JOURNAL OF ENVIRONMENTAL ENGINEERING AND LANDSCAPE MANAGEMENT
ISSN 1648–6897 / eISSN 1822–4199
2017 Volume 25(02)
https://doi.org/10.3846/16486897.2017.1326924

The special issue on
Biochar as an Option for Sustainable Resource Management

Supplementary information

A RECONNAISSANCE-SCALE GIS-BASED MULTICRITERIA DECISION ANALYSIS TO SUPPORT SUSTAINABLE BIOCHAR USE: POLAND AS A CASE STUDY

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SM 1. Biochar research across Europe

Poland (and other central and eastern European countries) has not been one of the most active countries with respect to biochar research (Fig. S1). Although few research articles and reports have been published on biochar in Poland, there is evidence that both researchers and practitioners are becoming increasingly interested in this topic. For instance, biochar-related multi-stakeholder clusters are being formed and a range of projects are being initiated, including both academic research and private companies increasingly interested in exploring business opportunities related to biochar. As an example of academia-private sector collaboration Figure S2 which shows a recently set-up field experiment focused on potential increase in maize productivity.

Other recent initiatives related to biochar in Poland include:

– project E2BEBIS (Environmental and Economic Benefits from Biochar clusters in the Central area), initiated in 2013; relates to environmental and economic benefits of creating biochar clusters in Central Europe. "E2BEBIS tackles the limited use of biochar in Central Europe, the lack of a proper legal framework on biochar on EU level, as well as on national levels in the participating countries, and the low awareness of the potential benefits of biochar among policy-makers and other stakeholders" (E2BEBIS 2017).
– project accepted by The National Center for Research and Development (start September 2014) about using biochar in horticulture, led by Agnieszka Medyńska-Juraszek (coauthor of this article).
– research on biochar is also being developed at few others universities in Poland such as Czestochowa University of Technology (https://is.pcz.pl/static/pdf/2012/zeszyt4/5_2012_Malinska.pdf, http://www.cire.pl/pliki/2/biowegiel.pdf), University of Life Science in Poznan (http://www.ineko.net.pl/pdf/36/03.pdf) and University of Life Sciences in Lublin http://www.up.lublin.pl/files/agrobio/strategia-rozwoju/2014-strategia-wydzialu-agro.pdf)

Fig. S1. Map of biochar field trials and research projects. European Biochar Research Network (2015). This map is not exhaustive but presents a visual summary of where biochar research has been concentrated to date

Fig. S2. Research project coordinated by Opole University of Technology looking into biochar's impact on soil and biomass properties, and biochar's potential to increase agricultural productivity. Left: maize growing on biochar (50t/ha); right (control) after four months of experiment duration.
Photo: Agnieszka Latawiec

SM 2. Soil organic matter and soil texture

To evaluate the abundance of soil with humus in Poland, most commonly used are the following ranges of soil organic matter contents:

<1% – Low,
1–2% – average,
2–3.5% – high,
>3.5% – very high.

In 2010, the organic matter content ranged between 0.76–6.05%. Average organic matter content was 1.97% and did not differ significantly from the average content observed in the previous years. Most of the analysed soils (over 60%) were characterized by organic matter content between 1–2%. Soils characterized with the content between 2–3% were observed in 30% of the analysed samples, while soils with the content above 3.5% were observed in almost 10% of the analysed samples. Soils with the content below 1% were found in approximately 2% of the analysed samples. Spatial distribution of different organic matter contents is associated with the climatic conditions: in the north and south part of the country the more favourable water balance favours organic matter accumulation via reduced decomposition. Because 58% of organic matter is organic carbon content therefore in 2010 mean content of organic carbon equaled to 1.14% with a range of 0.44–3.51%.

The majority of the soils in Poland (72%) need liming. Alkaline biochar will likely result in positive outcomes in acid soils, while adding alkaline biochar to neutral soils is unlikely to improve crop yields, unless it is heavy clay that needs draining, or dry soil where biochar can improve water holding capacity (Glaser *et al.* 2002). Although lime may be an easier and cheaper way of increasing soil pH than biochar (although this is yet to be investigated), biochar has additional advantages (carbon sequestration and other associated positive long-term impacts on soils) that may drive farmers' choice towards biochar uptake. Research related to farmers' decision making on preferences for soil enhancers and factors driving these preferences, is currently being undertaken (Latawiec *et al.* 2017).

Table S1. Classification of soil graining and mineral formation (based on Soil Science Society of Poland (PTG 2008))

	Classification (name) of the type of soil (granulometric group) according to the standard BN-78/9180-11		USDA classification (approximate equivalent grain size groups from standards BN-78/9180-11)	
	symbol	Name in Polish	symbol	Name in English
1	psp	piasek słabo gliniasty pylasty	LS	Loamy sand
2	pgl	piasek gliniasty lekki	LS	Loamy sand
3	pglp	piasek gliniasty lekki pylasty	LS	Loamy sand
4	pl	piasek luźny	S	Sand
5	plp	piasek luźny pylasty	S	Sand
6	ps	piasek słabo gliniasty	S	Sand

SM 3. Spatial prioritization for biochar use

Table S2. Share of agricultural area [% AA] with potential for biochar use

Region	Strong indication	Medium indication
Dolnośląskie	0.1	8.6
Kujawsko-pomorskie	1.0	15.8
Lubelskie	0.6	19.2
Lubuskie	0.4	21.5
Łódzkie	1.8	36.7
Małopolskie	0.7	20.5
Mazowieckie	3.9	35.9
Opolskie	0.1	8.7
Podkarpackie	2.5	10.0
Podlaskie	0.7	29.5
Pomorskie	0.7	13.5
Śląskie	5.6	44.5
Świętokrzyskie	2.7	17.1
Warmińsko-mazurskie	0.5	11.9
Wielkopolskie	1.1	25.4
Zachodniopomorskie	0.4	13.6
Poland	1.5	21.8

SM 4. Liming needs

Table S3. Liming needs in % of the area (CSO 2012)

Province (region)	Need for liming in % of the area				
	necessary	needed	advised	limited	not needed
Poland (average value)	**23**	**16**	**17**	**16**	**28**
Dolnośląskie	24	17	20	18	21
Kujawsko-pomorskie	12	11	13	16	48
Lubelskie	29	15	13	12	31
Lubuskie	15	18	21	20	26
Łódzkie	33	20	16	13	18
Małopolskie	40	14	13	11	22
Mazowieckie	33	17	15	11	24
Opolskie	12	18	30	24	16
Podkarpackie	45	16	13	10	16
Podlaskie	26	19	16	12	27

End of Table S3

Province (region)	Need for liming in % of the area				
	neces-sary	needed	advised	limited	not needed
Pomorskie	21	21	20	15	23
Śląskie	29	17	20	17	17
Świętokrzyskie	23	12	11	12	42
Warmińsko-mazurskie	21	18	18	15	28
Wielkopolskie	16	14	16	18	36
Zachodniopo-morskie	18	16	18	16	32

SM 5. Nutrient content and fertilizer use

The intrinsic CEC of biochar usually exceeds that of mineral soil or soil organic matter (Sohi *et al.* 2009) and biochar additions of 2% have been found to raise CEC by up to 20% (Laird *et al.* 2010). By increasing the availability of nutrients, biochar tends to facilitate microbial abundance and diversity (Thies, Rillig 2009). Biochar has also been shown to influence the availability and plant uptake of nutrients (Glaser *et al.* 2002; Van Zwieten *et al.* 2010).

Only 25% of soils in Poland are characterized as having satisfactory available phosphorus content (Lipiński 2013). In the case of available potassium, almost half of the country has low or very low contents of this element (SM6). Since productivity increases due to biochar tend to be greater on infertile soils (Glaser *et al.* 2002; Haefele *et al.* 2011), biochar could contribute to increasing nutrient availability in Poland. In addition, because biochar application tends to result in higher yield responses in sandy rather than in silty or clay soils (Haefele *et al.* 2011), this further reinforces the potential utility of biochar as an enhancer of poor soils in the country. Despite increasing use of mineral fertilizers in Poland since 1990, fertilizer use in Poland remains relatively low compared to European countries such as Germany or Norway (Supplementary Material) and the nutritional requirements of plants with respect to individual elements are still not met, mainly due to high fertilizer prices. The trade-off between costs of biochar production, the price of fertilizer and the ongoing value of use-efficiency will have to be investigated, to understand the potential benefit from biochar application.

Fig. S3. Available phosphorus (evaluation for the years 2007–2010 (Lipiński 2013))

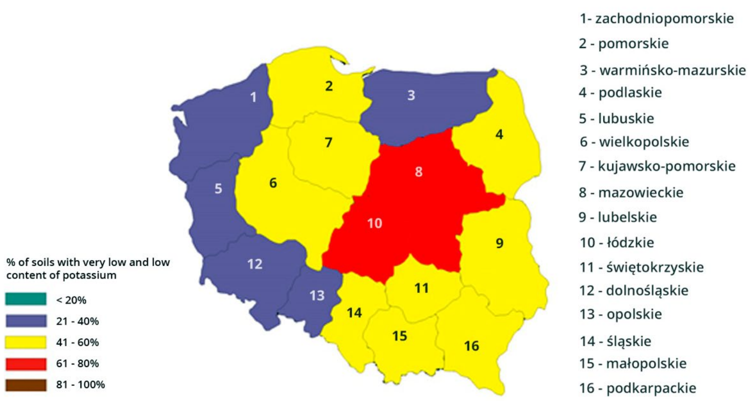

Fig. S4. Available potassium (evaluation for the years 2007–2010 (Lipiński 2013))

SM 6. The use of chemical fertilizers in Poland

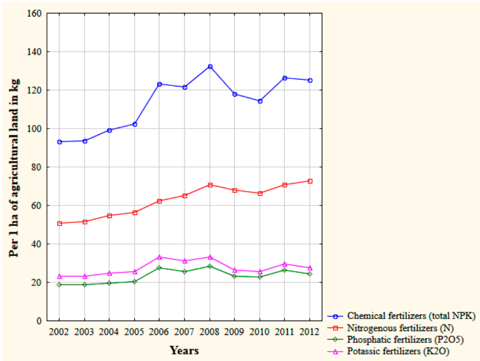

Fig. S5. Consumption of chemical fertilizers in terms of pure ingredient per 1 ha of agricultural land (Fotyma *et al.* 2009)

The use of mineral fertilizers in Poland over the past 12 years has been steadily growing. In 1992 fertilizer use amounted to 53 kg NPK ha^{-1}, but currently is at the level of 132 kg NPK ha^{-1}. Poland ranks near the European average in terms of the amount of N, while the average doses of P and K are relatively lower (Grotkiewicz 2017). Due to the low quality of the soil (low pH, low C organic matter content, light soils) the use of these components by plants, compared to other countries, is low and does not exceed 50%. The rest is lost mainly through leaching. The use of biochar could improve soil properties (increase pH and improve the supply of carbon and change the soil structure), which positively affects the uptake of nutrients by plants (Fotyma *et al.* 2009; Kopiński 2009).

Moreover, in Poland the use of manure to improve soil fertility and increase SOM is becoming annually more difficult due to a decline in livestock numbers (Michałek *et al.* 2013). On the other hand, despite increasing volumes of applied mineral fertilizers since the 1990s, fertilizer use still continues to be relatively low as compared to other Western countries such as Germany (Supplementary Material), thus the nutritional requirements of plants with respect to individual elements are still not covered, mainly due to high fertilizer prices. In that respect, biochar could reduce the need for fertilizer thus reducing costs. An interesting research angle could investigate a trade-off between the costs of implementation of biochar technology in Poland versus current costs of fertilizers.

The use of fertilizers worldwide

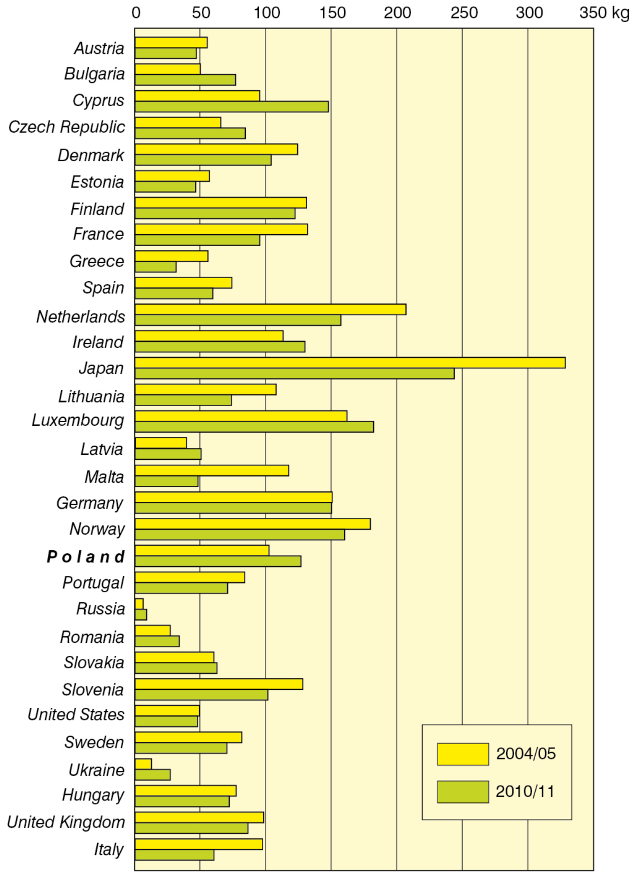

Fig. S6. Consumption of mineral or chemical fertilizers in terms of pure ingredient per 1 ha of agricultural land in selected countries (CSO 2013)

SM 7. Social acceptance and potential in horticulture

While positive results have been noted in terms of yield increases after biochar application, the problem related to social acceptance and to the ways biochar will be incorporated into agricultural practices remains. For example, in a project carried out in Zambia farmers who currently practise conservation farming have adopted biochar into their agricultural methods. Within conservation farming, farmers use small basins that are dug in the dry season and then the seeds and all fertilizer materials are placed in the basins and covered over. The advantage of such basins is that the area tilled is reduced in comparison to normal farming practice and farmers have added biochar to these basins. However, the biochar must have been produced during a period which was a time of rest for farmers. In addition, the methodology used to produce the biochar is a significant hurdle to overcome as current cooking practices do not generate enough biochar for use in the field. Clearly, although the reality in Poland may be different, the farmers may face a range of other similar practical barriers to the adoption of biochar in their everyday farming practice. Research to investigate socioeconomic opportunities and constraints related to biochar application in Poland is currently being undertaken (Latawiec *et al.* 2017).

In Poland, biochar may potentially be applied within agriculture and horticulture, by both small and larger-scale producers. Horticulture is one of the biggest and most important branches of food production in Poland which has one of the highest agricultural production potentials in Europe (Królczyk *et al.* 2014). Between 2000 and 2010 the area of agricultural land under horticultural production in Poland was 11% and according to forecasts, there will be a continuous increase of vegetable and fruit production over the next decade (Ziętara, Sobierajewski 2012). There has been very little biochar research with respect to horticuture in Poland, and the results are mixed. The main benefit of biochar use in horticulture is increase of yields with reduced use of fertilizers and water during production. In many published studies on this topic the main mechanism improving the growing condition of plants is the alternation of the physical and chemical properties of the soil, especially availability of nutrients and microbial activity.

SM 8. Life cycle assessment

Life cycle assessment (LCA) is fundamental to any study into the production, deployment and use of biochar and enables consideration of the broader implications and impacts. LCA is also essential for contributing to the information available to policymakers and decision-makers (Van Hoof *et al.* 2013) aiding to understand the way in which their choices can affect the natural environment and have unintended consequences (Brandao, Canals 2013). An example of the unintended consequences of an environmentally motivated policy, is the problems that occurred as a result of first-generation biofuel production for the implementation of the European Renewable Fuels Transport Obligation which came into force in 2007 (RFTO) (Gallagher 2008). The directive requires that European countries include 5% renewable fuels to be included in diesel fuel and this was anticipated to rise to 10%. This directive was amended in 2009 and again in December 2011 to include the renewable energy directive (RED) criteria which required that the biofuels be shown to be sustainably produced in addition to being produced from renewable resources. This amendment was as a result of the unintended consequences of increased staple food prices around the world as land previously used for food production was diverted to fuel crops production (Gallagher 2008). The UK government commissioned a report, "the Gallagher Review" to look at the unintended consequences of this policy. LCA and LCIA are methodologies which can compare different feedstock and sources of feedstock, thus providing information about the wider impacts of biochar production. Information about the wider impacts and implications that can be derived from rigorous and transparent LCA and LCIA studies with appropriate boundaries, functional units, and impact categories will enable decision-makers and policy designers to see the wider implications and consequences of biochar production.

Due to the wide range of feedstocks that can be used for biochar production (e.g. agricultural residues, purpose grown crops, forestry and wood industry waste, non-native invasive species, domestic waste streams), the impact of different feedstocks and where these are sourced from is critical (Cowie *et al.* 2012). The environmental implications of each is dependent on a range of different factors, including distance travelled to the pyrolysis plant, land-use change (including adverse effects of demand displacement) and alternative uses for the feedstock. The impact categories in LCA take into account these differences and help quantify the impact that specific predefined scenarios can have, and enable comparisons between different scenarios. Different technologies for producing biochar under a range of contexts and situations are also crucial for LCA.

SM 9. Current and potential use of different biomass sources in Poland

Table S4. Potential and energetic use of selected biomass sources in Poland (Gołaszewski *et al.* 2013)

Type of solid biomass	Potential		Utilization	
	PJ/year	%	PJ/year	% of potential
Straw	114	17.1	1.5	1.3
Hay	10	1.5	0	0
Wood from horticulture	15	2.3	1	6.7
Energy crops	212	31.9	0.3	0.1
Total of agricultural biomass	351	52.8	2.8	0.8
Forest resources	240	36.1	104.0	43.3
Wood waste	74	11.2	53.1	71.8
Total of solid biomass	665	100	160	–

The potential of straw for energy purposes

The forecast technical (blue), economic (red) and market (green) potential in terms of obtaining the straw for energy purposes in Poland is shown in Figure S7 (Michałek, Kuboń 2009). In 2010, the technical potential of obtaining the straw for energy purposes was estimated at 5.65 million tonnes, while in 2020 at 8.63 million tonnes. Over the period of time analyzed this is forecast to slightly increase in economic potential from 4.47 million tonnes in 2010, to 5.23 million tons in 2020. The largest changes are predicted for the potential of the straw market for energy purposes. It is estimated that in 2010 this will reach 0.90 million tons, in 2015 a value of 4.50 million tons, while in 2020, 5.29 million tons.

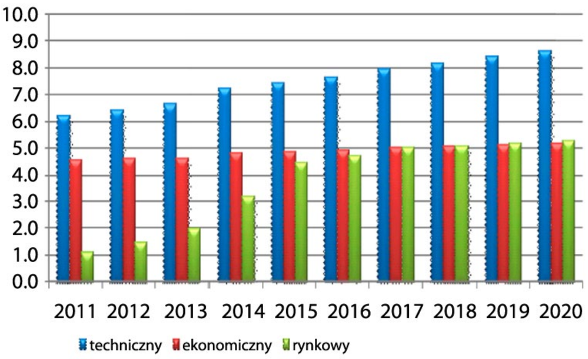

Fig. S7. The forecast technical (blue), economic (red) and market (green) potential in terms of obtaining the straw for energy purposes in Poland. (source: The Polish Chamber of Biomass 2017)

Fig. S8. Market potential of biomass from permanent grasslands (source: The Polish Chamber of Biomass 2017)

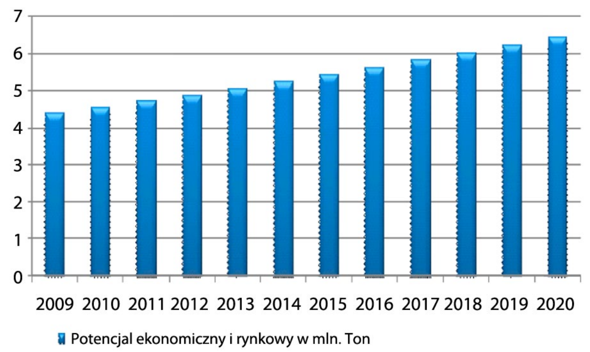

Fig. S9. The forecast market potential of forest biomass (from forest plantations) for energy purposes in Poland (source: The Polish Chamber of Biomass 2017)

Market potential of biomass from permanent grasslands is shown in Figure S8 (Michałek, Kuboń 2009). In the analyzed period of time a slight increase of technical capacity from permanent grasslands is predicted from 2.3 million tonnes of dry matter in 2010 to 2.71 million tons of dry matter in 2020. Predictions for economic potential will be comparable with the market potential of permanent grasslands and predict 23.8% growth of the market with 2.76 million tons of dry matter in 2010, to 3.62 million tons of dry matter in 2020.

The potential of forest biomass for energy purposes

Forests in Poland have diversified ownership structure. Most of them are in public ownership (82%), with the main part of them managed by the General Directorate of State Forests (78%), and the remainder are private forests (including individuals 17%). The forecast market potential of forest biomass for energy purposes from forest plantations in Poland is shown in Figure S 9. In 2010, the technical potential of forest biomass for energy purposes was estimated at 5.06 million tonnes, while in 2020 at 7.15 million tonnes. In the analyzed period of time the economic and market potential is predicted to increase from 4.56 million tons in 2010, to 6.43 million tons in 2020.

Biomass resources of perennial energy crops

Cultivation of perennial energy plants has hardly increased since 2006. The main reason for this seems to be the lack of a stable agricultural policy and the lack of guarantees of the prices and market. The initial attitude of the producers of electricity and heat was an aversion to the use of biomass co-firing. This problem was solved by the Regulation of the Minister of Economy of 14.08.2008. It was planned that producers of electricity and heat would be treated as partners in biomass production, would start long-term contracting of biomass and be presented with a clear pricing policy on biomass fuels. Most importantly dedicated plantations would emerge for the production of green energy. Unfortunately, such a breakthrough has not yet occurred in the formation of perennial plantations of energy crops. Another important reason was and is the farmers' and producers' approach to new types of plants (perennials, woody), lack of machinery and equipment for planting and harvesting, and the lack of prospects for the reception of raw materials. The market potential of biomass from perennial energy crops in 2009 was as follows: willow (*Salix viminalis)* ca. 75 000 tonnes of dry matter, Miscanthus spp. ca. 25000 tonnes of dry matter, *Sida hermaphrodita* about 1700 tonnes of dry matter. Poland has a large market potential of biomass, which can be designated for energy purposes. Poland has also a significant potential for the development of agro-energy, particularly in the production of perennial energy plants. However, there is a lack of development of dedicated energy crop perennial plantations, whose development seems to be one of the most promising directions of sustainable local development (Michałek *et al.* 2013). The influence of these socio-political factors and their influence on biochar production and adoption in Poland is yet to be investigated.

Regarding biochar and its energy use, from one tonne of biochar approximately 10 GJ of heat can be obtained in the form of exhaust fumes with a temperature of around 850–900 °C. By using them for the production of electric power, approximately 0.6 MWhe/tonne of biochar can be obtained (Bis 2015; Kobyłecki 2014; Kobyłecki, Bis 2006). Biochar obtained in this manner is characterised by a high energy content (calorific value on average of 25–30 MJ/kg in the operating state), a high content of elemental carbon (C > 80%) and moisture content of less than 1%. Its physical properties are similar to those of coal: 1 m3 of biochar has a mass of 135–220 kg and an energy density of 4.5–5.5 GJ/m3. Sulphur content does not exceed 0.1%. Biochar also has a reduced content of other harmful substances, such as e.g. mercury or chlorine (Bis 2015; Kobyłecki 2014; Kobyłecki, Bis 2006). The "green" electrical and thermal energy potentially produced during the production of biochar can potentially mitigate the effects of the climate and energy crisis (Wojtkowska-Łodej 2014). Depending on the biochar production technology and the sizes of thermolysis reactors, biochar can be used for alternative production of heat and electric power for the needs of family farms, commercial and industrial plants as well as local communities (Bis 2015). Furthermore, biochar can be used to heat private households, especially where there is the problem of smog, e.g. in Silesia, the region of Małopolska (Southern Poland) or metropolitan areas that struggle with the exceeded air pollution concentrations (GIOS 2016). Lower emission levels of carbon dioxide and sulphur compounds are an ideal solution from the point of view of environmental protection and also as means of support and development of low-emission economy (Kumar, Nanda 2016; Bis 2015; McHenry 2009).

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