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Biochar as an Option for Sustainable Resource Management

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

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Abstract. Although increasing numbers of research papers regarding biochar are being published worldwide, in some countries growing interest in biochar has only recently been observed; this is true of Poland. We analysed information on biochar research in Poland alongside lessons learned elsewhere in order to identify the significant opportunities and risks associated with biochar use. This data fed into a GIS-based multicriteria analysis to identify areas where biochar application could deliver greatest benefit. We found that 21.8% of agricultural land in Poland has at least moderate indication for biochar use (soil organic matter below 2% and pH below 5.5), while 1.5% was categorized as a priority as it also exhibited contamination. Potential barriers identified included biomass availability and associated risks of indirect land-use change due to possible national and transnational biomass production displacement. Biochar use could have positive global consequences as a climate change mitigation strategy, particularly relevant in a country with limited alternatives. Scaling up a mitigation technology that is viable on account of its co-benefits might

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be cost-effective, which could, in turn, adjust national perspectives and stronger involvement in developing mitigation policies at the regional level. Biochar has much promise in temperate conditions and further research should therefore be assigned to explore biochar's environmental and socio-economic impacts.

Keywords: biochar, carbon sequestration, GIS-based multicriteria analysis, land remediation, sustainable agricultural production.

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Introduction

Biochar is considered a tool of potential relevance to sustainable agricultural development (Sohi *et al.* 2010; Zimmerman *et al.* 2011; Jindo *et al.* 2012). It influences a range of soil physical, chemical and biological properties, in ways that tend to favour crop productivity (Lehmann, Josef 2009). This influence varies according to environmental factors, soil type and the type of biochar used (Biederman, Harpole 2013). Productivity increases attributed to biochar tend to have been greatest for soils with low pH and coarse texture (Cornelissen *et al.* 2013; Haefele *et al.* 2011; Sohi 2012; Yeboah *et al.* 2009). The meta-analysis of Jeffery *et al.* (2011) reported an overall grand mean crop yield increase of 10% with the range between –28 and 39%, while others report yield impacts ranging from –71% to 324% (Sohi *et al.* 2009). The largest yield increases have been reported where a combination of biochar and fertilizer has been used (Gathorne-Hardy *et al.* 2009; Peng *et al.* 2011).

The practice of applying charcoal to soil to improve soil fertility and mitigate contamination is not a new concept (Glaser *et al.* 2002). However, the scientific study of using biochar to improve the properties of soils is relatively new. Over recent years there has been increasing interest, mainly in developed countries, to substantiate the benefits and the mechanistic explanation for these outcomes. In parallel, field experiments have been undertaken in developing countries to investigate whether biochar is a cheap, practical and viable addition to fertilizers and organic inputs to increase soil quality and benefit yields on poor tropical soils (Cornelissen *et al.* 2013; Crane-Droesch *et al.* 2013; Yamato *et al.* 2006). Recent research also shows that biochar application should shift away from on-farm production and application of pure biochar, towards combined biochar-inorganic fertilizer products (Clare *et al.* 2014).

Considering temperate climate, an example of a European country, where limited research related to biochar has been carried out is Poland. Agriculture plays an important role in the economy of the country: it is the only sector where exports systematically exceed imports (CSO 2013). Favourable location of the country at the crossroads of main communication routes in Europe enables agricultural products from Poland to reach over half a billion of consumers. Yet, current agricultural productivity in Poland is relatively low, due to generally poor soil quality (acid soils of low organic matter content) and extensive farming (Królczyk *et al.* 2014; CSO 2012). Developing new sustainable and clean technologies to improve agricultural output is therefore a priority for the country. Average yields of wheat, one of the main crops, is 50% of its potential (FAO, IIASA 2010). Agricultural production is forecast to increase in the future, yet the area of arable land in Poland is diminishing due to urbanization and transport development, among other factors (Krasowicz *et al.* 2011; Jonczyk, Stalenga 2010). In addition, national legislation and international conventions oblige Poland to ensure greater environmental protection and management, known as "greening measures" to protect natural landscapes. To this end, a proportion of agricultural land must be managed as "Ecological Focus Areas" (BES 2013). The country is therefore an interesting example where it is necessary to develop new technologies to seek sustainable intensification of agricultural production. In recent years there has been increasing interest in biochar research in Poland (see Supplementary Material).

In this paper we provide a multi-level model for an appraisal of the potential benefits of biochar application, firstly by overlaying the spatial distribution of relevant soil variables within a GIS, and evaluating these results as the first step in a (reconnaissance-scale) multicriteria analysis. Each of the criteria feeding into this analysis are discussed in greater detail in their regional context. Finally, non-physical, and less tangible, socioeconomic and political factors which would need to be considered in a more detailed analysis, are briefly presented.

The development of spatial decision support systems (SDSS), such as GIS, and their successful integration with multicriteria decision-making methods (MCDM) has been well summarized by Malczewski (2004). One of the primary uses of such systems has been to evaluate rural land use options, a concept which predates computerization, in the form of conventional map overlays (FAO 1976). The "suitabilities" evaluated by such systems have typically been types of land use, as opposed to land treatments, but as both the technologies and the methodologies have advanced, the scope of such spatial analyses seems almost unlimited. Though still unusual, such analyses have included individual soil treatments (Passuello *et al.* 2012), and even biochar (Ahmed *et al.* 2010). An important factor in any spatial analysis is scale. While detailed land use planning decisions would be appropriate at a large scale, e.g. 1:25,000, here, at the countrywide scale, only reconnaissance level considerations are realistic.

With the increasing intensification of agriculture, many temperate countries interested in using biochar now have an opportunity to benefit from lessons learned elsewhere, so as to maximize agricultural productivity and protect ecosystem services. Poland, with its twin pressures of large areas of relatively low quality agricultural land, and losses of farmland to infrastructure, alongside endemic environmental concerns, is well placed to explore the potential of such long-term land improvement without the need for expensive or harmful intensification. Furthermore large areas of land which are marginal for agriculture in Poland could nevertheless produce feedstock for biochar. Although the focus here is on the regional context, general conclusions and implications for decision-making are transferable to other countries. The most pertinent research caveats discussed here may also be particularly relevant in the regions where biochar research has not been taken up. Hence, places with little or no data for the suitability of biochar, could benefit from the results of MCDM applied to physically and socioeconomically similar areas.

1. Methods

A content analysis was performed (Bryman 2008) to select the most pertinent factors underlying the successful application of biochar. Drawing on a literature review and expert opinion, the most likely factors that would drive successful use of biochar in temperate regions were determined to be soil pH, soil organic matter, soil texture and contaminant loads. These variables were overlaid spatially to produce the first map for Poland of potential areas that could benefit from biochar application in terms of increasing agricultural productivity and mitigating soil contamination.

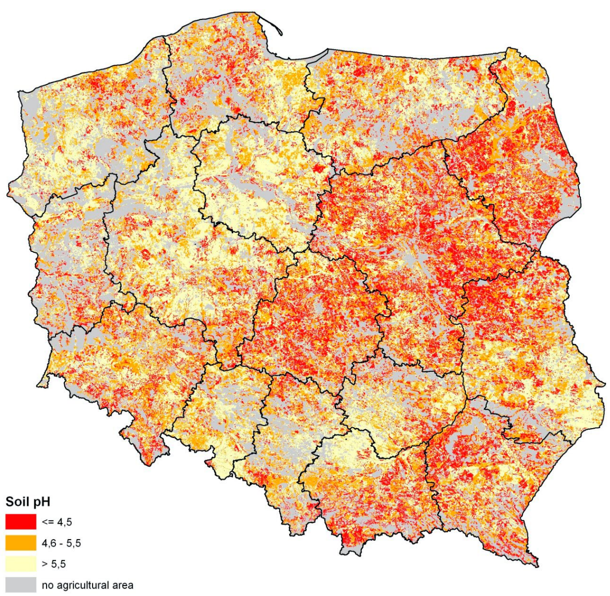

Fig. 1A. Soil acidity in Poland. The soils below pH 4.5 are very acidic and soils with pH range 4.5–5.5 are acidic according to criteria used in assessment of soils in Poland. Most of the country is covered by the areas of acid soils with pH below 5.5. Supplementary Material includes data on each category (medium and strong potential) per region in Poland

The soil acidity data layer (Fig. 1A) was derived through a ranking method, assigning topsoil pH data (pH in KCl) (Łopatka *et al.* 2007) at approximately 45 000 sampling locations (Terelak *et al.* 1997) to polygons of the digitized soil agricultural map (Stuczyński, Jadszczyszyn 2007). The soil contamination data layer (Fig. 1B) was produced through Inverse Distance Weighted (IDW) interpolation of topsoil total cadmium data representing the same 45 000 sampling locations (Terelak *et al.* 1997) followed by averaging values to polygons of soil in an agricultural map 1:100000 (Terelak *et al.* 1997). Cadmium was selected for calculation of metal inactivation needs due to its potential risk to uptake in the food chain (Siebielec *et al.* 2008). It has also been correlated to other metals of similar origin (industry, soil parent rock material), for example, zinc and lead. According to national regulations the threshold for Cd content in agricultural soils is 4 mg kg^{-1}, and this value was applied for mapping. Above this level the soils should be subjected to remediation. The Polish agricultural threshold value for Cd (of 4 mg kg^{-1}) is of immediate relevance to the framing of this manuscript and is in keeping with other threshold values applicable to the EU; for example, the UK Soil Guidance Values for allotment soils (1.8 mg kg^{-1}) and residential soils (10 mg kg^{-1}) (Martin *et al.* 2009). It is noteworthy that each country has its own thresholds for heavy metal contamination and criteria to evaluate contaminated land. Validation of interpolation was performed using an independent set of samples (216 locations across the country) and revealed standard errors of 0.94 and 0.54 for pH and Cd content, respectively.

All data was imported and overlaid using ArcGIS v.9.2 software. Upon the literature review and expert consultation, the following criteria were adopted to prioritize the areas for biochar application (strong indication): soils contaminated with cadmium (>4 mg kg^{-1}) or characterized by soil organic matter below 1% (very low content according to environmental legislation) and pH <= 4.5 (very acidic soil according to criteria used in assessment of soils in Poland) and being sands. Soil organic matter content and soil texture are shown in the Figure 1C and 1D, respectively. To classify areas as those with medium potential for biochar use the following criteria were used: soil organic matter below (or equal to) 2% (considered low by environmental guidelines) with pH lower or equal to 5.5 (considered acid soil) and with soil texture being

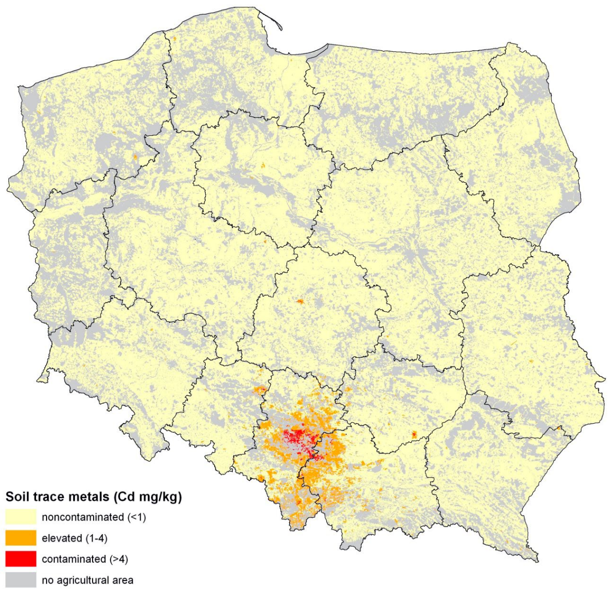

Fig. 1B. Soil contamination with trace metals (cadmium) in Poland. According to national regulations the threshold for Cd content in agricultural soils is 4 mg kg^{-1}. Above this level the soils should be subjected to remediation

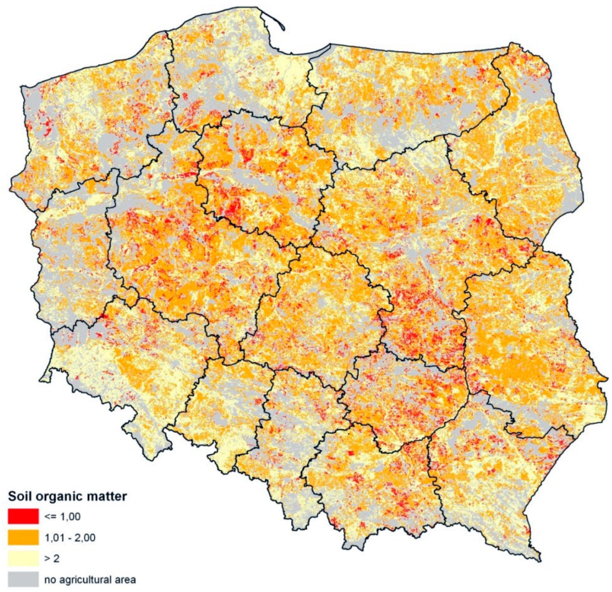

Fig. 1C. Soil organic matter in Poland (Stuczyński, Jadczyszyn 2007; discussion in the Supplementary Material)

sand or loamy sand. Any area with elevated levels of contamination would also be classified as having medium potential for biochar use. The flowchart of methodology is presented in the Figure 2.

2. Results and discussion

2.1. Increasing organic matter and acidity regulation

In Poland, most of the soils are characterized by low to average contents of soil organic matter (Fig. 1C). Soils classified as very acid and acid occupy over 50% of the country (Fig. 1A; Siebielec *et al.* 2012) and over 70% of the soils in the country require periodic liming to manage pH (Supplementary Material). On this account and given soil texture (high sand content), we found that 21.8% of the agricultural area in Poland is characterized by a medium potential for biochar use, while strong potential was found for 1.5% of the agricultural area in Poland (Fig. 3).

Soil acidity and low humus content are the biggest threats to soil quality in Poland according to the State Research Institute of Soil Science and Plant Cultivation (Siebielec *et al.* 2012). Furthermore, common agricultural crops in Poland, such as wheat and barley, require pH over 6.5 to give highest yields and lower pH results in lower yields (by 15–20% of the possible attainable yield) (Fotyma *et al.* 2009; Carver, Ownby 1995). Increasing pH of soils is therefore a priority and necessity within agricultural management in Poland. Furthermore, across Europe soil is under increasing pressure from inappropriate agricultural and industry practices, which undermine the capacity of soil to continue to perform its crucial ecosystem

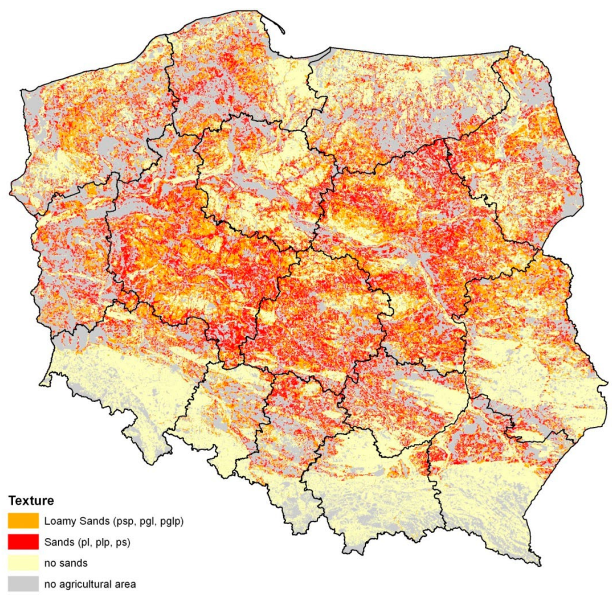

Fig. 1D. Soil texture in Poland

services (COM 2006a). Sixteen percent of Europe's total land area is affected by erosion (12% and 4% subject to water and wind erosion, respectively) while 45% of European soils have low organic matter content (COM 2006b).

In this context biochar is a potential tool to increase soil pH and soil organic matter content. The pH of biochar can vary from pH 4 to 12 (Lehmann 2007), but in general, when biochar is produced at a sufficient temperature (over 350 °C) for adequate time (which, depending on the oven and the pyrolysis type, can be up to a few hours) to ensure that biochar has little ash and a reasonable carbon content

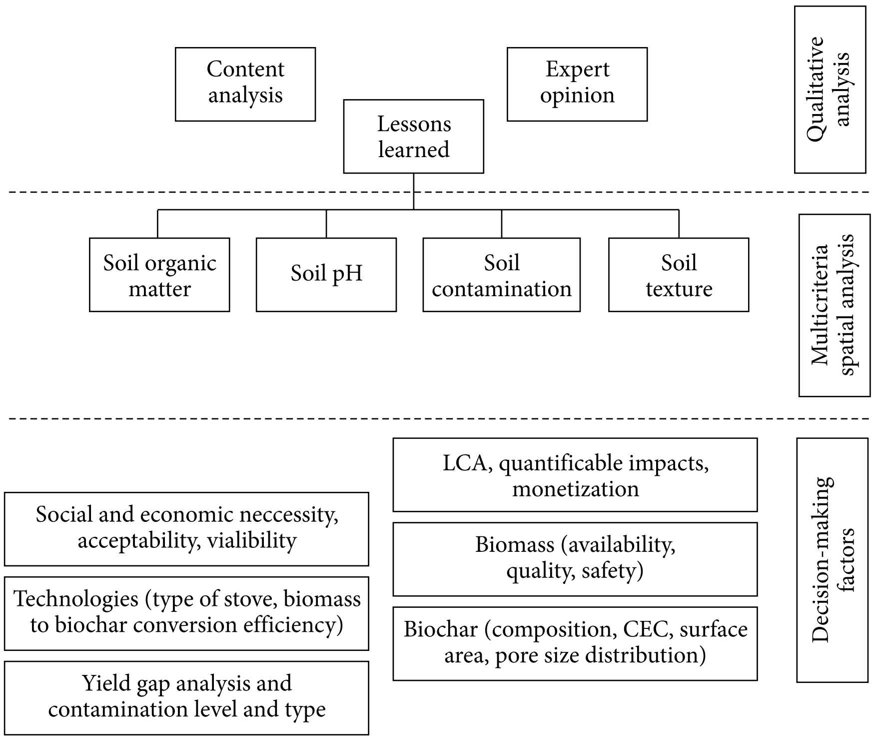

Fig. 2. Flowchart of the 3-step methodology to derive prioritization of biochar use for sustainable land management. First, the literature was reviewed to provide data input to spatial prioritization. In this study we used organic matter content, soil pH, soil texture and contamination level to arrive at the prioritization map. Subsequently we discuss other benefits of biochar and the most important practical considerations that must be taken into account before biochar is applied. Some considerations from the step 3 of this methodology could enrich spatial prioritization; their use however is subject to data availability (and therefore not included in this study)

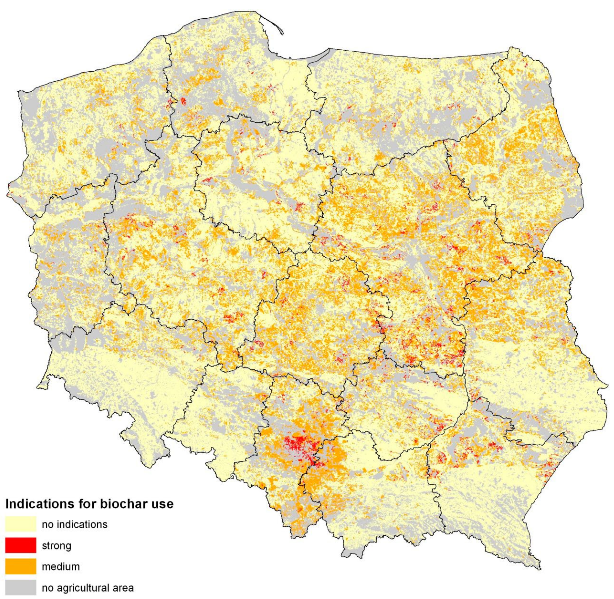

Fig. 3. Preliminary prioritization of areas that could benefit from biochar use. In orange are the areas with medium potential for biochar use: elevated cadmium OR (SOM <= 2 AND pH <= 5.5 AND (texture = sand OR loamy sand)), which equals 21.8% of the agricultural area. Red colour indicates strong potential for biochar application: soils contaminated with cadmium OR (SOM <= 1 AND pH <= 4.5 AND texture = sand), which equals to 1.5% of the agricultural area in Poland

(normally around or above 50%), it displays an alkaline pH (above 7). A number of studies on different types of biochar from different pyrolysis processes demonstrated a liming effect of biochar in the soil (Gaskin *et al.* 2010; Kloss *et al.* 2012, 2014; Singh *et al.* 2010; Uzoma *et al.* 2011). When biochar is added to an acidic soil, it tends to increase soil pH with a broadly beneficial effect, particularly with respect to nutrient cycling, e.g. biochar additions of 2% w/w have been found to raise pH by 1.0 (Laird *et al.* 2010). It has been claimed that adding inappropriately alkaline types of biochar can exacerbate an unfavourably high soil pH (Kishimoto, Sugiura 1985), however such soils tend to be highly buffered and in practice the effect is often neutral (Schmidt *et al.* 2014). Diminished soil acidity accompanied with yield improvement has been reported by many authors (Major *et al.* 2010; Van Zwieten *et al.* 2010; Vaccari *et al.* 2011). The effect of biochar on soil and yields is not only dependent on biochar but also on the soil characteristics such as soil texture, soil organic matter and pH. Most of the pot and field experiments were related to highly weathered, nutrient-poor tropical soils (Glaser *et al.* 2002; Blackwell *et al.* 2009; Sohi *et al.* 2010). According to Verheijen *et al.* (2010) the highest increase in soil pH is observed as a consequence of biochar addition when the initial pH of soil is low and positive effects on crop productivity might be a result of liming effect and nutrients cycling (Jeffery *et al.* 2011; Powlson *et al.* 2011; Rajkovich *et al.* 2012; Verheijen *et al.* 2010). In a recent review of 57 field experiments across all continents (Tammeorg 2014) observed the highest increase in crop productivity following biochar addition in sandy soils with a low soil matter organic content. Biochar also increased soil organic matter content and supported the retention of nutrients and water (Tammeorg 2014). Positive effects on soil and plants were found by Kuka *et al.* (2013) and Yang *et al.* (2013), which might partly be a result of the increase in pH. Sandy soils are likely to have greatest benefits from biochar than clayey soils (Atkinson *et al.* 2010), which is promising in the context of Polish soils.

2.2. Biochar and contaminated land remediation

Many years of intensive land use due to coal mining and metal ore smelting activities have resulted in serious contamination of some arable soils, especially in Upper Silesia (southern Poland) (Loska *et al.* 2004; Karczewska, Kabała 2010), therefore we found this area to have a strong potential to benefit from biochar use (Fig. 3). The degree of the contamination problem is not entirely known, but elevated concentrations of heavy metals, PAHs, oil derivatives have been reported in arable soils throughout Poland (Fig. 1B; Tóth *et al.* 2016a, 2016b; Siebielec *et al.* 2012). The in situ application of amendments to contaminated soils to bind pollutants (to provide conditions that promote plant growth and stimulate ecological restoration) have been reported worldwide, but in Poland such practices are rare.

Biochar is highly porous and has functional groups that enable it to interact with both organic and inorganic species present in soil (Amonette, Joseph 2009; Reid *et al.* 2013). Thus, there is potential to remediate contaminated soils through the sorption and entrapment of contaminants by biochar. Although the use of activated carbon to treat contaminated soils and sediments is well established (Hale *et al.* 2012; Werner *et al.* 2005; Zimmerman *et al.* 2004), the application of biochar as a partially activated material to treat contaminated soil is less investigated. Regarding inorganic contaminants, several studies have shown the potential for a range of biochar materials to ameliorate soil contaminated with metals and metalloids, these include: broiler litter derived biochar (Cu, Ni and Cd) (Uchimiya *et al.* 2010); hardwood-derived biochar (Cd and Zn) (Beesley *et al.* 2010); pecan-shell biochar (Zn) (Novak *et al.* 2009); biochar from orchard prunings (Cd, Pb and Zn) (Fellet *et al.* 2011); rice straw and bean straw biochar (Cd) (Zheng *et al.* 2015), and; sewage sludge bichar (As) (Khan *et al.* 2014).

Research carried out in Poland to date has principally focused on biochar binding of organic pollutants (Oleszczuk *et al.* 2014, 2012a, 2012b; Jośko *et al.* 2013) as well as for composting (Czekała *et al.* 2016; Malińska *et al.* 2014, 2016, 2017). Other pilot studies of biochar use have been made in south-west Poland in the remediation of soils contaminated with multiple trace metals (Cu, Pb, Zn, Cd, As, Ni) from copper smelters. These suggest that biochar made from wheat straw and miscanthus and used at 2% (w/w) concentration could reduce bioavailability of Cu, Zn and Pb and uptake by plants growing on highly contaminated soils (Medyńska-Juraszek 2014). We note, however, that biochar-metal associations, while they mitigate risks, do not necessarily reduce risks to below acceptable levels. Here it is important to acknowledge: i) the extent to which metal concentrations are elevated (in cases of gross contamination biochar may lack sufficient adsorptive capacity to fully mitigate metal risks) and ii) prevailing environmental conditions, such as pH and redox potential (as prevailing conditions may be unconducive to metal sorption; favouring metal dissolution to the soil pore water) (Zheng *et al.* 2015; Zhang *et al.* 2016). Nonetheless, given these initial bioremediation-focused studies that suggest that biochar amendment to soil is a useful tool in reducing environmental risk of pollutants, we emphasize the need for further investigation.

In addition to heavy metals, elevated concentrations of pesticides have been reported in Poland (Sutrawska, Kołodziejczyk 2006; Eurostat 2016). At such locations biochar, on account of its sorptive capacity, could ameliorate the impact of pesticides by reducing exposure of non-target receptors, for example, soil biota, groundwater, surface waters and aquatic organisms. Reduced pesticide availability in soils would also be anticipated to reduce pesticide uptake to food crops and further accumulation into the food chain. Such reduced soil-to-plant transfer of pesticides has been reported in biochar-amended soils for both insecticides (Pylypiw *et al.* 1997) and herbicides (Pylypiw *et al.* 1993). Direct biochar placement within soils or as a permeable barrier (e.g. trenching) in the riparian zone could provide mitigation of herbicide transfer to surface waters. Biochar may provide an important sink where excess runoff occurs but the knowledge on this topic is still scarce. Although in Poland little is known about pesticides residues in general, some areas of the country (such as Lower Silesia and Opole Silesia) were reported to have high residues of herbicides and fungicides in soils, water, plants and animal tissues, which corresponds to the high doses of pesticides used in these regions (Sutrawska, Kołodziejczyk 2006). Research into this area would be of particular use in order to prioritize biochar interventions in areas of greatest concern (Weissteiner *et al.* 2014; Biziuk 2009; Sutrawska, Kołodziejczyk 2006).

It is worth noting that the map of potential for biochar application presented here serves as visualization for a reconnaissance study. Even though our database of 45 000 sampling locations is the most detailed existing soil survey in Poland, uncertainty in individual locations may be considerable, since spatial variability of pH and metal content is high, as a result of soil management by farmers, parent rock and diversity of industrial sources of contaminants in post –industrial regions. Decision making on individual locations should therefore be complemented by the analysis of soil samples collected from the location of interest.

2.3. Physical effects in soil following biochar amendment

Like soil organic matter, biochar can counteract both aridity in sandy soils (Uzoma *et al.* 2011) and improve water drainage under inundated conditions of waterlogged clay soils (Asai *et al.* 2009). Biochar can enhance water holding capacity (WHC) and water use efficiency, which can help to reduce water demand (Peake *et al.* 2014). Biochar-amended soils have shown increases in WHC from 11 to 481% especially in sandier soils (Karhu *et al.* 2011; Southavong, Preston 2011; Uzoma *et al.* 2011). Sandy soils were therefore selected as priority areas in our spatial modelling.

Other physical effects of biochar include reduced bulk density (Laird *et al.* 2010), reduced tensile strength (Chan *et al.* 2007), and decreased soil strength (Busscher *et al.* 2010). The capacity of biochar to improve soil structure and cohesion has the potential to prevent erosion and counteract compaction, and is also directly aligned with European soil protection priorities (COM 2006a, 2006b). Since improving soil structure and WHC may lead to soil stabilization, results of such analysis would also have implications for flood-risk areas. More research is however required to assess the best candidate soils and to match this assessment with flood risks.

Poland is one of the countries in Europe with the least available water per capita (CSO 2013; Siebielec *et al.* 2012). The capacity of storage reservoirs in Poland is very limited (6% of the annual outflow of water), which does not provide adequate protection against periodic surpluses or deficits of water (Siebielec *et al.* 2012). Therefore using biochar to address low WHC in Poland agronomically is extremely relevant. Projected increases in evapotransporation under climate change further reinforce the potential mitigation strategies that biochar may offer to abate future water deficits (SOER 2010). As some authors showed (Devereux *et al.* 2012), it may be possible to reduce irrigation frequency or volume in coarse textured soils, soils with a large number of macropores or when large amounts of biochar are applied.

Another potential benefit from biochar use, unmapped here due to data scarcity, relates to nutrients. In terms of plant nutrition, biochar can have two effects: temporary fertilizing effects, on account of its ash content, and longer-term effects, such as changes to pH or cation exchange capacity (CEC). Discussion on potential benefits from biochar in the context of nutrient availability in Polish soil can be found in Supplementary Material.

2.4. Potential barriers to biochar utilization

Several important aspects relating to biochar application to soil need full consideration if biochar is to have a role to play in sustainable land management in Poland. Most pertinent are: 1) safety, 2) social acceptance, 3) lifecycle appraisal and, 4) availability of feedstock for biochar production.

2.4.1. Biochar safety

The over-riding prerequisite for any soil amendment is its safety. Biochar has the potential to introduce toxic chemicals into soil that could damage soil functions. Three groups of potentially toxic substances, namely: metals and metalloids (such as, As, Cu, Pb, Ni, Zn etc.); polycyclic aromatic hydrocarbons (PAHs); and dioxins, are the most likely agents to be present in biochar and to represent a toxicity hazard. Although environmental impacts attributable to metals, metalloids, PAHs and dioxins associated with biochar are likely to be minimal (Freddo *et al.* 2012; Hale *et al.* 2012), special care is required to ensure the feedstock materials, particularly if wastes, are not overly burdened with high concentrations of metals, metalloids, or chlorinated compounds (that may serve as dioxin precursors). In this regard virgin wood and crop waste residues are not tainted chlorinated compounds (e.g. associated with wood preservation) and these feedstocks have relatively low metal and metalloid loadings (Zheng *et al.* 2015) when compared to, for example, sewage sludge (Lu *et al.* 2016). In keeping with biochar guidance applicable to the EU, for example the Biochar Quality Mandate (Shackley *et al.* 2014) we advocate that biochar produced for application to agricultural land should be derived from virgin non-waste biomass feedstocks. Pyrolysis conditions should also be considered with caution, as lower pyrolysis temperatures (<400 °C) have been reported to give biochar products with greater PAH loadings when compared with biochars produced at higher pyrolysis temperatures (Freddo *et al.* 2012; Hale *et al.* 2012).

2.4.2. Social acceptance and inclusion into farmers' practice

Social aspects are often omitted in the assessment of emerging technologies but are paramount for long-term utility and effectiveness of an approach (Michałek, Kuboń 2009). Indeed, in order for regional scale advantages of biochar to be achieved, diverse stakeholders, populations and decision-makers, along with scientists, have to be actively interested in optimizing biochar technology in the context of their local environment.

Some specific research questions for biochar include: what is the social acceptance and consequence of implementing biochar into agricultural practice (e.g. job creation in sustainable agriculture)?; how would biochar work operationally and would it work for both large and small scale farmers?; would it work in small-holder closed systems (biomass production and use at the same farm)?; is there potential for biochar to be used in horticulture and organic farming?; and, finally, is it economically viable as compared with other alternatives such as the use of lime? These questions also include practical and logistical aspects of storage, transport, and farmers' incorporation of biochar into soil.

Another important aspect is to what extent the farmers would prefer to use their biomass for biochar production instead of receiving, sometimes substantial financial benefits from selling their biomass to power plants, which on the other hand, receive subsidies from the generation of "green energy". Conversely, this trend may finish, when the subsidies cease, while conversion of biomass to biochar may bring the farmers a range of more permanent benefits, such as improving the quality of soils, increasing agricultural productivity, carbon sequestration and potential payments from avoided emissions. Preliminary results show potential interest of the farmers in Poland to adopt biochar, and new studies on social acceptance of biochar application are currently being undertaken (Latawiec *et al.* 2017).

2.4.3. Feedstock biomass

Having identified candidate areas for biochar deployment based on soil conditions, two questions arise. Firstly, the feedstock that could be used to make biochar and secondly, the availability of these feedstocks, given competing current or future uses. It is widely reported that biochar deployment is biomass-intensive and may exacerbate the global challenge of meeting biomass demands from existing agricultural land (Strassburg *et al.* 2014). Increasing demand for biomass could lead to inadvertent adverse effects such as rebound – the economic effect of efficient use of inputs leading to increased use. This could lead to in-country pressure for biomass resources or trans-boundary effects from displacement (Strassburg *et al.* 2014). Decreased net emissions in Poland could result in leakage, i.e. net emissions elsewhere through indirect land-use change driven by demand for biomass. Production of biochar can also be costly and it will be essential to integrate biochar production with the recovery of energy.

The main source of biomass in Poland is wood and wheat straw (Gradziuk *et al.* 2001). Biomass crops such as shrub willow (Salix spp.) or elephant grass (Miscanthus giganteus) cultivation is minor, although cultivation of bioenergy crops has increased (see Supplementary Material). Use of green waste and sewage sludge is increasing rapidly. These might emerge as important lower-cost, point-source feedstock for production of biochar. Clearly, potential conflicts exist between the use of land for food production versus its use for energy crops, and the allocation of land with the express purpose of providing feedstock for biochar production could further add to the demands put on a limited resource (if the biochar production expands beyond the use of organic waste material). Thus it remains to be investigated whether current biomass production would be enough to meet possible demands for biochar in the future and whether it would be practically feasible to increase such production. However, 30.8% of Poland is under forest, largely on land unsuitable for agriculture and which might therefore provide readily available and potentially unwanted feedstock (such as coppice trimmings or sawmill waste) with no change of use or competition for the same resource.

2.5. Lifecycle appraisal

Life cycle assessment (LCA) is fundamental to any implementation of biochar and encompasses broader implications and impacts. This is important in the assessment of biochar use, due to the variety of feedstock used for its production and the diversity of technologies for its conversion (Cowie *et al.* 2012; Lehmann, Joseph 2009). The conversion process involves toxic gases (such as CO) as well as volatiles (that can emanate as smoke) and greenhouse gases (notably CH_4). These emissions could offset the avoided CO_2 emissions associated with carbon stabilization. Emissions from modern pyrolysis units and medium-sized retort kilns should be much lower than those from traditional simple kilns, though data are often commercially confidential in this area (Meyer *et al.* 2011; Adam 2009).

By comparing different feedstock materials and production technologies through the use of LCA the overall positive and negative outcomes of scenarios can be compared. It is vital to match the appropriate technology with the specific situation, using research and the experiences of previous projects which can be applied to biochar production on individual farms. For example, incorporating electricity generation (De Miranda *et al.* 2013), and studies into carbon sequestration potential of biochar would be a good starting point (Hammond *et al.* 2011; Roberts *et al.* 2010).

Conflicting reports about the stability of the biochar matrix also exist (Gurwick *et al.* 2013). Although biochar carbon is more stable than carbon in any other organic form (Lehmann *et al.* 2009) and there is evidence that it may also stabilize incumbent soil organic matter (Bach *et al.* 2016; Glaser *et al.* 2002; Lanza *et al.* 2016; Smith 2016), how long exactly biochar remains stable in the soil and the duration of its influence on soil physical and chemical properties is not entirely certain (Sohi 2012). Establishing the recalcitrance of biochar benefits is a clear priority if a comprehensive assessment of biochar lifecycle is to be achieved.

Determining how specific local conditions and requirements change the balance of impacts for biochar production and use is important as it will illustrate the ways in which technology and production methods cannot simply be transferred between different regions with the expectations that the same benefits will be derived (Sparrevik *et al.* 2011; Turtoni *et al.* 2011). A relatively new development in LCA is life cycle sustainability assessment (LCSA) which combines traditional LCA with life cycle integrated assessment (LCIA), which incorporates social and economic analysis in order to capture a more nuanced and holistic evaluation of the impacts. Poland is well placed to instigate a comprehensive research programme which would facilitate research into quantifying and testing contrasting impact categories to contribute to the development and robustness of this methodology. This approach is particularly relevant for Poland which is in a period of rapid change as EU regulations and policy influence its development. Using LCSA to quantify the multiple considerations when selecting feedstock will enable better judgements about feedstock type and availability. This would provide a unique opportunity to track changes, learn lessons and develop an understanding of the way in which actions on the ground impact the wider sustainability of a system. As an integral part of the assessment of biochar potential in Poland, LCA must be a part of any comprehensive research effort to maximize the potential benefits from biochar production and use.

Conclusions

Given lessons learned elsewhere, a large proportion of soils in Poland could potentially benefit from biochar application. Given the abundance of acid soils with low organic matter, high metal loadings, and low agricultural yields, biochar emerges as a potentially attractive option for soil enhancement. Deployed widely and strategically, it could contribute to increased national output of agricultural commodities, land remediation and co-benefits of climate change mitigation. There are, however, challenges to be addressed, such as biomass supply. We encourage collaboration on this topic, not only because the conclusions are important for the development of sustainable agriculture, but also for economies of countries elsewhere seeking increased agricultural productivity. Poland, like many other countries characterized by extensive agriculture, will need to increase agricultural production without expanding to areas spared for nature, so the question becomes how to increase agricultural productivity without adverse environmental effects. Biochar can not only potentially contribute towards these goals, and hence the overarching priorities of sustainable land management, but can also result in food production increase while mitigating pollution and climate change, thus helping to address these pressing global challenges.

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