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Classification of agricultural priority and reserved areas in Brandenburg under consideration of bio-economic climate simulations

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Abstract
Ensuring a crisis-proof food supply has become a key political issue. In Germany, official spatial planning allows the use of priority and reserved areas to secure land for agricultural use and regional food supply. The focus should be particularly on climate-resilient areas that also have a stable yield potential in the future. This paper supplements widely used, static approaches for determining priority and reserved areas with a dynamic bio-economic analysis that takes future climate scenarios into account. The results for the German federal state of Brandenburg show a high area equivalence between the static and dynamic approaches. In the case of data gaps, for example, static approaches such as soil quality indices can serve as an adequate proxy for future yield potentials. However, not all climate-robust areas can be classified as potential reserved or priority areas. Furthermore, areas that show low yield potential under future conditions are not released for other land uses. Feedback from stakeholders involved in the study showed that the use of the dynamic approach and a target value using the results of a foodshed model lead to broad acceptance. The method developed here can make a valuable contribution to climate change adaptation in spatial planning instruments.

Keywords: Climate resilient agriculture ▪ spatial planning ▪ regional planning ▪ economic resilience ▪ bioeconomic analysis ▪ peatland conservation

Bestimmung landwirtschaftlicher Vorrang- und Vorbehaltsgebiete in Brandenburg unter Berücksichtigung bio-ökonomischer Klimasimulationen

Zusammenfassung
Eine krisensichere Lebensmittelversorgung hat sich zu einem politischen Kernthema in Deutschland entwickelt. Durch Vorrang- und Vorbehaltsgebiete können raumordnerisch Flächen für die landwirtschaftliche Nutzung und die regionale Nahrungsversorgung gesichert werden. Dabei sollte der Fokus insbesondere auf klimarobusten Flächen liegen, die auch zukünftig ein stabiles Ertragspotenzial aufweisen. Der vorlie-

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gende Beitrag ergänzt weit verbreitete, statische Ansätze zur Bestimmung von Vorrang- und Vorbehaltsgebieten um eine dynamische bio-ökonomische Analyse unter Berücksichtigung zukünftiger Klimaszenarien. Die Ergebnisse für die Beispielregion Brandenburg zeigen eine hohe Flächenäquivalenz zwischen dem statischen und dem dynamischen Ansatz. Im Fall von beispielsweise Datenlücken können statische Ansätze wie Ackerzahlen als adäquater Indikator für zukünftige Ertragspotenziale dienen. So können jedoch nicht alle klimarobusten Gebiete als potenzielle landwirtschaftliche Vorbehalts- oder Vorzugsgebiete klassifiziert werden. Außerdem werden Flächen, welche unter zukünftigen Bedingungen ein geringes Ertragspotenzial zeigen, nicht für andere Landnutzungen frei gegeben. Das Feedback von in der Studie einbezogenen Interessengruppen zeigt, dass die Verwendung des dynamischen Ansatzes und eines Zielwerts unter Verwendung der Ergebnisse eines *foodshed*-Modells zu einer breiten Akzeptanz führt. Die hier entwickelte Methode kann einen wertvollen Beitrag zur Integration von Klimaanpassungselementen in raumordnerische Instrumente leisten.

Schlüsselwörter: Klimaresiliente Landwirtschaft ▪ Raumplanung ▪ Regionalplanung ▪ ökonomische Resilienz ▪ bioökonomische Analyse ▪ Moorschutz

1 Introduction

New climate policy measures related to renewable energy (Bundesregierung 2023), peat land conservation (BMUV 2022) or the land required for settlement, transport and industrial development all foster increasing land competition. Spatial planning in Germany aims to balance the different land-use demands. With an increased risk of flooding, declining groundwater levels, fragile forest areas and more tourism due to longer bathing seasons, spatial planning has to increasingly consider climate adaptation and mitigation strategies (Franck/Peithmann 2010). Spatial planning aims to develop, organize and secure overall societal needs through planning schemes and the coordination of spatial plans and instruments. This includes the harmonization of different land demands and conflict reconciliation (Scholich 2018). Spatial planning is usually cross-sectional and thus has to consider a multitude of land-use types and demands, e.g. for settlements, open space, renewable energies, securing raw materials, transport, in an integrated way (Mitschang 2021).

Regional planning is the lowest and most spatially explicit level of spatial planning in Germany, subordinated to state and federal spatial planning. In regional planning, objectives (*Ziele der Raumordnung*) and principles (*Grundsätze der Raumordnung*) can be enforced through the use of different instruments. Reserved areas (*Vorbehaltsgebiete*) and priority areas (*Vorranggebiete*) are both instruments designed to secure site-specific uses or functions. For this purpose, the primary functions or uses (e.g. agricultural production) are determined and other types of use can be excluded in the case of land-use conflicts. In reserved areas, the primary use must be taken into account in all planning, review and approval procedures, and can only be set aside in justified individual cases. In priority areas, all other spatially significant uses are forbidden if they are incompatible with the primary use or function (Scholich 2018). One example of the application of these instruments is in agricultural priority and reserved areas, which are used to reserve areas for agricultural use.

Climate change mitigation and adaptation often concern spatial aspects and were therefore included in the principles of spatial planning through the amendment of the Spatial Planning Act at the end of 2008.[1] However, in contrast to agricultural production, climate adaptation is still not per se spatially significant. In regional planning, only planning objectives with spatial significance can be considered. Initiatives aimed at addressing climate adaptation and mitigation may only be incorporated into regional plans if they explicitly address the associated spatially significant impacts. Therefore, there must be a spatially significant condition with which climate protection or climate adaptation measures in spatial planning can be effectively integrated (Wagner 2021: 12–14). Such a condition is provided, for example, by climate adaptation through the provision of climate-robust agricultural areas to ensure future agricultural production.

A further challenge is posed by the different planning horizons. Regional plans have no validity period but are generally adapted and updated in the medium term. Climate adaptation requires a long-term planning horizon that goes far beyond usual planning time horizons. However, it is precisely because of the long-prolonged timeframes that early spatial adaptation to climate change is important.

A considerable part of research on climate adaptation in regional planning focuses on the integration of renewable energy (Zaspel 2014). Other studies recommend a focus on informal coordination and planning processes over the use of designation tools such as priority and reserved areas for the protection of agricultural land that is particularly climate-resilient (Jacoby 2013). Regional plans that incorporate designation instruments mainly utilize static

[1] § 2 para 2 No. 6 Spatial Planning Act (*Raumordnungsgesetz*, ROG) of December 22, 2008 (Federal Law Gazette I p. 2986), last amended by Article 1 of the Act of March 22, 2023 (Federal Law Gazette 2023 I No. 88).

indicators to identify climate-robust agricultural areas such as soil quality parameters (Regionaler Planungsverband Leipzig-Westsachsen 2020; Regionale Planungsgemeinschaft Havelland-Fläming 2021), drought risk (Regionale Planungsgemeinschaft Havelland-Fläming 2021) or risk of waterlogging (Regionaler Planungsverband Leipzig-Westsachsen 2020). Other studies include additional indicators, such as wind and water erosion (Martinsen/Knothe/Thur 2014). However, to our knowledge, there is currently no designation method that considers dynamic changes in future climate conditions and their impact on yields.

Climate simulations for Eastern Germany predict an increase in drought and hot days over the summer as well as more precipitation in the winter, yet with strong regional differences. These developments are likely to reduce the available agricultural area with adequate yields in the future (Kersebaum/Nendel 2014). Static indicators may no longer be a suitable predictor, and dynamic approaches to regional planning that consider future climate conditions and impacts on agricultural yields might be more appropriate to identify climate-robust agricultural areas (Rose/Liao 2005; Meuwissen/Feindt/Spiegel et al. 2019).

The present study compares possible static and dynamic approaches for the identification of long-term climate-robust agricultural land. For practical application and visualization, the federal state of Brandenburg serves as a case study, further described in the subsequent section. The incorporation of bio-economic simulations aims to complement existing designation methods and allows for an area equivalence analysis. In an agricultural context the term describes analytical tools used to assess the interactions between biological conditions (such as crops, livestock and ecosystems) and socio-economic factors (such as prices, input costs and behavioural aspects) (Janssen/van Ittersum 2007). In this study the biological system refers to simulated climate scenarios and a soil-crop atmosphere interaction model, while the socio-economic factors refer to costs, prices and the resulting gross margin analysis.

The approach suggested in this study consists of six steps explained in more detail in the methodology section. Following the detailed description of the methodology, the data and software used in the investigation are described in more detail. In the results section, the approach is applied in the case study area. Finally, our method is critically discussed and key implications are outlined in the conclusions.

2 Methodology

2.1 Case study

We selected the federal state of Brandenburg, Germany, as a case study for developing and applying our designation approach, as it is one of the driest regions in Germany[2] and severely affected by climate change (Kersebaum/Nendel 2014). Brandenburg is located in the north-east of Germany and has a total area of 2,965,418 ha, of which around 45 % is used for agriculture.[3] The population comprises approximately 2.6 million people. In the centre of the state is Berlin (a state in its own right) with about 3.8 million inhabitants.[4] The average precipitation of 557 mm is far below the German average. Climate simulations predict a further increase in summer drought, increased precipitation in winter and 10 to 30 more hot days with temperatures above 30°C (von Czettritz/Hosseini-Yekani/Schuler et al. 2023: 7). Ensuring local food supply under these conditions is a political goal[5], but conflicts to some extent with other climate-relevant goals, such as peatland conservation (BMUV 2022) or grassland conservation (UBA 2023).[6]

2.2 Overview

Our designation methodology aimed to equally consider the objectives of climate adaptation, climate mitigation and regional food supply, and consisted of six steps (as illustrated in Figure 1) which are described in turn in the following sections.

2.3 Step 1: Exclusion of peat soils

Peatland soils have been subject to agricultural land use for many decades. This has caused mineralization processes that lead to a constant loss of organic matter and emission of greenhouse gases. However, under suitable circumstances these soils also have significant potential for carbon sequestration. Mitigation of greenhouse gas emissions and

[2] https://opendata.dwd.de/climate_environment/CDC/grids_germany/annual/drought_index/ (07.06.2024).

[3] https://data.geobasis-bb.de/geofachdaten/Landwirtschaft/dfbk.zip (07.06.2024).

[4] https://www.destatis.de/DE/Themen/Gesellschaft-Umwelt/Bevoelkerung/Bevoelkerungsstand/Tabellen/bevoelkerung-nichtdeutsch-laender.html (07.06.2024).

[5] www.bmel.de/DE/themen/internationales/agenda-2030/globale-ernaehrungssicherung.html (07.06.2024).

[6] https://www.umweltbundesamt.de/daten/land-forstwirtschaft/gruenlandumbruch (07.06.2024).

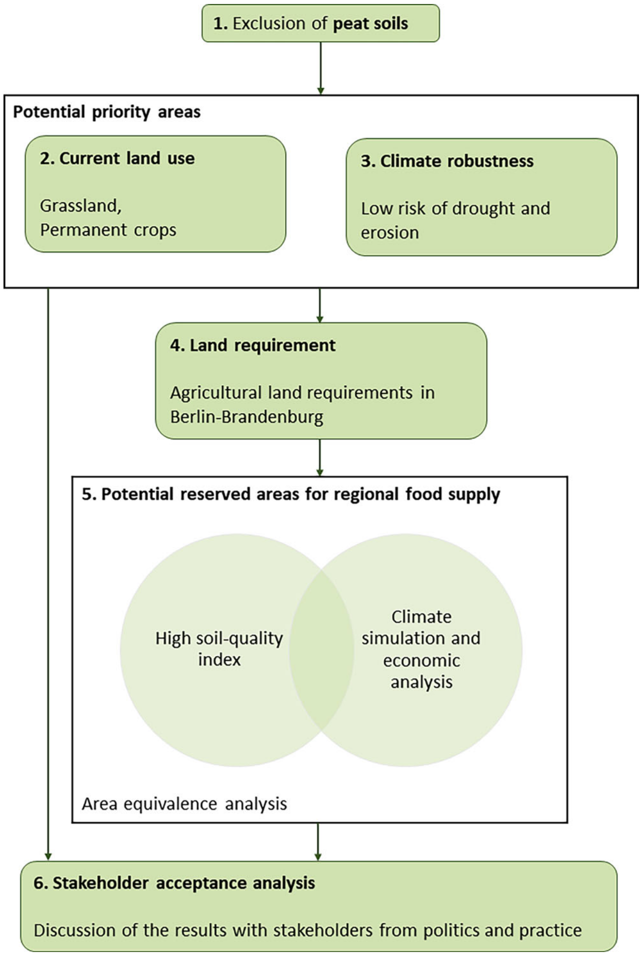

Figure 1 Graphic overview of the six steps of the methodology

sequestration of CO_2 align with the objectives of the new national peatland protection strategy (BMUV 2022). Some of the recommended peatland protection measures, such as voluntary rewetting, may conflict with the constraints imposed by designating certain areas as agricultural priority or reserved areas. To prevent any impediment to the timely implementation of peatland protection measures, it became apparent that it would be prudent to exclude the affected areas upfront, before determining potential agricultural priority or reserved zones. A map of the total agricultural area in Brandenburg was our starting point.[7] Additionally, we acquired maps illustrating peatland thickness.[8] These maps allowed us to categorize all peatland areas into two groups: those with mineralized peatland soils (where peatland thickness equals 0 cm) and those with soils containing organic material (where peatland thickness exceeds 0 cm). Consequently, we only excluded arable lands with a peat thickness greater than 0 cm from the total available agricultural area. This approach was taken to secure the preservation of areas with the highest carbon sequestration potential for peatland protection measures.

2.4 Potential priority areas

In Steps 2 and 3 (see Figure 1), potential priority areas for agricultural production were determined based on their current land use and a static analysis of climate robustness.

Climate robustness refers in this case to areas which allow for continuous agricultural production under future climatic conditions and is one major component of climate adaptation. Using the term robustness focuses on the inherent resilience of the agricultural sector, allowing for production under future conditions without substantial changes in the structure or input composition (Lin 2011). In the context of increasing land-use competition and advancing climate change, a focus on climate-robust agricultural areas is of great importance.

2.4.1 Step 2: Current land use

In Step 2 (see Figure 1), potential priority areas were identified based on their current use as grassland or permanent crops. Grassland conservation is a major priority in Germany[9], while the cultivation of permanent crops involves a longer-term commitment, which makes it difficult to use the land for other purposes. Therefore, these areas were identified as potential priority areas.

2.4.2 Step 3: Climate robustness

For the remaining arable area, we used the criterion "climate robustness" to identify additional potential priority areas (Step 3). The term robustness generally refers to the ability of a system to withstand (un)foreseen shocks as well as other stresses (Meuwissen/Feindt/Spiegel et al. 2019). Climate robustness specifically refers to shocks and stresses caused by climate change. In the static analysis, arable land with low drought, water and wind erosion risk is considered as climate robust.

For drought-related yield risk, the annual mean of the de Martonne drought index (dMI) was used.[10] The index is calculated by $dMI = \frac{N}{T+10}$, where N is the annual mean

[7] https://data.geobasis-bb.de/geofachdaten/Landwirtschaft/dfbk.zip (07.06.2024).

[8] https://mluk.brandenburg.de/mluk/de/umwelt/boden/vorsorgender-bodenschutz/moorbodenkarte/ (07.06.2024).

[9] https://www.umweltbundesamt.de/daten/land-forstwirtschaft/gruenlandumbruch (15.07.2024).

[10] https://opendata.dwd.de/climate_environment/CDC/grids_germany/annual/drought_index/ (07.06.2024).

precipitation in mm and T is the annual mean temperature in °C. The unit of the index is mm/°C. The smaller the index, the greater the drought risk. The factor 10 in the denominator is intended to prevent values below 0. The calculated values were divided into low to medium (26 mm/°C - 20 mm/°C) and high (19 mm/°C - 16 mm/°C) sensitivities (Gavrilov/An/Xu et al. 2019).

Wind erosion risk was determined based on the soil organic matter content, the soil type and the mean annual wind speed using a wind erosion risk classification. The underlining methodology has been published in detail in DIN 19706:2013 and results in a classification ranging from 0 to 5. Classes 0 to 3, denoting "none", "very low", "low" and "medium sensitivity" are regarded as favourable contributors to overall climate robustness (Martinsen/Knothe/Thur 2014).[11]

Water erosion risk was calculated based on the German adaptation of the Universal Soil Loss Equation[12] (*Allgemeine Bodenabtragsgleichung*, ABAG). The ABAG takes into account soil (K-factor), land-use differentiated, morphological (S-factor), geographic and climatic data (R-factor).[13] Based on the threshold recommended by the German Federal Institute for Geosciences and Natural Resources, soils with an erosion risk below 10 t/ha per year were assessed as having a low erosion risk.[14]

2.5 Step 4: Land requirement for regional food supply

Following the crises of the 2020s, such as the COVID-19 pandemic and the Ukraine war, resulting among other impacts in increasing price volatility, the often-underdeveloped regional supply chains of metropolitan regions have received increasing attention, and strengthening them is considered an important way to improve future crisis resilience (Zasada/Schmutz/Wascher et al. 2019).

However, regional production and the associated land demand have not been the focus of regional planning considerations. In order to integrate this aspect, we considered the findings of a foodshed model (Zasada/Schmutz/Wascher et al. 2019), which estimated the agricultural land necessary to sustain the regional food supply within the Berlin-Brandenburg metropolitan region to be approximately 1,250,000 ha. This foodshed model takes into account a range of factors including population growth, consumption patterns, waste rates and agricultural productivity to calculate the demand for agricultural products and the corresponding arable land required. This figure represents 85.6 % of the currently available agricultural land within the metropolitan region that must be secured for regional food supply. For simplicity, we rounded this value to 85 % in the subsequent analysis.

2.6 Step 5: Potential reserved areas for regional supply

Considering the potential priority areas already identified (Steps 2 and 3) and the regional land requirement (Step 4), additional potential reserved areas were identified that are more suitable to contribute to the regional food supply due to their higher current and future yield potential. To this end, two options were compared. The first option determined potential priority areas based on the current yield potential of soils drawn from a historical soil quality index (*Ackerzahl*) and is thus static. The second option was based on a dynamic, bio-economic simulation of future climate-influenced yields (Kersebaum/Wallor/Lorenz et al. 2019).

Productive soils are unevenly distributed among the different regions in Brandenburg. To avoid an exclusive concentration of potential priority areas and potential reserved areas in the most productive parts of the state, the following analysis was undertaken separately for the so-called natural areas (*Naturräume*) in Brandenburg. Natural areas are widely used across Germany to classify areas with similar physical-geographical attributes, also described as macrochore in geographical literature. The classification accounts for various geological, morphological, botanical and historical development factors (Scholz 2015). Brandenburg is composed of 14 natural areas as shown in Figure 2.

2.6.1 High-yield areas based on the soil-quality index (static)

The German soil-quality index was used as a proxy for yield potential. The index quantifies the ratio of the yield potential of each soil based on the Soil Valuation Act of 1934, which uses a uniform method to value agricultural land in Germany based on its yield capacity. The soil-quality index is a national relative indicator ranging from 0 to 100,

[11] https://www.govdata.de/web/guest/suchen/-/details/potentielle-erosionsgefahrdung-der-ackerboden-durch-wind-in-deutschland-1-1-000-000 (19.06.2024).

[12] The ABAG calculates the average annual soil erosion as a product of the erodibility (K-factor), regenerosity (R-factor), topography (slope length, slope inclination), soil cover and a factor for soil protection measures (Schwertmann/Vogl/Kainz 1987). The soil loss equation makes it possible to summarize the water erosion risk, which is influenced by various factors, in a single figure and thus to make better use of it, especially for spatial datasets.

[13] https://www.govdata.de/web/guest/suchen/-/details/potentielle-erosionsgefahrdung-der-ackerboden-durch-wasser-in-deutschland-1-1-000-000 (17.06.2024).

[14] https://www.bgr.bund.de/DE/Themen/Boden/Bilder/Bodenerosion/Bod_BoEro_KarteErodierbarkeitWasser_g.html?nn=4919548 (07.06.2024).

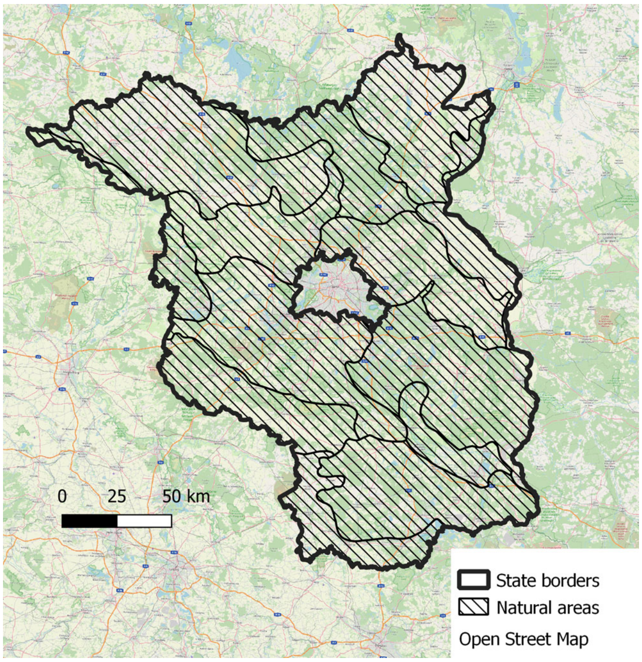

Figure 2 14 natural areas in Brandenburg according to Scholz (2015)

with the maximum set by the most productive soil. In Brandenburg, the highest soil-quality index is 88, although the average lies below 35. The values are based on information about geological formation as well as conditions of the soil, soil type, and general climate and water conditions.[15]

Marginal yield sites with a soil-quality index equal to or below 23 have only a very low yield potential (Hanff/Lau 2021: 46–104) and were therefore excluded. Subsequently, 85 % of the areas with the highest soil-quality index were determined for each natural area.

2.6.2 High-yield areas based on bio-economic simulations (dynamic)

Economic climate robustness was assessed using a dynamic bio-economic analysis of two climate projections based on two climate models from the CMIP5 ensemble (Andrews/Gregory/Webb et al. 2012). The variation in gross margins per hectare over a 30-year period (2040-2070) was based on the crop growth model HERMES (Kersebaum/Wallor/Lorenz et al. 2019) combined with an economic assessment. Based on these simulations, the area with the highest gross margins (85 %) in the years with the lowest yields (25 % quantile) was determined for each natural area. The yield levels vary strongly between the different climate scenarios. While the Max Planck Institute projects comparatively moderate climate changes for Brandenburg, the Hadley Institute assumes stronger temperature increases and increasing drought in the summer months (von Czettritz/Hosseini-Yekani/Schuler 2023). To reduce uncertainty, only the areas that consistently demonstrated robustness across all four climate projections were considered robust overall and classified as potential reserved areas.

2.7 Step 6: Stakeholder acceptance

Since changes in the current designation approach would affect multiple land users, considering the views and opinions of different stakeholders was considered essential to ensure the acceptance of potential designations of priority areas and reserved areas. To this end, we organized two stakeholder consultations to present and discuss our approach and the resulting maps. In total 60 participants attended the two events, representing a wide range of interest groups. 42 % of the participants represented interest groups, lobby groups and private companies from different sectors (e.g. renewable energy, trade associations and chambers of commerce), 30 % were directly involved in regional planning, 15 % were regional policymakers, 8 % were farmers and farmers' associations, and 5 % were from science and research. At the first workshop, it was ensured that the proportion of agricultural representatives was over 50 %. In the first step, stakeholder feedback was documented and summarized thematically. Contributions were divided into three categories: comprehension questions, positive feedback and criticism. Preferences regarding the threshold values used and the steps to be considered were clarified considering the local context of the study region. Feedback received was incorporated and presented again six weeks later, this time to a bigger and more diverse stakeholder group.

2.8 Data and software

The maps created for this study were based on the Digital Field Block Cadaster (DFBK).[16] The DFBK includes all aid-eligible agricultural land in Brandenburg and is mainly used as a reference system for agricultural subsidy applications. The dataset distinguishes field blocks and landscape elements as well as other, non-aid-eligible areas.

The location of peat soils (Step 1) was based on maps of the current peat thickness from the Brandenburg State Office for Mining, Geology and Raw Materials (LBGR). The

[15] https://maps.bonares.de/mapapps/resources/apps/bonares/index.html?lang=en&mid=a45c7a1f-3dc5-478f-9d25-50dacd607d02 (09.06.2024).

[16] https://data.geobasis-bb.de/geofachdaten/Landwirtschaft/dfbk.zip (09.06.2024).

dataset included the distribution and current condition (peat thickness to mineral subsoil in centimetres) of agricultural sites in Brandenburg. The data were based on 7,725 area-representative and randomized surveys from 2013. All resulting subplots were matched with the databases of the peat archive of the Humboldt University of Berlin (HU), the Soil Estimate (BS), the Forest Site Mapping (FSK), the Prussian Geological-Agronomic Maps (GK) and the Biotope Types and Land-Use Mapping (BTLNK). On this basis, the peat thickness for a 10 m grid in 2021 was determined without resembling.[17]

Data from the Climate Data Centre based on surveys by the German Weather Service were used to assess the drought-related yield risk. The data included the de Martonne drought index based on precipitation data from 1995 to 2022 in a 1 km x 1 km grid.[18] The determination of wind and water erosion risk was based on maps of the Federal Institute for Geosciences and Natural Resources (BGR) (Step 3).

Data on the soil quality index are publicly available through the official real estate cadastre information system (ALKIS). The polygons of the dataset are based on a 50x50m raster and consider local climatic as well as soil conditions.[19]

For the bio-economic analysis, yield data were based on the plant growth model HERMES (Kersebaum 2011) combined with micro-economic data. HERMES simulates yields of different crop rotations for a time span of 30 years (2040-2070) considering 276 detailed soil types and regional climate conditions and compares two climate models and two climate scenarios (Hadley Institute and Max Planck Institute, RCP 4.5 and 8.5). The simulated data includes not only yields, but also detailed management information, as well as fertilizer rates applied. For this study, two typical crop rotations for specialized arable farms (e.g., winter wheat, barley, canola and rye) and for livestock farms with forage production (e.g., winter rye, silage corn, fodder grass) were considered, in each case with and without a catch crop (Phacelia) and with different starting crops per rotation to create sequences in which all crops face the same weather conditions in the yearly calculations (Kersebaum/Wallor/Lorenz et al. 2019). The economic data are mainly from the Brandenburg data collection of the Brandenburg Ministry for the Environment and Climate Protection (Hanff/Lau 2021). This data collection has the advantage that it specifically determines prices and cost factors in the regional context of Brandenburg. For cost factors not simulated by the HERMES model, values for soil-type-specific practices were used as proxies based on the Brandenburg data collection. Missing data were partly obtained from other sources (KTBL 2022).

HERMES used soil profiles from the Soil Survey Map of the State of Brandenburg (1:300,000). The map (BUEK300)[20] was published by the Brandenburg State Office for Mining, Geology and Raw Materials (LBGR) in cooperation with the Brandenburg State Survey and Geobasis Information. It serves as an overview of essential soil types and has a higher degree of differentiation than other state overviews.[21] To combine the detailed soil data from the BUEK300 and the current land use on a field block level from the Digital Field Block Cadastre (DFBK), the two maps were merged for the bio-economic analysis.

The programming language R was used for all estimations in Steps 1 to 5, including the bio-economic analysis and the pre-processing of the data. For visualization, the GIS software package QGIS was used to generate all the maps included in the results section of this paper.

3 Results

3.1 Peat soils

Figure 3 shows the spatial distribution of peat soils that are not fully mineralized (peat thickness > 0) in Brandenburg. Of the 124,062 ha, 13,310 ha are used as arable land, 110,378 ha as grassland and 208 ha for permanent crops. If peatlands with a peat thickness of 0 were also included, the peatland area would increase by approximately 53 % to 189,203 ha.

The white area in the centre represents the state of Berlin. The black lines delineate the 14 distinct natural areas according to Scholz (2015).

3.2 Potential priority areas

Based on the type of land use, approximately 24 % of the

[17] https://mluk.brandenburg.de/mluk/de/umwelt/boden/vorsorgender-bodenschutz/moorbodenkarte/ (07.06.2024).

[18] https://opendata.dwd.de/climate_environment/CDC/grids_germany/annual/drought_index/ (09.06.2024).

[19] https://maps.bonares.de/mapapps/resources/apps/bonares/index.html?lang=en&mid=a45c7a1f-3dc5-478f-9d25-50dacd607d02 (09.06.2024).

[20] https://geoportal.brandenburg.de/detailansichtdienst/render?url=https://geoportal.brandenburg.de/gs-json/xml?fileid=f916fd97-f1e4-4516-a95c-7e9af9f98521 (07.06.2024).

[21] https://geoportal.brandenburg.de/detailansichtdienst/render?view=gdibb&url=https://geoportal.brandenburg.de/gs-json/xml?fileid=9e95f21f-4ecf-4682-9a44-e5f7609f6fa0 (07.06.2024).

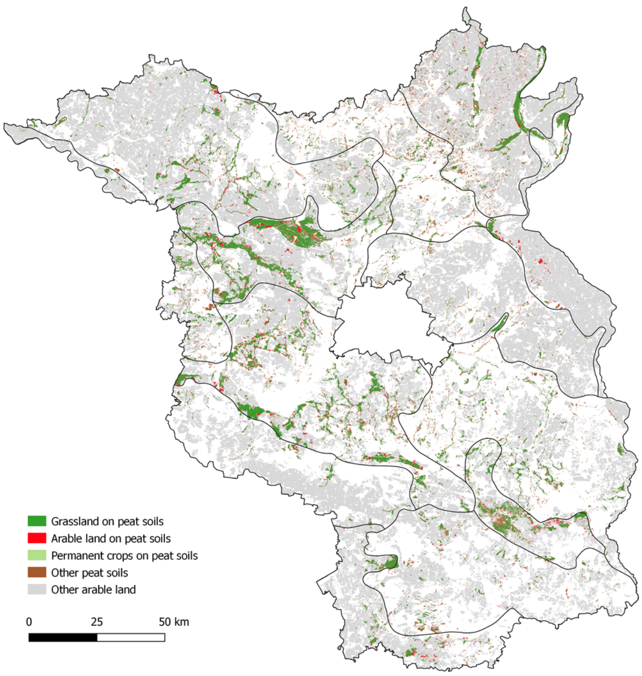

Figure 3 Peat soils with a peat thickness greater than 0 cm, categorized by current land use in Brandenburg

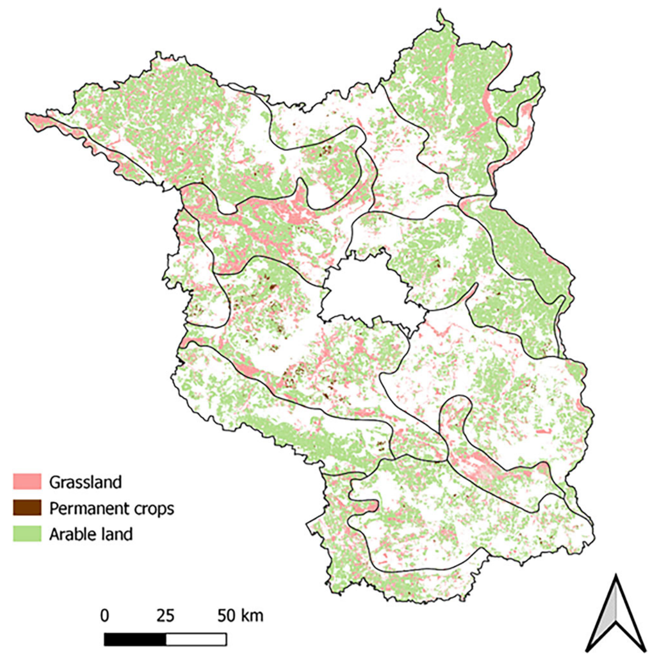

Figure 4 Agricultural area categorized by current land use in Brandenburg

agricultural land can be classified as potential priority areas, including 12,007 ha of permanent crops (1 %) and 312,650 ha of grassland (23 %) (see Figure 4).

The white area in the centre represents the state of Berlin. The black lines delineate the 14 distinct natural areas according to Scholz (2015)

Figure 5 shows the spatial distribution of the static climate robustness indicators, drought, water and wind erosion risk, as well as the intersecting areas indicating high climate robustness. Increased wind erosion risk occurs mainly on sandy soils with low soil organic matter content, which are widespread in Brandenburg, and in areas with high wind velocity and frequent storm events. Water erosion and drought risk depend mainly on local precipitation and the slope of the land.

Based on this static approach, 39 % of the agricultural land is identified as climate robust. Adding the areas classified based on the current land use, this results in 847,356 ha (approximately 63 % of agricultural land) which are candidate areas for potential priority area designation.

Specifically, low drought risk is defined as 26 mm/°C to 20 mm/°C, "none" to "medium sensitivity" is summarized as low wind erosion risk, while low water erosion risk denotes an annual erosion rate of less than 10 tons per hectare. Climate-robust arable lands are identified through the intersection of these criteria. The black lines delineate the 14 distinct natural areas according to Scholz (2015).

3.3 Potential reserved areas for regional food supply

3.3.1 High-yield areas based on soil-quality index

The exclusion of the least productive areas with a soil quality index of ≤ 23 results in a total of 201,359 ha across Brandenburg. To fulfil the land requirements for regional food supply (Step 3), 85 % of the most productive soils from the remaining areas were classified as potential reserved areas (657,297 ha). The resulting proportion of potential reserved areas ranges from 46 % to 79 % in the 14 natural areas. The potential reserved areas show a 52 % overlap with the potential priority areas that were already identified. When these previously determined potential priority areas are excluded, there is still an additional area of 315,123 ha of potential reserved areas (see Figure 6).

The black lines delineate the 14 distinct natural areas according to Scholz (2015)

3.3.2 Future robustness (bio-economic analysis)

The left map in Figure 7 shows the number of climate projections in which a spatial unit achieved robust gross margins. As the number increases, so too does the climate robustness of a unit. The map on the right shows spatial units with robust gross margins in all four projections. In total, 538,294 ha (40 %) were identified as being economically climate robust with this method. The identified areas show a 53 % overlap with the potential priority areas pre-

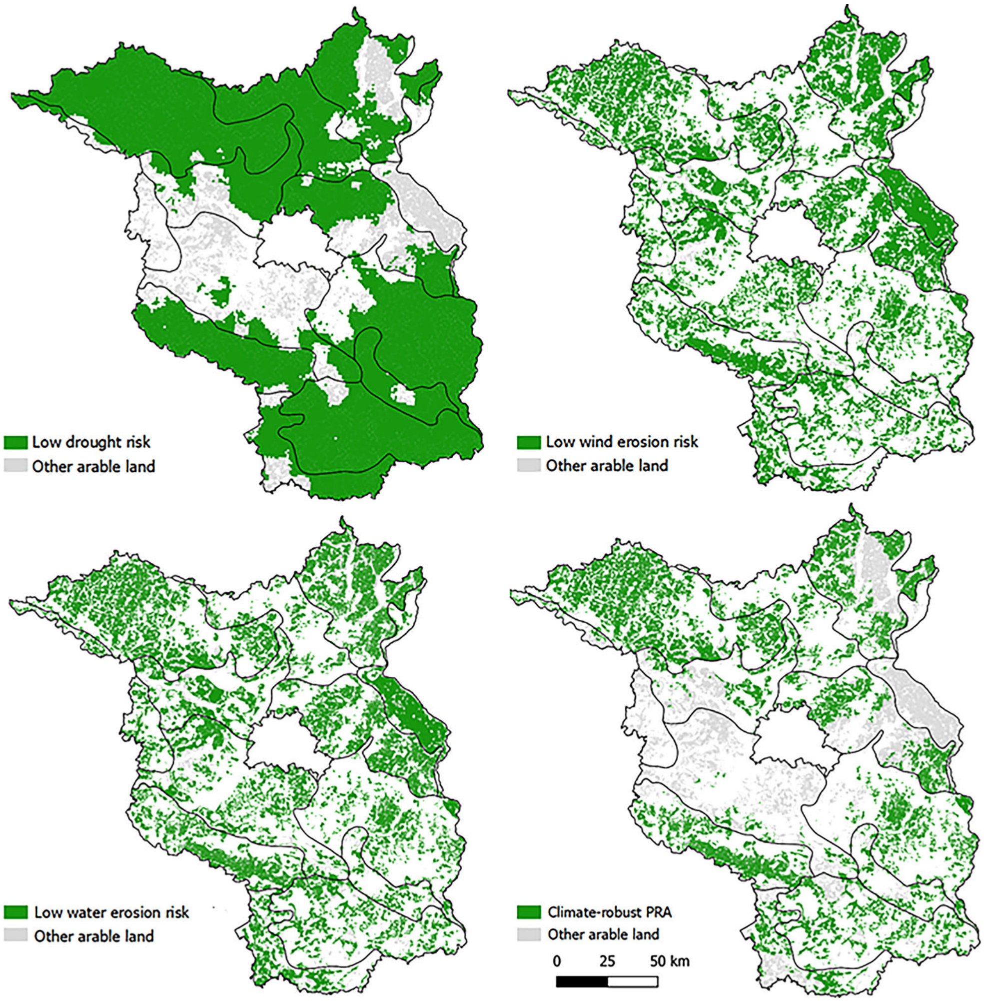

Figure 5 Areas characterized by low risk of drought, wind and water erosion

viously classified. Excluding these areas yields an area of 251,877 ha of climate-robust potential reserved areas (19 % of current agricultural land in Brandenburg).

Areas designated as potential reserved areas due to economic robustness across all four climate scenarios (2040-2070, Hadley Institute and Max Planck Institute, RCP 4.5 and 8.5) based on 30 years of simulated crop rotations. The black lines delineate the 14 distinct natural areas according to Scholz (2015)

3.3.3 Spatial distribution

Taking into account only agricultural areas that have not been classified as potential priority areas in Steps 2 and 3 (Figure 8, green and orange), the soil-quality index (Figure 8, blue and purple) leads to a higher share of additional potential reserved areas by five percentage points than the bio-economic analysis (Figure 8, red and purple).

Both the static and dynamic options delivered largely similar results, i.e. a high equivalence in terms of the land selected for potential reserved areas. The intersection of both options covers 14 % of the agricultural area. Additionally, 10 % of the agricultural area is currently high yielding based on the static assessment but does not appear to be robust under future climate conditions (Figure 8, blue). At the same time, 5 % of all the agricultural area is classified as climate robust but is currently not among the most productive (Figure 8, red). These climate-robust areas result from a relative assessment and generate the highest gross margin under future climate conditions. Whether future gross margins lie below or, in exceptional cases, above the current productivity level depends on the scenario and region. In total, the static approach leads to 15 % of agricultural land being classified as incorrectly assessed, taking into account future climate conditions. These areas are either not among the highest yielding under future conditions or will be among the highest yielding in the future but have not been classified as such.

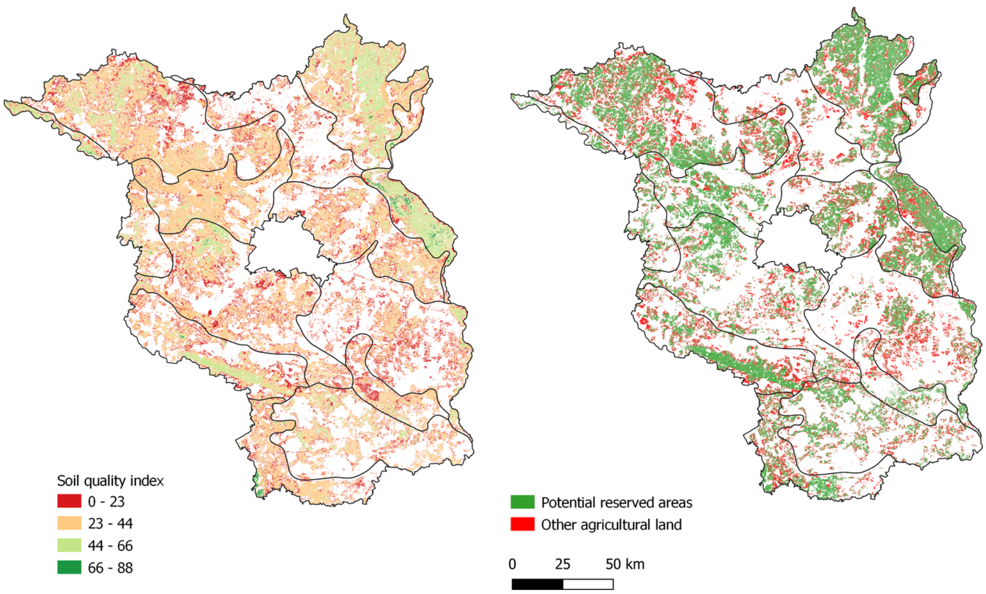

Figure 6 Distribution of the soil-quality index in Brandenburg (left); potential agricultural reserved areas (PRA) as determined using the soil-quality index (right)

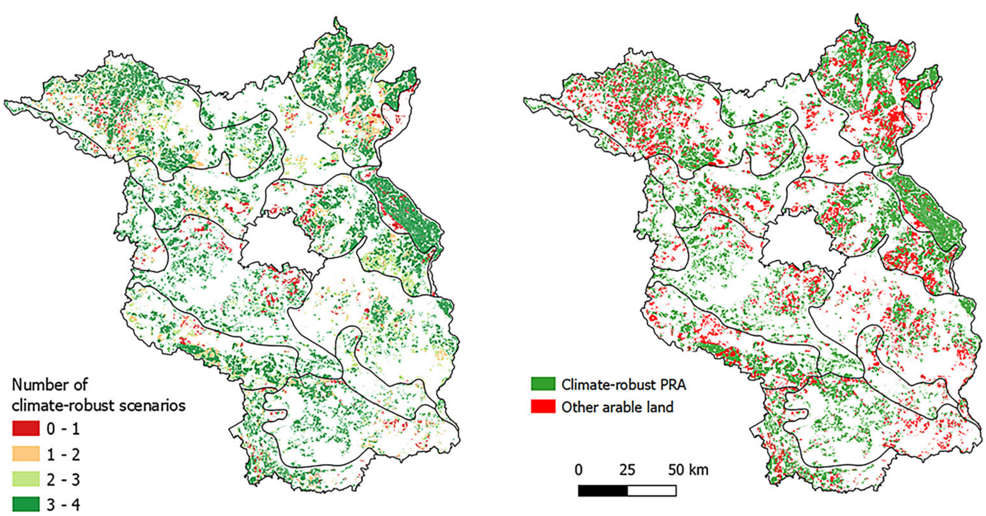

Figure 7 Number of climate scenarios classifying the area as climate resilient according to the bio-economic analysis (left)

Combining the previously determined potential priority areas with the intersection of the static and dynamic approach leads to a classification of 77 % of agricultural land (Figure 8, green, orange and purple) (see also Table 1). There is a shortfall of 8 % from the calculated target value of 85 %. The target value is primarily intended to provide a sense of magnitude. To achieve or even exceed the target, it is possible to use only one of the options (static or dynamic) for determining the potential priority area instead of the area equivalence.

The intersection of potential priority areas and potential reserved areas is depicted as potential priority areas on the map. Peatlands are exclusively comprised of peat soils with a peat thickness exceeding 0 cm. The black lines outline the 14 distinct natural areas according to Scholz (2015)

3.3.4 Stakeholder feedback

At both stakeholder events, our method received predominantly positive feedback. Stakeholders from politics and practice expressed their appreciation for the scientific foundations of the approach. To ensure broad stakeholder ac-

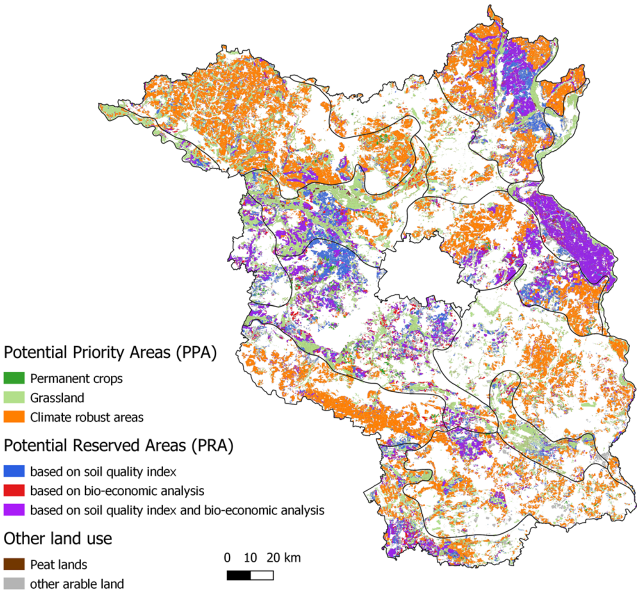

Figure 8 Spatial distribution of Potential Priority Areas (PPA) and Potential Reserved Areas (PRA)

Table 1 Total area and area share of potential priority areas (PPA) and potential reserved areas (PRA). For the depiction, the intersection of potential priority areas and potential reserved areas is counted as potential priority areas. Peatlands are exclusively comprised of peat soils with a peat thickness greater 0 cm

	Area [ha]	Percentage [%]
Brandenburg total area	2,964,086	
Agricultural area	**1,338,193**	**100**
Peat soils	124,062	9
Peat soils on arable land	13,310	1
Potential Priority Area (PPA)		
Grassland	312,650	23
Permanent crops	12,007	1
Climate-robust arable land	522,699	39
PPA Total	847,356	63
Potential Reserved Area (PRA)		
Based on soil-quality index	315,123	24
Based on bio-economic simulation	251,877	19
Combination of soil-quality index and bio-economic simulation	185,733	14
Total (PPA and combined PRA)	**1,033,089**	**77**

ceptance, it was seen as essential to use a comprehensive approach that encompasses many relevant aspects. Appreciation was directed towards the integration of the foodshed model results and the way in which peatlands were excluded based on distinguishing between mineral and peat soils, as this allowed the concise consideration of target values, a factor that is often neglected in spatial planning. The stakeholders showed a strong preference for the more flexible, less strict instrument of reserved areas, which, in justified instances, still allows for land conversion, in contrast to the more restrictive priority areas.

A significant portion of the critical feedback revolved around the possible practical implementation of the method. While participants acknowledged the increasing importance of climate-robust areas, concerns were raised about a potentially greater bureaucratic burden due to additional and more complex criteria. Planning is perceived to be slow-paced, and static soil-quality parameters might enable faster implementation. Indeed, given the substantial area overlap with the bio-economic analysis, the additional effort might not justify the additional benefit. Overall, using a combination of static and dynamic options to designate potential reserved areas received the strongest support.

4 Discussion

4.1 Interpretation of the results

In the final map depicting all potential priority areas and potential reserved areas (Figure 8), only peat soils that have not yet undergone complete mineralization (peat thickness > 0cm) are excluded prior to the designation. However, in the national peatland protection strategy (BMUV 2022), all peatland soils should be considered irrespective of their peatland thickness. Stakeholder consultations showed that a clear definition of peatland soils enables broader acceptance of the exclusion of peat soils among agricultural representatives. This could lead to faster implementation, while at the same time consideration of all peatlands including fully mineralized peat soils would increase the potential for climate change mitigation.

While permanent crops, grassland and climate-robust areas based on drought and erosion risk comprise about 40 % of the agricultural area, these criteria do not take yield levels or crop reliability into account.

Two alternatives were evaluated for determining supplemental potential reserved areas for regional food supply. The identification of high-yield soils using a soil-quality index reveals an overlap of approximately 50 % with areas designated through low drought and erosion risk assessment. This intersection suggests that a considerable portion of climate-robust land is also characterized by high productivity, although some high-yield land remains unaccounted for. In such cases, the soil-quality index can serve as a valuable supplementary tool.

The potential reserved areas identified with the bio-economic simulation overlap by 70 % with the potential reserved areas determined using the soil-quality index and by 50 % with the potential priority areas classified with the static analysis (drought and erosion risk). These overlaps indicate that to a certain extent the soil quality index can be a good proxy for future agricultural productivity. Approaches in similar studies using static indicators such as soil quality parameters (Regionaler Planungsverband Leipzig-Westsachsen 2020; Regionale Planungsgemeinschaft Havelland-Fläming 2021) or drought risk based on historical data (Regionale Planungsgemeinschaft Havelland-Fläming 2021) might still be relevant under future climatic conditions.

However, for future climate conditions, 15 % of agricultural land is not classified correctly through the soil-quality index. 10 % of these areas are either no longer among the highest yielding under future conditions and might be used more effectively for other land-use purposes, reducing land competition. The other third is included in the highest-yielding areas under future conditions but is missed by the classification. This neglects areas that could make an important contribution to the local food supply.

There are further spatially relevant land-use factors that were not considered in our study, for example transport, industry and housing. If these uses were also integrated in the analysis, certain portions of the designated areas could be allocated to alternative uses, so that additional potential priority areas and potential reserved areas would become necessary in order to reach the set target value.

4.2 Methodological aspects

The methods employed possess both advantages and limitations. Precipitation elevates the risk of water erosion while simultaneously mitigating drought vulnerability. Furthermore, the identification of areas prone to drought in Step 3 fails to consider soil water storage capacity and capillary rise from groundwater, leading to an overclassification of areas as being at risk. However, these aspects are considered in Step 5 through the bio-economic analysis.

The wind erosion index used fails to consider windbreaks. Wind erosion risk is most pronounced in areas with sparse land cover, the actual risk might therefore be lower. In summary, the assessment of climate-robust potential priority areas is comparatively strict, resulting in a relatively limited land allocation. As the final land designation falls short of the 85 % target, one potential approach could involve revising the thresholds accordingly.

The bio-economic analysis considers four scenarios: two climate scenarios calculated by two climate research institutes (Max Planck and Hadley Institutes). The climate models used forecast climatic changes, while extreme events are only simulated to a limited extent (Rötter/Appiah/Fichtler et al. 2018). Extreme weather events become more likely as climate change progresses (e.g. increase in storm squalls and hail), putting agricultural production at further risk (Trnka/Rötter/Ruiz-Ramos et al. 2014).

The crop growth model HERMES, which is the basis of the bio-economic analysis, considers adjusted management for each climate scenario, i.e. sowing and harvesting dates are automatically adjusted depending on meteorological and soil conditions. Adjustment of crop rotations can be simulated but has not been considered in this case. The calculated profitability takes into account climate-related production risks to a large extent. Market risks are neglected by using fixed prices. The use of different price scenarios may better reflect financial risks.

In the process of determining agricultural potential priority areas and potential reserved areas, social impacts beyond farm income are important aspects of climate resilience. Such aspects were, however, not included as their consideration may delay policy implementation.

4.3 Social relevance and outlook

In light of ongoing climate change, the preservation of climate-robust areas for regional food supply is increasingly crucial, while other sustainability topics, such as the conservation of peatlands for their climate sequestration potential, also have to be considered. Our analysis illustrates how potentially conflicting topics can be considered by spatial planning in a balanced approach with firm scientific foundations, fostering broad stakeholder acceptance.

The integration of various aspects enables a comprehensive assessment of climate-robust agricultural areas. The incorporation of both scientific criteria and practical stakeholder feedback makes the findings particularly interesting for policymakers and regional planners.

The method can be applied to other regions, provided that relevant data are available. For example, by implementing the modular crop system modelling framework SIMPLACE (Scientific Impact assessment and Modelling Platform for Advanced Crop and Ecosystem management), the method can be expanded to include other states or enable a comprehensive assessment across Germany (Kuhn/Enders/Gaiser et al. 2020; Enders/Vianna/Gaiser et al. 2023).

The framework for the planning and designation of climate-robust potential priority areas and potential reserved areas contributes to climate change adaptation. It accounts for both current and future yield potential and received wide support from both political and practical stakeholders.

5 Conclusion

This study presents a method that complements established static approaches for the classification of potential agricultural reserved and priority areas with a dynamic approach taking into account future yields under different climate scenarios.

The areas resulting from the dynamic bio-economic analysis show high area equivalence with the static results, suggesting that these widely accepted methods can serve as suitable proxies, especially when data is limited. However, even the combination of various static indicators failed to classify all climate-robust areas as potential agricultural reserved or priority areas. Using natural areas (macrochores) helped to avoid a concentration of potential priority and reserved areas in a few highly productive regions. Simultaneously, the use of static indicators such as a soil-quality index identified priority areas which will no longer be the highest yielding under future weather conditions and might therefore be used more effectively for other land uses. Additionally, stakeholder consultations showed that incorporating the dynamic approach and a target value using the results of a foodshed model fostered broad acceptance.

As land competition and climate change intensify, ensuring a reliable local food supply becomes increasingly crucial. Therefore, it is important to designate not just those areas that are currently productive but also those that can generate robust yields under future climate conditions to support local food supply and free less-yielding areas for other land uses. Our method can make a valuable contribution to climate adaptation in regional planning by supporting the process of designating agricultural priority and reserved areas.

Competing Interests The authors declare no competing interests.

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