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Agricultural land use changes – a scenario-based sustainability impact assessment for Brandenburg, Germany

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ABSTRACT

Decisions for agricultural management are taken at farm scale. However, such decisions may well impact upon regional sustainability. Two of the likely agricultural management responses to future challenges are extended use of irrigation and increased production of energy crops. The drivers for these are high commodity prices and subsidy policies for renewable energy. However, the impacts of these responses upon regional sustainability are unknown. Thus, we conducted integrated impact assessments for agricultural intensification scenarios in the federal state of Brandenburg, Germany, for 2025. One Irrigation scenario and one Energy scenario were contrasted with the Business As Usual (BAU) scenario. We applied nine indicators to analyze the economic, social and environmental effects at the regional, in this case district scale, which is the smallest administrative unit in Brandenburg. Assessment results were discussed in a stakeholder workshop involving 16 experts from the state government.

The simulated area shares of silage maize for fodder and energy were 29%, 37% and 49% for the BAU, Irrigation, and Energy scenarios, respectively. The Energy scenario increased bio-electricity production to 41% of the demand of Brandenburg, and it resulted in CO_2 savings of up to 3.5 million tons. However, it resulted in loss of biodiversity, loss of landscape scenery, increased soil erosion risk, and increased area demand for water protection requirements. The Irrigation scenario led to yield increases of 7% (rapeseed), 18% (wheat, sugar beet), and 40% (maize) compared to the BAU scenario. It also reduced the year-to-year yield variability. Water demand for irrigation was found to be in conflict with other water uses for two of the 14 districts. Spatial differentiation of scenario impacts showed that districts with medium to low yield potentials were more affected by negative impacts than districts with high yield potentials.

In this first comprehensive sustainability impact assessment of agricultural intensification scenarios at regional level, we showed that a considerable potential for agricultural intensification exists. The intensification is accompanied by adverse environmental and socio-economic impacts. The novelty lies in the multiscale integration of comprehensive, agricultural management simulations with regional level impact assessment, which was achieved with the adequate use of indicators. It provided relevant evidence for policy decision making. Stakeholders appreciated the integrative approach of the assessment, which substantiated ongoing discussions among the government bodies. The assessment approach and the Brandenburg case study may stay exemplary for other regions in the world where similar economic and policy driving forces are likely to lead to agricultural intensification.

1. Introduction

Globally, agriculture is facing an increasing demand for food, bio-based energy and fiber products. Nonetheless, numerous

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studies predict that agricultural techniques will adapt to the increasing demand (Makowski et al., 2013). However, adaptation poses challenges for the integration of environmental and socio-cultural services into agricultural production.

Farmers' adaptation to the increasing demand may include changes in the choice of crops, crop rotations, utilization of crops, and intensification of production. Trends include technical solutions to remove yield limiting factors, such as water availability for crops, and increasing use of agricultural biomass as a source of renewable energy. The latter is often supported by government legislation. For example, in Germany, the introduction of the Renewable Energy Law EEG in 2000 resulted in threefold increase of the area of maize (*Zea mays*) and of rapeseed (*Brassica napus*) for bioenergy, reaching 17.5% of the German cropland area in 2012 (FNR, 2012a). Also, the use of irrigation to increase and stabilize crop yields is becoming more attractive, especially in areas with limited rainfall and with soils with limited water holding capacity. Additional reasons for these changes are related to an increasing water demand of new, more productive cultivars, and the prospect of more irregular precipitation patterns due to climatic change. For example, at the current market prices for agricultural goods, irrigation in the German federal state of Brandenburg is already on the verge of becoming economically viable (Münch et al., 2014). Also, a connection between the production of bioenergy and irrigation exists: as farmers become fuel suppliers for power plants, it becomes more important to achieve stable yields even in dry years.

Agriculture is multifunctional. This means that in addition to (private) economic production, it contributes to public goods such as the character of rural landscapes and its ecosystem services (Wiggering et al., 2006; Van Zanten et al., 2013). A simple focus of agricultural management aimed solely at maximizing economic returns can lead to depletion of groundwater resources, erosion, loss of water quality, biodiversity loss and a reduction of socio-cultural services. Although these services become evident at landscape level, which has a spatial scale larger than a farm, it is the decision-making at farm level that affects these services. Sustainable development therefore requires consideration of the balance between the economic production functions of agriculture and environmental and social services. Policies are implemented to incentivize farmers to respect this balance by remunerating for the provision of public goods.

It is important, when making policy decisions that support sustainable development, to acknowledge present and future development trends and their potential economic, social and ecological impacts. Here, we use ex-ante impact assessment (Helming et al., 2011). This integrates state-of-the-art knowledge from various disciplines in order to highlight those risks and opportunities which are inherent in expected trends. We use scenarios of agricultural management to draft different development options. These scenarios provide the opportunity to explore possible future developments through a comparative analysis of alternative driving forces and trends. In spanning a range of options they help to explore rather than predict possible developments (Milestad et al., 2014). We use impact indicators to assess economic, social and environmental effects of the agricultural management scenarios.

The objectives of the study described in this paper were as follows: (i) to develop an indicator based impact assessment method that combines expertise on agricultural management, landscape, hydrology, soil erosion, biodiversity, stakeholder interaction, sustainability to create and analyze agricultural intensification scenarios and (ii) to conduct an integrated ex-ante assessment of regional sustainability impacts induced by farm level scenarios of bioenergy production and crop irrigation. Results had to assist policy stakeholders in identifying sustainability issues that require policy steering.

The scenarios were designed to integrate currently trending assumptions of driving forces and describe their effects on crop choice and crop management at the farm level. Decisions at the farm level were translated into crop distribution patterns at the hectare scale for analysis of scenario impacts. Results were aggregated to the district (NUTS3) scale to derive policy relevance of the assessment. Also, this aggregation allowed the representation of the landscape level of scenario impacts. Scenarios were developed for the year 2025: a time frame that is sufficiently long to allow for major changes in agricultural management, while still being short enough to allow for realistic predictions of climate effects and yield trends.

We chose the state of Brandenburg, Germany, as a case study area because several characteristics may make this area an example for the application of integrated assessments of agricultural development scenarios: large, specialized farms; low soil fertility; high technological level; yield limitations by water; subsidies for agricultural energy production. We anticipate that the trend of increased use of cropland for the production of renewable energy will continue and that irrigation will become more important in the future to increase and stabilize yields. The extent and speed of these changes in agricultural management are largely unknown, as are the sustainability implications of these changes. A few studies have dealt with specific aspects of bioenergy production in Germany (e.g., Dressler et al., 2012; Hennig and Gawor, 2012) and with specific agricultural adaptation scenarios at field sites (Nendel et al., 2014). However, to our knowledge, no integrated impact assessment studies exist that analyze the effects of agricultural intensification on environmental, social and economic indicators at regional level. Such a case study will help to generate spatially explicit systems knowledge of human–environment interactions in land change processes (Magliocca et al., 2014).

2. Materials and methods

2.1. Case study Brandenburg

Brandenburg is the fifth largest German state, and it has a land surface area of 29,640 km^2, of which 45% is agricultural land, most of which (75%) is arable land. Brandenburg surrounds the German capital Berlin and comprises 14 districts. The state's mineral soils are developed on glaciofluvial, periglacial and glacial deposits, aeolian deposits and river sand. Almost two-thirds of the state's territory, mainly with sandy and sandy loamy soil, has a water holding capacity lower than 140 mm (Table 1). Peat soils are excluded from crop cultivation by decree.

Agricultural practice is dominated by large farm enterprises with an average size of 238 ha, which is four times the German average. Mechanization is high, and the labor force is only 1.7 persons per 100 ha on average. Large-scale operations, hired labor and a high mechanization rate result in highly competitive

Table 1
Classification of the water holding capacity (mm) of soils in Brandenburg (area: 29,485 km^2).
Source: Schindler et al. (2004).

Cumulative area (%)	Range (mm)	Description[2]
21	≤80	Very low
34	>80–110	Low
62	>110–140	Moderate
77	>140–170	High
82	>170–200	Very high
100	>200	Extreme high

farm enterprises that are oriented towards profit maximization. A study on the regional impacts for Brandenburg of changes to the European Common Agricultural Policy (CAP) indicated that the dependency of farm enterprises on world market prices is high compared to the European average (Sieber et al., 2013).

The average rainfall in Brandenburg is 554 mm year^{-1} (1981–2010), which is low compared to the German average of 800 mm year^{-1} (German Weather Service, 2013). This limits the yield for rain-fed agriculture. Irrigation is currently used on only 2% of the cropland area (Statistical Office Brandenburg, 2012). Due to increasing world market prices for agricultural commodities and concerns about increasing water stress related to climate change, we expect that irrigation will become more important in the near future. However, there are concerns over dwindling groundwater resources related to this development. We analyzed the scenario effects for the 14 districts of Brandenburg. Table 2 lists the names, cropland areas and name codes of districts.

2.2. Analytical framework

We adapted and simplified the DPSIR framework of the European Environment Agency (Gabrielsen and Bosch, 2003) to structure the ex-ante impact assessment of agricultural intensification scenarios. Three steps were involved (Fig. 1): Step 1 was the scenario definition, including the driver-pressure part of DPSIR. The driving forces in German agriculture were characterized as Drivers. Pressures represented the changes of agricultural management, in this case an increased area of silage maize to be used in biogas power plants and an increased area of irrigated cropland. Step 2 comprised the analysis of the scenario effects on several economic, social and ecological states through the use of indicators. Step 3 involved presenting the assessment results to members of the federal state ministries and local administration. This was done to inform policy decision-making and to evaluate the relevance of anticipated changes with regards to impacts on achieving policy strategies. The responsepart of DPSIR was not covered by the analysis.

Sources of uncertainties of such an assessment approach are found in the applied models (structural uncertainty, parameter uncertainty), in the data used to drive the models and in the basic assumptions under which the models are used. In our case, we did not attempt to quantify the uncertainty that came with the models or data as this is subject to investigation in the model developer community (Asseng et al., 2013). The use of scenarios (Step 1), however, reduces the certainty requirement for model results, since scenarios are usually compared against each other and not evaluated in absolute terms. The scenario building process involves assuming conditions that are uncertain *per se* and this uncertainty can hardly be quantified. However, in the process of result communication (Step 3) uncertainty information plays a major role and in our case, spatial variability of model results was used to increase the addressees' awareness of the uncertainty of projections and the likelihood of scenarios becoming true.

2.3. Scenarios

Scenarios of future cropping practices were chosen based on their relevance to agricultural land use and sustainable development. They were based on the driving forces: high world market prices for agricultural goods, climate change projections, and state legislation to promote energy production from agricultural sources. Three scenarios were constructed (Table 3): a Business As Usual (BAU) scenario extrapolating current trends into the year 2025, an Energy scenario in which government subsidies for biogas production lead to further increase in the cultivation area of silage maize, and an Irrigation scenario in which all areas of silage maize, winter rapeseed, winter wheat and sugar beet were irrigated. In all scenarios, we assumed that silage maize for energy purposes was only used in biogas power plants. This is the typical energetic use of silage maize in Germany. The scenarios were chosen to continue current trends (irrigation, subsidies for 1st generation biofuel) and address agricultural production decisions. The first is because the current policy frame is likely to further support the trend. It also serves as role model for other countries in search for adaption measures to energy scarcities. The second is because our intention was to assess spatially explicit sustainability impacts of agricultural land use changes. Changes happening further down in the value chain such as the use of residues for bioenergy production (2nd generation biofuel) was not the focus of the study.

2.3.1. Translation of scenario assumptions (Drivers) into crop shares and crop distributions (Pressures)

To translate scenario assumptions into agricultural management and cropping decisions, we used a simplified linear programming optimization model for "region farms" that consists of all farm resources of one district, taking into account established farm structures, site characteristics, markets and agricultural policy. We assumed that farmers make their cropping choices mainly by optimizing net farm income. This is an assumption that reflects long term developments and that is relevant particularly in Brandenburg since its exceptionally large agricultural enterprises with hired labor enforce economic decision making. Economic professionality of the enterprises can also be seen in the fact that, according to the agricultural census 2010, 46% of farm managers hold a university degree (Federal Statistical Office Germany, 2011).

The approach used existing crop production data for each of five soil categories representing different levels of soil fertility (LELF, 2010), and it incorporated additional expert assessments of inputs and outputs for important cropping practices, including irrigation, yield development as influenced by genetic progress, climate change and management improvements. Crops were compared for their net margin based on default machinery cost figures (KTBL, 2012). The linear programming farm model was constructed for each district. Assumptions and constraints were (i) constant livestock fodder requirements, (ii) complete use of manure in the cropping systems, (iii) constant level of contract-based cropping systems, and (iv) adherence to crop rotation restrictions. On this basis, the model maximized the total net margin of the district by

Table 2
Districts of Brandenburg and their cropland areas.

Code	District	Cropland (1000 ha)	Code	District	Cropland (1000 ha)
BAR	Barnim	41.9	OPR	Ostprignitz-Ruppin	98.7
EE	Elbe-Elster	82.6	OSL	Oberspreewald-Lausitz	30.0
HVL	Havelland	67.5	PM	Potsdam-Mittelmark	84.3
LDS	Dahme-Spreewald	67.3	PR	Prignitz	123.7
LOS	Oder-Spree	66.7	SPN	Spree-Neisse	45.7
MOL	Märkisch-Oderland	120.2	TF	Teltow-Fläming	77.1
OHV	Oberhavel	56.7	UM	Uckermark	156.9

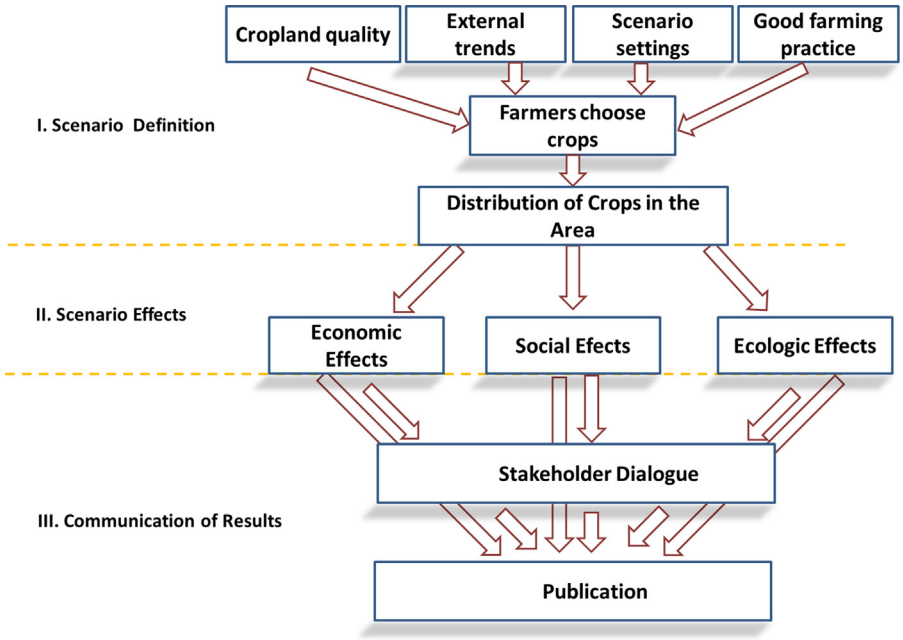

Fig. 1. The analytical framework of the study, comprising three steps: (1) scenario definition by translating external driving forces into decisions of agricultural management; (2) analysis of the effects of the scenario on economic, social and environmental indicators at the district scale; (3) communication of assessment results to decision-makers.

allocating part of the area of each soil category to the best-performing cropping practices, taking the restrictions into account. The result was a specific distribution of crops for each district and for each of the five soil categories.

For the assessment of six of the impact indicators (see Table 4), it was necessary to disaggregate the simulated crop distribution from the district scale to the hectare scale. This was done by using a Monte Carlo approach to distribute crops on a high-resolution soil suitability map, taking into account the total area share of each crop as derived from the linear programming described above (Wenkel et al., 2013). The approach implements the idea to distribute a list of crops and its proportions of the agricultural area according to the suitability of the soil at a certain location for each crop. The result was a soil suitability-based probability map of crop distributions at a 1 ha scale for the area of Brandenburg.

2.4. Scenario effects

For the analysis of scenario effects, we focused on issues that were considered sensitive to agricultural management and relevant to policies in the state of Brandenburg. This means that indicators had to be chosen that indicate at landscape level the impact of field scale agricultural management. Additionally, a balance between economic, social, and environmental dimensions was sought. One indicator was selected for each impact issue based on scientific credibility, sensitivity to agricultural scenario changes, applicability to regional conditions, and determinability. An overview of the chosen indicators is given in Table 4. Calculation methods for each indicator are briefly described below. The final results for all indicators were aggregated at the district level.

Table 3
Parameters describing the three agricultural scenarios: BAU, Energy, and Irrigation for 2025. The scenarios include assumptions about changes in prices, yields and agricultural management constraints related to animal husbandry, technology, and crop rotations.

Parameters	Scenarios 2025		
	Business As Usual (BAU)	Energy	Irrigation
Prices/cost (relative to 2011)	Net margin from agricultural goods +10%	Same as BAU and net income from silage maize for biogas +20%	Same as BAU
Irrigation	No irrigation	Same as BAU	All areas of silage maize, winter wheat, winter rapeseed and sugar beet are irrigated for optimum productivity
Fallow land	Fallow land reduced from 4% of cropland area in 2011 to 2% in 2025		
Yield development (relative to annual yields in 2011) (ranges reflect different site qualities)	(Based on expert judgement):		
	Silage maize:	+1.2 – 1.8 t ha^{-1}	
	Winter barley:	+0 t ha^{-1}	
	Winter rapeseed:	+0.55–0.60 t ha^{-1}	
	Winter rye:	+0 – 0.15 t ha^{-1}	
	Winter wheat:	+0.45–0.60 t ha^{-1}	
	Sugar beet:	+7.50 t ha^{-1}	
Animal husbandry (relative to 2011)	Constant		
Technology (relative to 2011)	Constant		
Restriction incrop rotations	50% of winter rapeseed uses winter barley as the previous crop; sugar beet area constant due to existing contracts		

Table 4
Overview of indicators used to assess scenario impacts. Nine indicators were chosen, representing two economic, one social and six environmental themes relevant to the sustainable development of agricultural landscapes. Indicators were determined at the district and/or ha level.

Indicator	Unit	Sustainability dimension			Spatial reference		Model/Method used	Reference
		Econ.	Soc.	Environ.	District	ha		
Crop yields	t ha^{-1}	X				X	YIELDSTAT	Mirschel et al. (2014)
Irrigation water demand	mm ha^{-1}	X				X	ZUWABE	Mirschel et al. (2012)
Water constraints for irrigation	Irrigation water demand in % of groundwater recharge, classified: low/medium/high			X		X	Contextual data analysis	–
Electricity demand covered	%			X	X		Contextual data analysis	–
Landscape scenery	Nominal scale		X		X		Contextual data analysis	–
Greenhouse gas savings	t CO_2-equ. per district			X	X		Contextual data analysis	–
Biodiversity	Nominal scale			X		X	Habitat suitability model	Brandt and Glemnitz (2013)
Erosion risk	t per district			X		X	USLE adapted	Wishmeier and Smith (1978)
Area demand for water quality protection	km^2, % Cropland			X		X	Contextual data analysis	–

2.4.1. Indicator 1: crop yields

Crop yields were calculated by using the statistical hybrid model YIELDSTAT (YIELD estimation based on Statistics, Mirschel et al., 2014) and a model for the spatial distribution of crops in a region. Both models were controlled via the Spatial Analysis and Modeling Tool SAMT (Spatial Analysis and Modeling Tool, Wieland et al., 2006). Spatial crop distribution on a hectare scale was calculated by using statistical information about crop production at the state level, by performing calculations of crop-specific economic benefit, by developing a soil-based suitability map for crop growth and by using a set of algorithms that combines optimization routines and stochastic (Monte Carlo) elements. The scenario simulations were run under the following assumptions: no change in crop and soil management (conventional farming, soil tillage using a plough). Future climate was provided from the STAR2 climate data set for Brandenburg (2K scenario). Annual results were calculated for the time period 2020–2030 and averaged.

2.4.2. Indicator 2: irrigation water demand

Water is the most limiting factor for agricultural yields in Brandenburg. For this reason, irrigation is essential to stabilize and increase yields. Irrigation water demand (IWD) was calculated by using the model ZUWABE (Zusatzwasserbedarf (irrigation water demand), Mirschel et al., 2012), which is implemented in SAMT (Wieland et al., 2006). Soil types were grouped into four categories of different water storage capacities. Crop-specific irrigation water benchmarks for the soil categories were calculated by considering crop-specific irrigation periods, climatic water balance within the irrigation period, soil water storage capacity, soil water content at the start of the irrigation period, and rooting depth. Calculations considered the anticipated climatic water balance for the period 2020–2030 and a predicted decrease in crop transpiration caused by rising atmospheric CO_2 concentrations. Input data were the medium scale agricultural site mapping for arable land (Schmidt and Diemann, 1991), simulated crop distributions at the hectare scale and the STAR2 future climate data for Brandenburg (2K scenario).

The dynamic agro-ecosystem simulation model MONICA (model for nitrogen and carbon dynamics in agro-ecosystems, Nendel et al., 2011) was used to back up the simulations of the model YIELDSTAT and ZUWABE. MONICA has been tested against crop and soil monitoring data from Brandenburg. As a process-based model, it may be more sensitive to environmental changes than YIELDSTAT and ZUWABE. However, in a spatial application, statistical model approaches prove more robust against outliers. Therefore, MONICA results were used in an iterative process to compare and assure the results of the other two models.

2.4.3. Indicator 3: water constraints for irrigation

The water constraints for irrigation constitute spatially differentiated indicators for detecting those parts of the state where groundwater-borne irrigation could pose problems for other water users, including groundwater-dependent ecosystems (peatland). A critical water balance was considered in this study when IWD was above 25% of the supplied groundwater recharge. Water balance was calculated as the spatially differentiated long-term mean annual groundwater recharge over the period 1976–2005 (100%) minus IWD (see above). Calculations were performed at the spatial level of polygons of hydrogeological units based on classified properties of the upper groundwater-bearing layer (Merz et al., 2009). Polygon results were resampled and aggregated at the district level. Relative water demand was clustered into three categories: IWD $<$ 16% ground water recharge (low), 16% $\leq$ IWD $\leq$ 25% ground water recharge (medium), and IWD $>$ 25% groundwater recharge (high).

2.4.4. Indicator 4: share of electricity demand covered by the production of biogas

The production of biogas in Germany serves the purpose of increasing the share of renewable resources used in the production of electricity. The share of electricity demand covered was calculated by dividing the net electricity produced by the electricity demand projected for the state of Brandenburg in 2025.

The electricity produced was based on silage maize yields for energy generation. These were multiplied by typical values for the amount of methane produced per ton of silage maize and by the average conversion efficiency of biogas plants (FNR, 2012b). Net production of electricity was calculated by subtracting an average value of 7.9% of electricity demand for the biogas plant operations (FNR, 2010). Electricity demand for the year 2025 was based on the

targets of the energy policy of the federal state of Brandenburg, which aim for a reduction of 10% between 2007 and 2030.

2.4.5. Indicator 5: the scenic value of landscape

The scenic value of landscape is an important factor for the quality of life in rural areas. It determines, in part, the recreational value of agricultural landscapes. In this study, scenario impacts on landscape scenery were determined by applying the principle of Ecological Risk Analysis as established in the German Environmental Impact Assessment. This analysis makes it possible to compare landscapes capacities under different human land use scenarios. Changes in landscape scenery caused by scenario differences were determined by identifying sensitive areas and demand areas. Sensitive areas have high landscape values; demand areas are designated for recreational or touristic purposes. Disposition was determined as the share of sensitive and demand cropland areas divided by the total cropland area in a district.

The effect of scenarios upon the scenic value of landscape was estimated in a three-step approach. First, the aesthetic impressions of crops were determined by using eight criteria: colors, light and shadow, exposure; odor; body and structure, border situations; dynamics; and orientation. Second, the effects of the relative area shares of crops were assessed at a three-stage ordinal scale using these criteria. As a result, the ratio of grain and rapeseed areas to maize areas (GRM) proved to be a critical indicator integrating step one and two. Third, the disposition value was divided by the GRM to form an impact indicator representing ecological risk.

2.4.6. Indicator 6: greenhouse gas savings

Germany intends to substitute fossil fuels and reduce total greenhouse gas emissions by increasing the production of electricity from renewable sources. Greenhouse gas savings through the substitution of fossil fuels by biogas were calculated based on the yields of silage maize for energy generation. We assumed that all biogas plants are heat and power plants. The coefficients for methane generation per ton of biomass, the efficiency of conversion and the electricity demand for biogas plant operations were based on typical values (FNR 2010, 2012b). Greenhouse gas savings per kWh produced were calculated under the assumption that only fossil fuels would be substituted.

2.4.7. Indicator 7: biodiversity

The biodiversity strategy of Germany (National Strategy on Biological Diversity, 2007) uses bird species as core indicators of the biodiversity of agricultural landscapes. We used the same indicators to analyze the potential conflicts between scenarios and biodiversity strategies. The indicator aggregates the population trends of ten arable bird species, of which we considered seven that either (i) breed on arable land: *Skylark* (*Alauda arvensis*), *Corn bunting* (*Miliaria calandra*), *Lapwing* (*Vanellus vanellus*) and *Winchat* (*Saxicola rubetra*), or (ii) feed regularly on arable land: red-backed shrike (*Lanius collurio*), *Yellowhammer* (*Emberiza citrinella*) and *Woodlark* (*Lullula arborea*). We applied a habitat suitability model (Brandt and Glemnitz, 2013), which calculates the 'intrinsic habitat value' according to Anderson and Fergusson (2006) over the growing season based on the following data: vegetation structure of the crop species (vegetation height and density; real field data), habitat demands of the bird species, agricultural management (sequences of agricultural activities = disturbances).

2.4.8. Indicator 8: erosion risk

Some crops (e.g., maize, rapeseed) are more vulnerable to soil erosion by water than others (e.g., cereals), which is why the crop distribution within the scenarios may affect soil erosion risk. Erosion risk was calculated by using a German adaptation of the universal soil loss equation model (USLE – Wischmeier and Smith, 1978). Whilst it should not be used for precise estimates of soil loss, it is suitable for appraising erosion trends resulting from changes in agricultural management (Deumlich et al., 2005). The equation comprises six factors: rainfall and runoff (R-factor), soil erodibility (K-factor), slope length (L-factor), slope steepness (S-factor), cover and management (C-factor), and support practice (P-factor). Potential long-term average soil loss is calculated as the product of the individual factors. In this study, the scenarios affect only the C-factor because every combination of crop and management is associated with a specific C-factor. The results were calculated on the scale of field blocks[1] (as of May 2011) and aggregated at the NUTS3 level.

2.4.9. Indicator 9: area demand for water quality protection

An increase in maize cultivation area may enhance nutrient transport into nearby water bodies. Maize fields are considered to be hot spots of surface and groundwater pollution because of the large distance between plant rows and because maize is a preferred crop for manure application from livestock or biogas plants (Jaafar and Walling, 2010). An "end-of-pipe" method was applied to assess the water quality impairment of the scenarios, using area demand for water protection as an indicator. We calculated the area demand for riparian buffer zones against soluble and solid matter entries into the water bodies. Buffer zones of 20 m between maize fields and running waters of 1st and 2nd order (according to the German Water Law) and around standing waters are most effective with respect to both retention of solid matter transported by surface runoff and retention/transformation of dissolved substances transported by groundwater runoff (DWA, 2012). Area demand was calculated by overlaying maps of field blocks and crop distribution for the scenarios and by considering the distribution of running waters of 1st and 2nd order in the state of Brandenburg. Existing riparian buffer zones were not considered.

2.5. Involvement of stakeholders

Stakeholders from local government were engaged in the scenario study to (i) discuss scenario results with regards to their relevance, opportunities and threats, (ii) provide feedback on the scenario features, (iii) contribute to the identification of research needs, and (iv) identify future cooperation interests. Stakeholder engagement in research on regional land use can vary considerably from information sharing to interactive participation and joint decision-making (Knierim et al., 2010). In our case, the level of consultation was essential, which means that stakeholders had to be appropriately informed about and invited to discuss the results of the impact assessment study (Pretty, 1995). The selection of the stakeholders was guided by the aim to broadly represent public decision-makers, both from the investigated impact areas, and from organization generally involved in sustainable development. Among the 16 stakeholders participating in the workshop, there were 6 experts from the Ministry for Environment representing the divisions of water management, biodiversity and soil conservation, one experts from the Ministry of Agriculture and one from the Ministry of Economy. Four experts represented the two state agencies for environment and for agriculture. Four stakeholders represented non-government institutions, namely the farmers' association, the Brandenburg Sustainability Council, and a private, economic networking agency. In preparation for the stakeholder

[1] A field block is a contiguous area of arable land that is surrounded by topographic borders (e.g., forest, roads, cultivated ground, water courses, ditches). A field block can be managed by one or more farmers. In Germany, each field block is identified by a uniform 16-digit number (FLIK).

workshop, efforts were made to reduce the scenario results to seven key statements. A workshop of 2.5 h duration was designed, which included expert inputs, facilitated discussions and opinion polls. An interactive voting tool was used to determine how stakeholders perceived the degree of novelty and relevance of the results. After the meeting, minutes were disseminated. To facilitate uptake of the results, the findings of the study were compiled into a brochure for decision-makers (Gutzler and Helming, 2013).

3. Results and discussion

3.1. Scenario estimations of area shares of most important crops in 2025

The land use distributions for different scenarios are shown in Fig. 2. For the BAU scenario, silage maize for energy and fodder had the highest area share (29%), followed by rye (21%), wheat (13%) rapeseed (16%) and barley (8%). The Irrigation and Energy scenarios resulted in 6% and 20% increases of the maize cultivation area, respectively, compared to the BAU scenario. In both cases, the increase in maize area was a result of the increased profitability of this crop due to increased yield and yield stability in the Irrigation scenario, and due to the financial subsidies for the production of renewable energy assumed in the Energy scenario. The increase in the area share of maize was accompanied by reductions in all other crops, particularly rye and rapeseed. Rye is the least economically feasible crop, and rapeseed turned out not to be economically competitive in the Energy scenario. The share of barley was small in all three scenarios, and it was mainly cultivated for crop rotation purposes. Sugar beet was below 1% area share in all scenarios. The results imply a drastic increase in the maize share for both intensification scenarios compared to the BAU scenarios. However, even the maximum of 49% maize in the Energy scenario remained below the EU-CAP greening threshold of a maximum 70% share for one crop. This is due to the scenario settings, in which crop rotations (according to phytosanitary requirements and preceding crop effects) were a constraint for management decisions.

3.2. Scenario effects at the district level for Brandenburg in 2025

3.2.1. Crop yields

Within the period 2020–2030, simulated crop yields fluctuated due to year-to-year weather variation. In the BAU scenario, the standard deviation ranged from 10 to 15% for spring crops (silage maize, sugar beet) and from 5 to 10% for winter crops. Simulated crop yields for the three scenarios and for the 14 districts are presented in Table 5. The results of the Irrigation scenario showed that irrigation was able to support significantly higher yields, to increase yield stability, and to reduce cropping risk. The yield increases were highest for silage maize (34–48%) and lowest for winter rapeseed (3–9%). For winter wheat and sugar beet, simulations resulted in yield increases of 16% and 23%, respectively. Because of the increased yields and improved yield stability, irrigation could be an effective measure to adapt to climate change. This is because climate change impacts in this study area are predicted to shift rainfall from summer to winter periods thereby aggravating water stress during the vegetation period, and to increase the rainfall variability between years, which in turn increases yield variability. In addition, irrigation is important for farms growing silage maize for biogas production, because they have to comply with long-term contracts for annual biomass delivery.

No significant change in crop yield was detected between the BAU and Energy scenarios. The crop yield of silage maize was reduced by 0.75 t ha^{-1} on average in the Energy scenario compared to the BAU scenario. This may be because the larger cultivation area for maize in the Energy scenario also includes sites of lower productivity.

Patterns of simulated yield levels across the 14 districts of Brandenburg showed little variation between the scenarios. The highest simulated average crop yields were in the districts PR, UM, MOL, and EE. With the highest share of arable land, PR, UM and MOL are also the districts with the highest agricultural production (Table 2). In contrast, PM, LDS and LOS had the lowest average crop yields.

Modeling results revealed that considerable yield effects can be expected with the introduction of crop irrigation.

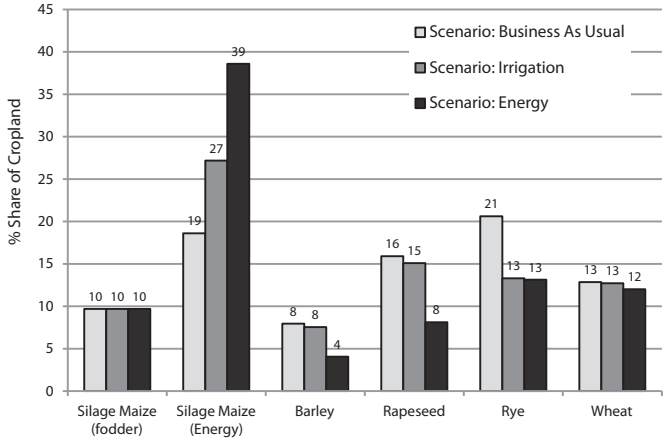

Fig. 2. Simulated area shares of main crops for the three scenarios for 2025 in Brandenburg. The main scenario differences occur in the case of silage maize for energy. Increased maize share resulted in reduced shares of rye, rapeseed and barley.

3.2.2. Irrigation water demand (IWD)

The IWD calculations showed that, to achieve an unconstrained biomass and yield accumulation, the spring crops (maize, sugar beet) need much more irrigation water than the winter crops (wheat, rapeseed) (Table 6). The reason is that the time period for irrigation stretches from early June until the first decade of September for silage maize and from early July until the second decade of September for sugar beet, whereas for winter wheat it stretches only from early May until the end of June and for rapeseed it stretches from the second decade of April to the second decade of May. The between-district variation in IWD was related to the precipitation pattern within Brandenburg and to the soil quality-related yield potential. For spring crops, EE had the lowest IWD and the lowest crop yield increase, whereas OPR (silage maize) and MOL (sugar beet) had the highest IWD and crop yield increase. For winter crops, IWD and crop yield increase were highest in LDS and lowest in BAR (winter wheat) and UM (winter rapeseed). In any case, crop yield increases caused by irrigation were positively correlated with IWD.

3.2.3. Water constraints for irrigation

In Brandenburg, a total of 3350 million m^3 of groundwater is recharged per year, taken as an average of the years 1976–2005 (MUGV, 2009). The IWD in the Irrigation scenario amounted to 667 million m^3 per year, which was 20% of the annual groundwater recharge. Only in the two districts UM and MOL did the IWD amount to more than 25% of the annual groundwater recharge. In those districts, IWD was particularly high for sugar beet and maize. In seven other districts, IWD was between 16% and 25% of the groundwater recharge (Fig. 3).

Although Brandenburg has a low annual rainfall compared to other German states, we found that there is sufficient groundwater

Table 5
Calculated average crop yields 2020–2030 for silage maize, sugar beet, winter rapeseed, winter rye and winter wheat in the three scenarios (BAU: Business As Usual; I: Irrigation; E: Energy) for the districts of Brandenburg. Compared to the BAU scenario, the irrigation scenario resulted in yield increases of 3–9% for rapeseed and 34–48% for silage maize in the 14 districts. No significant crop yield differences were simulated for the BAU scenario or the energy scenario.

	Silage maize			Sugar beet			Winter rapeseed			Winter rye			Winter wheat		
	t ha^{-1}			t ha^{-1}			t ha^{-1}			t ha^{-1}			t ha^{-1}		
District	BAU	I	E	BAU	I	E	BAU	I	E	BAU	I	E	BAU	I	E
BAR	34.7	49.2	33.6	58.1	69.5	58.5	3.7	3.9	3.7	4.6	4.6	4.6	6.4	7.6	6.5
EE	37.0	49.7	35.8	60.9	70.3	60.8	3.8	4.1	3.8	4.8	4.8	4.9	6.6	7.7	6.6
HVL	35.1	49.2	33.8	59.2	69.9	59.1	3.7	3.9	3.7	4.6	4.6	4.6	6.6	7.8	6.6
LDS	31.9	46.5	30.2	60.0	70.8	60.4	3.5	3.7	3.5	4.3	4.3	4.3	6.0	7.4	6.1
LOS	31.5	45.6	30.4	60.1	69.8	60.2	3.6	3.8	3.6	4.2	4.2	4.2	6.5	7.8	6.6
MOL	35.0	49.9	34.3	58.0	69.9	57.9	3.5	3.7	3.5	4.3	4.3	4.4	6.8	7.9	6.8
OHV	33.6	48.4	32.5	60.2	71.3	60.3	3.6	3.8	3.6	4.5	4.5	4.6	6.0	7.3	6.1
OPR	33.2	49.0	30.3	61.4	71.4	61.1	3.6	3.8	3.7	4.2	4.2	4.3	6.2	7.5	6.2
OSL	36.7	50.6	34.0	59.9	69.5	59.6	3.7	4.0	3.8	4.6	4.5	4.6	6.5	7.6	6.5
PM	31.6	46.2	29.2	58.2	68.8	58.2	3.3	3.6	3.4	4.1	4.1	4.1	6.2	7.5	6.3
PR	37.5	51.0	36.8	61.6	71.2	61.6	4.0	4.2	4.0	5.0	5.0	5.0	6.8	8.0	6.9
SPN	36.6	50.4	33.3	60.4	70.2	60.2	3.6	3.8	3.6	4.4	4.4	4.4	6.6	7.8	6.7
TF	33.1	47.2	31.9	58.4	68.8	58.5	3.4	3.7	3.5	4.5	4.5	4.5	6.5	7.8	6.6
UM	35.4	49.5	34.4	58.0	69.1	58.1	3.8	3.9	3.8	4.8	4.8	4.9	7.2	8.4	7.2
Brandenburg	34.3	48.6	33.6	58.8	69.6	58.8	3.6	3.9	3.7	4.5	4.5	4.5	6.6	7.8	6.6

Table 6
Irrigation scenario for 2025: calculated irrigation water demands (IWD) and respective crop yield increases for the 14 districts of Brandenburg. Spring crops need more irrigation water than winter crops. Variations of IWD between districts were related to soil quality and precipitation patterns between districts.

	Silage maize		Winter wheat		Winter rapeseed		Sugar beet	
	Irrigation water demand (mm)	Crop yield increase (t ha^{-1})	Irrigation water demand (mm)	Crop yield increase (t ha^{-1})	Irrigation water demand (mm)	Crop yield increase (t ha^{-1})	Irrigation water demand (mm)	Crop yield increase (t ha^{-1})
BAR	124	14.9	72	1.1	19	0.2	115	10.9
EE	109	13.0	81	1.2	27	0.3	98	9.3
HVL	119	14.2	78	1.2	26	0.3	113	10.7
LDS	123	14.8	89	1.3	28	0.3	108	10.3
LOS	122	14.6	80	1.2	25	0.2	99	9.4
MOL	125	15.0	74	1.1	21	0.2	119	11.3
OHV	126	15.1	84	1.3	25	0.3	116	11.1
OPR	134	16.1	87	1.3	26	0.3	108	10.2
OSL	118	14.2	81	1.2	26	0.3	105	10.0
PM	124	14.9	83	1.2	27	0.3	113	10.7
PR	115	13.8	78	1.2	19	0.2	100	9.5
SPN	118	14.1	85	1.3	27	0.3	104	9.9
TF	119	14.3	79	1.2	27	0.3	109	10.3
UM	119	14.3	75	1.1	18	0.2	117	11.1
Brandenburg	121	14.5	80	1.2	24	0.2	113	10.7

recharge in most districts to provide a basis for crop irrigation. This was in contrast to the position taken by the federal state office for environmental protection in Brandenburg (see stakeholder workshop) that might be biased by frequent dry spells and the decline in groundwater and lake levels observed between the 1980s and approximately 2007. Water availability was defined and calculated here under the worst-case assumption of no return flow from irrigation into groundwater, meaning that all of the water pumped up would transpire or evaporate. Two factors were spatially differentiating water availability: (1) the share of arable land to be irrigated in a region, (2) the local groundwater conditions, which may account for an occasional small-scale supply shortfall. Provided that the local conditions are thoroughly taken into consideration, the results may encourage farmers to expand irrigated crop production in Brandenburg. However, local and area-specific problems are possible if todays irrigated area is increased. For example, groundwater-dependent ecosystems may locally compete with field irrigation for water use.

For the following indicators, the estimated scenario effects are presented at the district level in Fig. 4. To allow comparisons of the scenario effects of various indicators and to allow differentiation between the districts of Brandenburg, all indicator values were normalized. This was achieved by expressing all indicator values as values relative to the mean and standard deviation of the respective values of the BAU scenario. The results were then grouped into 5 classes of deviation from the mean BAU value (Fig. 4).

3.2.4. Share of electricity demand covered by the production of biogas

The share of net electricity demand of Brandenburg that can be covered by the production of biogas was estimated to rise from 21% in the BAU scenario to 34% in the Irrigation scenario and 46% in the Energy scenario. This would require between 19% (BAU) and 39% (Energy scenario) of the total cropland to be used exclusively for the production of energy. These sites would no longer be available for food, feed or fiber production.

However, this value is a rather optimistic estimate, because the net electricity demand does not account for energy losses in the distribution grid. Furthermore, the assumed demand in 2025 is based on political targets that include a 10% reduction in electricity consumption. Even in Brandenburg, where population density is

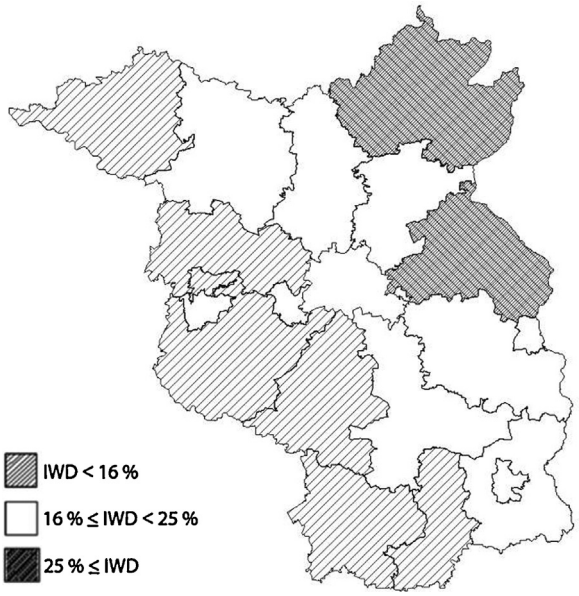

Fig. 3. Water constraints for irrigation expressed as irrigation water demand (IWD) of the Irrigation scenario relative to groundwater recharge. An IWD of more than 25% of annual groundwater recharge was found to be critical with regard to competent water uses. This threshold was estimated to be reached only in two of the 14 districts in Brandenburg.

low and cropland accounts for a large share of demand, 48% of the total cropland must be cultivated with maize to cover the projected electricity demand and still produce the required amount of animal fodder.

3.2.5. Scenic value of landscape

Assessment of the aesthetic value of different crop types showed that grain and rapeseed were perceived as beautiful, whereas the perception of maize was ambivalent, and sugar beet was considered a less attractive crop. Regarding the relative crop shares, the visual perception of the BAU scenario was best, followed by the Irrigation scenario and the Energy scenario. This was true for the federal state Brandenburg as a whole as well as for the individual districts (Fig. 4). The Irrigation scenario was particularly disadvantageous with respect to landscape scenery in the districts HVL and PM. In the Energy scenario, the landscape scenery of an additional five districts was negatively affected. Together, these districts represented 50% of all districts with negative scenery effects. However, except for UM, these districts were not those that experienced yield increases and high irrigation water demand. Obviously, sensitivity to landscape scenery deterioration was not necessarily associated with areas of high potential for yield increase.

3.2.6. Greenhouse gas savings

The results showed that the production of biogas can save between 8.1 t (Energy scenario) and 9.5 t (Irrigation scenario) of CO_2 equivalents per hectare of silage maize production. Higher yields led to higher greenhouse gas savings. We calculated total savings of 1.2 million tons (Irrigation scenario) and 1.7 million tons (Energy scenario) of CO_2 equivalents compared to the BAU scenario. This would constitute a saving of between 4.4% and 6.2% relative to the total emissions of Brandenburg in 2011.

Using a high amount of silage maize in biogas plants to produce heat and energy could contribute to lowering the greenhouse gas emissions. However, the results must be considered as upper limits of achievable savings because a number of factors were not included in the calculations. The method used relied on official figures published by the German Ministry for the Environment. Those figures were based on the assumption that energy produced from renewable sources will replace only fossil fuels and not other renewable energy sources. Furthermore, a high percentage of cropland used for bio-energy may increase the import of agricultural goods from other countries. Such effects were not considered in the calculations. For the Irrigation scenario, we did not include any emissions caused by the irrigation machinery, which would further increase the total emissions in that scenario.

3.2.7. Biodiversity

All three land use scenarios were in conflict with the National Biodiversity Strategy for Germany, which seeks to halt and reverse the decline in bird populations. The habitat suitability index did not differ for the Irrigation and Energy scenarios, but it was better for the BAU scenario (Fig. 4). The simulated changes varied between bird species and between districts. Only one of the four indicator species nesting on arable land, the *Lapwing (V. vanellus),* benefited from the land use changes, whereas the *Whinchat (Saxiola rubreta)* was hardly affected. For the *Skylark (A. arvensis)* and the *Corn bunting (M. calandra),* however, the reduction of suitable crops for breeding was dramatic. The increase of maize cultivation (Energy scenario) decreased the available habitat area by 28.2% (*Corn bunting*) and 21.3% (*Skylark*).

The variation between districts was the result of regionally varying land use change, which was a function of soil quality. The greatest decrease in the habitat suitability index was found in districts with medium to low yield potential, and the effects in the most productive arable regions were smaller. Comparing the scenario effects with the yield potential of the districts, we found that negative effects increased with decreasing yield potential, from −7.3% (breeding index change between BAU and Energy scenario) in the districts with highest yields up to −46.1% in districts with medium yields. However, for the districts with the lowest yield potential, the trend was reversed because there were only minor changes in the cropping patterns. Agricultural intensification is widely accepted as being a cause of bird population declines on farmland during the last three decades. As part of a European bird monitoring project, Guerrero et al. (2012) found that landscape factors (e.g., biotope inventory) accounted for most of the variation in ground-nesting farmland bird individual and breeding pair densities between the regions, and crop field factors (crops and their management) were found to be more important for explaining the persistence of the populations. The present approach is one of the first to integrate the habitat requirements of indicator species, regional land use structure and land management into an ex-ante analysis. Some of our findings were counterintuitive: the decline in habitat suitability was highest in the areas with medium fertility. This was due to the availability of fewer cropping options in these areas, which led to a decrease in crop species.

3.2.8. Erosion risk

Rainfall erosivity in Brandenburg is low compared to other European regions. However, a few heavy rainstorms produce considerable erosion at times of insufficient soil cover or in sites with heterogeneous relief. Typically, erosion is a problem in fields with steep and/or converging slopes. An increase in the area of maize cultivation or an increase in the share of maize in crop rotations increases the risk of erosion because of the late protection of the soil surface with plant cover and because of the linear structure and high distance of the maize rows. Soil erosion already exists in the BAU scenario. Any further increase in soil erosion exacerbated the situation of affected areas and neighboring areas. For the Irrigation and Energy scenarios, the

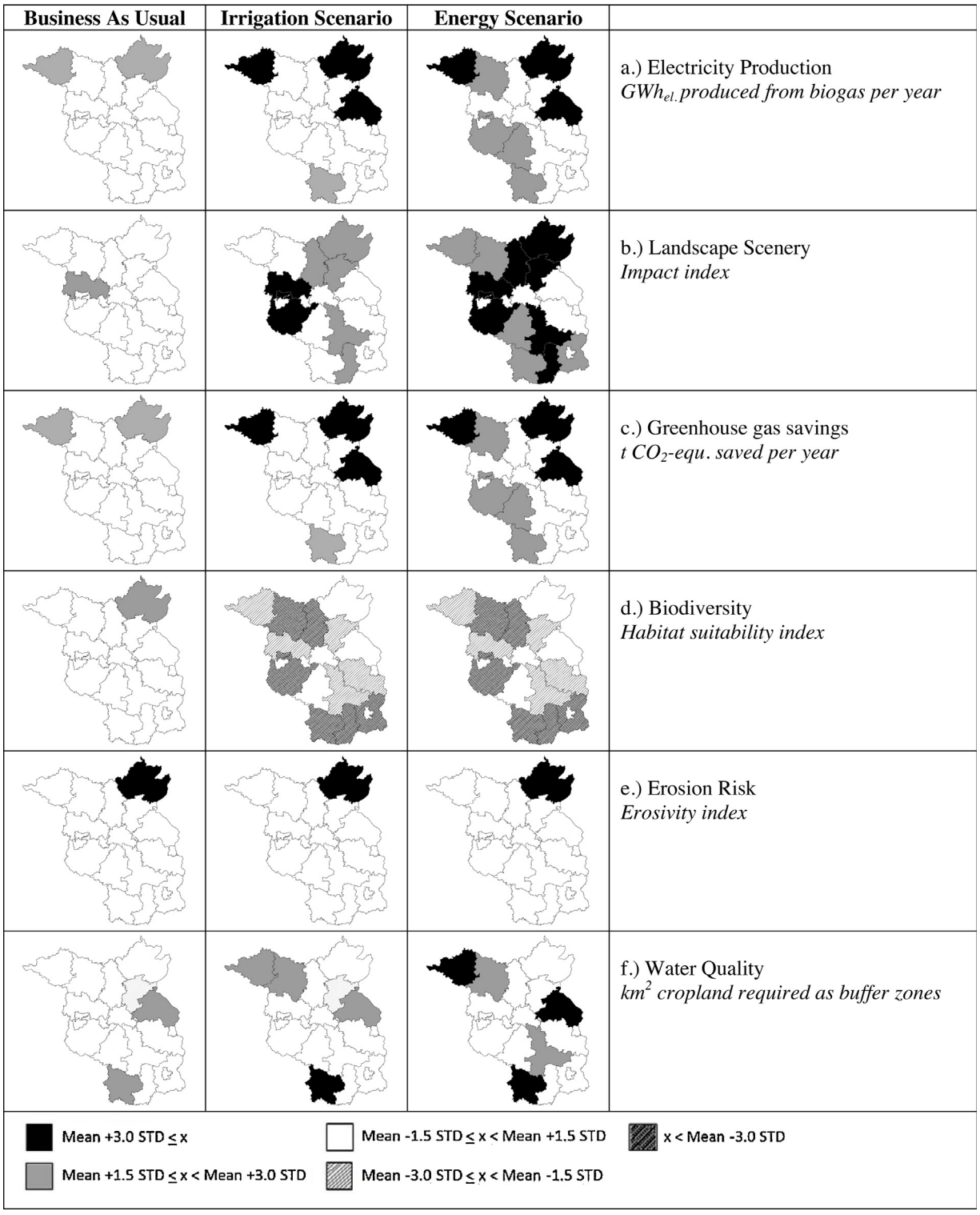

Fig. 4. Impacts of three agricultural intensification scenarios: Business As Usual, Irrigation and Energy for 2025 at the district level in Brandenburg. Normalized values relative to the mean and standard deviation of the BAU scenario are displayed.

largest increase in erosion risk affects the district UM, which was also identified as the most vulnerable in the BAU scenario (Fig. 4). However, individual fields can also bear particularly high erosion risk in other districts.

The higher share of maize cultivation in the Irrigation and Energy scenarios had negative effects on soil erosion. An additional effect of irrigation on soil erosion was not considered in the calculations, but such an effect may occur in cases of high irrigation on slope sites. A reduction of erosion risk requires management decisions in accordance with the site-specific conditions and with particular attention to soil protection. Even conservation tillage cannot prevent soil loss in areas with high erosion risk (high slope steepness and horizontal curvature) if crops such as maize are cultivated.

3.2.9. Area demand for water quality protection

The total riparian length of the running waters of the state of Brandenburg is approximately 38,000 km, of which approximately 80% is accounted for by artificial collector ditches in ameliorated lowland areas such as fen peatland. Under the scenario assumptions, the length of the required riparian zones increases from 3743 km (BAU) to 6332 km (Energy scenario). This equates to 10–16% of all water ways. At a buffer zone width of 20 m, this corresponds to 0.5–0.8% of the total arable land area in Brandenburg, or 1.9% of the arable land under maize cultivation in that zone.

The areas to be designated for water protection differed between districts in accordance with the density of their water body networks and the simulated acreages of arable land for maize cultivation. The districts EE, MOL and PR were affected most because the scenarios placed the highest portion of maize-cultivated area in those districts (1.85%, 3.16% and 1.90%, respectively). However, the density of running waters in these districts is rather low: 0.89 km km^{-2} in MOL, 1.63 km km^{-2} in EE, and 1.47 km km^{-2} in PR.

Usually, the allocation of riparian buffer zones for water protection is not appreciated by land owners because of economic losses and changes in property rights. However, when the area of maize cultivation is extended for energy production, the costs for water management will be increased anyway to implement the binding targets of EU Water Framework Directive. Our scenario calculations show that, for the state of Brandenburg, which is one of the German states with the low density of water bodies (outside of its river lowlands), the required protection area is less than 2% of the simulated maize area.

3.2.10. District level distributions

When the 14 districts of Brandenburg were compared across the three scenarios, an interesting pattern was found. Four districts, EE, MOL, PR, and UM, showed the highest yield potential for all three scenarios. Of those districts, MOL and UM had the highest water demand for irrigation and revealed water availability constraints in the Irrigation scenario. For UM, additional negative effects on erosion risk and landscape scenery were identified. The area demand for water quality protection was particularly high in EE, MOL and PR. In conclusion, the trade-offs of agricultural intensification with water quantity and water quality were most evident in the four districts with the highest yield potential. In contrast, the trade-offs of agricultural intensification with landscape scenery and biodiversity were most evident in districts with moderate yield potential. The identification of those regional variations in trade-offs is useful for district level decision-making because it enables the identification of those regions where agricultural intensification may cause the least negative side effects and where is requires countermeasures such as the establishment of riparian zones or habitat zones.

3.3. Stakeholder involvement in the assessment of results

All results of this comprehensive study were condensed to a few key statements to make them communicable to the invited stakeholders. The overall participation in the discussions during the stakeholder workshop was extensive and actively involved almost every participant.

Questions and comments on the study were as diverse as the group's composition and were sometimes controversial. One point of interest had to do with the social and economic impacts at the district level that will be subject to a follow-up study. Another discussion point was the energy topic–the future role of maize and other resources for biomass production. Doubts were raised with regards to the congruency of water availability estimations with older studies. Broad interest was shown in environmental indicators. Whereas 2/3 of the participants were astonished by at least part of the results (mainly water availability), the remaining third found their estimates confirmed. There were 10 participants who were interested in cooperating in further impact assessments.

The results of the stakeholder discussions are scientifically relevant for several reasons. First, adequate documentation of stakeholder involvement and perception of scientific findings is a prerequisite for a systematic appraisal of the results (Scherhaufer et al., 2013) and constitutes an essential component of a sound impact assessment. Second, the stakeholder views represent a diversity of interests that come into play when addressing changes in agricultural practices, and they underline the importance of dialogue between science, practice and policy (Knierim et al., 2010). Third, only at certain points (e.g., related to the energy maize issue) when the discussions became 'hot' did we fully understand the challenges of conveying modeling results.

There were a number of methodological gains that resulted from stakeholder involvement. First of all, it became obvious that an open learning attitude is key for all actors involved and hence, appropriate conditions have to be created by the study coordinators (Collins and Ison, 2009). In particular, scientists largely underestimated the efforts necessary to elaborate the results in a way that can be digested by stakeholders. It took several iterations of discussion and consensus finding to come up with the key statements. On the other hand, the stakeholder discussions about regional water availability showed that commonly accepted knowledge needs to be regularly tested and updated by research. Lastly, discussions about the Energy scenario showed that many stakeholders had already made up their minds before the meeting. As a majority confirmed their willingness to further cooperate in such type of studies, we conclude that the information provided through this impact assessment study is a suitable evidence base for stakeholder. But the stakeholders' involvement into assessment has to be timely so that it corresponds to both, the state of political developments and the state of scientific insights. In the case presented here, 'consultation' was appropriate, while for the future, a more procedural and interactive participation might be possible (Pretty, 1995).

4. Conclusion

In this paper, we demonstrated the application of a series of indicators in a comprehensive sustainability impact assessment of agricultural intensification at the regional level. It revealed the potential of irrigation for increasing and stabilizing yields. This information is important for both, at farm level for farmers' decision making on agricultural management, and at regional level for policy decision making on sustainability governance. Scenario assumptions were set such that good agricultural practices (crop rotations, preceding crop effects) were respected, resulting in a maximum maize share of 49% for the Energy scenario. This value is below the threshold set in the greening of the CAP (70%). In reality, without additional policy restrictions, the maize share may reach higher values. However, the simulated levels already show the adverse impacts of increasing maize share on biodiversity, landscape scenery, water quality and erosion risk. Policy-makers need to decide whether they will accept the side effects associated with an increasing maize share.

The between-district variation of the scenario results was particularly interesting. Those regions that are expected to suffer most of the adverse impacts of agricultural intensification, according to soil quality, have only medium yield expectations. High and low yield potential regions turned out to be less affected. Obviously, those medium-yield-potential regions feature areas

with high landscape values that are attractive for biodiversity habitats and recreation. Additionally, they have a high share of surface water bodies, resulting in high area demands for water quality protection. In contrast, high-yield-potential regions have fewer areas of high landscape value and less connectivity between water bodies. Low-yield-potential areas were less affected by the simulated scenario changes. Therefore, the scenario impacts were also low. The landscape characteristic that determine the agricultural scenario impacts have yet to be analyzed in detail. Such analysis would facilitate the transferability of results to other regions and situations.

Our study was aimed at the science-policy interface. We sought to provide policy decision-makers with relevant state-of-the-art information about the effects of anticipated intensification trends in agriculture. This required a contextual upscaling of farm level assumptions and hectare scale yield simulations to administrative units at the regional level. Additionally, the analyzed impact issues had to be relevant at the spatial level of policy relevance. The selection of indicators was guided by this challenge. The result was an overview of regional sustainability impacts induced by farm-level decision-making. This approach proved relevant for decision-makers. Simulation results were partly new to decision makers (yield expectations), they partly confirmed their estimates (soil erosion, biodiversity), and they partly challenged common sense (water demand and water availability). In any case, important evidence was presented that formed a basis for policy decision-making. The study revealed the need for researchers at the science-policy interface to emphasize the broader sustainability impacts and focus on trade-off studies rather than analyzing single impacts without the sustainability context. With the combined use of multiple indicators this became possible.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.ecolind.2014.09.004.

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