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Using spatial multi-criteria decision analysis to develop new and sustainable directions for the future use of agricultural land in Denmark

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A R T I C L E I N F O

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A B S T R A C T

Close to 60 per cent of the Danish land area is used for arable farming. EU regulations as well as public preferences create increasing pressures for changing agricultural land use in a more environmentally sustainable direction incorporating the multiple ecosystem services affected by agriculture. In this paper we present a spatially explicit multi-criteria decision analysis model which describes the trade-offs between the rent obtained from land in agricultural use on the one hand and selected ecosystem services on the other. The model is based on an extensive geographical dataset. This include maps on soil types, carbon content, sensitivity to nutrient losses, High Nature Value scores etc., which in combination with environmental criteria facilitates the ranking of all agricultural fields in Denmark according to their current overall worth to society in terms of land rent as well as other ecosystem services. Picking from a ranked list, we identify areas that may be considered efficient candidates for land use change considerations. Subsequently, the model is applied to identify suitable candidate areas for land use change in scenarios attaching different weights to various environmental services. In this way, four scenarios for Danish agricultural land use in 2050 are analysed. The results highlight that the possible realization of each of these mutually exclusive scenarios will require decision makers to consider very different development paths and land use changes for the Danish agricultural area.

1. Introduction

Agriculture plays a major role for the environment in Denmark with close to 60 per cent of the land area being used for arable farming (Statistics Denmark, 2017). The intensive agricultural use of the land conflicts with other societal interests primarily in terms of environmental protection, wildlife conservation and other types of ecosystem services (Odgaard et al., 2017, Turner et al., 2016). Growing public concerns about food safety and quality, nature management, ground water protection etc. provide ample reason for considering changes in land use practices. In addition, the EU Biodiversity Strategy 2020 calls for improvements of ecosystem services with the integration of their economic values into national and EU accounting and reporting systems (Maes et al., 2013).

With a vast array of interests represented in the population as a whole, compromises will have to be made in order to balance the many opposite minded interests, in this case between rent maximizing agricultural land use and the provision of various environmental services. These goods and services, however, come in different forms of which some are quantified in monetary terms while others are not (Saarikoski et al., 2016, Strijker et al., 2000). Due to the incommensurability of non-monetized benefits a unique optimal solution to such a decision problem does not exist (Bogetoft and Pruzan, 1997). This leaves decision makers with a tremendously complex task of balancing trade-offs between opposing interests covering multiple criteria. Multi-Criteria Decision Analysis (MCDA) offers a consistent framework for supporting this type of decision-making by reducing the number of dimensions to a manageable level for decision makers (Malczewski, 1999).

The *spatial* MCDA model takes multi-criteria decision analysis a step further by incorporating geographical information (Gregory and Long, 2009, Gregory et al., 2012). Previous studies have shown the applicability of the spatial MCDA model to agricultural policy analysis, however only at a local scale (Feizizadeh and Blaschke, 2013,

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Latinopoulos, 2009; Vogdrup-Schmidt et al., 2017). Denmark has exceptionally detailed geo-related data in the form of high resolution digital land-use maps comprising farm production statistics as well as environmental characteristics (Kristensen and Jørgensen, 2012). Most of these data are available at a national scale. In this paper we show how this data base has been incorporated into a spatially explicit MCDA model covering the entire agricultural area in Denmark. The model visualizes the trade-offs between agricultural production on the one hand and environmental protection and other ecosystem services on the other.

The comprehensive geographical dataset facilitates the ranking all agricultural fields in Denmark according to their current worth to society in terms of land rent as well as environmental services. Based on such a ranking it is possible to identify areas that may be considered suitable candidates for land use change, since changing land use in these areas will constitute the lowest possible cost to society. Subsequently, the model is used to identify optimal candidate areas for land use change, i.e. to identify the most preferred alternatives with respect to environmental characteristics. This requires the specification of relevant stakeholders' and decision-makers' preferences for these characteristics. Attaching different criteria weights in line with four mutually exclusive scenarios for Danish agricultural land use in 2050, we utilize the MCDA model to identify specific agricultural areas where land use will change in line with the envisioned scenarios. Subsequently, we analyse a range of consequences of the land use changes in each scenario.

2. Method

Multi-criteria decision analysis (MCDA) refers to a set of formal approaches intended to support decision making when faced with multiple and often conflicting objectives. In essence, MCDA achieves this by consistently listing relevant attributes and making explicit how each of these contributes to the various objectives, commonly referred to as criteria. MCDA is particularly relevant when monetary estimates of costs and benefits are not available or difficult to obtain (Malczewski, 1999). For instance, many of the agricultural externalities addressed in the present analysis have not (yet) been evaluated in monetary terms, rendering a Cost-Benefit Analysis difficult to implement.

While Cost-Benefit Analysis compares all positive and negative impacts of a given project in monetary terms, MCDA defines score functions which are used for transforming all impacts into scores for each criterion. The scores are normalized to range between 0 and 1, with 1 indicating the maximum contribution to the overall objective, and 0 indicating the opposite. These scores are then aggregated using a set of criteria weights which indicate the relative importance of each criterion relative to the other criteria. This way, a total score can be calculated. The criteria weights should ideally reflect the preferences of society. Assessing such preferences is however far from trivial.

Bogetoft and Pruzan (1991) categorize the approaches to the formulation of preferences into two main groups: (i) a priori or posteriori formulation of preferences and (ii) continuous formulation of preferences. Two players appear: the decision-maker and the analyst. The analyst is responsible for generating technical solution suggestions and presents these for the decision-maker – this could be a single person or a group of stakeholders. In the first main group (of approaches to preferences formulation) the analyst investigates different efficient and technically feasible solution suggestions and presents these for the decision maker (posteriori); or preferences are revealed ahead of the solution suggestion generation (a priori). The decision-maker examines the suggestions put forth and makes a decision. In the other main group the solution generation is interactive as the analyst presents a list of alternatives for the decision-maker. The decision-maker expresses her preferences and then the analyst produces yet another proposition. The process ends when the decision-maker has identified the preferred solution.

A central question arises when using MCDA; how to identify the relevant decision makers, who can legitimately attach relative importance of weights to the different attributes and criteria on behalf of society as social preferences. In this context it is likely that operating with groups of great size and wide social width will be difficult. Instead, one could imagine the use of a representative selection of political decision makers to perform the trade-off procedures, which the multi-criteria methods presuppose. Smaller focus groups consisting of representatively selected citizens of society are yet another option. However, different stakeholders typically have different perspectives and opinions on how the criteria should be prioritized. This complicates the aggregation of the different stakeholders' weights into “weights of society”.

Multi-criteria decision analysis has been used extensively with the fields of natural resource management and conservation. Especially dealing with land use change considerations, the spatial MCDA is a valuable tool not only due to its ability to incorporate geographic conditions and dependencies but also because it serves as a powerful communicative tool in the decision process (Mendoza and Martins, 2006).

A common MCDA approach to finding an optimal decision alternative, *x,* is to maximize an objective function, *v(x),* given a feasible set of alternatives, *X* (Bogetoft and Pruzan, 1997):

$$\begin{aligned} &\text{Max } v(x) \\ &\quad \text{s.t.} \\ &x \in X \end{aligned}$$

The operationalization of the maximization problem above entails describing the objective function in terms of a range of criteria, attributes and weights. A range of methods can be applied. Simple additive weighting, also known as weighted linear combination (WLC), is the most commonly used approach (Malczewski, 1999) and follows the formula:

$$A_j = \sum_j w_j{}^* y_{ij}$$
$$\text{s.t.}$$
$$w_j \geqslant 0 \text{ and } \sum_{j=1}^{m} w_j = 1$$

where A_j is the overall score of the alternative based on the weight, w_j, and the score, y_{ij}, of the i'th alternative in respect to the j'th attribute. This is subject to the common normalization of weights to the interval of 0–1 with their sum being 1. Alternatives with the highest scores in descending order are the most suitable for reaching the goal (Mendoza and Martins, 2006). Extensive research has addressed the suitability of WLC and other non-linear weighting methods. It is however beyond the scope of this paper to discuss these aspects in detail. We use the WLC as it is generally considered a straightforward and intuitive approach that is easy to communicate to decision makers and suitable for initial analysis to disclose trade-offs (Malczewski, 1999; Malczewski, 2000; Drobne and Lisec, 2009). Further detailed analysis into the suitability of the WLC relative to other weighting procedures would be desirable prior to actual policy applications of model results.

3. Design

Involving political decision-makers and stakeholders, representative focus groups, or even conducting questionnaire surveys is generally considered the proper way to identify and incorporate social preferences into the MCDA model. Part of the research project[1], which this paper is based on, involved conducting ‘future workshops’ (Jungk and Müllert, 1987) involving relevant stakeholders from the Danish Environment Agency, agricultural organizations, environmental NGOs

[1] http://fremtidenslandbrug.dk/future-farming/.

and Danish universities. Two future workshops were held in order to help identify scenarios, relevant criteria, attributes and weights for the MCDA analysis. A project feedback group involving the same stakeholders were involved throughout the project to ensure validity and political feasibility of the developed scenarios as well as the MCDA implementation.

The future workshops and a scientific advisory group followed the steps below, largely in chronological order, in their process of developing the final MCDA models:

1. Development of scenarios
2. Selection of criteria
3. Assigning of criteria weights
4. Selection of attributes
5. Assigning of attribute weights
6. Determining score functions

Descriptions and justifications for the choices made in each step are presented in the following.

3.1. Development of scenarios

The participants in the future workshops outlined four different scenarios to represent different possible futures for the Danish agricultural area. Each of the four scenarios was labelled with a name indicating the distinct purpose of the scenario: 1) “Green growth”, 2) “Urban and rural”, 3) “Bio-based society”, and 4) “Rich nature”. The future workshops as well as the project feedback group were intended to ensure a reasonable societal representation. The scientific advisory group gave informed advice on which ecosystem services to incorporate and which data layers that was applicable to the four scenarios.

3.2. Selection of criteria and assigning of criteria weights

The future workshop participants also helped define a set of criteria weights for each scenario based on the likely societal preferences given the distinct purpose of the scenario. Hence, the relative weights differ across the four scenarios as well as from the equal weights used in the baseline (explained below). Thus, the approach to preference formulation in this MCDA belongs to group one (i), i.e. a priori formulation of preferences (Bogetoft and Pruzan, 1991).

The future workshops were also instrumental in identifying the five main criteria to be included in the MCDA analysis: Biodiversity, Aquatic environment, Soil fertility, Climate, and Economics. These were chosen to represent ecosystem services relevant for Danish agricultural areas within the limits set by the overall project and applicable to all four scenarios. Clearly, this is a simplified approach dictated by the resources available for the project. Obviously, a larger range of ecosystem services are associated with agricultural land use (Maes et al., 2013; Sukhdev et al., 2010), but these criteria were determined to cover the main ecosystem services provided by agricultural land in Denmark.

The starting-point for the analyses of scenarios is the construction of a baseline MCDA framework which reflects the social worth of the current utilization of land in terms of score values. Areas where the model returns a high score are of great importance to society in current utilization and conversely for areas obtaining a low score. An initial neutral stance on weights was made for the baseline, assigning equal weights among the five criteria. The four scenarios which were implemented using each their own particular set of weights then illustrate the sensitivity of the outcome to changes in these relative weights among the criteria. We used ArcGIS (ESRI, 2012) to align geographical data on attributes and criteria, and the spatial MCDA software ILWIS was used for model simulations (University of Twente, 2013).

The overall purpose of the MCDA analyses of the four policy scenarios was to identify the areas where it would be most advantageous for society to change land utilization in order to achieve the specific objectives for each of the scenarios. Thereby, the model identified areas in Denmark where specific area-based instruments could be optimally implemented, given the societal preferences assumed by the participants in the future workshops as well as the advisory group. The results from the MCDA model analyses, combined with additional calculations and data processing, constitute the basis for the actual selection of areas.

The geographical database used in the spatial MCDA model consists of a break-down of the agricultural area into a grid consisting of 50x50 meter cells covering the entire agricultural area in Denmark. Thus, each cell has a size of 0.25 ha. For each cell, data consists of a range of more or less readily available spatially explicit environmental attributes which are identified and grouped together for each criteria, reflecting their relevance as indicators of the criteria. In addition, data on economic returns (land rent) and employment was calculated for each cell (see Appendix A for details). All variables are converted to scores using score functions. The MCDA model aggregates all these scores into a total score for each cell, using the defined set of criteria weights. The higher the total score, the relatively greater the societal value of the current land use in the cell. Consequently, it is possible to directly compare the scores of all the individual cells. The relative suitability of each cell can then be judged according to the specific purpose, e.g. land use change. The model does not explicitly indicate the extent of agricultural land for which land use should change, but the suitability scores indicate *where* land use change should take place.

The so-called criteria tree of the baseline can be seen in Table 1. In

Table 1
Criteria tree of the baseline.

Criteria	Criteria weight	Attribute	Attribute weight	Impact on total score
Biodiversity	0.20	HNV Index	0.90	Positive
		Field size	0.10	Negative
Aquatic environment	0.20	Organically farmed area	0.15	Positive
		Life stock density	0.15	Negative
		Retention capacity	0.15	Positive
		Area in crop rotation	0.15	Negative
		Peat soil in crop rotation	0.15	Negative
		Reduction requirements	0.25	Negative
Soil fertility	0.20	Livestock density	0.25	Positive
		Dexter index	0.75	Negative
Climate	0.20	Ruminants	0.25	Negative
		Livestock density	0.25	Negative
		Crop rotation area	0.25	Negative
		Peat soil in crop rotation	0.25	Negative
Economics	0.20	Land rent	0.75	Positive
		Employment	0.25	Positive

the baseline the five criteria have been assigned equal weights. This decision reflects an attempt[2] to be neutral in the baseline scenario with respect to the trade-off between the criteria. Each criterion is subdivided into attributes, normalized to the interval 0–1, with individual weights. Also, the criteria tree indicates whether an attribute has a positive or negative impact on the total score. The total score is calculated as follows:

$$\text{Total score} = 0.2\text{x Score}_{\text{Biodiversity}} + 0.2\text{x Score}_{\text{Aquatic environment}} + 0.2\text{x Score}_{\text{Soil fertility}} + 0.2\text{x Score}_{\text{Climate}} + 0.2\text{x Score}_{\text{Economics}}$$

Due to the normalization of all scores in the interval 0–1, the total score will also be a value within this interval.

3.3. Selection of attributes and assigning of attribute weights

Table 1 shows that the score value for the criterion Biodiversity was obtained as a joint function of the scores for the attributes High Nature Value (HNV) Index (Brunbjerg et al., 2016) and the size of the field if it was under crop rotation. Recognising that of these two attributes, the HNV Index constitutes the much stronger indicator of biodiversity[3], it was decided to use a differentiated weighting system for aggregating the attribute scores. The HNV index was thus assigned a weight of 0.9, while the size of the field only contributed with a weight of 0.1.

The aquatic environment criterion score was measured by six different attributes. In this context aquatic environment primarily covered surface water and pollution of this. It was assumed that organic farming had a lesser negative impact on the aquatic environment than conventional farming. Likewise, the higher the area's capacity to retain nitrogen fertilizer added to the soil (the retention capacity), the less the negative impact on the aquatic environment. By contrast, the aquatic environment was expected to be negatively influenced by a high livestock density (due to a higher manure load), areas in crop rotation and peat soil areas in crop rotation. The latter is due to more nitrate leaching from such areas than from permanent grass. Finally, reduction requirements from the existing Danish Action Plan for the Aquatic Environment (Vandmiljøplan, 2004) were included as an indicator since greater reduction requirements reflected a relatively higher existing pressure on the aquatic environment in the designated area. The latter factor was assigned the greatest weight of 0.25. This was due to the fact that it may be seen as a direct assessment of the current state of the aquatic environment in a given area, whereas the other attributes may be considered more indirect indicators. These remaining indicators were all assigned equal weights of 0.15.

For soil fertility disproportional weighting was applied assigning the greatest weight (0.75) to data for the Dexter index which is a measure of soil fragility where reduced fertility is considered a consequence of carbon (organic substances) removal (Schjønning et al., 2012). In addition, the number of livestock units per hectare was also considered a relevant indicator of soil fertility, but with a smaller weight of 0.25. This was based on the premise that more livestock units lead to more animal manure being applied, which in turn contributes to the soil's carbon balance and fertility.

For climate, equal weights (0.25) were applied to the relevant underlying data since no obvious arguments for differentiated weighting was found. All four attributes were expected to have a negative climate impact. The emission of greenhouse gasses from ruminants (in terms of methane from enteric fermentation) is larger than for other types of livestock and higher livestock densities lead to higher levels of emissions. Soil under crop rotation has higher levels of CO_2 emissions compared to soils which are not under crop rotation such as permanent grass. This is due to higher levels of carbon sequestering for the latter. Peat soil in crop rotation was assumed to be in the process of decomposition which releases otherwise organically bound carbon from these soils. This explains the greater emission level of peat soils in crop rotation compared to other types of soil.

Finally, for the economics factors disproportional weighting was applied attributing a considerably higher weight to land rent (0.75) than to employment (0.25). Both of these variables are given a positive impact on the score because a higher land rent and higher employment are considered as beneficial for society.

3.4. Determining score functions

Essential for the application of MCDA modelling is the specification of the normalized score functions for each individual attribute. In other words, how are attribute data values measured in units such as hectares, tonnes or Danish kroner converted into score values between 0 and 1? For the baseline model the score functions were defined in such a way that the higher the social value of the measured data value in a given cell the higher the score value assigned to the cell. By contrast, low score values were assigned to cells containing a data value that was considered to be of relatively low value to society. Furthermore, in some cases the arguments of the score function is based on the distribution of the underlying data. A number of dummy-variables (taking the value 0 or 1) are included in the model. Fig. 1 illustrates and presents arguments for the score functions used for the HNV index and Field size attributes which form the basis for the score for the biodiversity criterion. Appendix B provides a full overview of all score functions used.

4. Scenarios and final MCDA models

4.1. Baseline

As mentioned, the four scenarios were developed to represent various development paths that Danish agriculture could follow towards 2050. All scenarios incorporate various forms of land-use change and have very different and distinct goals. However, the four scenarios are so varied that they in themselves represent the basis of the sensitivity analysis of this paper.

The baseline represents the current utilization and computed value to society of agricultural land in its present use. To let the total scores obtained from the spatial MCDA reflect the suitability of each cell in terms of changing land use, most of the score functions from the baseline model were inversed when applied to the scenarios. The functional relations in the score functions are essentially unchanged with regard to the specification in Table 1 and Fig. 1 – they are just flipped vertically. In other words, we use the spatial MCDA model to select areas for a potential change in land utilization and not as in the baseline model to determine the value of the current utilization. This illustrates that the areas with current high value should obviously not be converted whereas the areas of little current value have the greatest potential in a land use change scenario. However, the two models are not all together diametrical opposites (which could result in two identical models just with different signs), since the score function belonging to the biodiversity criteria are kept exactly as in the baseline model. This is done in accordance with a specific recommendation from

[2] We acknowledge that neutrality may be considered somewhat illusory when it comes to assigning weights. Any set of weights, also equal weights, will always reflect a specific preference structure implying some ranking or prioritization of the criteria.

[3] The HNV index already represents a joint weighting of several relevant biodiversity indicators, which was composed into one score thereby representing a greater amount of the underlying data. The specific weights employed here are obviously somewhat arbitrary in that there is no theoretical or empirical evidence of *how* much more important the HNV index is relative to field size. Notwithstanding this, these relative attribute weights are kept constant throughout the analysis. While potentially interesting, it is considered beyond the scope of the current paper to further investigate consequences of assuming other relative attribute weights.

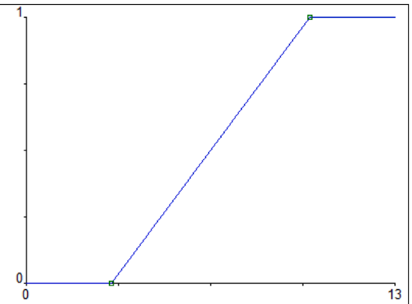
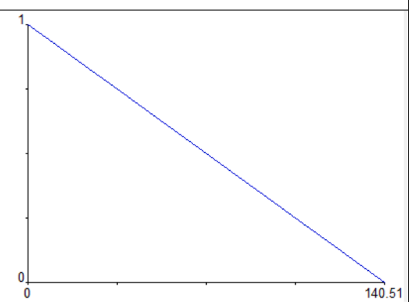
HNV Index	The High Nature Value (HNV) index is designed to assign scores from 0 to 13 to agricultural fields based on their relative nature value as measured by a range of nature indicators. A detailed description is available in Brunbjerg et al. (2016). Generally, the greater the HNV index, the greater the biodiversity value of a given field. HNV index values of less than 3 are here assessed to have virtually no nature value of interest to the given context. Fields obtaining the value of 3 or less are therefore all assigned a score of 0. Areas achieving a value of 10 or above are considered to contribute with more or less equally high biodiversity value. In the interval from 3 to 10 a linear function is assumed.	
Field size	The larger a field under crop rotation is the lower is the value for biodiversity. This is based on the observation that large homogenous fields display a lower level of biodiversity relative to smaller and more fragmented fields (Altieri 1999). 140.51 hectares was the maximum field size in the data set.	

Fig. 1. Score functions for attributes of the Biodiversity criterion. The x-axis is the measured data value for the attribute and the y-axis is the score value. See Appendix B for details.

the Danish Ministry of Environment concerning the "Fireman's rule" which is used a guiding principle in practical environmental protection in Denmark. The rule prescribes that one should, first of all, safeguard the nature areas where the current nature values are the greatest (Ministry of Environment, 2014). For this reason farming areas identified for conversion should be areas attached to existing nature areas where the HNV index is relatively high, all else equal.

4.2. Green growth

The purpose of the Green growth scenario was to identify agricultural areas where it would be most beneficial to implement environmental and climate sustainability measures. The criteria aquatic environment and climate were each assigned the highest weights of 0.35, implying that each of these criteria determines 35 per cent of the total score of the scenario. Prioritization of the aquatic environment is a consequence of politically specified reduction targets for nutrients and pesticide application while the prioritization of climate is closely related to the national obligations to reduce greenhouse gas emissions. In this scenario less importance was attached to biodiversity, soil fertility, economic returns to agriculture and employment. Consequently, these attributes were assigned weights of 0.1. An underlying feature of the green growth scenario was a focus on both enhanced agricultural productivity and reduced stress to the environment and climate. It was based on high technological development to secure a productive agricultural sector.

4.3. Urban and rural

The primary objective in this scenario was to create development and employment in rural areas through an increased focus on high-quality products, local marketing and sales, and low-input organic circular farming. Organic circular faming as an environmental policy tool was chosen because this type of activity has the potential of increasing on-farm employment. The application of the MCDA model was limited in this scenario because neither distance to urban areas nor rural districts themselves could be included as attributes. Consequently, the model was applied to identify vulnerable agricultural areas which could be converted to organic circular farming. Therefore, the aquatic environment was given the highest weight of 0.4 while climate, economics and biodiversity were given equal weights of 0.2. Soil fertility was not considered to be of any importance in this scenario and was therefore given the weight of zero.

4.4. Bio-based society

In this scenario, the main objective for Danish agriculture in the future was defined to focus on delivering raw materials for production of renewable materials and energy. The overall purpose of this was to develop towards a society relying heavily on renewable bio-energy. A weight of 0.5 was assigned to economics, while climate and soil fertility each were given a weight of 0.2. The aquatic environment and biodiversity were considered of very low importance in this scenario and, thus, assigned weights of 0.05 each.

Table 2
Applied criteria weights of the MCDA model for each scenario.

Scenario	Criterion					
	Biodiversity	Aquatic environment	Soil fertility	Climate	Economics	Scenario objectives
Baseline	0.20	0.20	0.20	0.20	0.20	Baseline
Green growth	0.10	0.35	0.10	0.35	0.10	Enhanced, sustainable productivity
Urban and rural	0.20	0.40	0.00	0.20	0.20	Rural development, organic circular farming
Bio-based society	0.05	0.05	0.20	0.20	0.50	Renewable bio-energy production
Rich nature	0.50	0.25	0.10	0.05	0.10	Increased biodiversity

4.5. Rich nature

The purpose of this scenario was to create the greatest possible level of biodiversity and a rich nature. Therefore, the most essential criterion was biodiversity which was assigned a weight of 0.5. To increase aquatic biodiversity the aquatic environment attribute was given the second largest weight of 0.25. Being considered as less important in this context, soil fertility and economics were assigned weights of 0.1, and climate 0.05.

Table 2 summarizes the weights specified by the expert group for each criterion in all of the four scenarios as well as the baseline.

5. Results

5.1. Baseline

The MCDA model was run for the baseline to illustrate the relative values of the current agricultural area utilization. Fig. 2 shows the geographical score distribution. Orange to red colours indicate a relatively high score value whereas green colour indicates lower scores and blue colour indicates the lowest level of score values. At first glance one could be tempted to conclude that a change in area utilization – everything else equal – should happen in the bluish and greenish areas on the map since these constitute the relatively lowest social values under the current utilization. Whether or not this will actually be the case depends on the intended changes in area utilization and for which purposes these are made.

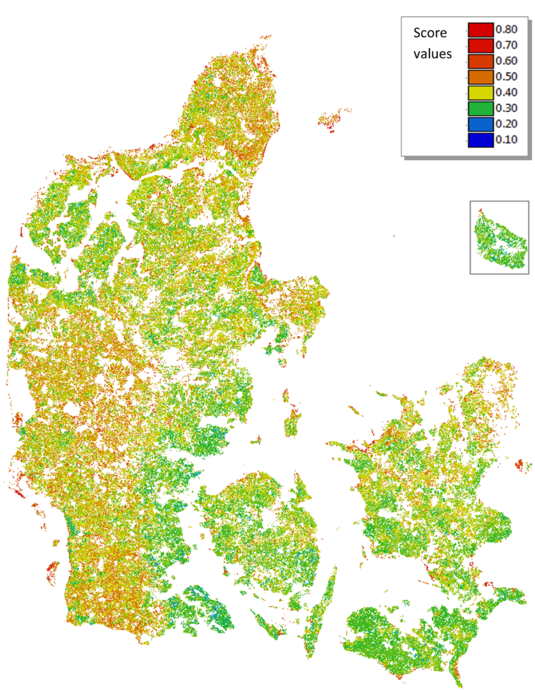


Fig. 2. Total score map of the baseline.

5.2. Scenarios

The spatial MCDA model was adapted and run for each of the four scenarios as described above. The total score maps of Fig. 3 show where any land-use change measures under a given scenario should ideally be implemented in order to reach the goal of the scenario at the lowest possible loss in societal value. This is opposite to the baseline which showed the societal value given the current agricultural use. It is evident from Fig. 3 that the scenarios lead to very different geographical outcomes.

The geographical distribution of total scores of the Green growth and Urban and rural scenarios appear similar to each other. This is primarily due to the criterion Aquatic environment being assigned relatively high weights (0.35 and 0.40) in both scenarios. Implementation of measures should, according to the suitability scores, be focused in the North-Western part of the country, where there is a concentration of high score areas. Depending on the how large a total area is to be included for land-use change measures further efforts should be located in the South-Western part, whereas the islands in the Eastern part of the country would be left largely untouched in these scenarios due to low suitability scores.

In the Bio-based society scenario no overall geographical patterns seem to emerge and the differences appear to be of a more local character. This is related to the high weight attached to the attributes land rent and employment (0.5). The score maps for these parameters contain no distinct regional patterns or divergences. Efforts aimed to increase bio-based production could be implemented across the country as areas attained a high score are spread fairly evenly across the country.

For the Rich nature scenario the total score map shows that most areas appear with a relatively low score. Only a few high score areas (red and yellow colour) appear on the map indicating the most suitable areas for land use change. The areas least suitable for land use change (blue areas) are located primarily in the Southwestern and Western parts of the country as well as scattered in the Northern and North western parts of the country.

The primary cause of the differences across the scenarios originates from the weights associated with each scenario (Table 2). The specific weights are meant to reflect the relative societal importance of the criteria in a given scenario setting.

5.3. Consequences of land use change

Using the suitability scores calculated under each scenario to target specific land use change policies corresponding with the purposes of each scenario, it is possible to conduct post-analysis calculations for any of the attributes in order to assess the aggregate consequences of the specific policies. As part of the scenario development work, a range of specific policy measures for each scenario that would imply various land use changes by year 2050 was defined (see Jørgensen et al., 2015 for details). Table 3 provides a summary breakdown of the land use changes envisioned in the four scenarios in 2050 compared to the baseline. The four scenarios involve roughly a similar total agricultural area. However, permanent grass lands (632,000 ha) and energy crops

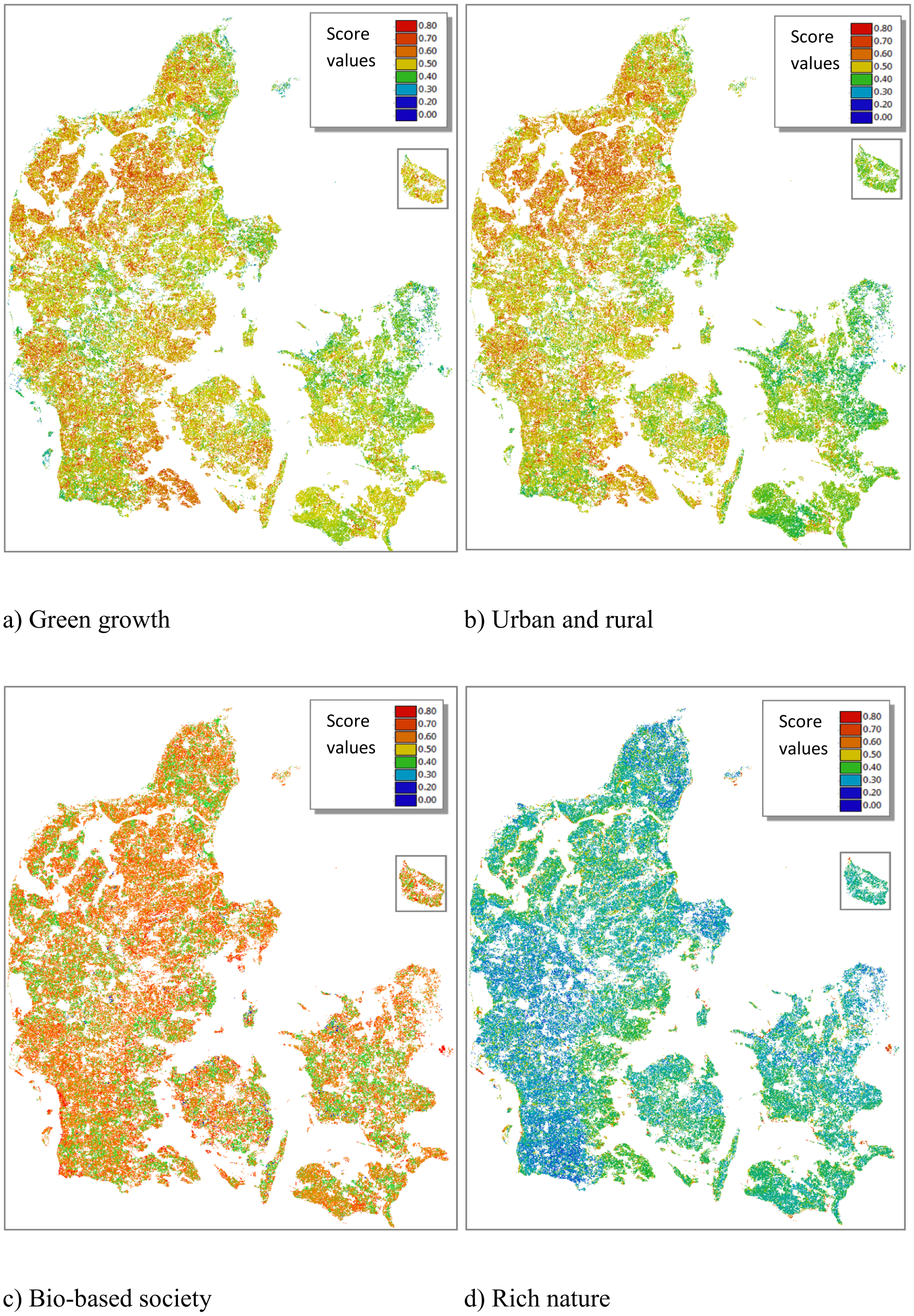


Fig. 3. Total score maps for the four scenarios a) Green growth, b) Urban and rural, c) Bio-based, and d) Rich nature.

Table 3
Breakdown of land use (in 1000's of hectares) in the baseline compared with the four scenarios for Denmark in year 2050.

Scenario	Baseline	Green growth	Urban and rural	Bio-based society	Rich nature
Total agricultural area	2659	2286	2286	2286	2191
Cultivated area	2327	1454	1914	1454	1609
Permanent grass	332	632	372	632	582
Energy crops	6	200	0	200	0
Afforestation	608	673	673	673	768

(200,000 ha) are major elements in the Green growth and Bio-based society scenarios due to their importance for bio-based energy. In the Rich nature scenario permanent grass also plays a significant role (582,000 ha), this time, however, with the intention of creating natural habitats. Afforestation features most prominently in the Rich nature scenario (768,000 ha) but also in the three other scenarios (673,000 ha). This difference is due to large biodiversity gains expected from afforestation and so mostly applicable to the Rich nature scenario. The measures envisioned can thus have very different goals across scenarios. While the targeted areas have been selected by using the MCDA model suitability scores, the changes in agricultural land use have been defined by the project group based on input from

Table 4
Annual changes in land rent and employment across the four scenarios towards 2050.

Scenario/change	Green growth	Urban and rural	Bio-based society	Rich nature
Land rent (billion DKK/year)	−1.26	0.11	−1.03	−1.53
Land rent (% change)	−14.3	1.2	−11.7	−17.3
Employment (man years)	−1700	−1100	−1350	−1200

Table 5
Total CO_2 reductions in millions of ton towards 2050 in the four scenarios.

	Green growth	Urban and rural	Bio-based society	Rich nature
Total CO_2 reduction (million tons)	7.0	0.2	8.3	1.8

stakeholders in the future workshops as well as from the advisory group. The defined measures to be taken were based on the goals of each scenario. Thus, for the purpose of this paper the measures were already set but differences across scenarios and specification of measures allow for a highly detailed analysis of the consequences of each scenario.

The changes in agricultural land use will create corresponding changes in the economic conditions for agriculture. The geographically specified MCDA model facilitates detailed analysis of changes in the land rent accruing to agriculture as well as employment effects. Table 4 gives an overview of the economic consequences of the targeted policy measures implemented for each scenario. The Urban and rural scenario accounts for the only positive effect on land rent (1.2%) whereas the Rich nature scenario involves a 17.3% land rent loss as a result of the conversion of arable land to natural habitats (see Jørgensen et al., 2015 for details). These losses and gains in land rent should be evaluated in regards to the spatial land use changes detailed in Table 3 and other effects such as CO_2 reductions.

Other effects could include nature indicators, pesticide and nutrient use, and climate related issues. The calculated CO_2 reductions due to land use changes towards 2050 are reported in Table 5 for each scenario. The Green growth and Bio-based society scenarios have a large climate change mitigation potential with the possibility of storing 7.0 million or 8.3 million tons of CO_2 towards 2050. However, the Rich nature scenario focusing on the enhancement of nature values does relatively little in terms of climate change mitigation (1.8 million tons).

All consequences both spatially, physically, and economically are to be evaluated against one another, but any final decision to actually implement a specific scenario in real life will always be a political one. Our spatial MCDA model is essentially a helpful tool applicable for making all the involved trade-offs as transparent as possible to both decision-makers and the general public, not only during the decision-making process but also after a political decision has been made.

6. Conclusions

In this paper, we have presented a decision support tool using a spatially explicit MCDA model. The primary purpose of the analyses was to show how the exceptionally detailed geo-related data available in Denmark can be structured and applied to support decision making regarding land use.

Initially the model was set up for a baseline scenario where all criteria had equal weight. We then adapted the model to each of four different scenarios for how the agricultural landscape in Denmark might look in year 2050. For each of these scenarios a specific set of weights were applied to illustrate potential social preferences and trade-offs between the criteria and values of the scenario. The different weights applied in the individual scenarios were the main reason for the different results provided by the adapted MCDA-models. Accordingly, the determination of the applied weights must be considered the greatest challenge in an MCDA-analysis. In principle, the weights represent society's preferences, which should be reflected in political decision making. In the current analysis the weights were informed by two future workshops and an advisory group involving a range of scientific experts and relevant stakeholders. Nonetheless, the applied weights should only be considered as an illustrative suggestion of what could be seen as relevant with respect to the objectives of the individual scenarios.

For all four scenarios score values were calculated using the MCDA model. By comparing the score values across cells, an expression of the relative social value is obtained with respect to changes in the current land utilization. High values indicate a relatively great societal advantage associated with a land use change. Thus, to obtain the greatest benefits from changes in land use one should pick areas using a "top-down" approach, i.e. starting with the areas which have obtained the highest score values according to the specific purpose. In our case, the purpose was to identify areas particularly relevant for land-use change, and the score values were thus interpreted as suitability scores. In the results we calculated consequences from the selected areas as examples. In an actual policy application of the spatial MCDA model relevant decision makers would decide how much land is to be converted. The model would support them in pointing out the best suited areas.

The scenario analyses have illustrated the applicability of the spatial MCDA model in solving complex trade-off issues associated with land use changes. This indicates that the spatial MCDA approach represents a valuable tool in policy decision making regarding biodiversity strategies at the national as well as the EU level. For example, political decisions in terms of national environmental policy programmes and EU requirements can be translated into very detailed land use changes at the local level. The modelling experiments highlight the need for decision makers to articulate their preferences with respect to different development paths and land use changes. Potentially, the visualized outcome of alternative spatial MCDA modelling scenarios can stimulate the interests in such considerations.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolind.2019.03.056.

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