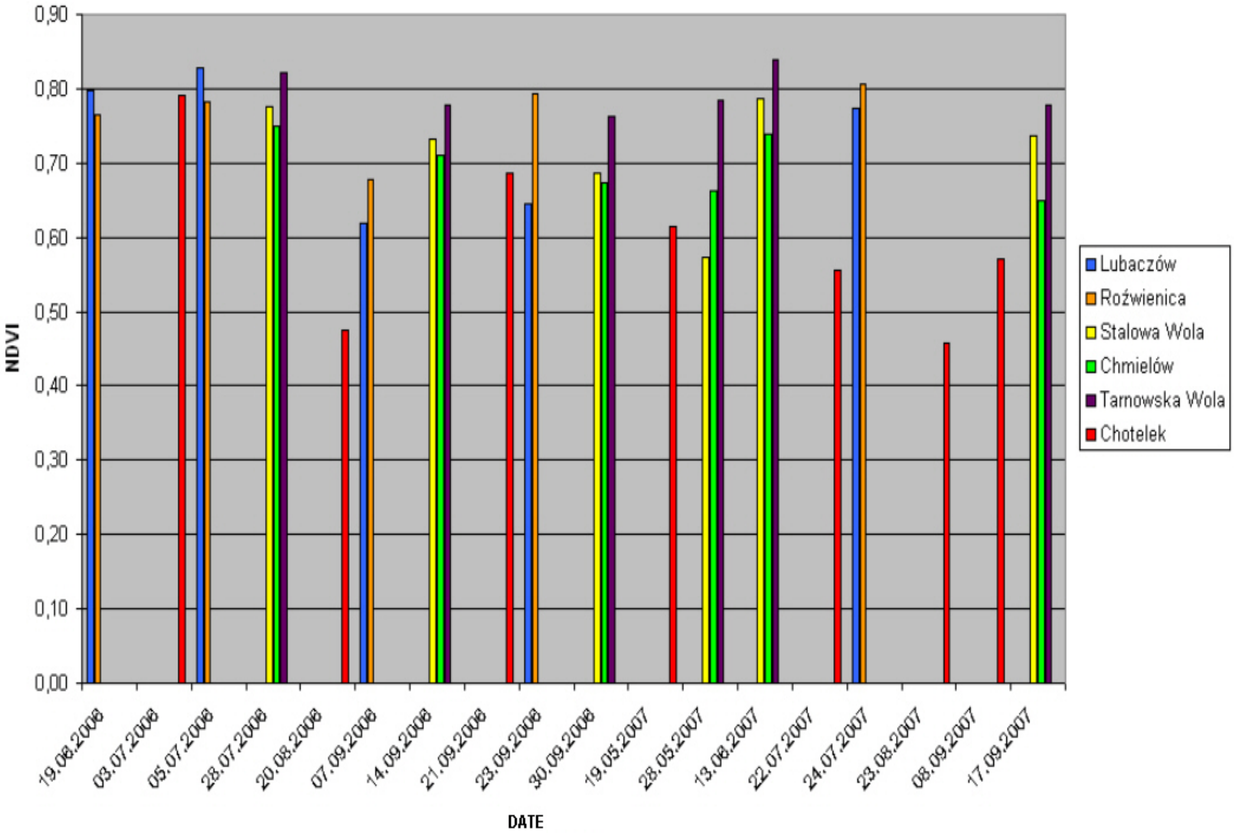


Figure 42. Changes of NDVI TM index for 6 plantations in southern Poland in 2006 – 2007 period
Source: in-house preparation on the basis on IGiK resources.

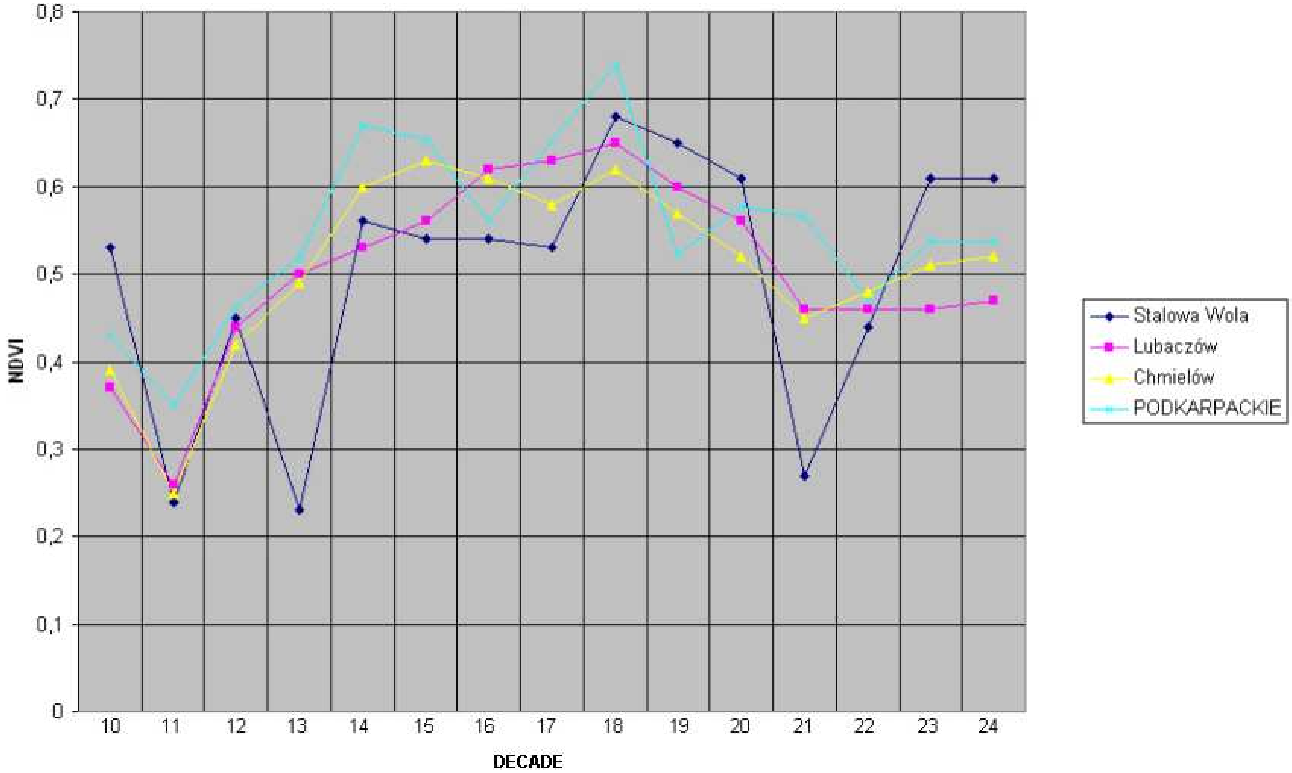


Figure 43. Changes of NDVI NOAA index in 2005 vegetation period
Source: in-house preparation on the basis of IGiK resources

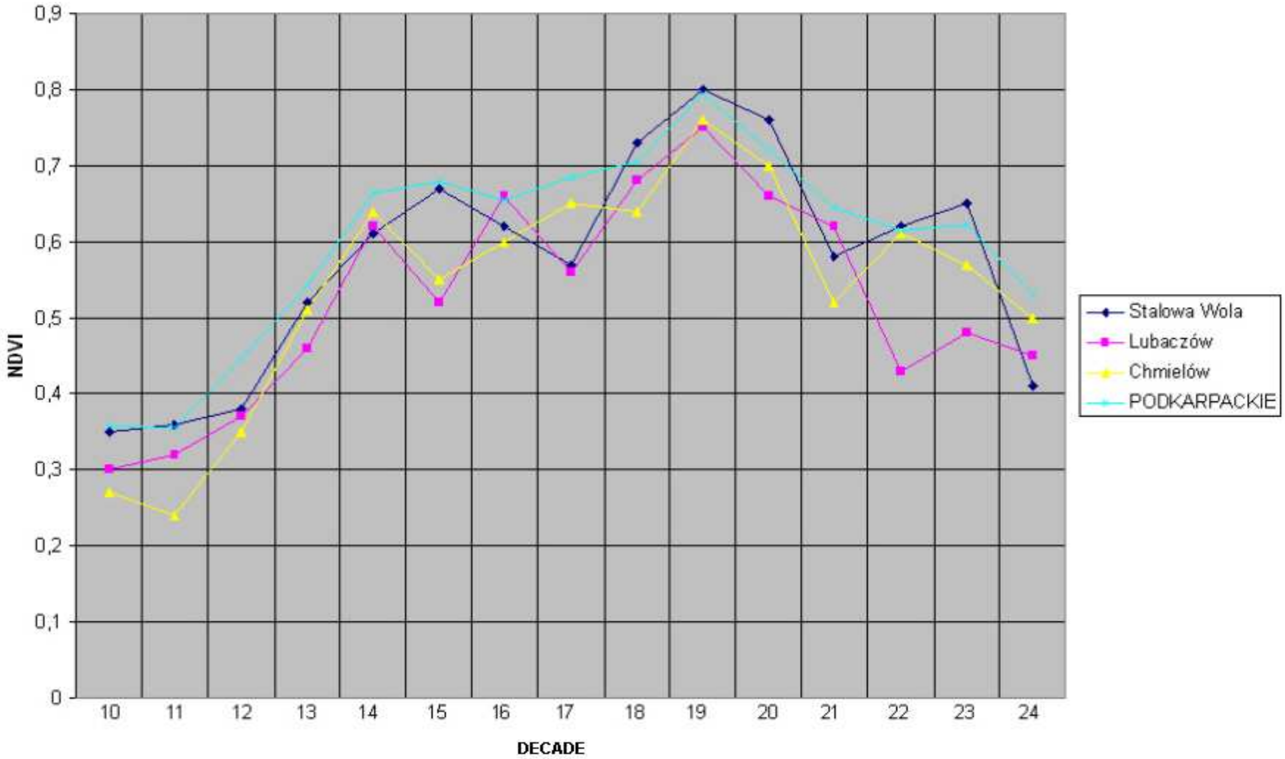


Figure 44. Changes of NDVI NOAA index in 2006 vegetation period
Source: in-house preparation on the basis of IGiK resources

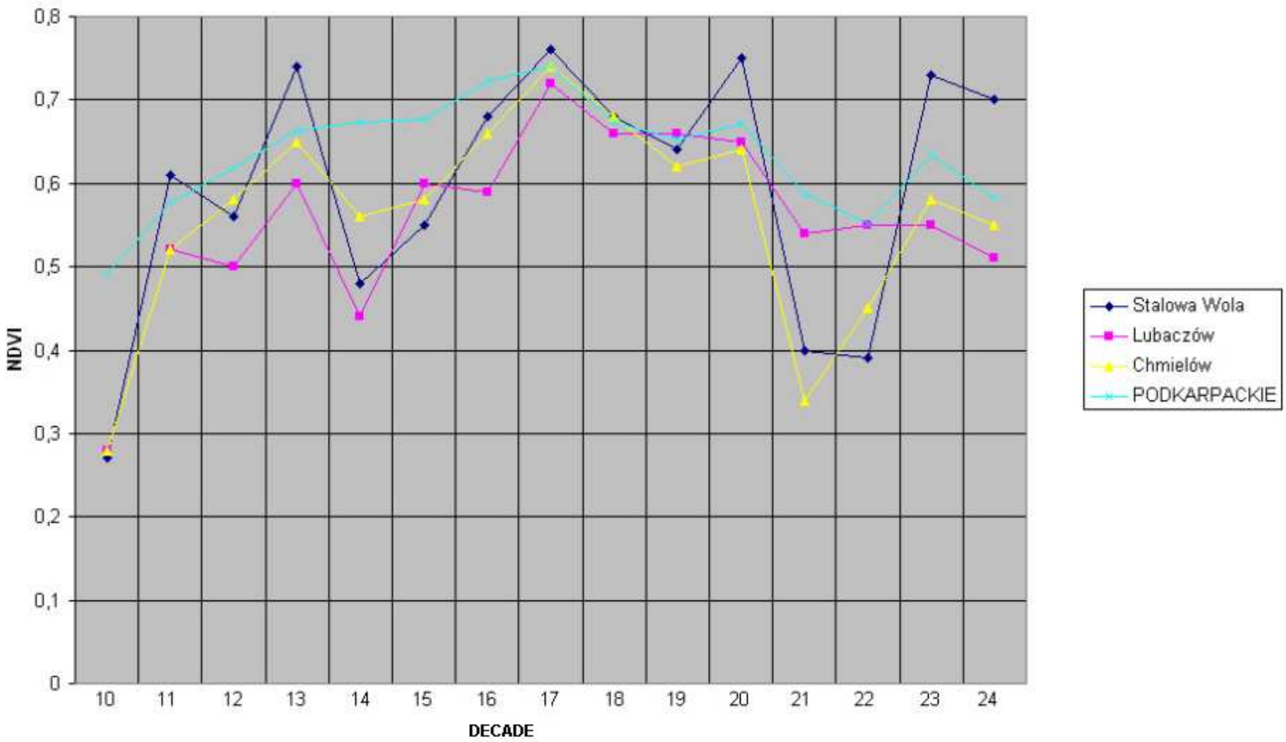


Figure 45. Changes of NDVI NOAA index in 2007 vegetation period
Source: in-house preparation on the basis of IGiK resources

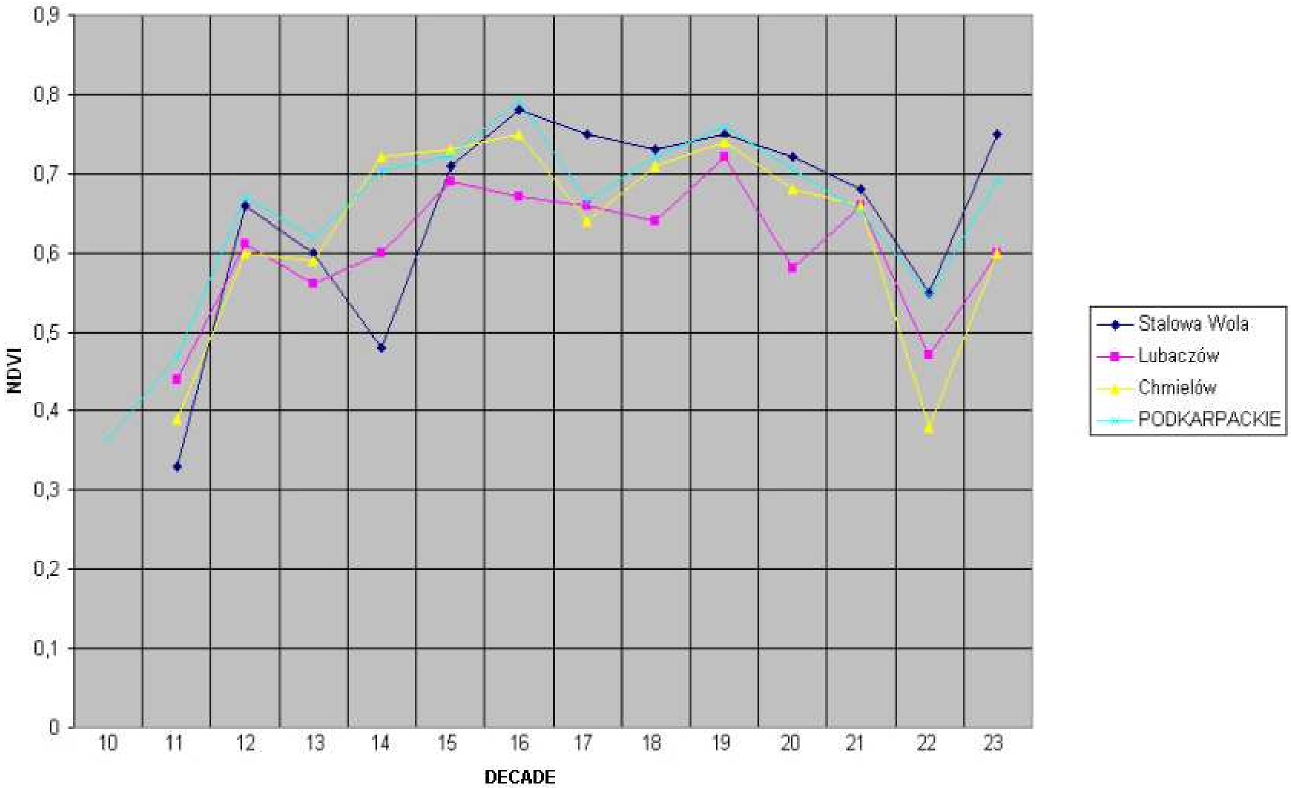


Figure 46. Changes of NDVI NOAA index in 2008 vegetation period
Source: in-house preparation on the basis of IGiK resources.

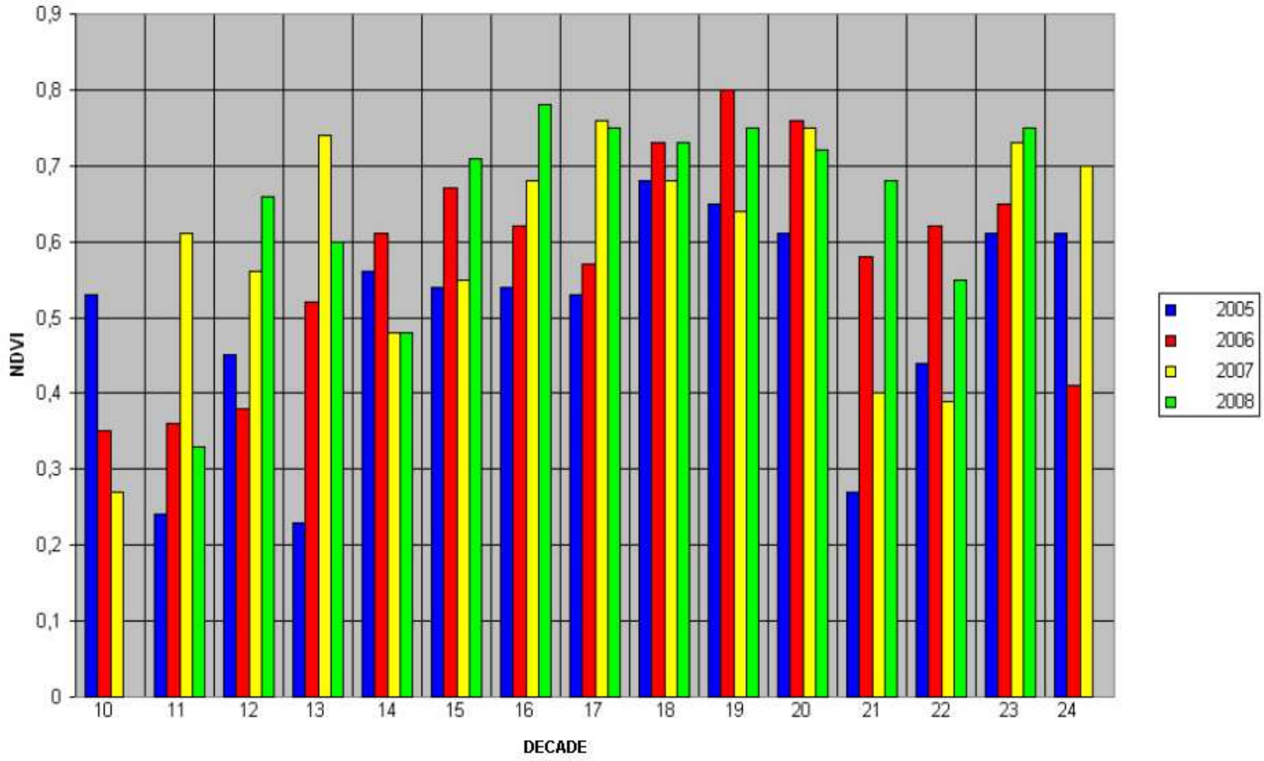


Figure 47. Analysis of NDVI NOAA changes for Stalowa Wola plantation in 2005 – 2008 period
Source: in-house preparation on the basis of IGiK resources

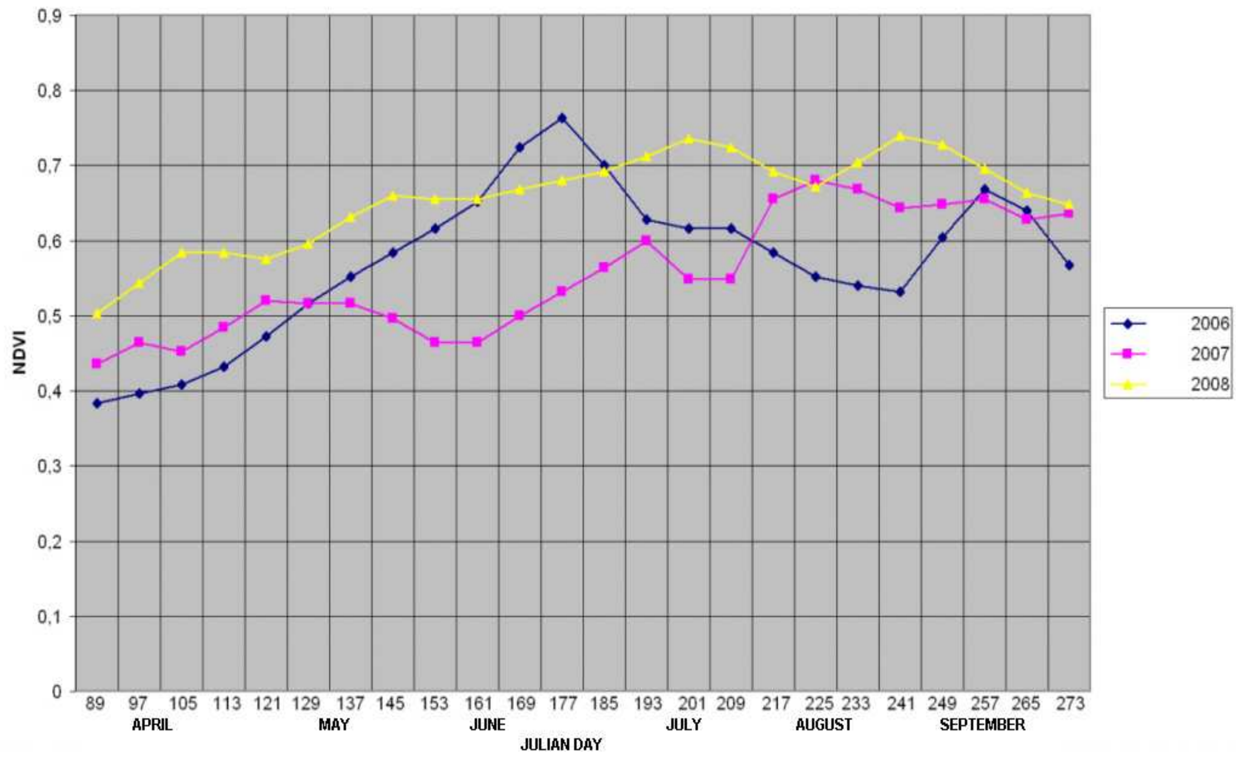


Figure. 48. Changes of NDVI MODIS index for Marcelewo plantation in 2006 – 2008 vegetation periods.
Source: in-house preparation on the basis of IGiK resources.

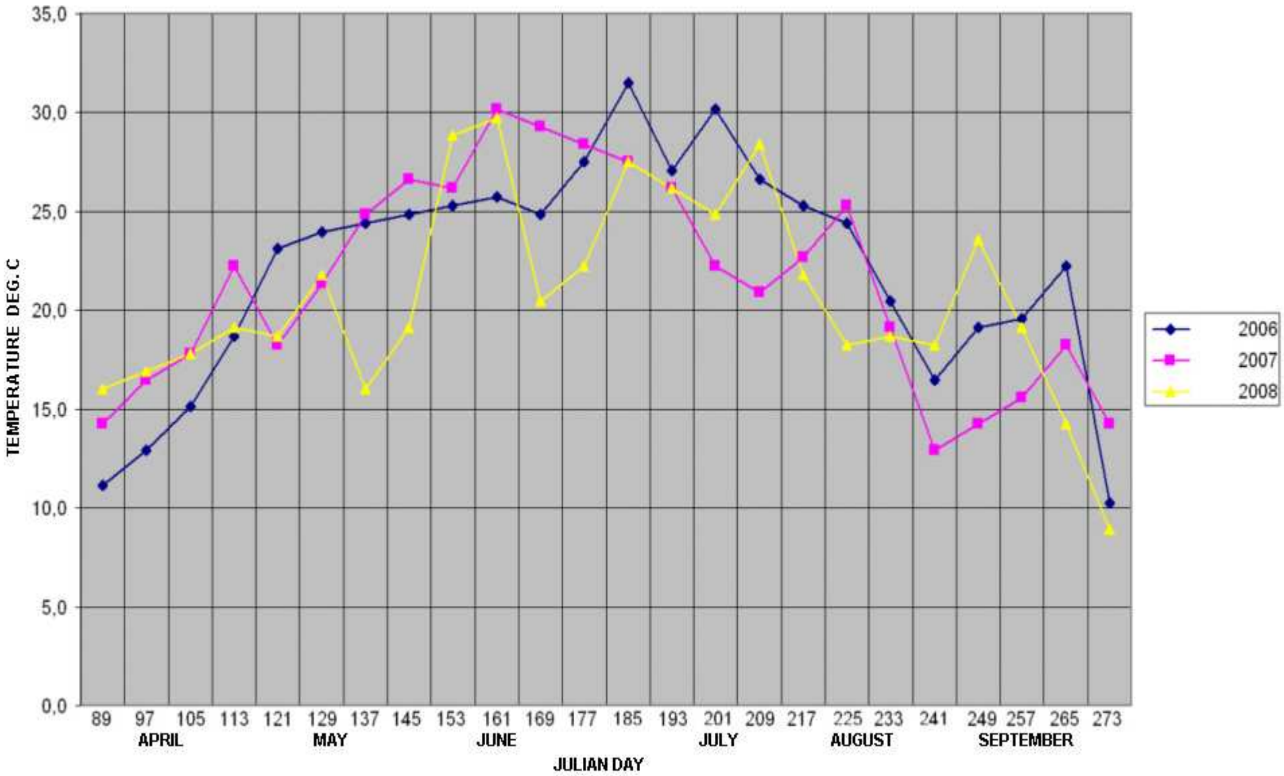


Figure. 49. Changes of MODIS radiation temperature for Marcelewo plantation in 2006 – 2008 vegetation periods
Source: in-house preparation on the basis of IGiK resources.

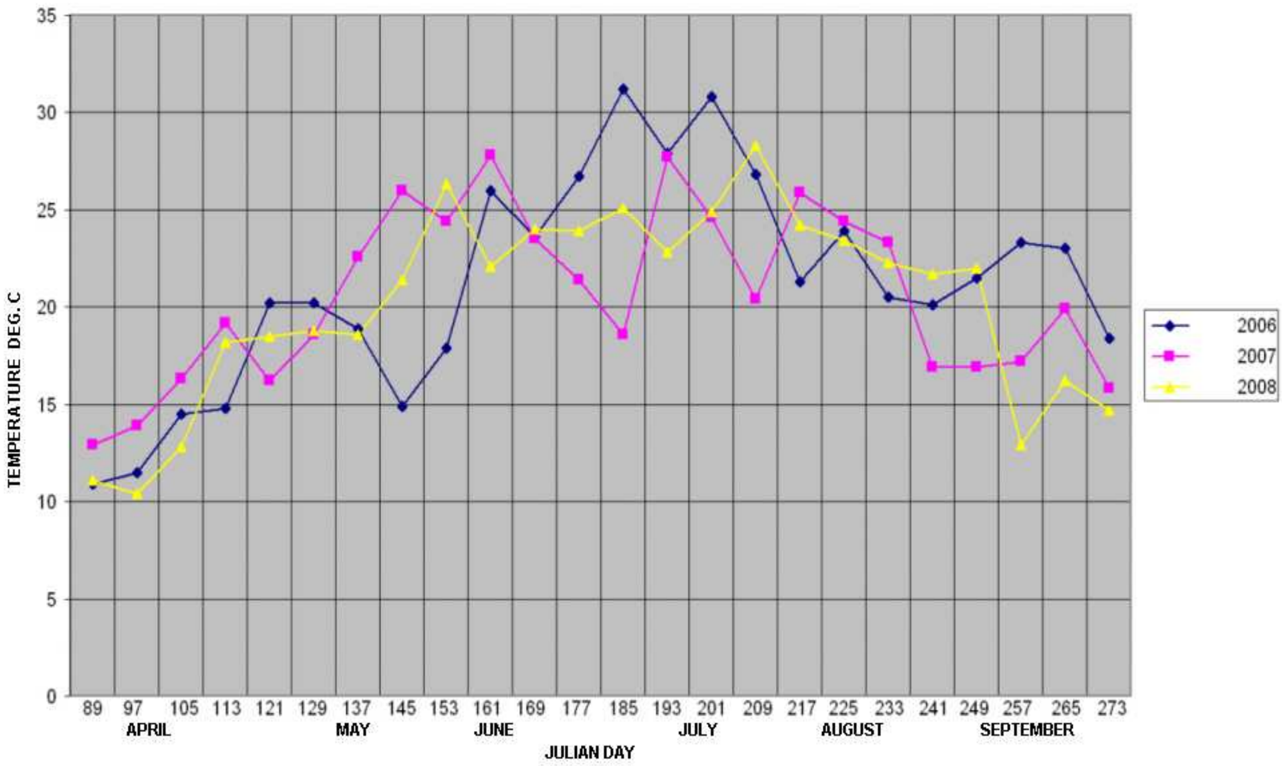


Figure 50. Changes of maximum air temperature for Marcelewo plantation in 2006 – 2008 vegetation periods
Source: in-house preparation on the basis of IGiK resources.

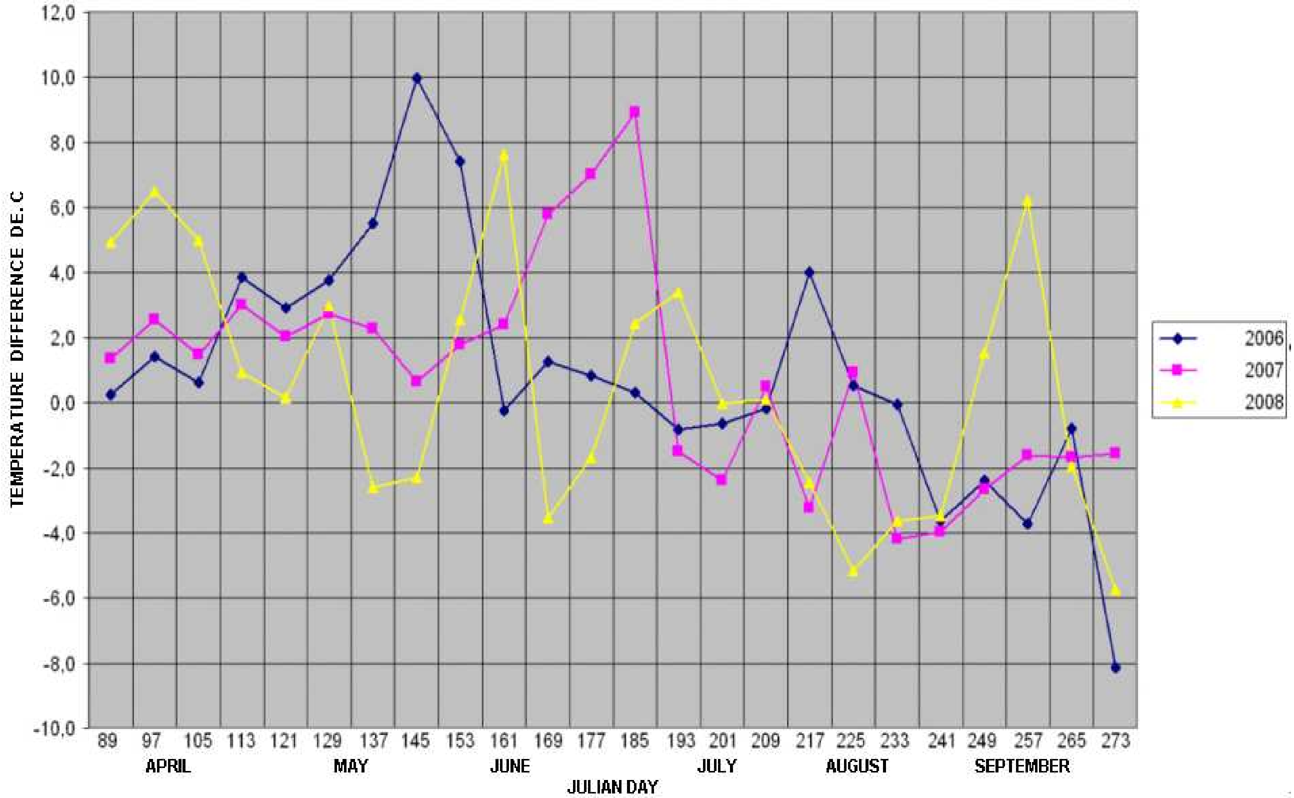


Figure 51. Changes of differences between radiation and air temperature for Marcelewo plantation (2006-2008).
Source: in-house preparation on the basis of IGiK resources.

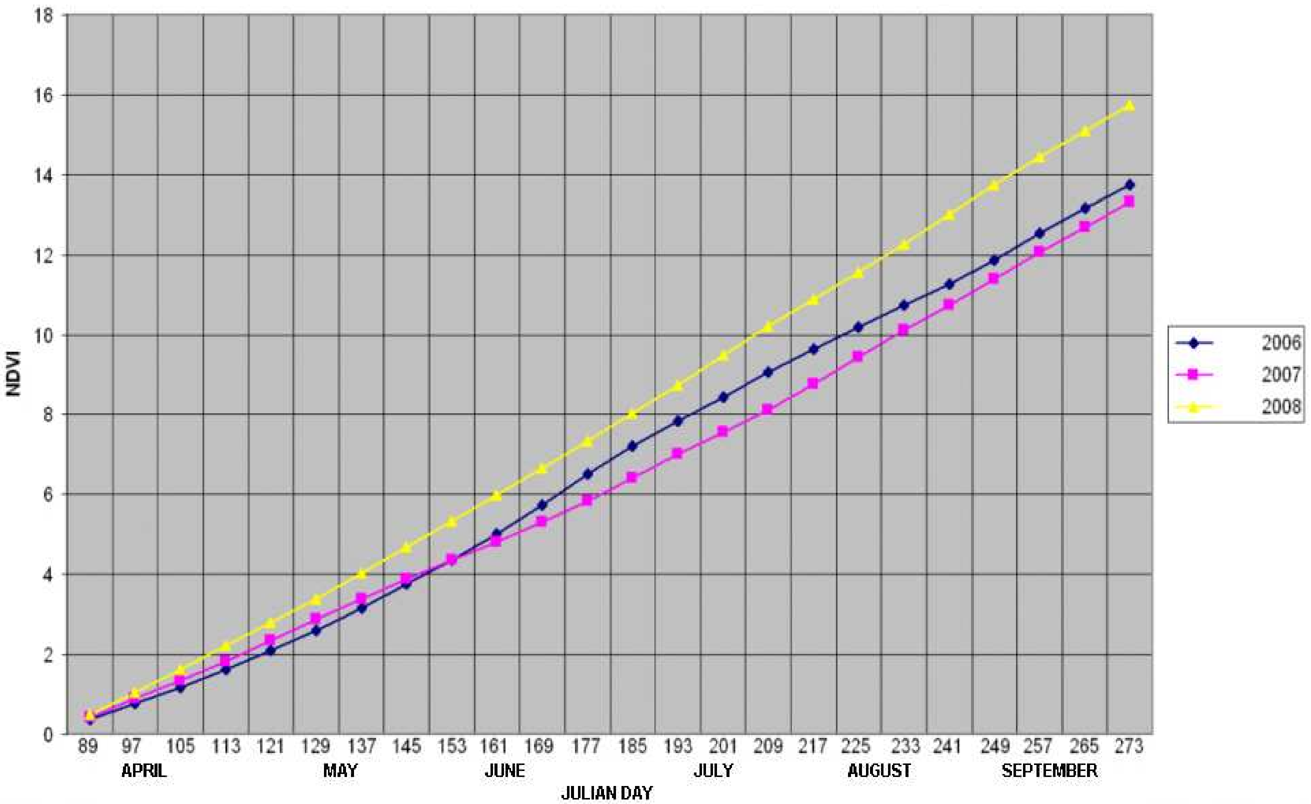


Figure 52. Changes of cumulated NDVI MODIS index for Marcelewo plantation in 2006 – 2008.
Source: in-house preparation on the basis of IGiK resources.

6.2 Can we simulate runoff from agriculture-dominated watersheds? Comparison of the DrainMod, SWAT, HBV, SOUP and INCA models applied for the Skuterud catchment.

Johannes Deelstra, Csilla Farkas, Alexander Engebretsen, Sigrun H. Kværnø, Stein Beldring, Alicja Olszewska and Lars Nesheim.

Summary

Models are indispensable tools in facilitating decision making relative to the implementation of mitigation measures to improve water quality with the objective to achieve good ecological status by 2015 as embodied in the EU - Water Framework Directive. Different models can be used to predict nutrient and soil loss from agricultural dominated catchments, however a prerequisite is that the dominating hydrological flow processes are represented. This chapter presents results of an application of 5 different models (SWAT, DRAINMOD, COUP, HBV, INCA) to Skuterud, an agricultural dominated catchment. The catchment is located in south-eastern Norway, approximately 35 km south of Oslo and is since 1993 part of JOVA – the Norwegian Agricultural Environmental Monitoring Programme. The total are of the catchment is 450 ha, with arable land constituting 61%, forest covering 29 % while the rest is urban area (8%) and bog (2%). The models were parameterised, calibrated and compared with respect to i) spatial resolution, ii) the processes considered, iii) data and parameters required, iv) initial and boundary conditions and v) goodness of fit to the measured runoff at the catchment outlet. Two of the models (DRAINMOD, COUP) are one-dimensional, profile-based models concentrating mainly on physically based representation of the hydrological processes, while the HBV, INCA and SWAT are semi-distributed catchment models describing the surface and subsurface runoff generation processes in an integrated way. In overall, a good agreement between the measured and simulated runoff was obtained for the different models when integrating the results over a week or longer periods. However efforts have to be made to obtain improved results also on a daily basis, especially as models are potentially useful tools in assessing the possible consequences of climate change on hydrology, nutrient and soil loss. The results indicated that forest appears to be very important for the water balance in the catchment, and additional information about the different water balance elements for forests seems to be crucial. The results showed wide variation in model behaviour with respect to the simulation of different water balance elements (i.e. evapotranspiration, surface and subsurface runoff) for various land use types. Additional information is required to reduce the uncertainty of the different water balance elements to be able to carry out an objective-oriented model selection.

Introduction

Agriculture is one of the main contributors of nutrient loads to open water courses, being to a large degree responsible for the eutrophication of inland and coastal waters. Water is the transport mechanism for nutrients and soil particles to open water courses and groundwater and therefore a good understanding of the hydrology is important in selecting the right mitigation measures to improve water quality. In a study carried out in the Baltic and Nordic countries, Vagstad et al. [2004] was found that the hydrology played an important role in explaining the differences in nutrient losses between catchments. Catchments having a large contribution of groundwater runoff in the total runoff, in general had lower nitrogen losses. Artificial drainage of agricultural land is an important hydrological path way and can lead to an increase in nitrate-nitrogen runoff, its magnitude however influenced by soil type, drain spacing and drain depth [Skaggs et al. 1980]. Tiemeyer et al. [2006] made similar observations and showed in addition that measurement scale can essentially influence calculated nutrient loss. At the same time do subsurface drainage systems reduce the overland flow and the risk for surface runoff induced erosion and phosphorus loss [Turtola and Paajanen, 1995]. Deelstra et al. [2007], when characterizing the hydrology in agricultural dominated catchments, showed that large diurnal variation in discharge could occur, often caused by a combination of scale, soil type, subsurface drainage intensity and topography. Especially in the Nordic countries hydrological flow paths can be influenced during the winter season with below zero temperatures affecting nutrient loss and soil erosion [Deelstra et al., 2009]. Knowledge about these flow processes in hydrology is important with respect to 1) their impact on nutrient and soil loss processes in catchments, 2) the choice and implementation of suitable mitigation measures to abate present and future pollution problems, 3) the design of hydro-technical implementations and 4) the effects of replacing traditional land use and soil management systems by new ones, e.g. growing energy crops on water and nutrient transport in the soil and water bodies.

This becomes even more important when considering the influence of climate change on hydrological flow paths, nutrient and soil loss. In this respect models can be indispensable tools to facilitate decision making relative to the implementation of mitigation measures to improve water quality with the objective to achieve good ecological status by 2015 as embodied in the EU - Water Framework Directive. Different models can be used to predict nutrient and soil loss from agricultural dominated catchments, however a prerequisite is that the dominating hydrological flow processes are represented. As models will be applied to catchments, an additional requirement will be that they are able to simulate the water balance for various land use types ranging from agricultural crops to different types of forest.

This chapter presents results of an application of 5 different models (SWAT, DRAINMOD, COUP, HBV, INCA) to the Skuterud, agricultural dominated catchment with a land use covering agriculture, forest, bog and urban area.

Materials and methods

Catchment description

The Skuterud catchment was chosen as the pilot area for model comparison studies. Skuterud catchment is since 1993 part of JOVA – the Norwegian Agricultural Environmental Monitoring Programme. The catchment is located in south-eastern Norway, approximately 35 km south of Oslo. The total area of the catchment is 450 ha, with arable land constituting 61%, forest covering 29 % while the rest is urban area (8%) and bog (2%). A large database containing detailed information about runoff, nutrient and soil loss is available in addition to data on farming practices, soil physical and chemical properties and meteorological data (Deelstra et al., 2005). The long-term mean annual temperature for Skuterud is 5.3°C. The mean annual temperature for 1993 – 2007 was 6.2 ^{o}C, varying from 4.6 – 7.2^{o}C (Table 50). The highest temperatures occur during the growing season from May to August. Below - zero temperatures can already occur in November but in general the winter starts in December and can last until March, however with significant variation over the years. The average yearly potential evapotranspiration (PET) is 535 mm and varies from 463 – 691 mm. The long term annual precipitation is 785 mm while the average precipitation during the observation period was 857 mm, varying from 651 to 1200 mm. In general the highest precipitation occurs after the growing season during the period from October to December. The meteorological data was obtained from the climatological station at IMT/Norwegian University of Life Sciences (1961 – 1990) at Ås, located approximately 4 km south-west from the Skuterud catchment.

Table 50. Yearly temperature, precipitation, evapotranspiration, runoff, nitrogen and soil loss at the Skuterud catchment for 1993 – 2007.

	Average	Maximum	Minimum
Temperature (^oC)	6.2	7.2	4.6
Precipitation (mm)	857	1200	651
PET (mm)	535	691	463
Runoff (mm)	528	919	278
Nitrogen loss (kg ha^{-1})	30	45	17
Soil loss (kg ha^{-1})	779	2009	170

The highest runoff and nutrient loss occurs during the off-season from September – March. The average yearly runoff is 528 mm. There is a large variation in the yearly runoff for the period 1993 – 2007 (Table 50). Similar variations in the nitrogen and soil loss are observed. There is a strong seasonality in runoff generation. On average only 13% of the yearly runoff is generated during the summer season from May – August while 90% of the yearly runoff is discharged in less than 150 days. Surface runoff can occur during the autumn due to excessive precipitation over longer period. However more often surface runoff is generated due to precipitation/snowmelt in combination with frozen soils which can occur both during autumn but more frequent during snowmelt at the end of the winter season.

Model description

Five different dynamic mathematical models were parameterised, calibrated and compared with respect to i) spatial resolution, ii) the processes considered, iii) data and parameters required, iv) initial and boundary conditions and v) goodness of fit to the measured runoff at the catchment outlet. Two of the models – Drainmod [Skaggs, 1990] and Coup [Jansson and Karlberg, 2004] – are one-dimensional, profile-based models concentrating mainly on physically based representation of the hydrological processes, while the HBV [Sælthun, 1996], INCA [Butterfield et al., 2008] and SWAT [Arnold et al., 2002] are semi-distributed catchment models describing the surface and subsurface runoff generation processes in an integrated way. A short description of each model is presented below. The comparison of the main processes incorporated in the five models is given in Table 51.

The ***DRAINMOD*** model was developed to simulate the hydrology of poorly drained soils with high water table [Skaggs, 1990]. The latest version combines the original DRAINMOD hydrology model with DRAINMOD-NII (nitrogen sub-model) and DRAINMOD-S (salinity sub-model) into a Windows based program. It predicts the effects of drainage and associated water management practices on water table depths, the soil water regime and crop yields. The model calculates surface runoff, changes in soil water content, subsurface drainage flow and evapotranspiration on a daily basis in response to given inputs consisting of meteorological data, measured or calculated potential evapotranspiration, soil and crop properties and drainage design parameters. Approximate methods are used to evaluate the various mechanisms of soil water movement and storage. Complex numerical methods are avoided by assuming a drained to equilibrium state for the soil water distribution above the water table. The model has been adjusted to cold conditions by incorporating the heat flow equation to predict soil temperature [Lou et al., 2000]. When freezing conditions are indicated by below zero temperatures, the model calculates ice content in the soil profile and modifies soil hydraulic conductivity and infiltration rate accordingly. Snow is predicted to accumulate on the ground until air temperature rises above a snowmelt base temperature. Soil surface temperature is recalculated when snow cover exists. Daily snowmelt water is added to rainfall, which may infiltrate or run off depending on freezing conditions. Different versions of DRAINMOD have been developed, among others to simulate the hydrology of wetlands and forests [Amataya et al, 1997; Skaggs et al., 2005; Tian et al., 2010].

The coupled heat and mass transfer model for soil-plant-atmosphere systems, “***Coup***” [Jansson and Karlberg 2004] is a process-based, one-dimensional model simulating vertical water, heat, carbon, nitrogen and solute transport in a soil profile. Coup model is based on the previous SOIL + SOILN models. Water flow in unfrozen and partially frozen soil is calculated using Richard’s equation (Darcy’s law combined with the law of mass conservation). A two-domain approach can optionally be chosen to account for macrospore flow. Coup calculates heat fluxes in the soil profile by the general heat flow equation in combination with the law of energy conservation, including parameters like heat capacity and thermal conductivity, both adjusted to account for the influence of soil ice content. Snow dynamics is also simulated: Precipitation falls as rain, snow or a mixture, depending on certain air temperature thresholds. Melting and refreezing of the snowpack is simulated using either an empirical function including global radiation, air temperature and soil heat flux, or an energy balance approach. Free water is released from the snow pack according to snow retention capacity. Water infiltrates into partly frozen soil through pores that are still filled with liquid water, or through large, air-filled pores. The amount of ice and liquid water in the soil change dynamically as total water content and soil temperature change, and depend on a freezing point depression function. A redistribution of liquid water may occur as infiltrating water refreezes, releasing heat which melts water in smaller, ice-filled pores. When the soil’s infiltration capacity and surface water storage capacity is exceeded, surface runoff is generated by a first order rate process. Subsurface drainage can be calculated by empirical and/or physically based equations. Groundwater flow is considered as a sink term in the model. Evapotranspiration is calculated from the Penman-Monteith equation. The Coup model is able to simulate the water balance for different land uses and has among others been used for forested areas (Alavi et al., 2001; Persson, 1995)

Table 51. Comparison of the five different models with respect to hydrological processes

Model layer		Processes	DrainMod	Coup	HBV	INCA	SWAT
Above ground vegetation zone		Precipitation	Driving	Driving	Driving	Driving	Driving
		Snow dynamics/snowmelt	Calculated	Calculated	Calculated	Calculated	Calculated
		Interception	Indirectly	Calculated	Calculated	Indirectly	Calculated
		Transpiration	Indirectly	Calculated	Calculated	Indirectly	Calculated
	Soil surface	Evaporation	Indirectly	Calculated	Calculated	Indirectly	Calculated
Unsaturated zone		Surface runoff	Calculated	Calculated	Calculated	Calculated	Indirectly
		Infiltration	Calculated	Calculated	Indirectly	Indirectly	Indirectly
		Bypass/ macropore flow	NO	Calculated	Indirectly	NO	Calculated
		Plant water uptake	Indirectly	Calculated	Indirectly	Indirectly	Calculated
		Soil water redistribution	NO	Calculated	Calculated	NO	Uniform
		Capillary rise	Calculated	Calculated	NO	NO	NO
		Water flow in frozen soil	Indirectly	Calculated	Calculated	NO	at saturation
		Lateral flow to stream	NO	NO	Calculated	Calculated	Calculated
		Subsurface drainage flow	Indirectly	Calculated	NO	Indirectly	Indirectly
		Percolation to sat. zone	Calculated	Calculated	Calculated	Calculated	Calculated
	Saturated zone	Lateral inflow	Parameter	Parameter	NO	NO	NO
		Capillary rise to unsat. zone	NO	Calculated	Calculated	NO	Indirectly
		Recharge to deep aquifer	NO	NO	NO	NO	Calculated
		Base flow	NO	NO	Calculated	Calculated	Calculated
CONFINING LAYER							
DEEP AQUIFER							

The ***HBV*** model is a semi-distributed, conceptual hydrological model that describes the essential characteristics of the precipitation-runoff process; it simulates the volumes of water stored as snow and subsurface water, and the stream flow. The model performs water balance calculations for 10 elevation bands within a watershed in order to take into account the altitude variation of the driving precipitation and temperature data. Each elevation band may be divided into a maximum of four computational elements; two land use zones with different vegetation and soil types, a lake area and a glacier area. It has components for accumulation, spatial distribution and ablation of snow, interception storage, spatial distribution of soil moisture storage, evapotranspiration, groundwater storage and runoff response, lake evaporation and glacier mass balance. Potential evapotranspiration is a function of air temperature, however, the effects of seasonally varying vegetation characteristics are considered. Water evaporates from interception storage at the potential rate, while evaporation from the soil is reduced below the potential rate when soil moisture storage is below field capacity. The algorithms of the model were described by Bergström [1995] and Sælthun [1996].

The ***INCA*** model is a processed based dynamic model describing water and mass transport in the plant/soil system and in the stream and can be used for various land use/vegetation types. In the INCA model, hydrological effective rainfall is the input to the soil water storage, driving water flow through the catchment. Hydrology within a catchment is modelled using a simple two-box approach, with key reservoirs of water in the reactive soil zone and deeper groundwater zone. Flows from the soil and groundwater zones are controlled by residence times in the reservoirs. The Base Flow Index is used to split between the volume of water stored in the soil and the groundwater [Wade et al., 2002]. Calculation of river flow is based on mass balance of flow and on a multi-reach description of the river system [Whitehead et al., 1998]. The model incorporates an empirical function for simulating soil temperature changes below the seasonal snow pack and a simple degree-day model to simulate the depth of the snow pack [Rankinen et al., 2004]. The heat flux from the snow surface to the soil is calculated by the heat conduction equation.

The **S**oil and **W**ater **A**ssessment **T**ool (***SWAT***) [Neitsch, Arnold et al. 2005] is a continuous time, semi-distributed watershed-scale model that operates on a daily time step. SWAT is physically based and developed to quantify the impact of land management practices in large, complex watersheds. SWAT requires information about weather, soil properties, topography, vegetation, and land management practices in the watershed. The physical processes associated with water movement, sediment movement, crop growth, nutrient cycling, etc. are directly modelled by SWAT using these input data. For modelling purposes, a watershed may be partitioned into a number of subwatersheds or subbasins which are spatially connected. Input information for each subbasin is grouped into hydrologic response units or HRUs. HRUs are lumped land areas comprised of unique land cover, soil, slope, and management combinations. Runoff is predicted separately for each HRU and routed to obtain the total runoff for the watershed. SWAT calculates canopy storage (water intercepted by vegetative surfaces), infiltration, redistribution (movement of water through a soil profile after input of water), evapotranspiration (ET and PET), lateral subsurface flow, base flow and surface runoff. Surface runoff is computed using a modification of the SCS curve number method. The curve number method varies non-linearly with the moisture content of the soil. The curve number drops as the soil approaches the wilting point and increases to near 100 as soil approaches saturation. The model increases runoff for frozen soils but still allows significant infiltration when the frozen soils are dry.

Models set up and parameterisation

The five models were run with the same driving meteorological variables and available soil and vegetation data for the Skuterud catchment. Common initial and lower boundary conditions were defined for all the models. Those parameters that were common in at least two models were set to the same value based on the available information and literature.

In case of distributed models, one simulation consisted of one model run, while the profile-based models (Coup, DRAINMOD) were run separately for agricultural and forest areas. Minor land use types in the catchment (urban and bog) were left out from the simulations and considered as forest areas. The total catchment runoff was obtained by calculating the area weighted runoff from Drainmod and Coup. The models were run for the period between January 1, 1993 and December 31, 2007. The year 1993 was considered as a "warming up" period to eliminate initial bias. The calibration and validation periods were defined from 1 January 1994 to 31 December 1999 and from 1 January 2000 to 31 December 2007, respectively. The models were calibrated individually by tuning on model parameters to minimise the difference between the measured and simulated runoff.

The determination coefficient (R^2) and the Nash-Sutcliffe statistics (N-S) were used for models evaluation. The model outputs were compared with the measured runoff at the catchment outlet. The water balance elements (transpiration, surface and subsurface share of the total runoff) were evaluated, using the available information from the catchment and literature data. We also compared the models results for the different seasons, focusing on winter and snow melt periods.

Results and discussion

Figure 53 presents the R^2- and N-S statistics, based on the simulations for the period from 1994 to 2007 comparing the measured and simulated runoff data on a daily, weekly, monthly and yearly base. The R^2- and N-S statistics were in the same order of magnitude for all the models, indicating that even one dimensional model like DrainMod and COUP can be used for simulating runoff dynamics at catchment level.

The SWAT showed the largest deviation between the daily and yearly integration. Model performances, in general, improved when integrating the results over longer time periods, indicating that the daily runoff dynamics were not simulated satisfactorily, while the weekly and monthly runoff was simulated quite well. The N-S and R^2 statistics for the models varied from approximately 0.30 - 0.65 to 0.70 - 0.90 when aggregated on daily and yearly basis, respectively. On a yearly basis, the SWAT model gave the best estimate for the total runoff at the catchment outlet, while the other four models gave more reliable estimates for daily, weekly and monthly dynamics. This is an indication, that the SWAT model needs further tuning with respect to redistribution of water between the different compartments, i.e. surface/subsurface drainage and base flow runoff and residence time of water between the root zone and the catchment outlet.

Selected water balance elements, calculated for the arable and forested areas as well as for the whole Skuterud catchment are given in Figure 54. When using the one-dimensional models Coup and Drainmod, the total simulated catchment runoff was obtained as the weighted average of the runoff obtained for forest and arable land separately. Calibration was done with emphasis on obtaining realistic values for the different water balance elements for both forested and agricultural land use. However this was a difficult task because only the total runoff at the catchment outlet was measured. An additional problem was the lack of data for water balance elements for forested land use in Norway.

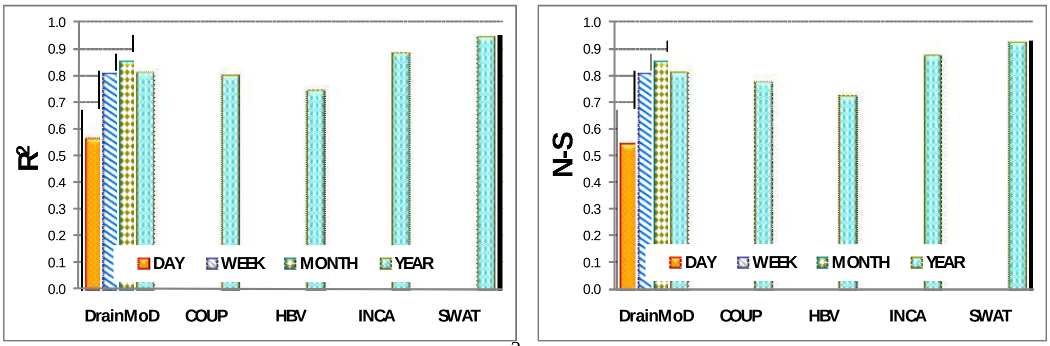


Figure 53. Determination coefficients (R^2) and Nash-Sutcliff statistics, calculated from runoff data integrated over various time periods for the five different models

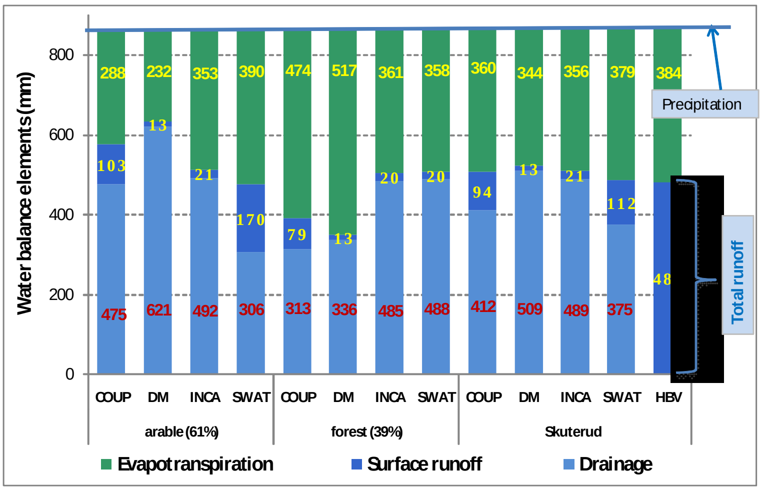


Figure 54. Water balance elements, calculated for the arable land, forest and the whole Skuterud catchment using different models

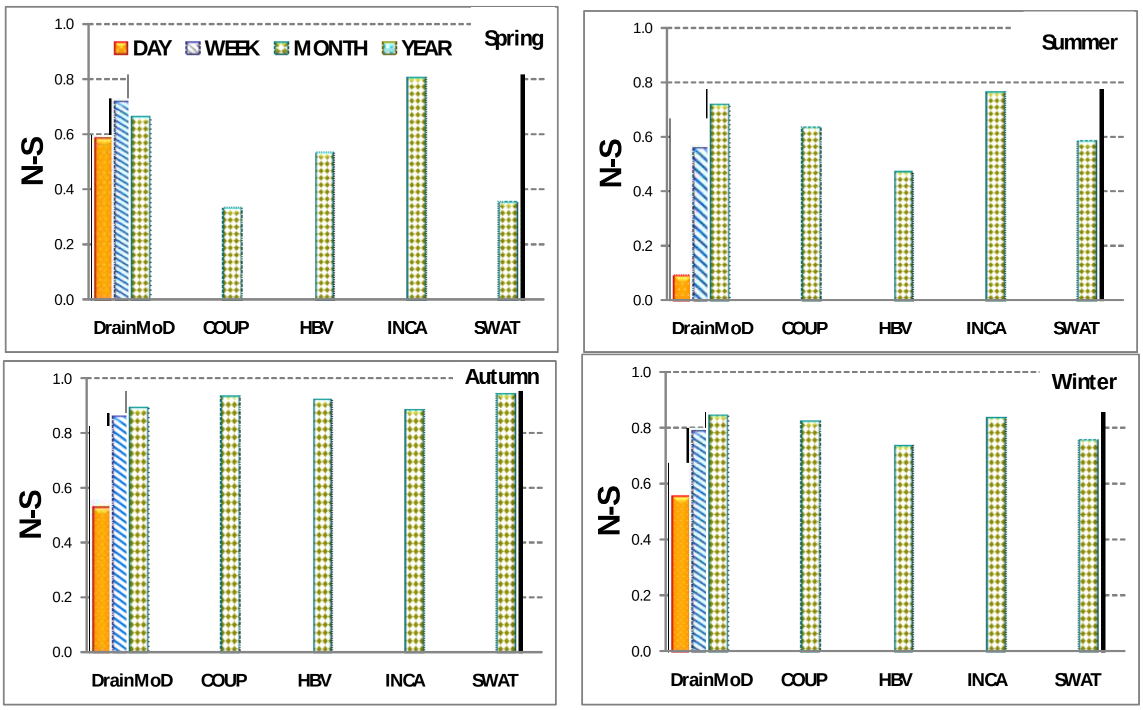


Figure 55. N-S statistics, calculated for spring and winter simulations with different models

The first thing considered was the difference between the measured precipitation in Ås and the measured discharge from the catchment. On average for the 15-year long simulation period this difference was 338 mm/yr, varying from 273 - 428 mm/yr. These values appear to be somewhat small, compared to the evapotranspiration (ET) values, estimated in Ås using other approaches. For example, in two plot studies carried out in Ås, the average difference between precipitation and discharge was 342 and 403 mm [Kværnø and Bechmann, 2010]. In a lysimeter study with four different soils cropped with cereal, evapotranspiration from May to November was estimated to be around 330 mm on non-irrigated, winter-protected soil columns, and around 390 mm on irrigated, not winter-protected soil columns (Uhlen et al., 1996). According to these results, we assume that the catchment-scale simulation models gave better estimates of ET for arable land (353 mm- INCA and 390 mm –SWAT) than the profile-based models (Figure 54). The profile based models need further parameterization and calibration to improve evapotranspiration predictions.

Concerning evapotranspiration from forested areas, no overall conclusions can be drawn due to lack of measured data for soil and plant properties and runoff dynamics in Norway. In general it is assumed that ET from forest is somewhat higher than from arable land, and since the expected ET on arable land most likely approaches or exceeds 400 mm, the overall ET from the Skuterud catchment is probably higher than the calculated precipitation-runoff difference. Possible explanations for the smaller than expected difference in Skuterud is that the measured discharge may contain uncertainties due to measurement errors originating from submerged flow condition during periods with high runoff, incorrect catchment boundaries and the in this case incorrect inclusion of the urban areas as part of the forested land use. Also, there are uncertainties in the precipitation measurements, including effects of local variation (meteorological station is located some kilometres away from the catchment) and measurement errors due to the effects of wind drift on precipitation.

Knowledge about the partitioning of total runoff into surface- and subsurface runoff is of special importance with regard to the Water Framework Directive and the implementation of mitigation measures to decrease soil - and nutrient loss for improving water quality. The surface runoff from the agricultural areas generated by the Coup and SWAT models is 18 and 35% of the total runoff respectively and is only 2 and 4% for the DRAINMOD and Inca models (see Figure 54). For all the models, except SWAT, the total runoff generated for the forested area is less than for the agricultural area.

It is hard to decide which model performed best in partitioning of total runoff into surface and subsurface runoff since very few measured data are available. For four sites on drained marine clay soils the share of measured surface runoff to the total runoff was in the range 10 - 30 % on average [Kværnø and Bechmann 2010]. Considering these findings, the Coup and SWAT models performed best in partitioning the total runoff from agricultural land.

Evaluation of the models on a seasonal basis showed, that the models performed well in the autumn period, having N-S values ranging from 0.53 to 0.81 and from 0.88 to 0.94 on a daily and monthly bases, respectively (Figure 55). The statistics for the winter period are also satisfactory. The summer period shows poor results, probably due to uncertainties in simulating evapotranspiration and because at low flow amounts the relative error can be high.

The period of snow melting, when the major part of soil and nutrients loss occurs, is crucial in simulations. At the same time, this period gives the biggest challenge in simulations, because of the complexity of processes. Contrary to the Coup and SWAT models, INCA and the DrainMod showed good performance for the spring period. Differences in model performance can be due to the complexity of the models and the need for more precise parameter tuning to capture the dynamics of the processes involved.

Conclusions

In overall, a good agreement between the measured and simulated runoff was obtained for the different models when integrating the results over a week or longer periods. However efforts have to be made to obtain improved results also on a daily basis, especially as models are potentially useful tools in assessing the possible consequences of climate change on hydrology, nutrient and soil loss. In some cases the more simple models (DrainMod and HBV/INCA), gave better prediction of the catchment runoff compared to the more complex models (Coup and SWAT). This indicates that some of the processes were not yet carefully parameterised in the more complex models, and need further investigation and calibration. Model simulations indicate that forest appears to be very important for the water balance in the catchment, and therefore obtaining proper information about the different water balance elements for forests seems to be crucial.

Hydrological pathways are important in the transport of soil and nutrients. Models used in integrated water resources management should provide both surface and subsurface runoff as output. However improved information on the relative contribution of the different runoff components at catchment scale is of utmost importance to be able to calibrate these models.

Our results indicate that profile based 1D models can be used for evaluating the runoff from small catchments, where the travel time from root zone to the outlet is relatively small either due to short distances or the effect of drains. In this case models have to be calibrated separately for all the representative soil – land use combinations and modelling results need to be compared with catchment outlet measurements by integrating them according to their area weights.

None of the models excelled with respect to all the evaluation criteria. The results showed wide variation in model behaviour with respect to the simulation of different water balance elements (i.e. evapotranspiration, surface and subsurface runoff) for various land use types. We conclude that additional information is required to reduce the uncertainty of the different water balance elements and that further model calibration is needed to be able to carry out an objective-oriented model selection.

Tables

Figures

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