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A spatial framework for prioritizing biochar application to arable land: A case study for Sweden

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ABSTRACT

The biochar-agriculture nexus can potentially generate several benefits ranging from soil carbon sequestration to the reduction in nutrient leaching from arable soils. However, leveraging these benefits requires spatially-explicit information on suitable locations for biochar application. This study provides a flexible multicriteria framework that delivers spatial indications on biochar prioritization through a biochar use indication map (BUIM). The framework was exemplified as a case study for Swedish arable land through three different prioritization narratives. The BUIM for all the narratives revealed that a significant fraction of the Swedish arable land could potentially benefit from biochar application. Furthermore, arable land that scored high for a given narrative did not necessarily score high in the others, thus indicating that biochar application schemes can be adjusted to various objectives and local needs. The framework presented here aims to promote the exploration of different avenues for deploying biochar in the agricultural sector.

List of abbreviations

AHP	Analytical Hierarchy Process
BUIM	Biochar Use Indication Map
CDR	Carbon dioxide (CO_2) removal
CH_4	Methane
GHG	Greenhouse gas
GIS	Geographic Information System
$GtCO_{2e}$	Gigatonne of carbon dioxide equivalent
ha	Hectare
MCA	Multicriteria Analysis
N	Nitrogen
NO_3^-	Nitrate
N_2O	Nitrous Oxide
SOC	Soil Organic Carbon
SOM	Soil Organic Matter

1. Introduction

In 2018, agricultural land management and crop cultivation accounted for almost 5.5% (2.68 $GtCO_{2e}$) of the total global anthropogenic greenhouse gas (GHG) emissions (Climate Watch, 2020). This number is expected to increase as reducing the climate impact of the agricultural sector with a growing population remains challenging (Duff and Lenox, 2019). With limited land resources, feeding 9.7 billion people by 2050 on a warming planet would directly translate to agricultural intensification (Foley et al., 2011; Godfray et al., 2010), leading to a plethora of other environmental issues as well (Al-Kaisi and Lowery, 2017). Ameliorating such anthropogenic stresses on the planet has led to legislative policies on agriculture paying heed to environmental and climate change objectives (EU, 2021). The agriculture sector's contribution in restricting global warming to +2°C or even +1.5°C above pre-industrial levels requires coupling strategies for CO_2 reduction and CO_2 removal (CDR) (IPCC, 2018). In this endeavor, biochar produced through biomass pyrolysis can be a promising solution for CDR via arable land (Minx et al., 2018; Woolf et al., 2010), especially due to its several co-benefits.

As an agricultural soil amendment, biochar has been shown to have multiple benefits (Schmidt et al., 2021), ranging from improvements in crop yield (Jeffery et al., 2017; Ye et al., 2020) and soil organic carbon

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(SOC) (Blanco-Canqui et al., 2020), to the reduction of NO_3^- leaching (Borchard et al., 2019) and, N_2O (Joseph et al., 2018) and CH_4 emissions (Jeffery et al., 2016). A summary of biochar effects on crop and arable soil parameters is highlighted in Supplementary Table 1. These multifunctional benefits elevate the status of biochar from a CDR-only technology to a valuable agricultural amendment with added climate benefits, thus increasing its utility (Azzi et al., 2021). However, these agricultural benefits are not assured, and in some cases, biochar application might even have adverse effects on soil and crop properties (Joseph et al., 2021).

Soil and crop reactions to the addition of biochar can be positive, neutral, or negative. Such agronomic effects depend primarily on four major factors. These factors are (i) local climate, (ii) soil properties, (iii) biochar properties, and (iv) biochar application rate. All these factors must be accounted for before undertaking any major application project (Lehmann et al., 2021). For biochar application assessments (ranging from local to continental scales), spatial parameters such as local climate and soil properties can aid in identifying areas where biochar application can be prioritized. Developing such biochar priority maps can answer multiple questions, like evaluating the potential of biochar-based CDR from arable land or the localization of production and marketing of biochar based on biomass resource availability. Consequently, results from such studies can aid policymakers and businesses in deciding whether scaling up biochar applications for arable land makes sense or not. Additionally, these priority maps can also provide a guidance on selecting the most optimal location for siting of pyrolysis plants.

There is a lack of spatial studies concerning biochar application to arable land. Consequently, there is limited knowledge on why, where, and how biochar could be applied. The first peer-reviewed study on the prioritization of biochar to arable land was conceived by Latawiec et al. (2017), where a three-step reconnaissance-scale method to support sustainable biochar use was presented. Their method combined qualitative and multicriteria analysis (MCA) to identify suitable areas for biochar application on arable land. In the qualitative analysis, they identified soil pH, soil organic matter (SOM), soil texture, and contaminant loads as essential factors driving the efficacious use of biochar in temperate regions. The third step of their method highlighted decision-making factors for biochar application, such as pyrolysis technology, environmental impacts, monetization, and biomass availability. However, due to data limitations, their study did not include its implementation. In a more recent study by Kutlu et al. (2021), a similar biochar prioritization exercise was carried out with the context of improving SOC in Turkish soils. The two-step MCA model shown in their study derives a biochar suitability map by aggregating potential areas with factor maps. The potential areas in their study are derived from site suitability analysis based on land-use and SOC content restrictions, and the factor maps are derived from soil pH and sand content. Both of these studies reveal a bias in designing the MCA, which lacks the question on different motives for prioritizing biochar and its integration in the methodological framework. The present study builds upon these existing efforts and addresses this bias by providing a refined framework adjustable to different application contexts. This refinement is done assuming that different stakeholders have different priorities for applying biochar to arable land.

Hence, the overarching aim of the study is to provide a flexible framework for biochar prioritization in arable land. By flexible, we imply adaptability to the stakeholder's requirements. The specific goals are to (i) define different prioritization narratives for biochar application within the Swedish context and (ii) exemplify these narratives by providing a biochar use indication map taking Swedish arable land as a case study. A possible application of the present study is to guide policymakers and businesses in exploring diverse prioritization narratives for biochar use in agriculture and promote future research on diverse application contexts.

2. Method

We develop a four-step framework for prioritizing biochar in arable land (Fig. 1). The first step of this framework involves identifying and defining a prioritization narrative, i.e., a scenario for biochar application. The second step entails selecting criteria specific to the prioritization exercise. For example, in a case where reduction in nitrogen leaching from arable land is prioritized, site-specific N leaching information should be incorporated into the modeling framework. In the third step, MCA is performed, and priorities are assigned to the selected criteria. The prioritization can be achieved through several techniques, ranging from a simple parameter ranking exercise to a more complex method using the analytical hierarchy process (AHP) (Saaty, 1988). In the final step of this process, the ranked criteria are combined to provide spatial indications on where biochar should be prioritized.

2.1. *Prioritization narratives for Swedish case study*

Challenges in agriculture are diverse and are intensifying due to many factors, such as climate change-induced global warming (Caparas et al., 2021) or excessive fertilizer use (West et al., 2014). Biochar, with its diverse positive effects, can support agriculture by countering many such challenges (Lehmann et al., 2021). Hence, our analysis considers three different narratives for biochar prioritization in Swedish arable land. The prioritization narratives considered for this study are (i) improving soil quality, (ii) improving crop resilience, and (iii) reducing nitrogen leaching. These narratives are further elaborated in Table 1.

2.2. *Criteria selection*

The biochar use indication on arable land is derived from the prioritization narratives described in Section 2.1. The next step involves identifying the relevant criteria for a particular narrative and its eventual prioritization using the MCA approach.

For all narratives, the soil texture, pH, and SOM were used as base criteria to derive the biochar use indication map (BUIM). These criteria were selected based on the evidence provided by several studies on biochar application in arable land. For example, in a meta-study concerning the effects of biochar and soil properties on crop yield, Dai et al. (2020) observed that biochar application on acidic and sandy soil improved productivity, indicating that soil texture and pH are suitable as base criteria. These base criteria are also consistent with the study by Latawiec et al. (2017), where they overlaid these criteria to derive areas that could benefit from biochar application. For the narratives on reducing nitrogen leaching and improving crop resilience, additional criteria on N leaching and ground moisture, respectively, are included in the modeling framework. For the narrative improving soil quality, there were no additional criteria. The selected criteria and their relevance for different prioritization narratives are described below. Further details on sources, ranges, and spatial patterns of these criteria for Sweden are provided in Supplementary Information – I, section 2.

2.3. *Soil texture*

Several studies have indicated that biochar application in arable land with coarse-textured soils has more benefits for various crop and soil properties, including a reduction in N leaching and is less so when applied on fine-textured soils (Ajayi and Horn, 2017; Suliman et al., 2017). This consonance is due to biochars' influence on essential soil hydraulic criteria like available water content, saturated hydraulic conductivity, field capacity, and permanent wilting point (Edeh et al., 2020). Biochar addition to sandy soils has also been indicated to improve SOM content and nutrient mineralization (Wang et al., 2016). Thus, for the present study, priority for biochar application was assigned to arable soils with higher sand content. The distribution of clay, sand, and silt content of arable land in the study area can be seen in

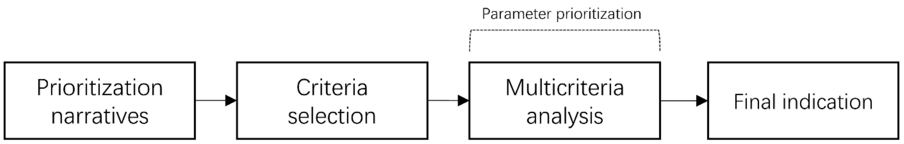

Fig. 1. Flow chart for biochar prioritization to arable land.

Supplementary Fig. 4.

Table 1
Prioritization narratives for the Swedish case study[1].

Prioritization narrative	Description	Rationale	Important criteria[2]	Property influenced
Improving soil quality	This is a base context where biochar amendment is applied to the soil to improve the site-specific soil properties.	Biochar has been shown to improve soil quality by affecting several soil properties like improving SOM[3], texture, and raising the pH of acidic soils (Schmidt et al., 2021).	SOM, soil texture, soil pH	SOM, available water content, pH
Improving crop resilience	In this context, the biochar amendment is prioritized in areas vulnerable to drought or low soil moisture.	Biochar application has shown to increase the crop available soil water content by 45%, 21%, and 14% in coarse-textured, medium-textured, and fine-textured soils, respectively (Razzaghi et al., 2020).	Soil moisture, SOM, soil texture, soil pH	Available water content
Reducing nitrogen leaching	In this context, biochar application to arable land is prioritized in areas vulnerable to N leaching.	Biochar use on arable land has demonstrated a significant reduction (26% - 32%) in cumulative NO_3^- leaching with at least 30 days observation period. More significant NO_3^- leaching reductions were associated with prolonged residence time (Borchard et al., 2019; Sha et al., 2019). Furthermore, biochar application might also significantly reduce N_2O emissions (Cayuela et al., 2014).	N leaching, SOM, soil texture, soil pH	N_2O and NH_3 emissions and NO_3^- leaching

[1] See supplementary table 1 for more detailed information on how biochar affects different soil and crop parameters.

[2] Insights into why these criteria are considered important for different prioritization narratives are shown in Section 2.2

[3] SOM: Soil organic matter

2.4. *Soil pH*

Biochar application to arable land has shown to decrease soil acidity and improve crop yield by enhancing soil fertility (Hailegnaw et al., 2019; Shetty and Prakash, 2020). However, this effect strongly depends on the type of biochar being applied (Ajayi and Horn, 2017) and the type of soil in which the biochar is being applied (Hailegnaw et al., 2019; Zhang et al., 2019). This effect, also known as liming, is best seen in acidic soils (Jeffery et al., 2011). Thus, for this symbiosis to yield maximum benefits, biochar prioritization was done in areas with soil pH ≤ 6. More details on spatial distribution of soil pH in the study area is provided in Section 2.3 of supplementary information – I.

2.5. *Soil organic matter*

SOM affects several soil properties, including the capacity to retain water and nutrients, and promotes efficient drainage and aeration while also minimizing erosion (Oldfield et al., 2019; Robertson et al., 2014). SOM management has been identified as a vital component for ensuring crop productivity and decreasing reliance on fertilizers (Foley et al., 2011). In this regard, biochar can be a potent amendment for increasing SOM (Wang et al., 2016) with the objective of improving crop productivity. To ensure maximum benefits for improving soil quality and crop resilience, biochar application was prioritized in areas having low SOM content, as these areas will have a greater capacity to augment the SOM while also improving crop productivity. On the other hand, for the narrative of reducing nitrogen leaching, areas with higher SOM were assigned higher scores for biochar prioritization as mineralization of SOM might have an additive effect on N leaching (University of Nebraska - Lincoln, 2015). See Section 2.4 of supplementary information – I for more details on the spatial distribution of SOM in the study area.

2.6. *Ground moisture*

Research has shown that biochar amendment improves the water-holding capacity of soils and prevents it from moisture stress (Schmidt et al., 2021), thus making crops more resilient. Low ground moisture is selected as a priority criterion within the narrative of “improving crop resilience.” The low ground moisture criteria depict the number of days with low ground moisture per annum as per the RCP 4.5 scenario for 2021 – 2050 (SMHI, 2021). Therefore, to ensure crop resilience in the future, biochar was prioritized in areas where the number of low ground moisture days was predicted to be higher. Section 2.5 of supplementary information – I provides more details on the spatial distribution of low ground moisture days in the study area.

2.7. *Nitrogen (N) leakage*

N loss through volatilization and leaching expedites crop productivity loss and leads to excess NO_3^- in groundwater, N_2O emissions, and eutrophication (Nguyen et al., 2017). Biochar has been shown to alleviate these issues, albeit the effects depend strongly on the type of biomass, pyrolysis method, and application rate (Joseph et al., 2021; Li et al., 2018; Schmidt et al., 2021). Thus for the narrative of reducing nitrogen leaching, biochar application was prioritized in areas where N leaching was high (SMED, 2021). See Section 2.6 of supplementary information – I for more details on the spatial distribution of N leaching criterion.

2.8. Multicriteria analysis

Fig. 2 shows the methodological framework for deriving the biochar use indication map. The target areas are delineated in the first step by selecting the arable land. In the next step, the criteria are prioritized based on their relative importance for a particular narrative. The priorities are calculated using the AHP technique (Saaty, 1988, 1977). Following this, the criteria are combined using the weighted linear combination (Drobne and Lisec, 2009) to derive the final BUIM.

2.8.1. Analytic hierarchy process (AHP)

AHP is widely used for multicriteria analysis and facilitates problem-solving by establishing weights for the selected criteria. This method establishes criteria weights by performing a pairwise comparison. An off-diagonal relationship is established between the selected criteria on a 9-point scale during the pairwise comparison. The lower range of the scale denotes equal importance between the compared criteria, and the higher range denotes absolute importance for the given problem context. The scales are further elaborated in Supplementary Table 4. The criteria weights are finally established by normalizing the comparisons. This normalization is performed by first dividing the column elements by the sum of each column, then the concurrent row elements are summed and divided by the total number of row elements to get the final weights for each criterion (Saaty, 1988).

The logical consistency of the pairwise comparisons is evaluated using a consistency index (CI) (Saaty, 2003). Ideally, comparisons with sufficient consistency should have a consistency ratio < 0.10 (10%). The consistency ratio is the ratio between the CI (Equation 1) and the pairwise matrix,

$$CI = \frac{\lambda_{\max} - n}{n - 1} \tag{1}$$

where $\lambda_{\max}$ is the highest principal eigenvalue of the pairwise matrix, and n is the number of criteria.

The pairwise comparison was performed through a collaborative dialogue between the authors. For example, in the case of reducing nitrogen leaching, in addition to the nitrogen leaching criteria, SOM received a relatively higher weight when compared to pH and texture . This weight was obtained based on the logic that the mineralization of N from N-rich organic matter might have an additive effect on leaching. This subjective logic was translated to numeric values based on Supplementary Table 4 and used for comparison with other criteria in the pairwise comparison (Supplementary Table 7). Detailed exemplification of the AHP method, including estimation of weights for the selected narratives and scaling of criteria ranges to scores is shown in Supplementary information – I, Section 3. Table 2 presents the weights and scores of the criteria estimated using the AHP method.

2.8.2. Weighted linear combination (WLC)

The BUIM is calculated using WLC (Drobne and Lisec, 2009). WLC is often applied in GIS-based multicriteria analysis, where the weighted criteria are combined by summation. WLC for the present study was performed in a GIS environment. Equation 2 shows the formula for the WLC employed in the present study, where BUIM is the biochar use indication map, n is the number of criteria, C_s is the criteria score, and C_w is the criteria weight.

$$BUIM = \sum_{i=1}^{n} C_s C_w \tag{2}$$

2.9. Spatial correlation analysis

We also performed a spatial correlation analysis to understand how the spatial distribution of the priority score for a particular narrative compared to the distribution of the priority score of other narratives. This was done to understand whether some or all narratives yielded similar scores for some areas. The band collection statistics tool (ESRI, 2022) was used to compute the correlation matrices. A positive correlation coefficient (r) value close to one indicates a direct relationship between the two narratives, whereas values close to zero indicate no relation.

3. Results and discussion

In this study, we present a multicriteria framework for biochar application in arable soils driven by different prioritization narratives. The framework provides a priority map (BUIM) highlighting suitable locations for biochar application in different narrative contexts. This framework is exemplified by taking Swedish arable land as a case study with three different prioritization narratives highlighted in Table 1. The BUIM calculated using Equation 2 provides priority scores (unitless) on a linear scale ranging from 1 to 5. The priority score is divided into four equal ranges (1 – 2, 2 – 3, 3 – 4, 4 – 5). The lower values (closer to 1) of

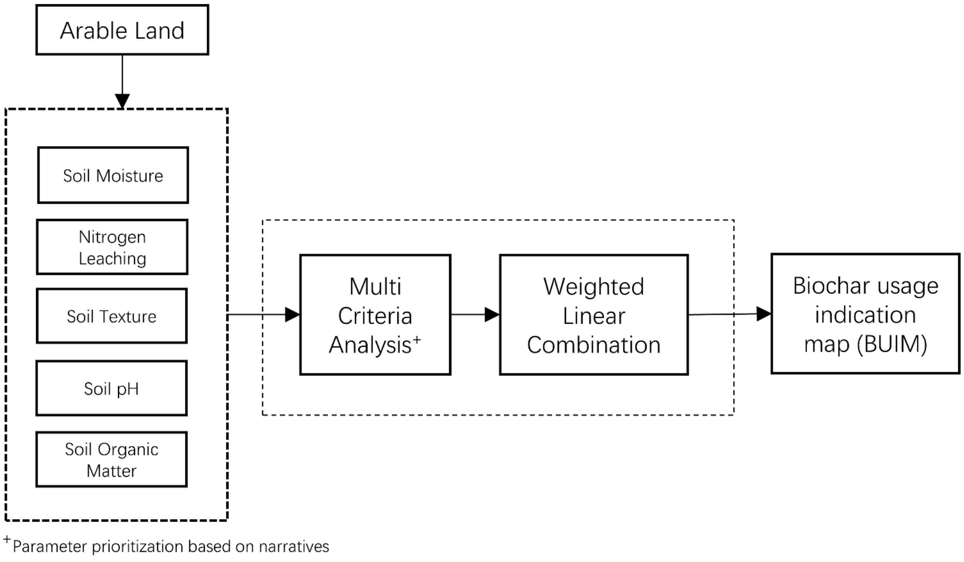

Fig. 2. Methodological framework for deriving biochar use indication map.

Table 2
Range and weights resulting from the prioritization exercise.

Criteria	Range	Score	Improving soil quality Weight	Improving crop resilience Weight	Reducing Nitrogen Leaching Criteria	Range	Score	Weight
Low Ground Moisture Days (Days / Year)	9.5 – 13.5	1	-	0.511	**N Leaching (kg/ha)**	0.0 – 6.6	1	0.514
	13.5 – 17.4	2				6.6 – 13.3	2	
	17.4 – 21.3	3				13.3 – 19.9	3	
	21.3 – 25.3	4				19.9 – 26.6	4	
	25.3 – 29.2	5				26.6 – 33.2	5	
Soil pH	8.2 – 7.1	1	0.200	0.045				0.050
	7.1 - 6.0	2						
	6.0 – 5.8	3						
	5.8 – 5.6	4						
	5.6 – 5.4	5						
Soil organic matter (%)	19.0 – 5.7	1	0.200	0.153	**Soil organic matter (%)**	0.9 – 3.4	1	0.278
	5.7 – 4.7	2				3.4 – 4.0	2	
	4.7 – 4.0	3				4.0 – 4.7	3	
	4.0 – 3.4	4				4.7 – 5.7	4	
	3.4 – 0.9	5				5.7 – 19.0	5	
Soil Texture (Sand %)	0 – 20	1	0.600	0.292				0.159
	21 – 36	2						
	37 – 52	3						
	53 – 66	4						
	67 - 100	5						

this range indicate a lower priority for biochar application, and higher values (closer to 5) indicates a higher priority for biochar application for a particular spatial block of 1 ha (100 m × 100 m pixel).

Fig. 3 shows the results of the prioritization exercise for the different narratives. For all narratives, clustering of either high or low priority scores is observed in some parts of the study area. An example of such clustering for improving crop resilience is shown in Fig. 4. This is further elaborated in Fig. 5, where it can be noticed that the spatial distribution of high priority scores (4 – 5) is primarily established on the distribution of soil texture. Such distribution of BUIM is observed despite a higher weight being assigned to the low ground moisture criteria. This implies that the final BUIM model considers the scores (highlighting spatial

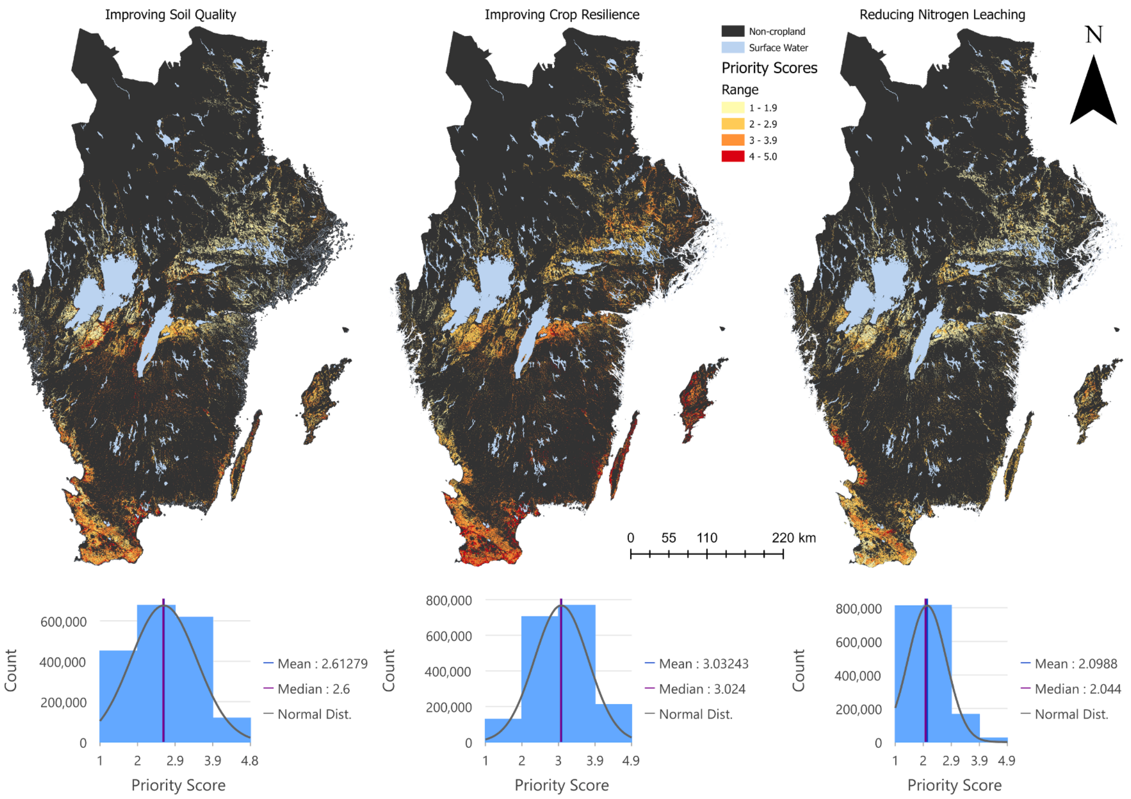

Fig. 3. Biochar use indication map showing priority scores for biochar use on Swedish arable land for for the three narratives; Improving soil quality (left), Improving crop resilience (center), and Reducing nitrogen leakage (right). Higher scores indicate a higher priority. The histograms indicates the frequency distribution of priority scores for different priority ranges.

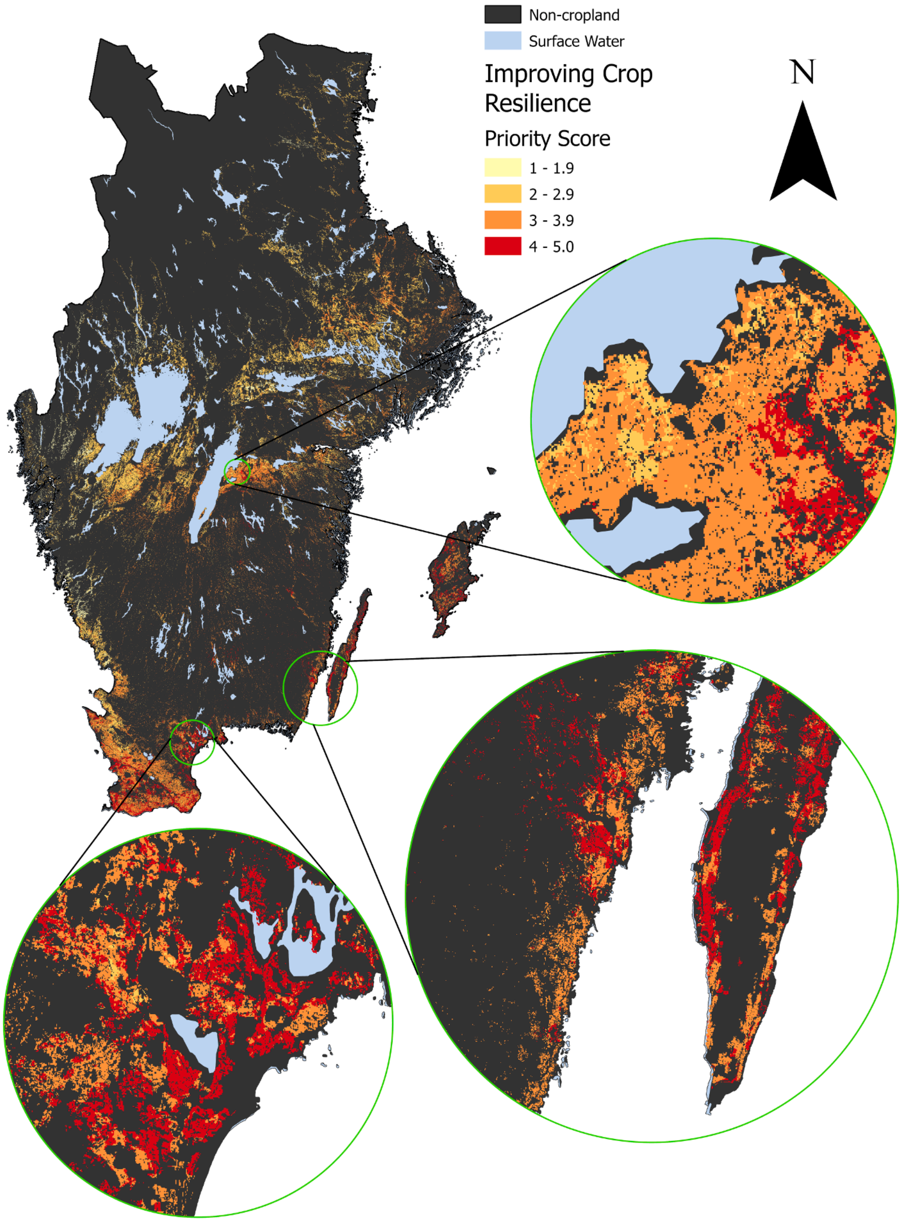

Fig. 4. Zoomed image for showing clustered priority score for the narrative of Improving crop resilience. Continuous assemblage of priority score patches can be seen in the zoomed circles.

distributions) and weights (priorities) of all concerned criteria for a particular narrative.

Biochar improves soil quality through several physical and chemical processes like reducing soil bulk density leading to improved water holding capacity (Omondi et al., 2016) or improving the SOM (Jílkova and Angst, 2022; Smebye et al., 2016; Tian et al., 2016). However, this effect is strongly dependent on the type of soil where biochar is being applied (Atkinson, 2018; Jaafar et al., 2015; Kuo et al., 2020). Research has shown that agronomic and soil benefits of biochar application are more evident on coarse-textured and acidic soils (Farhangi-Abriz et al., 2021; Jeffery et al., 2011; Razzaghi et al., 2020). To incorporate this phenomenon in the present framework, higher scores (representing more priority for biochar application) were assigned to coarse-textured and acidic soils. As a result, for improving soil quality, soils in about 573 000 ha (24%) of arable land, lying in the higher spectrum of the priority range (4 – 5), were found to potentially benefit from biochar application (Supplementary Table 9). Most of these sites were found in the south and south-west of the study area in the counties of Skåne and Västra Götaland (Fig. 6). In terms of county-wise distribution, in addition to Skåne and Västra Götaland, significant proportions of arable land in Blekinge, Gotland, Halland, Jönköping, Kalmar, and Kronoberg were observed to lie in the higher spectrum of the priority range (4 – 5) that could potentially benefit from biochar application (Supplementary Table 10).

Hoiling (1973) defines resilience as the tendency of a system to regain its organizational structure and productivity following a disturbance. Thus, a resilient cropping system caters to food production even if it encounters extreme climate events like heatwaves or droughts (Lin, 2011). The frequency of extreme climate events is likely to increase in the near future (Böhnisch et al., 2021; Crespi et al., 2020; European Commission, 2021), thus necessitating resilient cropping systems to ensure food security. In this regard, several studies have indicated that biochar tends to be a buffer for crops against climate-change-induced extreme events like droughts by ensuring sufficient soil moisture (Ajayi and Horn, 2017; Koide et al., 2015). This effect is even more pronounced in coarse-textured soils (Li et al., 2021). Thus, for the

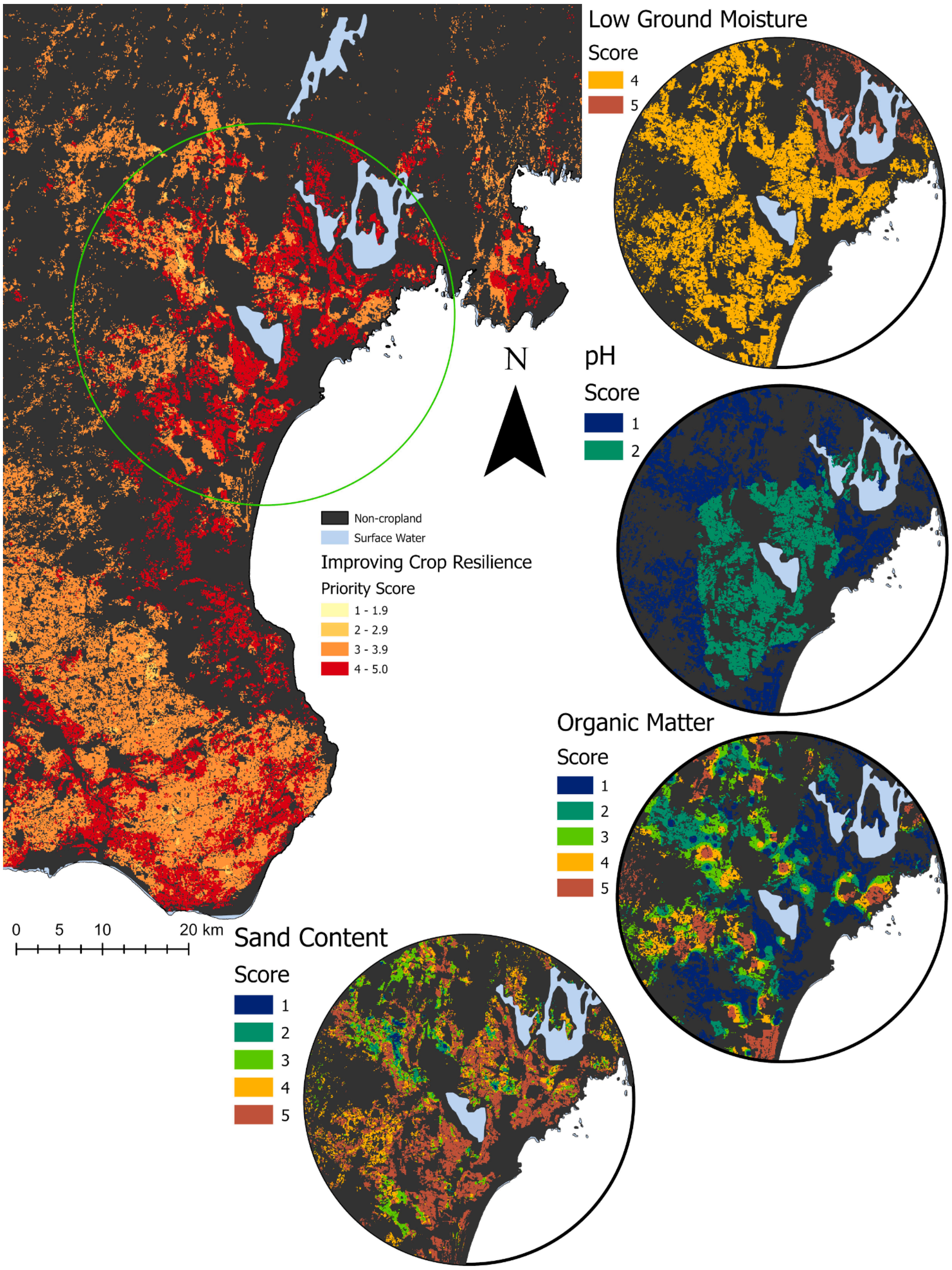

Fig. 5. Zoomed image of criteria (Low ground moisture, pH, Organic matter and Sand content) affecting priority score for the narrative of Improving crop resilience. The spatial distribution of sand content and low ground moisture drive the high priority scores (4 – 5, highlighted in red) for improving crop resilience.

narrative of improving crop resilience, higher weights were assigned to areas with low ground moisture and soil texture, with coarse-textured soils (i.e., soils with higher sand content) having higher scores. This resulted in about 913 000 ha (40%) of the arable land in the study area lying in the higher spectrum of the priority range (4 – 5), potentially benefitting from biochar application (Supplementary Table 9). The distribution of high priority scores was primarily concentrated in the counties of Skåne, Kalmar, and Gotland (Figs. 3, 6, and Supplementary Table 11). As per SMHI's model projections (SMHI, 2021), the eastern part of the study area will predominantly have more dry days in the future compared to the west. As highlighted in Fig. 3, coupling of low ground moisture days with sandy soils in the south and southeast of the study area further escalates the risk of crop failures by inducing moisture stress. Therefore, these areas could potentially reap benefits from biochar application.

Modern agriculture, through its use of mineral fertilizers and high concentration of animal husbandry, is the most significant contributor to N-induced environmental pollution (Foley et al., 2005; Rockström et al., 2009). The use of N-based fertilizers is associated with accelerated emissions of N_2O (Park et al., 2012) and leaching of NO_3^- (Bijay-Singh and Craswell, 2021; Di and Cameron, 2002), both of which are harmful to the climate and the natural environment. Biochar amendment to agricultural soils has shown to potentially reduce N_2O emissions and NO_3^- leaching (Borchard et al., 2019; Lee et al., 2018), this effect is even more conspicuous in coarse-textured soils (Kuo et al., 2020). Thus, for the narrative of reducing nitrogen leaching, higher weights were assigned to the areas with N leaching, SOM, and soil texture, with soils with higher sand content having higher scores. Further, mineralization of SOM coupled with N fertilization may have an additive effect on NO_3^- leaching (University of Nebraska - Lincoln, 2015), thus, along with a higher weight to the SOM criteria, higher scores were also assigned to areas with higher SOM content (Table 2). Consequently, the BUIM

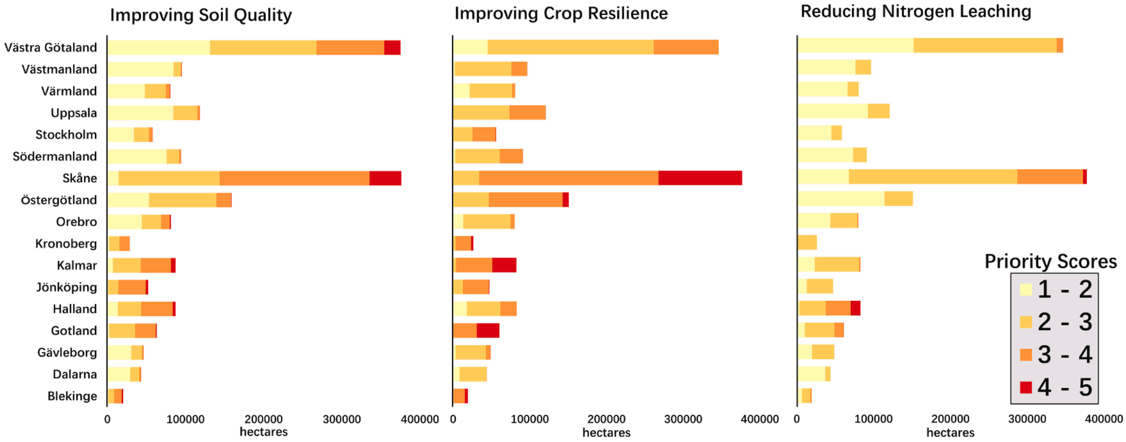

Fig. 6. County-wise distribution of priority scores for the selected narratives.

revealed that biochar application in about 162 000 ha (7%) of the arable land (lying in the higher spectrum of the priority range (4 – 5)) in the study area could potentially result in reduced N leaching (Supplementary Table 9). Furthermore, as most of these high-priority areas are located in the coastal counties of Skåne, Halland, and Gotland (Figs. 3, 6, and Supplementary Table 12), biochar application can potentially contribute to reducing N leaching to the Baltic Sea, more than 97% of which still suffers from eutrophication due to past or present excessive inputs of N and P (HELCOM, 2018).

This study provides a flexible framework for prioritizing biochar application to arable land. The flexibility in the framework lies in its adaptability to stakeholders' preferences. Adaptability derives both from the selection of a narrative and its quantitative criteria and from the relative weighting of the selected criteria within the MCA. The BUIM was obtained through an MCA approach where priorities (numerical weights, Table 2) were assigned to the selected criteria based on the prioritization narratives. In general, the priority criterion (low ground moisture days for improving crop resilience and N leaching for reducing nitrogen leaching) had higher weights than the base criteria, which partially dictated the outcome of the BUIM. For example, in the case of reducing nitrogen leaching, areas with higher values of N leaching (south and south-west of the study area and the island county of Gotland, Supplementary Fig. 8) had higher priority scores for biochar application. However, the base criteria also had a certain weight (Supplementary Table 7) in the MCA, highlighting their importance in the overall objective. Employing AHP to obtain criteria weights helped make the subjective comparisons numerically explicit. This exercise assured the inclusion of lessons learned from empirical studies highlighting conditions where biochar works best to provide different services. The present study aimed to test and illustrate the biochar prioritization framework. Thus, an example of expert opinion guiding the AHP for the weighting of priority criteria was demonstrated. The prioritization could be performed using a different scheme or by including a wider range of stakeholders, individuals making separate assessments that are weighed together. Different scoring schemes are anticipated to have an impact on the final BUIM. Section 5 of Supplementary Information - I shows an example of an alternative scoring scheme as a sensitivity analysis. The results of sensitivity analysis indicate that, at finer scales the BUIM is more sensitive to changes in scoring schemes. The results of this study are not directly comparable to any other published studies due to differences in the adopted methodology and the location of the study area. However, the present study advances the limited existing literature on biochar GIS-MCA, which employ a simple overlay method for site suitability assessments (Kutlu et al., 2021; Latawiec et al., 2017) by providing a priority-based MCA framework for biochar prioritization based on different narratives.

The results of spatial correlation analysis revealed that the narratives of improving soil quality and crop resilience were strongly correlated, with an *r*-value of 0.62. This strong association is attributed to (i) the pairwise comparisons where, in both cases, a higher weight was assigned to the soil texture criteria (Supplementary Table 5, 6), and (ii) to the underlying distribution of the criteria ranges, which were identical for both cases (Table 2). In contrast, for reducing nitrogen leaching, this association was found to be weak and very-weak for improving soil quality (*r*=0.31) and improving crop resilience (*r*=0.19), respectively (Table 3). The weak correlation of the priority scores for the narrative of reducing nitrogen leaching is primarily attributed to the scoring of SOM for these narratives. In Table 2, it can be seen that for the narratives of improving soil quality and crop resilience, the scoring for SOM ranges follows a descending order (i.e., areas with higher values of SOM are assigned lower scores), whereas, for the narrative of reducing nitrogen leaching, the scoring for SOM ranges follows an ascending order (i.e., areas with lower values of SOM are assigned lower scores and vice versa). Thus, the resultant BUIM had a different distribution for all the three narratives. Therefore, arable land that scored a high priority score for a given narrative did not necessarily score high in the others, thus indicating that biochar application schemes can vary when being adjusted to different objectives and local needs.

The final BUIM is built upon spatial data obtained from different sources having different accuracies and spatial resolutions. Additionally, due to the absence of quality spatial data for the base criteria, soil pH and SOM were interpolated using data from field measurements to fit the requirements of the present study. The interpolation process carried an uncertainty (reported as standard error) in itself, as highlighted in Supplementary Information – II. This meant that the interpolation errors in pH and SOM propagated to the BUIM during the WLC process, in addition to the spatial errors originating from differences in data accuracies and resolutions. Validating the final BUIM with field data is not possible, owing to the theoretical nature of the present work. However, site-specific measurement of the selected criteria is strongly recommended to ensure accuracy during biochar application in arable land.

Perhaps one of the reasons for the dearth of spatial studies on biochar application in arable land is the complexity of the relationship between biochar and soil. The effect of biochar on crop and soil properties depends on several factors such as local soil and climatic conditions or the

Table 3
Spatial correlation between BUIM priority scores of different scenarios for the Swedish case study. Values represent the correlation coefficient (*r*).

	1	2	3
Improving Soil Quality (*1*)	-	0.619	0.310
Improving Crop Resilience (*2*)	0.619	-	0.188
Reducing Nitrogen Leaching (*3*)	0.310	0.188	-

biomass feedstock or pyrolysis technique, among other things (Joseph et al., 2021, 2010; Schmidt et al., 2021). It could be argued that this work makes the simplifying assumption that only the selected criteria would drive the successful use of biochar for a particular prioritization narrative. Although there is a certain amount of veracity to the statement, incorporating every criterion and modeling the inter-related dependencies at such geographical scales is challenging and unfeasible, and further, the results or the methodology may not be replicable for other regions. However, as the framework presented in this study is flexible to incorporate additional criteria with prioritization, modeling BUIM with more empirical knowledge and data availability requires modified narratives and additional data.

4. Conclusions

This study provides a framework for biochar prioritization in arable land. The framework derives a biochar use indication map highlighting regions for biochar prioritization on a linear scale ranging from 1 (low priority) to 5 (high priority). The framework is based on a 4-step procedure initially driven by a prioritization narrative which sets the context for biochar use in the arable land. To exemplify the framework, we defined three distinct narratives, i.e., improving soil quality, improving crop resilience, and reducing nitrogen leaching. After setting the context, the next step entailed criteria selection and prioritization. For prioritizing the criteria, we used the AHP methodology to ascertain the criteria weights. The AHP method transformed the subjective criteria comparisons to explicit numerical values (weights), which were eventually used to produce the BUIM following the weighted linear combination. The resultant BUIM for the different narratives in the Swedish case study highlighted that significant proportions of the arable land could potentially benefit from biochar application. For the narrative of improving soil quality, the indication with higher priority scores (3 – 5) covered about 25% of arable land in the study area. For the narratives of improving crop resilience and reducing nitrogen leaching, this value was 39% and 7%, respectively. Overall, the results of this study indicate that a priority-based framework for biochar application could help identify the magnitude and location of areas where biochar application could be beneficial.

CRediT authorship contribution statement

Shivesh Kishore Karan: Methodology, Software, Formal analysis, Writing – original draft. **Fabian Osslund:** Conceptualization, Methodology, Writing – review & editing. **Elias Sebastian Azzi:** Conceptualization, Methodology, Writing – review & editing. **Erik Karltun:** Methodology. **Cecilia Sundberg:** Conceptualization, Methodology, Resources, Supervision, Writing – review & editing.

Declaration of Competing Interest

SKK, FO, EK and CS declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. ESA reports a relationship with Puro.Earth Oy that includes: consulting or advisory.

Data Availability

Data will be made available on request.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.resconrec.2022.106769.

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