Spatial potential for paludicultures to reduce agricultural greenhouse gas emissions: an analytic tool

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SUMMARY

Following the recent international agreements on climate action, there is an urgent need to reduce agricultural greenhouse gas (GHG) emissions. Wet cultivation of peatlands (paludiculture) can combine low GHG emissions with productive use of the land, but methods for identifying suitable areas at regional and local scales are lacking. In this study we present a spatial assessment tool for two paludiculture species, namely *Phragmites australis* and *Typha latifolia*. This tool is built in a Geographic Information System (GIS) and is designed to perform a quantitative and qualitative analysis of the cultivation potential of land that is currently used for agriculture or peat extraction, within a defined geographical area. It uses a graded assessment process with a plot based analysis. A case study application shows that the tool can deliver first estimates of the potential cultivation area, but further research is needed to enhance its flexibility and scope of application. In its present form it may be used as a decision support instrument for specific sites.

KEY WORDS: assessment tool, climate protection, decision support, GIS, peatland, spatial planning

INTRODUCTION

The increasing concentration of greenhouse gases (GHGs) in the atmosphere leads to intensification of the greenhouse effect (Stahl & Berner 2000). Although peatlands cover only 3 % of the earth's surface, they store approximately 500 gigatons of carbon (Joosten *et al.* 2013), which is more than twice the amount of carbon stored in all forests worldwide (Schröder *et al.* 2013). Thus, peatlands are important carbon reservoirs that balance the atmospheric carbon concentration. The absorption of atmospheric carbon by peatland vegetation and its subsequent storage in peat requires permanently wet conditions (Joosten *et al.* 2013). The drainage of natural peatlands (mires) for agriculture rescinds their function as carbon sinks and transforms them into carbon sources (Höper & Blankenburg 2000, Joosten *et al.* 2013). Intensive agricultural management and the input of fertilisers additionally provoke the emission of nitrous oxide (Joosten *et al.* 2013) with a climate effect 265 times stronger than carbon dioxide (Myhre *et al*. 2013).

Since the beginning of the industrial era Germany has lost about 99 % of its intact mires due to human activities (Couwenberg & Joosten 2001). Drainage for agriculture and forestry has led to the destruction of 67 % of this country's bogs and 95 % of its fens (Höper & Blankenburg 2000). Drösler *et al.* (2013) note that drained peatlands are now the second largest national source of GHGs after the energy sector. The largest share of greenhouse gas emissions from land under agricultural use in Germany comes from drained peatlands, and amounts to almost one-third of all agricultural greenhouse gas emissions (Hirschfeld *et al.* 2008). Consequently, the reduction of greenhouse gas emissions that could be achieved by rewetting drained peatlands which are currently used for agriculture could contribute significantly to climate protection.

Peatland restoration programmes have generally focused on rewetting drained bogs and fens for nature conservation purposes (Höper & Blankenburg 2000) and have thus imposed a requirement for agricultural use of the land to be terminated (Wichtmann & Wichmann 2011). Paludiculture, defined as "the agricultural use of wet and rewetted peatlands" (Giannini *et al.* 2017), can contribute to the mitigation of agricultural GHG emissions but still allow the production of renewable raw materials (Kowatsch 2007, Wichtmann & Wichmann 2011, Schröder *et al.* 2013) and thus offer an economically viable alternative for farmers (Gaudig *et al.* 2014b).

The cultivation of wetland biomass requires both special equipment (technical demands) and sites with suitable characteristics (Schröder *et al.* 2016, Wichmann 2016, Wichmann *et al.* 2016). All aspects of the practice of paludiculture have been considerably developed over recent years (cf. Wichtmann & Wichmann 2011, Wichtmann & Haberl 2012, Gaudig *et al.* 2014a). Several studies have estimated the cultivation potential of pilot regions (Wichmann & Wichtmann 2009, Joosten *et al.* 2014) or undertaken spatial assessments at coarse scale without considering site-specific characteristics (Kowatsch *et al.* 2008). However, universal spatial approaches that can identify cultivation potential at both local and regional levels are still lacking (Oehmke *et al.* 2014). Therefore, the aim of the present research is to develop a simple and practical planning tool that enables the assessment of regional and local potential for paludiculture with reasonable effort (cf. von Haaren 2004a). The focus of the study presented here was to identify opportunities for GHG mitigation potential through paludiculture on land that is already used for agricultural purposes. We describe development of the tool and a test implementation for two study areas.

METHODS

Development of the assessment tool

The requirements and restrictions for paludiculture provide the first determinant for the scope of the tool. In its development, *Phragmites australis* and *Typha latifolia* were selected as example species. Both are reeds with similar morphology, habitat needs and biomass yields (cf. Rodewald-Rudescu 1974, Dierßen & Dierßen 2001, Oehmke & Abel 2016). Thus, the first step in tool development was a literature review to ascertain the habitat requirements and restrictions of these species. For the purposes of this study, the spatial scope of potential paludiculture sites was limited to agricultural land including former peat extraction areas that are now under agricultural use.

In the assessment, four aspects were addressed:

1. Legal framework. Cultivation is restricted by the legal framework of environmental and nature protection legislation (Haberl *et al.* 2016).

2. Habitat requirements can be equated to the abiotic environment needed for the permanent establishment of a species; they constitute the basis for establishment of a stable population (Nentwig *et al.* 2004).

3. Economic success (high yields and available markets) can be regarded as the driving force for a targeted cultivation of reeds which demands site conditions other than natural succession (Wichmann 2016). Thus, the technical demands of potential cultivation areas should also be taken into account (Wichmann & Wichtmann 2009).

4. GHG mitigation. The above requirements were complemented by an analysis of GHG mitigation potential.

The structure of the assessment tool builds on these four aspects and deals with them thematically in four successive “assessment categories” (Figure 1). As the objective is to develop a simple and practical tool, it should employ a standardised valuation approach that integrates quantitative and qualitative aspects. Criteria should be operationalised through one or more indicators, and corresponding measurable variables should be used to extract spatial information. This approach follows established valuation techniques in landscape planning as described by von Haaren (2004b).

Test application of the tool

The tool was tested on two sites. The data analysis was implemented within a Geographic Information System (GIS) environment (ArcGIS 10.4.1, ESRI) which enabled the mapping of spatial information. Different sets of vector data, raster data, Web Map Service (WMS) and non-spatial data (Table 1) were collected in the GIS database and information on measurable variables for each agricultural field was extracted from (attribute) tables and raster attributes. Each field then received a rating corresponding to the site conditions identified. The base map for presentation of the results was a vector file representing all fields in the study area. The creation of new attribute tables allowed field-wise reporting of the assessment results, which were presented as maps (in colour) and text descriptions.

RESULTS

The assessment tool

The information required to run the tool consists of spatial data on current agricultural land use, protected areas, soil types and grain sizes, hydrological mire types and peat depth, depth of the water table in winter and summer, the climatic water balance, water discharge, relief and infrastructure.

The assessment tool provides a set of instructions (in German) including: (1) application rules needed for correct functionality of the tool; (2) a set of criteria with corresponding valuation tables; and (3) matrices for the aggregation of partial results. The ‘criteria’ section incorporates: (A) the geographical scope and type of paludiculture; (B) the three valuation categories for identification of potential *Phragmites australis* and *Typha latifolia* cultivation areas, based on six criteria and fifteen corresponding indicators; and (C) one valuation category with one criterion and three related indicators for the estimation of GHG mitigation potential (Figure 1). The valuation tables needed to rank present site conditions may differ between the two example

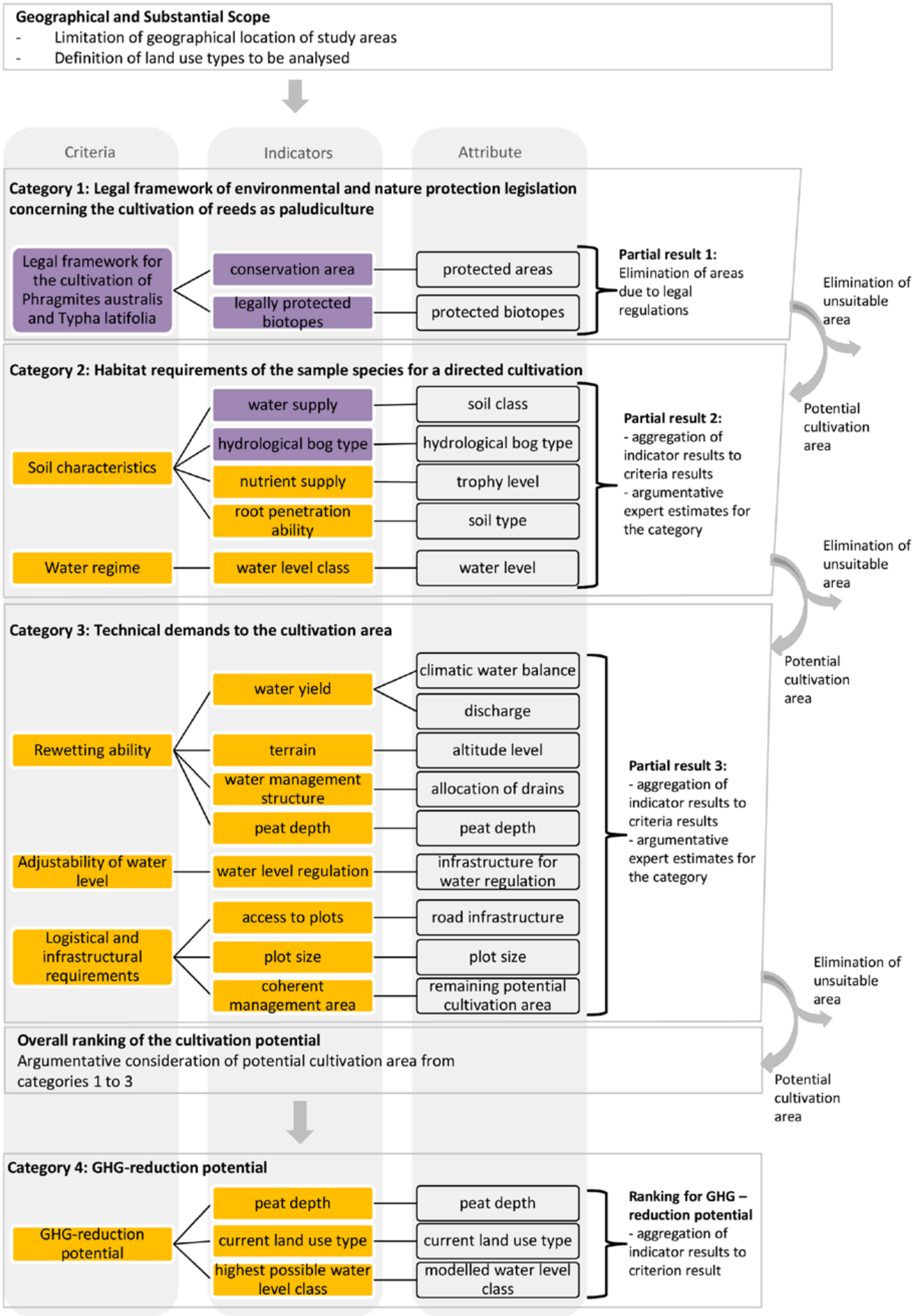

Figure 1. Structure of the tool. The analytic process follows the sequence from Category 1 to Category 3 and deals with indicators within each category in the order presented here. Indicators and criteria shaded in orange have ordinal scales; those shaded in purple have nominal scales. A significant reduction of effort required for analysis is achieved by eliminating 'unsuitable' area after every assessment step.

species because of their partly different habitat requirements.

The study area is analysed step by step, in order of the four valuation categories and their indicators. An important feature of the tool is the stepwise reduction of ‘suitable’ area by elimination of ‘unsuitable’ areas after valuation for each criterion. Only areas that remain after the Category 3 valuation receive an aggregated rating for cultivation potential. Consequently, the assessment of GHG mitigation potential is applied only to areas with cultivation potential for at least one of the example species.

The valuation is operated through a standardised assessment with defined criteria and the use of a fixed range of values. The tool incorporates a quantitative and a qualitative part. We define the quantitative cultivation potential as “hectares of potential cultivation area”. The size of the potential cultivation area determines the potential harvested yield. The qualitative cultivation potential describes the suitability of a site for cultivation of the target species. Quality is rated on a four-level ordinal scale (cf. von Haaren 2004b) with the levels: ‘good’, ‘medium’, ‘bad’ and ‘unsuitable’. Fields assigned to the first three levels are regarded as potential cultivation area. ‘Unsuitable’ plots do not count as potential cultivation area and are excluded from further valuation. To illustrate, Figure 2 shows a map of fields with cultivation potential for *Phragmites australis*, assessed on the basis of water table depth.

Table 1. Datasets used for application of the assessment tool to the study areas Lange Lohe – Boller Moor and Ochsenmoor.

Dataset	Information	Author (provider)	Data type
Information on agricultural aid, Lower Saxony	-field geometry -agricultural land use type	Servicezentrum Landentwicklung und Agrarförderung (SLA 2016)	vector
Authoritative real estate cadastre information system (ALKIS)	-agricultural land use type -land cover other than agriculture (forest, mire, non-vegetated area)	Landesamt für Geoinformation und Landesvermessung Niedersachsen (LGLN), (provided by Geofachdaten Landkreis Diepholz)	vector
Pedological map 1:50.000 (BÜK50)	-groundwater table -soil type -soil class	LBEG (2014), provided by Geofachdaten Landkreis Diepholz	vector
Delineation of protected areas in Lower Saxony	-nature protection areas -nature parks -EU bird reserves -EU FFH reserves	Niedersächsisches Landesamt für Wasserwirtschaft, Küsten- und Naturschutz (NLWKN)	vector
Selective biotope mapping, Lower Saxony	-legally protected biotopes	NLWKN	vector
Precipitation, long-term mean values 1981–2010, Reference site: Diepholz	-precipitation	Deutscher Wetterdienst	online document
Hydrological Atlas of Germany 2005	-potential evapotranspiration -discharge	Bundesanstalt für Gewässerkunde	online application
Topography map 1:25.000 (TK25)	-ditches -road infrastructure	LGLN (provided by Geofachdaten Landkreis Diepholz)	Web Map Service (WMS)
Digital terrain model, grid width 200 m (DTM200)	-relief	Bundesamt für Kartographie und Geodäsie	raster
Pedological investigations	-peat depth	Landesamt für Bergbau, Energie und Geologie (LBEG)	online application
Oral communication	-peat depth	Naturschutzstation Dümmer	oral

Assessment on the basis of other indicators is conducted on a nominal scale (Figure 1). The criteria, their indicators and measurable attributes, as well as their valuation, follow from: (1) normative aspects and interpretations of legal frameworks in nature protection; (2) plant ecological concepts and site conditions; (3) guidelines and technical requirements for the cultivation of reeds based on recent science; and (4) the premise that high GHG-emission reductions can be achieved and the associated requirements (cf. Stegemann & Zeitz 2001, Höper 2007, Couwenberg *et al.* 2008, Drösler *et al.* 2013, Freibauer *et al.* 2016). Since high biomass production is crucial to safeguarding the incomes of farmers (Haber & Salzwedel 1992), a 'good' valuation reflects potential for the greatest possible production of biomass, the establishment of stable and dominant populations of the target species, and a possibility for sustainable and permanent production. In the case of GHG mitigation potential, the rating scale is defined by the potential reduction in emissions.

Since the tool has a multi-criteria approach, partial valuation results at different levels must be aggregated before they can be used to support decision-making (cf. von Haaren 2004b, Scholles 2008). The multi-criteria approach in landscape planning uses a set of indicators to describe the various aspects that are relevant to the decision-making process. The suitability of (site) conditions for a project is described by rating each indicator (ibid.), and a subsequent aggregation of ratings presents the evidence in a targeted and concise

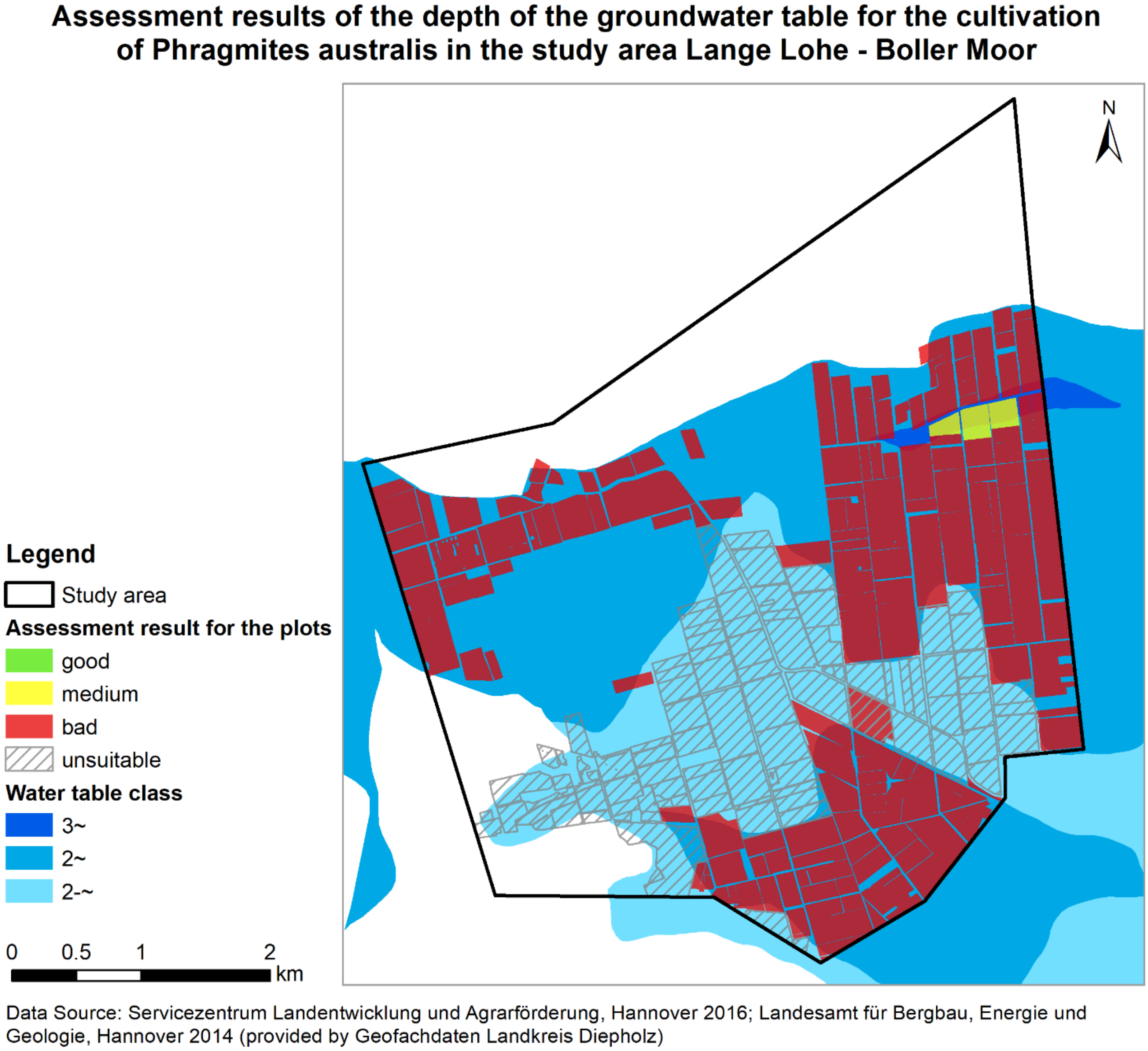

Figure 2. Example map visualisation of the evaluation of groundwater level in the study area Lange Lohe - Boller Moor for *Phragmites australis* paludiculture.

fashion (Singh *et al.* 2002). In the present study this aggregation is conducted with the help of aggregation matrices (Figure 3) containing logic operation rules, a procedure which is described for landscape planning by von Haaren (2004b). As multi-level aggregation leads to loss of information (von Haaren 2004b), in order to come to an overall result across the three categories, further aggregation of criteria within and across the respective valuation categories is performed through systematic expert reasoning with regard to the relative importance of each criterion.

Test application in study areas

The tool was tested on two sites, both located in the German federal state of Lower Saxony in the county of Diepholz (Northern German lowland; Figure 4). The first site is "Lange Lohe - Boller Moor" (LL; 2242.1 ha) and the second is "Ochsenmoor" (OM; 1334.1 ha). The areas of agricultural land within these sites are 1656.5 ha (LL) and 986 ha (OM), including all types of agricultural use (cropland, grassland, permanent crops, orchards, fallow land, etc.). The two sites differ in terms of current land use; while cropland covers 69.3 % and grassland 28.9 % of LL, only 7.1 % of OM is used as cropland and 87.4 % as grassland. The remaining areas are under other agricultural uses that are excluded from the assessment since they are not considered appropriate for conversion to paludiculture. Thus, the total areas assessed are ~ 1644 ha (1644.1 ha) (LL) and ~ 933 ha (932.6 ha) (OM).

Both study areas are subject to restrictions resulting from nature protection legislation. The nature reserves "Drebbersches Moor" and "Boller Moor", together with other legally protected biotopes, reduce the assessed area of LL by 295 ha so that, after this first step, 1349 ha remain in the assessment. Similarly, the nature reserve "Ochsenmoor" and other legally protected biotopes reduce the assessed area of OM by 9 ha and an additional 857 ha of permanent grassland within Natura 2000 areas is also excluded. Overall, only 67 ha of OM (less than 10 % of the agricultural area) remain after assessment of the first category. For this reason, further description of the results focuses on LL alone.

The results of the habitat valuation differ for the different criteria. Site characteristics relating to the soil are mainly 'good' for both species, although large areas have the soil type gley rather than peat. The area is characterised by periodically wet to semi-dry conditions with a dominance of soil moisture classes 2~ and 2-~ (i.e. deeply drained, cf. Koska 2001). Wichmann & Wichtmann (2009) indicate soil moisture class 2+ as the drought limit for establishment of stable populations of *Phragmites australis*. Thus, despite the 'good' soil conditions, a major part (37 %) of the LL study area is 'unsuitable' for cultivation of *Phragmites australis* on the basis of

Nutrient supply		Root penetration ability		Criterion: Soil characteristics
good	+	good	=	good
good	+	medium	=	good
medium	+	good	=	medium
medium	+	medium	=	medium
bad	+	good	=	medium
bad	+	medium	=	bad

Figure 3. Matrix with logic operation rules for aggregation of the indicators 'nutrient supply' and 'root penetration ability' to the criterion 'soil characteristics'.

current groundwater level. The remaining 63 % emerges with only 'bad' potential. *Typha latifolia* differs from *Phragmites australis* in that its good performance is much more strongly related to wet and flooded site conditions (Oehmke & Abel 2016), and it does not tolerate extreme water table fluctuations (LfU 2001). Under current conditions, there is no cultivation potential for *Typha latifolia*. Rewetting would increase the cultivation potential for both species, in terms of both quantity and quality. For *Typha latifolia* the potential cultivation area would increase from 0 ha to 893 ha, and for *Phragmites australis* it would increase from 774 ha to 1150 ha. Not only the quantity but also the quality of conditions would remain better for the cultivation of *Phragmites australis*.

With respect to technical demands, the small plot size is the most limiting factor for cultivation of both example crops. The average plot size in the LL study area is about 4 ha and only three plots reach the recommended size of 15 ha (Wichtmann & Haberl 2012). In contrast, access to the plots from a developed road infrastructure is 'good' for more than 51 % and 'medium' for 47 % of the study area.

The overall ranking for the LL study area shows cultivation potential after rewetting on 1093 ha for *Phragmites australis* and 867 ha for *Typha latifolia*. Qualitatively, the cultivation potential is better for *Phragmites australis* than for *Typha latifolia*. Considering both test areas 34 % of LL and 94 % of OM is 'unsuitable' for cultivation of reeds (Figure 5).

Potential for reduction of GHG emissions

Estimations of potential GHG-emission reductions are based on the maximum potential cultivation area, i.e. 1093 ha for LL and 57 ha for OM. The indicators peat depth, current land use type and potential groundwater table after rewetting are aggregated to deliver the final result for this category. For LL the assessment assigns 'medium' mitigation potential to 64 % of the potential cultivation area and 'high' potential to 8 %, while no reduction of GHG

Figure 4. Location of the study areas in Germany and in their physio-geographical context.

emissions can be expected on 23 %. The results are mainly determined by shallow or absent peat layers and the (im)possibility of rewetting. For OM, 41 % of the potential cultivation area shows 'high' GHG mitigation potential. About 51 % of the area cannot be rewetted and, thus, no mitigation of GHG emissions can be achieved.

DISCUSSION

Structure and method of the analytic tool

The key feature of the analytic tool is its structure. One of the objectives for its development was to reduce the effort required for data analysis, which is achieved through stepwise elimination of unsuitable areas. Especially, conducting the analysis of nature protection legislation in the early stages of the assessment significantly reduces the workload for the following steps (cf. Figure 5). The order of criteria presented here approaches the problem from the perspective of current land use options and prepends those that can be analysed with minimum effort. However, the analysis with regard to other criteria of plots or fields that are eliminated early is thus ruled out. Modifying the order of categories would not change the final results, but the order chosen significantly affects the interim results obtained during the analytical process. Moving the analysis of nature protection legislation to the final stage would enable the estimation of cultivation and GHG-mitigation potential according to site characteristics without political restrictions, and this could inform a discussion on future land use scenarios and their implications for climate protection under changed political conditions. Thus, the ordering of categories should be chosen flexibly and tailored to the aim of the investigation.

Another advantage is the standardised assessment approach, which enables simple implementation of a multi-criterion analysis. The tool is composed of four categories with, in total, seven criteria and 18 subordinate indicators. This multitude of indicators is required in order to cover as many relevant factors as possible when determining the cultivation potential. However, as von Haaren (2004b) remarks, multi-level aggregation and the combination of different thematic fields restricts exactness. The concept of the tool demands the aggregation of results across three levels (from indicators to criteria, to categories, to the final result). This process is very complex since most of the indicators are assessed on a four-level rating scale producing a multitude of possible results in each step, even though this scale is insufficient to exactly reflect the on-site conditions. We note that summarising 18 independent indicator values in a single final result may lead to inexactness and to a levelling of the final qualitative valuation.

All of the assessment steps are needed for the quantitative estimation of cultivation potential. On the other hand, the analysis of qualitative cultivation potential should look at specific results without aggregation, in the context of the aim of the investigation. Such a focus on individual indicators enables clearer insight into the strengths and weaknesses of a particular site. Rewetting possibilities are a limiting factor for paludicultures (cf. Wichtmann *et al.* 2009, Dietrich *et al.* 1999) and

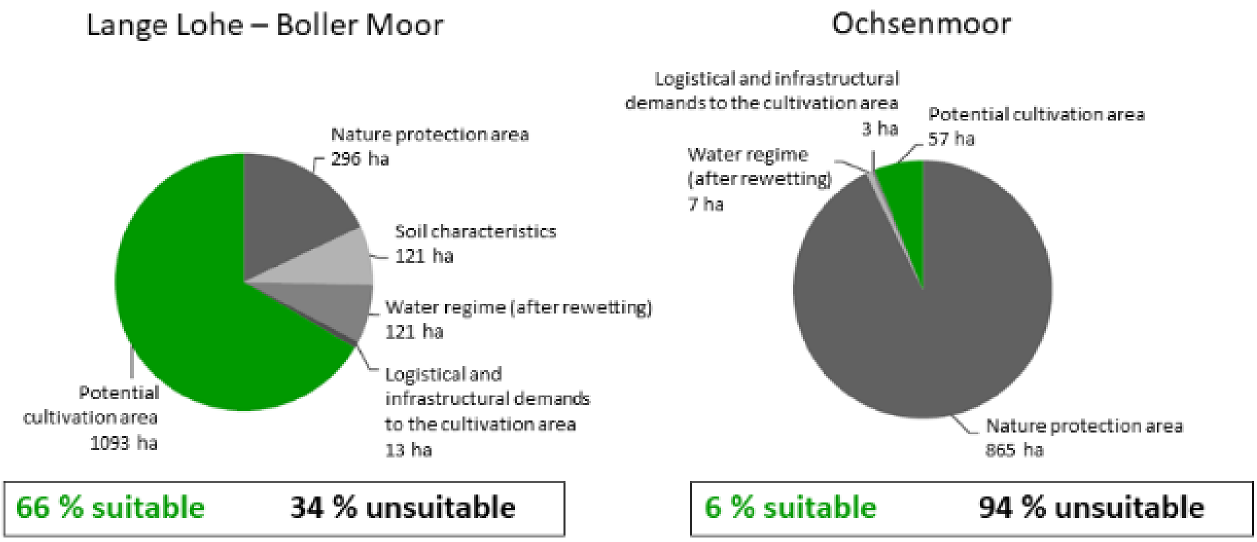

Figure 5. Elimination of potential cultivation area by criteria, and maximum remaining cultivation potential for reed, in the study areas "Lange Lohe - Boller Moor" (LL; n = 1644 ha) and "Ochsenmoor" (OM; n = 933 ha).

depend on natural site conditions - such as climate - that cannot be changed, as well as on technical infrastructure that it may be possible to change. The test application reveals that the tool offers simple handling and little effort is needed to run it in its current state, but it is also restricted in exactness and flexibility. In this regard, more research is required in order to restructure the tool to meet further issues and enhance the flexibility and accuracy of results.

Eligibility of criteria and methodology to assess the cultivation potential

In general, the chosen criteria and indicators are regarded as suitable and sufficient for the determination of cultivation potential and GHG-mitigation potential. However, some criteria (e.g. rewetting potential) can lead to detailed results only if site-specific (hydrological) evaluations are carried out (Haas & Cyffka 2011). Site specific characteristics like the hydraulic conductivity of the peat, which is affected by subsidence (Schmidt 1994) and sealing layers (Bartels 1994, Roth & Succow 2001), cannot be captured by this tool. Due to changes in the hydraulic properties of the degraded peat, keeping rewetted areas wet throughout the year often requires (shallow) flooding (Rosenthal & Hölzel 2009). Therefore, only vague statements can be made concerning rewetting possibilities. Since the assessments of GHG-emission reduction are based mainly on the rewetting possibilities, these results incorporate the same uncertainties.

The tool applies a universal methodology that enables the assessment of local and regional potential for paludiculture in northern Germany. It meets the requirement for spatial differentiation of site-specific characteristics and thus goes farther than the approach taken by Kowatsch *et al.* (2008), whose potential analysis at federal state level excludes the consideration of site conditions. However, the tool is analytic, and in-situ investigations are also needed for the establishment of paludicultures. In conclusion, it is suitable for local analyses to help define viable land use options and support decision-making in landscape planning at an early stage (cf. von Haaren 2004b).

Impact of normative values on the cultivation potential of reeds

The allocation of ranges of values and the scaling of attributes is based on normative values for Categories 1 and 3 and refers to physiological aspects for Category 2. Since normative values remain changeable, and especially because current nature conservation legislation prohibits the cultivation of reeds, changes resulting from any legislative modifications should be discussed. Paludiculture is currently not an approved agricultural land use (Czybulka & Kölsch 2016). This status leads to elaborate application procedures and often requires exemption clauses for harvesting of the cultivated biomass (Czybulka & Kölsch 2016). Application of the analytic tool shows that the main restrictions relate to artificially cultivated reeds, which can attain the status of legally protected biotopes (§ 7 (2) Nr. 4 BNatSchG - Federal Nature Conservation Act); and the current agricultural policy of the European Union (EU) (Figure 5). The objectives of the EU Common Agricultural Policy (CAP) relating to climate and environmental protection, which are implemented through “greening” (Regulation EU 1307/2013 on direct payments for agricultural holdings), focus on the protection of permanent grasslands and wetlands without considering the even stronger effects for climate protection provided by paludiculture. Kowatsch *et al.* (2008) note that paludiculture can reduce average CO_2-equivalent GHG emissions from converted cropland and intensively managed grassland by 15 t ha^{-1} y^{-1}. Furthermore, the fact that paludiculture is not yet an approved agricultural land use in the EU prohibits direct payments from the first pillar of the CAP as well as financial support from the fund for rural development. Since it is doubtful that paludiculture can be implemented economically without this funding (cf. Czybulka & Kölsch 2016), the recognition of paludiculture as an agricultural land use for the next funding period of the CAP (2021–2027) is of great importance. This would also simplify handling in terms of protected areas, legally protected biotopes and species protection, since agricultural land use is privileged. Gaudig *et al.* (2014b) share the opinion that the cultivation of protected species must not restrict their exploitation. Similarly, Timmermann *et al.* (2009) regard the rewetting of degraded peatlands as a reasonable future land use option in relation to species and habitat protection. The discussion shows that legislative and political changes could increase the quantitative cultivation potential for reeds and, thus, also the potential for reduction of GHG emissions from agricultural land.

CONCLUSIONS

The analytic tool that was developed enables a simple quantification of the cultivation potential for *Phragmites australis* and *Typha latifolia* within a clearly delineated area. At this point *Phragmites australis* and *Typha latifolia* serve as example species. The analytic tool could also be used for the assessment of other types of paludiculture such as Sphagnum farming and alder cultivation if adapted for those species.

Development of the structure of the tool towards a modular system would enable the separation of thematic units and their reorganisation to address specific problems. Moreover, it would allow the addition of further aspects without exceeding a certain level of complexity (Figure 6). Useful extensions may be the analysis of synergies and conflicts between paludiculture and nature protection objectives or the connection to existing infrastructure for recovery of the harvested biomass.

Finally, we reiterate that changes at the political level are required to allow the development of paludiculture into a sustainable land use which will contribute to the reduction of GHG emissions from agricultural land.

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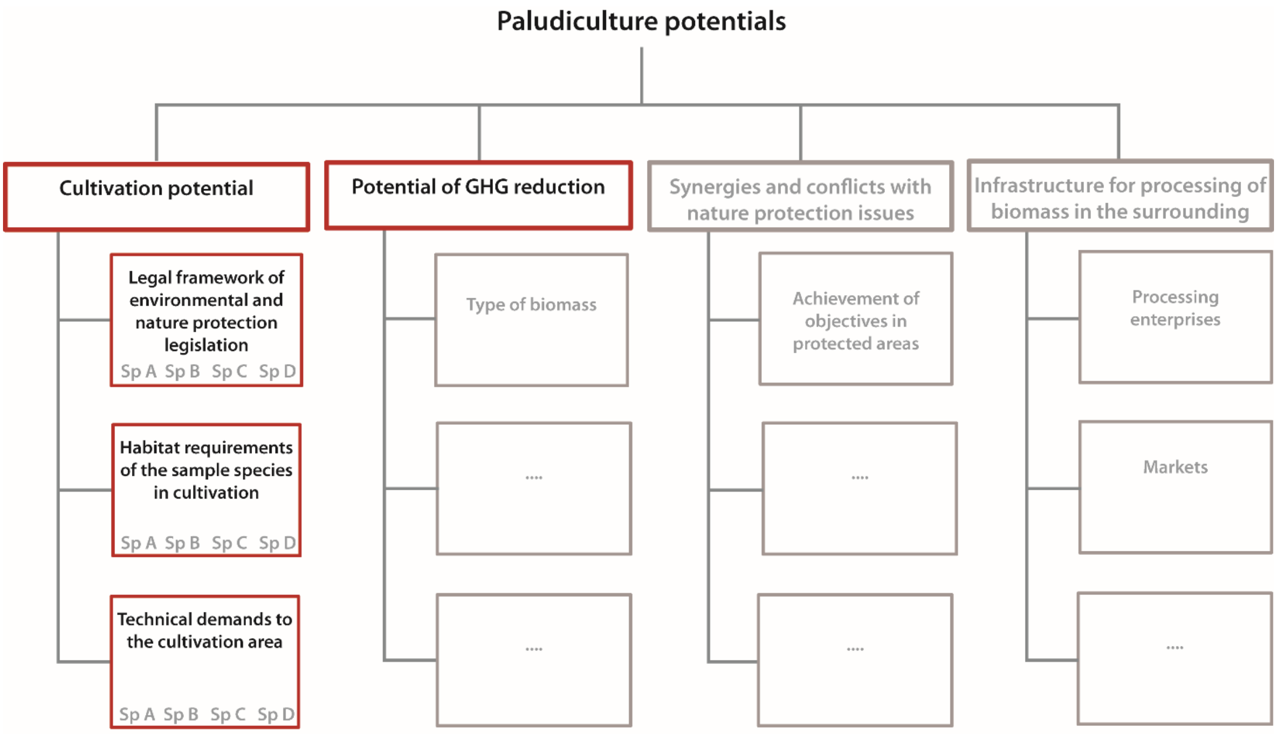

Figure 6: A possible future development of the assessment tool presented here into a modular system. Modifying the structure of the tool in this way has potential to allow the integration of more thematic aspects without impairing its flexibility.

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