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Adapting Cropping Patterns to Climate Change: Risk Management Effectiveness of Diversification and Irrigation in Brandenburg (Germany)

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Abstract: Climate-induced production risk is expected to increase in the future. This study assesses the effectiveness of adapting crop rotations on arable farms in Brandenburg as a tool to enhance climate resilience. Two risk-minimizing measures are investigated: crop diversification and the inclusion of irrigated crops. Based on state-wide simulated yield data, the study compares two different scenarios. In the first scenario, the most profitable crop rotations based on predicted future weather conditions are chosen for each agro-ecological zone. In the second scenario, cropping plans are derived based on an adaption of the Target MOTAD (Minimization of Total Absolute Deviation) model taking climate-induced risks into account. A comparison of the scenarios shows a high risk reduction effect of diversification, while the economic risk reduction effect of irrigation only increases slightly. The trade-off between the highest possible gross margins and lower possible losses varies depending on the soil and climate conditions. Diversification contributed most to economic resilience in areas with moderate to low agricultural productivity. Subsidies focusing on diversification in less productive areas might be a tool to increase economic resilience with low risk-avoidance costs.

Keywords: Target-MOTAD; crop diversification; economic resilience; irrigation; HERMES; climate risk

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1. Introduction

Climate change is causing more and more uncertainty in agricultural production. Increasing variability in future weather conditions is expected to intensify adverse weather patterns. For example, rising temperatures together with new precipitation patterns might result in more drought periods putting agricultural production at risk [1]. However, the magnitude of these risks for the agricultural sector varies between different parts of the world and on a national level within Germany. Precipitation in the state of Brandenburg in eastern Germany is already below the national average [2]. Additionally, Brandenburg has mainly morainic sandy soils with low water storage capacity, while precipitation over spring and summer is expected to decrease [3]. At the same time, extended growing periods and warmer mean temperatures might offer new opportunities by allowing for new crops to grow in some areas [4,5]. A variety of measures have been suggested aiming to adapt to climate-induced uncertainty. Insurances and savings aim to enhance farm resilience through the financialization of risk [6]. Other measures such as diversification and irrigation aim to minimize the climate-induced risk within the production process.

There is a variety of ways in which crop diversification can decrease climate-induced risks and improve farm resilience [1,2]. Studies have shown that diversification can reduce production risks by suppressing pest outbreaks and damping pathogen transmission, which are expected to worsen under future climate conditions [3]. At the landscape level, crop diversification can reduce the need for pesticide application, while enhancing biodiversity [4,5] and stabilizing yields through ecological intensification [6]. At the same time, production risks resulting from higher weather variability can be buffered by less dependency on single crops [3,7]. However, evidence is still lacking at different scales and in a wider variety of contexts [6].

Despite the broad potential of diverse cropping systems, economic incentives have led to the cultivation of few selected crops in agricultural landscapes [3]. Due to the increasing use of mineral fertilizer, plant protection products and biotechnological advancements, farmers have been less dependent on crop rotations to control weeds and pests [8,9]. As a result, crop rotations have been simplified in recent decades [10]. However, increasing climate variability might induce new economic benefits to crop diversification as a risk-reducing measure in agricultural landscapes.

A second measure aiming to reduce production risk by increasing and stabilizing yields is the implementation of irrigation systems. In addition to the yield-stabilizing effect, irrigation can also improve nutrient uptake on marginal soils with volatile precipitation, common in eastern Germany. In Brandenburg, a lack of snow in winter and longer periods with low levels of precipitation is not just a predicted phenomenon but has already been an issue in the past years. Local press have been recommending irrigation systems as the primary measure but also point to diversification as an alternative for more resilient agriculture [11]. After the dry summers of 2018 and 2019 with major losses in the grain and potato harvests in Brandenburg, the German field irrigation association started reporting a boom in the implementation of irrigation systems [11]. However, the use of groundwater and surface water for agricultural purposes requires a legal permit, which is only granted if the applicant can prove sufficient groundwater supply on the basis of costly expert reports. Local authorities refer to other tools to minimize risks such as insurance [12]. However, even if irrigation is legally admitted, it is not economically viable for all farms. Agricultural journals for practitioners and scientific research point out the high costs and the need for economic evaluations that consider all crops in a rotation [13,14].

Economic resilience generally refers to the "ability or capacity of a system to absorb or cushion against damage or loss" (Rose and Liao, 2005). Diversification and irrigation are both tools suggested to increase economic resilience by stabilizing farmers' incomes. However, they target two different types of resilience capacities. Inherent resilience describes the resilience capacity already built into a system (Lin, 2011), similar to the term robustness, describing a system's capacity to "withstand stresses and (un)anticipated shocks", used by Meuwissen et al. [13]. The diversification of crops refers to the inherent resilience of arable farming in Brandenburg. Adaptive resilience, on the other hand, defines the resilience capacity due to additional effort or a change in the composition of input and production factors without changing the structure of the system, mainly in crisis situations [13,14]. The implementation of an irrigation system refers to the adaptive resilience of the system in crisis situations such as dry summers. The combination of inherent and adaptive resilience provides a more holistic and differentiated approach to economic resilience under climate-induced risks.

Due to the increasing importance of economic resilience, this study attempts to fill the research gap of context-specific economic assessment of crop diversification and irrigation. Comparing two cropping plan scenarios in which Scenario 1 assumes the cultivation of the most profitable crop rotation based on predicted future weather conditions, and Scenario 2 assumes the cultivation of cropping plans derived from a risk-minimizing model, with a focus on crop diversification and irrigation, allows the following research question to be answered.

Research Questions

1. How do risk mitigation strategies versus profit maximization affect cropping patterns in Brandenburg under climate change, given adaptation through cropping diversification and irrigation?

2. How effective are crop diversification and irrigation as risk management measures when it comes to adapting cropping patterns to climate change?

2. Materials and Methods

This study presents a regional farm model that focuses on arable farming in Brandenburg, considering future climate conditions. Crop diversification and the inclusion of irrigated crops are investigated as two risk-minimizing strategies to increase climate resilience. The data basis is obtained from the soil–crop–atmosphere model, HERMES, which is presented in more detail in the following section. It provides 30 years (2040–2070) of crop rotations, encompassing yield, yield variance, crop rotation effects, resource use and management practices. The analysis includes simulations for four different climate scenarios, considering 276 agro-ecological zones (AEZ) within the state, each sharing similar soil and climatic conditions [15]. Although the primary focus is on arable farming, livestock production is partially incorporated through the inclusion of fodder crops in specific crop rotations. The share of fodder production included in the cropping patterns results from economic optimization. To verify a realistic approximation of livestock production in Brandenburg, the numbers were compared with real-life data from Hanff and Lau [16]. The economic analysis is based on a mathematical programming approach to maximize overall gross margins over 30 years and for each agro-ecological zone.

Two scenarios are established with the same input data, allowing a comprehensive comparison of cropping patterns, generated income, economic production risks and risk-avoidance costs. In the first scenario, the most profitable crop rotation is chosen, based only on average expected yields and taking into account predicted future weather conditions. In contrast, the second scenario employs an adapted version of the Target MOTAD (Minimization Of Total Absolute Deviation) model, taking climate-induced risks into account. The model minimizes negative deviations from a set target value, considering a tolerance level that determines the acceptable loss of income for risk minimization.

The next sections present the scenarios in more detail, followed by a section introducing the soil–crop–atmosphere interaction model. The final sections explain the data sources of the micro-economic analyses.

2.1. Scenario 1 (Maximization of Average Gross Margin: GMMax)

Scenario 1 assumes profit-maximizing behavior by farmers. The primary objective in the scenario is to maximize the average gross margins per hectare. Drawing from simulated yield data, spanning 30 years (2040–2070) for various crop rotations (as detailed in Section 2.3), the crop rotations that maximize the average gross margin per hectare are selected.

To estimate the gross margins, the study considers the yield data multiplied by market prices, subtracting the annual operational costs per rotation, and adding the average subsidies received in the area. It is essential to maintain the selected crop rotations in subsequent years to account for the crop rotation effect. However, if climatic changes render agriculture unprofitable, fields can be left fallow, providing a flexible approach to adapting to evolving environmental conditions.

2.2. Scenario 2 (Risk Minimization: RiskMin)

The second scenario enables risk-averse behavior by utilizing an implementation of the Target MOTAD (Minimization of Total Absolute Deviation) model to identify cropping patterns that minimize risk. The model operates as a two-attribute risk and return framework, aiming to achieve the best trade-off between the highest gross margin and the risk of falling below a specified target gross margin (Deviation). Compared to other risk decision-making approaches, the model ensures second-order stochastic dominance (SSD) and computational efficiency [17]. In this study, the model is adapted into a bio-economic framework, seamlessly integrating economic optimization with simulated climate and plant-growth data (Figure 1).

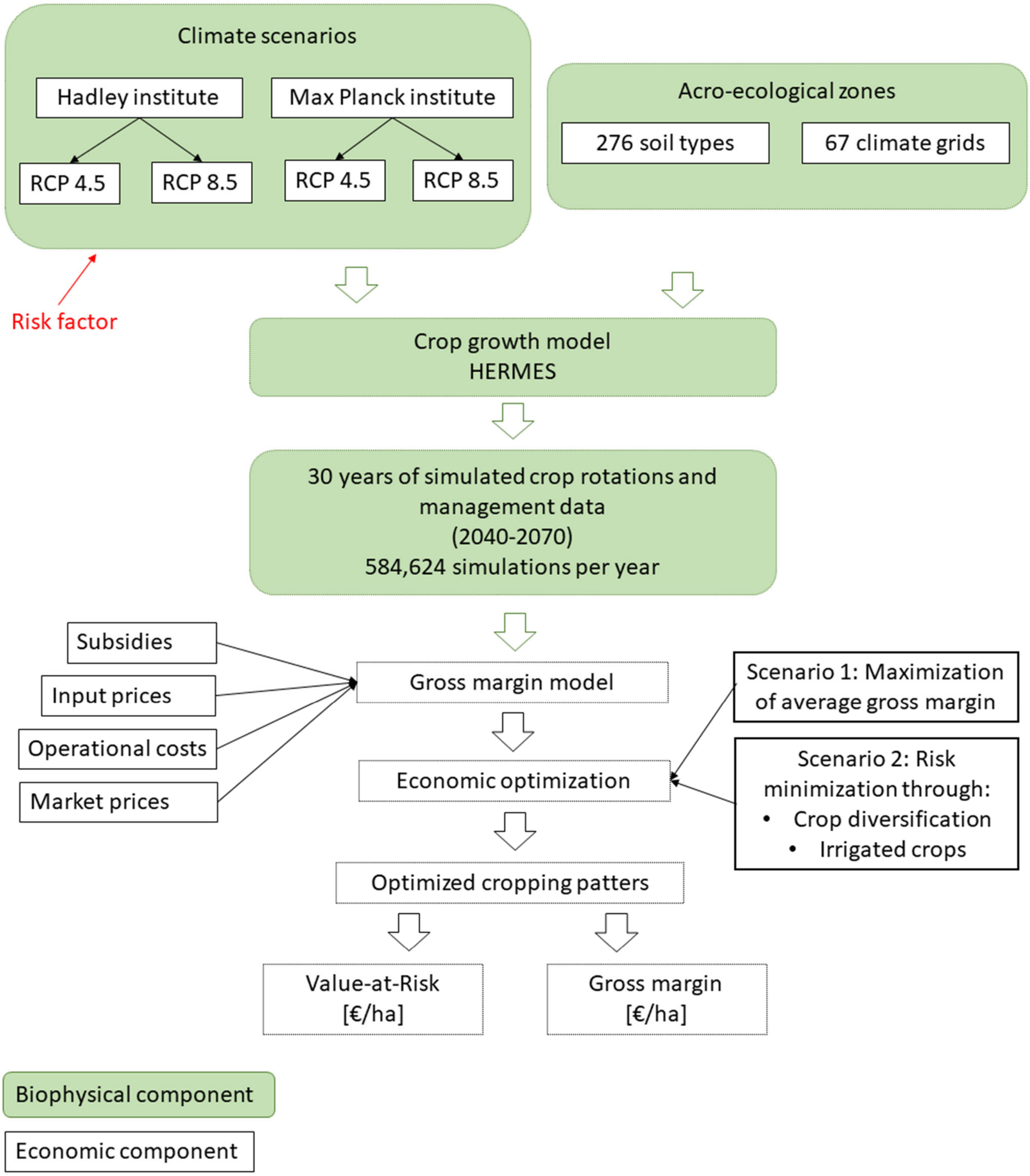


Figure 1. Model overview.

This study focuses exclusively on the risk reduction potential in arable farming. Total production volume and capacity limitations relevant to livestock production are therefore neglected in the model. This allows the model to optimize per hectare, independently of the size of actual field blocks in each agro-ecological zone (AEZ). Subsequently, the results are scaled by the actual area size to reflect real-world conditions. The extent of fodder production results from the optimization model and is verified through a comparison with current production patterns in Brandenburg.

To emphasize the climate and weather-related yield risk, fixed prices are used for all commodities. The model is estimated for all agricultural areas of Brandenburg, assuming arable farming in all AEZs. This comprehensive approach ensures a thorough examination of cropping patterns and risk minimization strategies across the entire region.

Objective function

$$\underset{X}{Minimize} TND = \sum_{t=1}^{T} \sum_{clim=1}^{S} DEV_{t,clim} \quad \text{s.t.} \tag{1}$$

Land constraint

$$\sum_{rot=1}^{N} X_{rot,t} \leq 1 \quad t = 1, \ldots, T \tag{2}$$

Crop rotation

$$X_{t,rot} \geq X_{t+1,rot} \quad t = 1, \ldots, T \quad rot = 1, \ldots, N \tag{3}$$

Tolerance level

$$\sum_{t=1}^{T} \sum_{rot=1}^{N} acm_{t,\,rot} X_{t,rot} \geq (1-\alpha)\, GM^* \quad t = 1, \ldots, T \quad rot = 1, \ldots, N \tag{4}$$

Deviation

$$RI_{t,clim} \geq tgm - DEV_{t,clim} \quad t = 1, \ldots, T \quad clim = 1, \ldots, S \tag{5}$$

Random income

$$RI_{t,clim} = \sum_{rot=1}^{N} cm_{t,rot,clim} X_{t,rot} \quad t = 1, \ldots, T \quad clim = 1, \ldots, S \tag{6}$$

Non-negativity

$$X_{t,rot} \geq 0 \quad t = 1, \ldots, T \quad rot = 1, \ldots, N \tag{7}$$

The objective of the model is the minimization of the total negative deviation (TND) per year (t) and climate scenario ($clim$) from the target gross margin (Equation (1)). The term deviation (DEV) describes the difference between the random income ($RI_{t,clim}$) and the set target gross margin (tgm) (Inequality 5). The random income is defined as the unaveraged gross margins throughout the years (2040–2070) and climate scenarios, shown in Table 1 (Equation (6)). Assuming farmers want to avoid losses below their historical income level, the area-weighted average resulting from profit maximization (Scenario 1) for the years 1970–2010 was used with EUR 141.64 gross margin per hectare as a target level.

Inequality 4 defines the tolerance level alpha. The tolerance level describes the acceptable loss in gross margin, compared to the optimal value resulting from the maximization in Scenario 1 (GM^*) in order to reduce the production risk; in other words, the maximum willingness to pay for risk minimization. The left-hand side of Inequality 4 calculates the average gross margin, which is the sum of all average contribution margins (*acm*) multiplied by the area shares (X).

Inequality 3 ensures that the economic model adheres to the defined crop rotations. The subscript *rot* does not refer to individual crops but the crop rotations defined by the plant-growth model HERMES (Section 2.3). Following the simulated crop rotations allows us to look at crop rotation effects and ensures that the crop rotations reflect reality with a holistic view of legal and agronomic conditions.

For ease of comparison, the model optimizes based on a standard size of 1 hectare. Consequently, land constraints are implemented to ensure that the sum of the area shares never exceeds 1 (Inequality 2). Additionally, Inequality 7 guarantees that there are no negative area shares.

2.3. HERMES

The HERMES (v03.1.1—BBB Sept 2022) model of Kersebaum et al. [15] gives a strong data foundation including yield risks under current and future climate scenarios for economic optimizations. HERMES models soil–crop–atmosphere interactions for the agriculturally used soils in Brandenburg (Germany) and can be used to assess the multi-criteria performance of crop rotation designs and management [18,19]. It considers soil heterogeneity, groundwater levels, weather conditions and crop rotation designs. Soil heterogeneity is expressed through the consideration of 276 different soil types based on the BÜK300 soil map by Krug et al. [20]. To represent the climate diversity in the state of Brandenburg, the area is divided into 25 × 25 km climate grids. In combination, that results in around 2000 AEZ. The AEZs differ largely in size. The average size is 151 ha. However, there are some outliers: 95% of AEZ are below 584 ha. For the HERMES simulation, we defined five representative crop rotation types with a total of fourteen crops. The individual rotations are soil quality specific, based on a soil productivity classification (SPC). Each rotation has been simulated with/without catch crops. To avoid a bias through the chosen starting crop, the simulations have been replicated by the number of crops per rotation with shifting starting crops. For the scenarios allowing for irrigation, all 5 rotations have been included. For all rain-fed scenarios, Rotation 5 has been excluded. Rotation 5 includes high-value crops (sugar beet, potatoes) which, due to other limiting factors such as market access, cannot be grown in all parts of Brandenburg. We distinguish the following 5 rotations:

1. Most common crops;
2. Lupins and most common crops;
3. Focus on fodder (pasture) and cereals;
4. Focus on fodder (alfalfa) and cereals;
5. Irrigated (value) crops.

HERMES simulates yields based on one historical baseline scenario (Joint Research Center) and two future climate scenarios (RCP 4.5 and RCP 8.5) translated by two different models (by the Hadley Center and by the Max Planck Institute) into a time frame of 30 years. The baseline scenario covers the period from 1980 to 2010, and the future scenarios extend over the years 2040–2070. The data include daily minimum, average and maximum surface air temperature, precipitation, wind speed at 10m height, global radiation and actual vapor pressure at 25 km resolution. More detailed information can be found in the work of Webber et al. [21].

The climate scenarios are defined below in Table 1. Tmean is the average temperature and Prec_mean is the average precipitation throughout the year. The following columns show the two variables as a 3-month average (for example, DJF = December, January, February). Hot days are the days per year with a mean temperature above 30 °C. Major changes can be seen especially in the precipitation over the summer months. The highest decrease in precipitation is predicted in the Hadley scenario with RCP 4.5, while the Max Planck scenarios are more optimistic and even predict increases in precipitation. The Hadley scenarios also predict a higher rise in mean temperature throughout the year, especially over the summer. Climate change in Brandenburg is characterized primarily by rising summer temperatures and droughts as well as increased precipitation in the winter months.

Table 1. Main characteristics of the climate scenarios (RCP 4.5, 8.5) and climate models (Baseline, Hadley Center, Max Planck Institute).

	Mean Temperature					Mean Precipitation					Hot Days
Scenario	**Annual**	**Dec–Feb**	**Mar–May**	**Jun–Aug**	**Sep–Nov**	**Annual**	**Dec–Feb**	**Mar–May**	**Jun–Aug**	**Sep–Nov**	**Annual**
	°C					mm					
Baseline	9.50	0.90	9.10	18.10	9.70	557.10	121.00	128.70	182.70	124.70	7.70
Absolute changes compared to baseline											
HAD45 2055	3.00	2.90	1.60	3.70	2.70	−59.80	15.00	−3.90	−57.90	11.50	27.50
MPI45 2055	1.50	1.50	1.10	1.70	1.40	9.20	17.80	0.90	−16.00	5.10	9.70
HAD85 2055	3.40	3.00	1.90	4.20	3.70	−17.20	19.20	1.20	−41.00	1.50	30.10
MPI85 2055	1.70	1.80	0.90	2.10	2.00	12.20	19.70	6.80	−16.30	−2.90	12.50

2.4. Economic Data

The yield and management data resulting from HERMES are used as the basis for the economic analysis, including the water used for irrigation and the amount of nitrogen (N) used for fertilization. Costs and additional management practices used for the estimation of the contribution margins are based on the state-funded data collection by Hanff and Lau [16]. Costs and prices in the database are grouped along the same five soil productivity classifications (SPC) that are used in HERMES for adapting the crop rotations to the soil quality. SPCs are a local classification from 1 to 5 depending on the expected yield on a specific field and closely related to the soil quality index (1–100). Farmers use less fertilizer and other input factors, including labor, on less productive soils knowing they will generate a lower output in yield per input factor compared to more productive soils.

The net-producer prices are a 3-year average (2017–2020). All prices are net prices and, therefore, do not include a value-added tax. The prices for fertilizers (N-P-K), seeds, pesticides, fuel, labor and machine costs and cooperative member fees are based on the Brandenburg database by Hanff and Lau (2021). The amount of N fertilizer applied is simulated by the HERMES model. Each cost factor varies depending on the crop and SPC. Subsidies include the basic subsidy and the greening factor for a 250-hectare farm in Brandenburg, including an additional subsidy for disadvantaged areas in Brandenburg resulting in 291 EUR/hectare. The price for fuel is based on Hanff and Lau (2021) with a tax-free wholesale price of 0.9052 EUR/l. In order to focus on climate-induced production risks over market risks, fixed prices are assumed throughout the simulated 30-year period.

The irrigation costs depend on the amount of irrigation water used and are therefore estimated in more detail. The cost structure and prices are based on the KTBL database (KTBL, 2021). Irrigation costs consist of three parts (Equation (8)). c_f is the sum of fixed costs per hectare. c_p are the costs for the pump including electricity costs of EUR 0.024 per kWh and $\sum c_v$ is the sum of variable costs, which are both dependent on the amount of water used for irrigation Irr. c_a are the labor and machine costs per hectare.

$$c_i = \sum \frac{c_f}{ha} + c_p\ Irr + \sum c_v\ Irr + c_a \quad (8)$$

Irrigation costs are dependent on the type of irrigation system. Stationary systems cause higher fixed costs compared to mobile systems but lower variable costs per hectare. They are therefore mainly used in large irrigated areas. Due to the average farm size in Brandenburg of 280 ha, a stationary system has been used as an example. Further costs that are included are fixed costs for the construction of a 40 m deep water well, the power supply for a field distance of 500 m and variable costs for a 12 bar suction pump ($c_p\ Irr$).

2.5. Value-at-Risk

In order to measure and compare the level of production risk resulting from the two economic models the Value-at-Risk (VaR) per hectare for each AEZ has been estimated. The VaR summarizes the statistically possible loss at a certain probability level of a portfolio [22]. In this case, the loss describes the economic loss per hectare in less productive years, resulting from climate-induced risks. Through the chosen probability level, the risk attitude of farmers can be accounted for. For this study, a probability level of 0.05 has been chosen. In other words, with a probability of 95% farmers will generate an annual gross margin above the Value-at-Risk.

The VaR is not minimized by the Target MOTAD model directly. Instead, the VaR is utilized as a means to assess and quantify the risk resulting from the cropping patterns in both scenarios in a comprehensive and easily interpretable manner. By comparing the VaR with the respective risk avoidance costs, it is possible to determine the risk management effectiveness of the two adaptation measures (crop diversification and irrigation). This approach allows for a more thorough understanding of the risk associated with the model's outputs.

3. Results

A summary of the main findings is shown in Table 2. The table includes gross margins and the VaR (probability level = 0.05) as area-weighted averages for Brandenburg. To investigate the sensitivity of the results to different parameters, both scenarios were estimated separately while varying each parameter. This involved estimating the scenarios with and without high-value crops (potatoes/sugar beet), as well as with and without the option for farmers to irrigate. Additionally, the tolerance level in the Target MOTAD model, representing the maximum allowable decrease in gross margin for risk minimization, was adjusted and analyzed. Scenario 1 does not take the tolerance level into account. Therefore, the results stay constant unless the other two parameters are adapted. By systematically altering these parameters and conducting the estimations, the study captured the influence of each parameter on the results, thereby providing insights into the sensitivity of the results.

Table 2. Area-weighted annual gross margins and Value-at-Risk for Brandenburg. Depending on the inclusion of high-value crops (potatoes/sugar beet), the possibility of irrigation, the tolerance level of allowed deviation from the target level (alpha) and Scenario 1 (GMMax)/Scenario 2 (RiskMin).

Model Parameters			Average Annual Number of Crops		Mean GM EUR/ha		Value-at-Risk EUR/ha	
High-Value Crops	**Irrigation**	**Alpha**	**GMMax**	**RiskMin**	**GMMax**	**RiskMin**	**GMMax**	**RiskMin**
No	No	0.1	1.0	3.5	238.8	214.9	400.3	31.2
No	No	0.05	1.0	3.1	238.8	226.8	400.3	97.9
No	No	0.01	1.0	2.3	238.8	236.4	400.3	270.6
Yes	Yes	0.05	1.0	4.4	1408.9	1338.5	734.0	245.7
No	Yes	0.05	1.0	3.0	240.4	228.4	399.1	98.0

The average gross margin is higher in Scenario 1 independent of the changing parameters. The difference in average gross margin between the scenarios equals the tolerance level. This difference in gross margin between the two scenarios can be interpreted as risk-avoidance costs per hectare under specific soil and climate conditions. Regardless of the specific parameters chosen, it can be observed that in Scenario 2, the Value-at-Risk (VaR) is consistently significantly lower compared to Scenario 1. This outcome highlights the effectiveness of the Target MOTAD model in minimizing economic risk. The table also shows that the relationship between risk avoidance costs and the risk reduction effect varies, which will be discussed in more detail below.

The column "Average annual number of crops" shows the number of crops cultivated on average in one year. Even though the study does not implement a full farm model, this can give insights by looking at the cropping patterns in combination with the economic effects through the gross margins and VaR. The setup of the model assumes that there is arable farming in all parts of Brandenburg and each farm has all fields in one AEZ. Therefore, the "Average annual number of crops" does not necessarily imply crop diversification within one field, but due to big farm sizes within Brandenburg, can be interpreted as the cultivation of different crop rotations on neighboring field blocks. In Scenario 1, a profit-maximizing crop rotation is chosen; therefore, the average number of crops in each year is one. In Scenario 2, potential losses are reduced by cultivating a variety of crop rotations each year. The number of crops shown in the tables below refers to the average number of crops within one year, leading to spatial diversification. The number of crops grown throughout the 30 years is slightly higher between four and five in Scenario 2 and between three and four in Scenario 1.

The following section presents a more detailed analysis of the rain-fed results, looking exclusively at how diversification affects the results. The final section then presents the results of the model runs with irrigation, facilitating a comparison between the risk mitigation effects of irrigation and diversification. This section highlights the distinct contributions of both irrigation and diversification in minimizing risks and sheds light on their relative effectiveness in managing risk under different conditions.

3.1. Diversification

There is a trade-off between a reduction in possible losses and a decrease in the average gross margin. Figure 2 shows the area-weighted average gross margin and the VaR (0.05) for different tolerance levels. A tolerance level of 0 is equal to the results from the profit-maximizing scenario with an average gross margin of 238.78 EUR/ha and a corresponding VaR of 214.9 EUR/ha. The lowest average gross margin (alpha = 0.1) in the figure is EUR 23.88 lower with 214.9 EUR/ha. The VaR with the same level of alpha decreases by around EUR 369.1 to 31.24 EUR/ha. As can be seen in the figure, with each increase in tolerance level a greater reduction in VaR can be achieved.

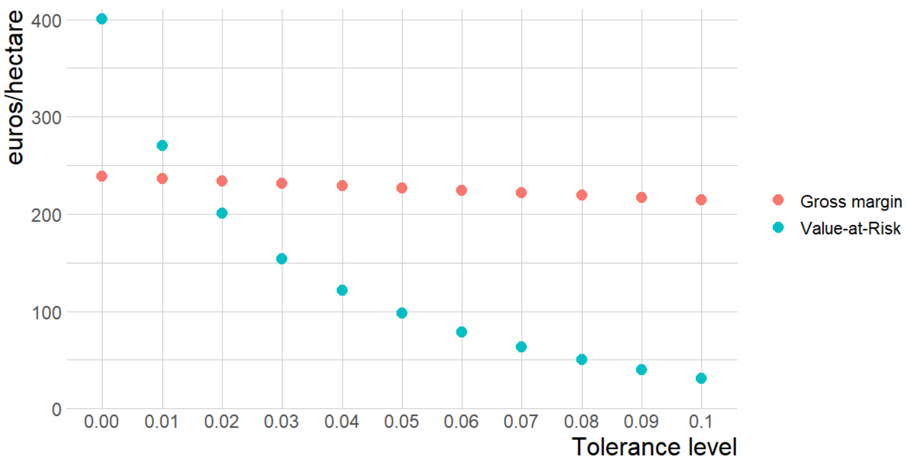


Figure 2. Area-weighted average gross margin and Value-at-Risk for different tolerance levels (deviation from maximum gross margin).

Figure 2 and Table 2 show average values for the state of Brandenburg. However, the economic effects of diversification vary between the different AEZs. In particular, the trade-off between reducing risks and the highest possible average gross margin depends on the general level of agricultural productivity. Figure 3 visualizes this risk-management effectiveness. The map shows the percentage decrease in VaR which can be achieved through diversification by a one percent decrease in gross margin (rain-fed scenario, excluding high-value crops, tolerance level = 0.05). The statewide mean of this effectiveness is 13.64%. Lighter colors such as in the northern parts of Märkisch-Oderland (marked in light green) indicate a smaller decrease in VaR. The grey lines on the map show the borders of individual counties. Märkisch-Oderland in the eastern part of Brandenburg has some of the more productive soils and the highest average gross margin within the state. The county marked Pdm (Potsdam) in the center of the map has the lowest average gross margin. Diversification as a tool for risk avoidance appears to be less effective in the highest and least productive AEZs and most effective in moderate AEZs. Due to the exclusive focus on arable farming, the map does not represent the actual agricultural production within Brandenburg, but rather a hypothetical scenario with a high share of arable farming and constant livestock numbers.

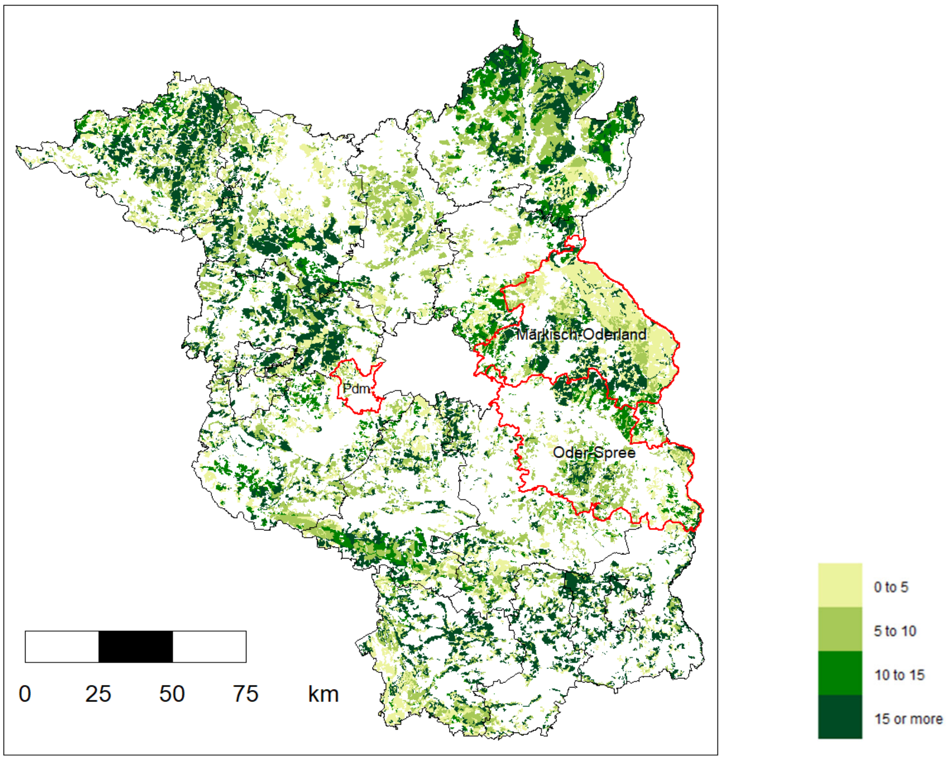


Figure 3. Risk-management effectiveness of diversification (rain-fed, tolerance level = 0.05). Non-agricultural land is marked in white.

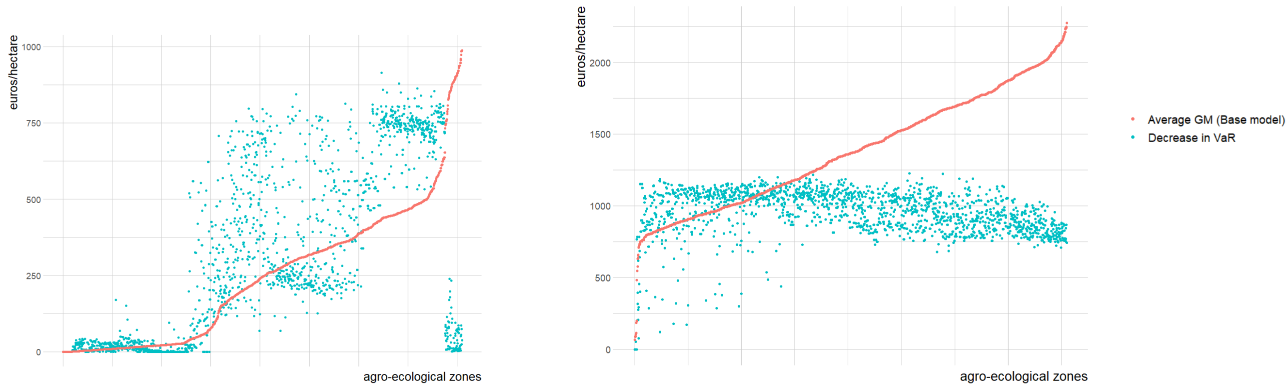
In order to look into the effectiveness of diversification as a tool for reducing climate-induced risks in more detail, Märkisch-Oderland (MOL) with the highest average gross margin, Potsdam (Pdm) with the lowest average gross margin and Oder-Spree (ODS) with a moderate gross margin are looked at in more detail in Table 3.

Table 3. Area-weighted gross margins, Value-at-Risk and risk-management effectiveness per county. High-value crops are not included and the tolerance level from Target is 0.05.

	Average Number of Crops Annually		Gross Margin (EUR/ha)		Value-at-Risk (EUR/ha)		Effectiveness (%)
	GMMax	RiskMin	GMMax	RiskMin	GMMax	RiskMin	
Brandenburg	1.0	3.1	238.8	226.8	400.3	97.9	15.1
MOL	1.0	3.0	447.5	425.1	136.2	−75.8	8.9
ODS	1.0	2.8	180.3	171.2	366.7	106.7	14.2
Potsdam	1.0	2.9	102.6	97.5	270.6	142.7	9.5

The three counties shown in Table 3 differ in soil productivity, as indicated by the average gross margin. MOL has some of the most productive soils within Brandenburg, while ODS lies slightly below average and Pdm is far below average. A comparison of the three counties can be used to assess the economic effect of diversification on areas with different levels of agricultural productivity. Table 3 shows the differences in average gross margin, VaR and risk-management effectiveness. The relative change in gross margin in the counties is close to the tolerance level set to 0.05. Therefore, the difference in absolute numbers is higher in MOL. MOL does not only have a higher average gross margin but also a lower average VaR reducing the potential for risk minimization. In absolute numbers as well as relative changes, the difference in VaR between the two models is higher in PdM and highest in ODS. The effectiveness (decrease in VaR per one percent decrease in gross margin) is highest in ODS, while the other two counties are far below the state average. Diversification as a tool to reduce production risks appears to be less effective in the most productive areas.

The left graph in Figure 4 shows the average gross margins per AEZ in Scenario 1 sorted from lowest to highest and the reduction in VaR achievable through diversification. If farmers stop production should a field generate financial losses multiple years in a row, both scenarios allow for fields in these AEZs to become fallow. The low production levels in the least productive AEZs in Figure 4 not only result in low gross margins but also limit the potential to additionally reduce production risk. This phenomenon also explains the limited reduction in VaR in Pdm compared to ODS shown in Table 3.



(**a**) (**b**)

Figure 4. Average gross margin and decrease in Value-at-Risk by agro-ecological zone sorted by average gross margin. (**a**) Rain-fed, (**b**) irrigated.

Besides the least productive areas, the graph shows that diversifying crop rotations leads to lower financial risks for the majority of AEZs. However, the extent to which the VaR can be reduced through crop diversification appears to differ highly between the different AEZs (Figure 3). There appears to be variation in the risk-management effectiveness within the moderate AEZs, with no clear pattern. However, on AEZs with the highest economic agricultural productivity, diversification appears to be less effective, which underlines the findings shown in Table 3.

3.2. Irrigation

All previous figures exclusively showed rain-fed results. Future climate change is expected to further decrease precipitation over the summer months and increase the probability of drought periods. Previous results showed that based on the simulated yield data, agricultural production is not economically feasible in all parts of the state under future climatic conditions. Therefore, both scenarios have been estimated additionally allowing for irrigation. This does not mean that area-wide irrigation is adopted. Irrigation is relatively expensive and the model chooses to irrigate only if it is a feasible option, based on the expected increase in yield and the additional costs.

In Scenario 1, maximizing gross margins leads to an irrigated area of 19.09% when high-value crops are included. When high-value crops, in this case potato and sugar beet, are excluded, it decreases drastically to 1.48%. In the second scenario, the share of irrigated area increases to 24.44% including high-value crops but does not show the same effect without (1.44%). The rise in irrigation when minimizing negative deviation including high value in the crop rotations indicates the risk-reducing effect of irrigation. However, the importance of irrigation appears to depend on the cultivation of highly profitable crops and seems to not reduce the need for diversification. Even with the inclusion of high-value crops, around four crops are grown annually in each AEZ and three when only common crops are included (Table 2). Table 4 shows the difference in gross margin, VaR and the number of crops grown annually in each AEZ between the rain-fed and irrigated scenarios, excluding high-value crops. The table shows that the share of the irrigated area is highest in MOL; however, the overall level is low in all states. The option for irrigation increases the level of gross margin slightly but does not lead to an additional reduction in VaR. In Potsdam, the county with the lowest average gross margin, the VaR increases by 5% compared to the rain-fed results, while the gross margin increases by 3%.

Table 4. Area weighted gross margins and Value-at-Risk per county. Difference in VaR and GM between the rain-fed and irrigated results for scenario 2 (RiskMin). High value crops are not included and the tolerance level from maximum gross margin is 0.05.

	Share of Irrigated Area [%]	Gross Margin [€/ha]		ΔGM [%]	Value-at-Risk [€/ha]		ΔVaR [%]	Average Number of Crops Annually	
	Irr.	RAIN-FED	Irr.		Rain-Fed	Irr.		Rain-Fed	Irr.
Brandenburg	1.44	226.84	228.4	0.7	97.86	97.98	0.1	3.0	3.0
MOL	1.51	425.08	426.04	0.2	−75.84	−76.19	0.5	3.0	3.2
ODS	1.37	171.22	172.14	0.5	106.7	107.56	0.8	2.7	3.0
Potsdam	1.31	97.48	100.09	2.7	142.68	149.92	5.0	2.9	2.8

Figure 4 shows the average gross margins per hectare in each AEZ in Scenario 1 sorted from lowest to highest and the reduction in VaR achievable through diversification in absolute numbers. For comparison, the graph on the left shows the results from the rain-fed results and on the right side the irrigated results. Potato and sugar beet are included under irrigation since irrigation appears to be primarily relevant for high-value crop rotations. Compared to previous figures, the inclusion of high-value crops and the option to irrigate leads to the production in all AEZs being profitable. No fallow AEZs can be observed due to higher average gross margins. In contrast to the rain-fed results, the Target MOTAD model leads to a major decrease in VaR in almost all AEZs, including the most productive areas. Highly productive areas appear to depend on the inclusion of irrigated high-value crops in order to benefit from diversification in terms of risk reduction. However, the biggest reduction in production risk in both scenarios can be observed in moderate AEZs.

3.3. Cropping Patterns

Crop diversification increases the number of crops grown in each AEZ simultaneously in each year. This does not necessarily increase the number of crops grown throughout Brandenburg. A slight increase in crop diversity was only observed when irrigated high-value crops were included, even though the share of irrigated areas was relatively low. However, the share of additional crops concerns a very small proportion of the area.

In Scenario 1, excluding irrigated high-value crops, seven crops are cultivated throughout the simulated period (2040–2070). However, triticale is only cultivated in some small parts of Brandenburg making up below 0.007%. In other words, profit maximization without irrigated high-value crops leads to the cultivation of six major crops: winter barley with an average area share of 8.3%, lupine with 12.8%, silage corn with 14.2%, winter wheat with 16.1%, winter rape with 17.5% and winter rye with the biggest share of 31.1%.

In Scenario 2 (alpha 0.05), under the same conditions (no irrigated high-value crops) the number of cultivated crops throughout Brandenburg does not increase. The share of triticale stays marginal at 0.08%. The same six major crops are cultivated: winter barley with an average area share of 7.7%, silage corn with 13.8%, lupine with 13.8%, winter wheat with 16.5%, winter rape with 16.8% and winter rye with the biggest share of 31.5%.

However, with the introduction of high-value crops, the number of crops doubles between the scenarios. Scenario 1 results in 22.3% sugar beet, 19.6% potatoes, 19.6% winter wheat, 19.4% winter rape and 19.1% silage corn. Such a high share of high-value crops is only possible because the model does not limit market access. Under Scenario 2, the introduction of irrigated high-value crops not only leads to diversification on the farm level but also increases the number of crops cultivated in Brandenburg in the simulated time frame. However, the share of the additional crops is marginally low, similar to the triticale in the rain-fed results. Sugar beet and potatoes still have a high share with 22.0% and 19.8%. Winter wheat (19.8%), silage corn (18.5%) and winter rape (19.4%) are similarly important. Furthermore, lupines, winger barley, winter rye, triticale and alfalfa each have minor shares.

To summarize, crop diversification on the farm level does not necessarily increase the crop diversity in Brandenburg. However, crop diversity might increase when looking at individual years.

4. Discussion

Increasing crop diversity is one important measure aiming to reduce climate-induced production risks. Cultivating a higher number of crops leads to a lower average gross margin compared to growing only a small number of crops. Therefore, farmers have to accept a tradeoff between reduced potential losses and a decrease in average gross margin. To which extent the production risks can be reduced with a certain loss in gross margin differs depending on soil and climatic conditions (AEZs). The benefit from diverse crop production appears to be lowest in highly productive areas and highest in areas with moderate and low average gross margins. Even though the risk-management effectiveness varies between different sites within Brandenburg, diversification appears to play an important role in economic resilience throughout Brandenburg.

The share of fodder production included in the cropping patterns results from the economic optimizations. In order to verify a realistic approximation of livestock production in Brandenburg, the numbers were compared with data from Hanff and Lau [16]. In Brandenburg, the extent of silage corn production differs between different soil productivity areas. In the most productive areas of Brandenburg, 10.6% of the total agricultural area is used for silage corn cultivation. In the least productive areas, the share is slightly higher at 14.4%. Interestingly, the highest share of silage corn production, reaching 27.4%, is observed in regions with moderate soil productivity. Across all scenarios, the cropping patterns resulting from the economic optimization lead to a share of silage corn production similar to the observed numbers, with an average of 14%. This indicates that the resulting cropping patterns are consistent with real-life livestock production in Brandenburg. In contrast, the share of high-value crops does not align with current cropping patterns. Due to limited market access and other factors, the rather high production level in the irrigated scenarios (1 and 2) does not represent realistic cropping patterns. Limiting the share of potato and sugar beet is likely to decrease the irrigated area even further.

Irrigation already plays only a secondary role as a measure for decreasing production risk. Taking into account climate-induced future risk in growing plans only leads to a minor increase in irrigated areas. Irrigation is not economically feasible in wide parts of the state due to the high costs. When high-value crops are excluded from the scenarios, the share of irrigated areas lies below 2% of all agricultural areas in both scenarios. In this study, legal limitations regarding irrigation are not accounted for. Not all farms in Brandenburg have water rights for irrigation. Additionally, the actual water availability has not been considered. Several dry years in succession might result in insufficient water for irrigation. However, if predominantly the summer drought increases, while heavy rain intensifies over the winter, it is possible that the groundwater level does not necessarily decline. Considering legal barriers and water scarcity would most likely decrease the share of irrigated areas even further. Nevertheless, farmers with livestock may be motivated to irrigate in order to secure their fodder provision.

The considered climate change predictions forecast a decrease in precipitation over the summer months. Precipitation in Brandenburg is already relatively low, and the agricultural sector has been struggling for years. However, climate change is expected to increase the probability of extreme weather events such as floods and droughts. Due to the uncertainty of the occurrence of extreme events, the future climate conditions in this study do not account for such. Including the risk of extreme droughts might increase the relevance of irrigation as a tool to stabilize yields, while heavy rain throughout the winter months might increase groundwater availability.

The economic assessment in this study estimates trade-offs between the expected average gross margin and potential losses due to climate-induced risks. However, some simplifications had to be made. In real life, costs per hectare depend on the field size. In some cases, crop diversification leads to smaller areas per crop. However, due to the large average farm sizes in Brandenburg, there is no need to grow multiple crops on one field block to diversify. Unlike crop diversification within one field, no investment in new machinery and only minor adjustments in labor costs are required.

This study focuses mainly on the economic effects of diversification and irrigation. Crop diversification can bring major environmental benefits that have not been considered, such as improved soil fertility [23], carbon sequestration [23,24], overall biodiversity [25] and pest control [26].

Additionally, the simulated yield and management data used as a baseline for the bio-economic model do not account for soil heterogeneity within the AEZs. Crop diversification that accounts for soil heterogeneity can be a tool for more efficient resource use [15,27,28] with economic and environmental benefits. Consideration of improved resource use and ecological impacts will most likely further increase the importance of diversification and lower the risk-avoidance costs.

A further simplification had to be made with regard to prices. In order to be able to focus on climate-induced production risks, fixed prices were assumed. Market risks such as changes in input or market prices are likely to increase (climate-induced) uncertainty in the future. How climate change will affect prices in the agricultural sector is hard to predict. However, it is likely that real prices will increase. Progressing variability might amplify the relevance of the findings of this study by increasing the importance of diverse resilient farms. At the same time, rising input prices could alter the estimated trade-offs.

The target level in the Target MOTAD model is set to the area-weighted average value in the baseline climate scenario (1970–2010). This is based on the assumption that farmers are used to a certain level of income and will avoid having to adapt to major economic losses in the future. However, it could be argued that farmers will change their expectations with future climate change. Additionally, the same Target level has been used for all AEZs. Therefore, very unproductive areas are taken out of production in a series of unproductive years. Farmers in areas with below-average soils might already be used to a lower gross margin or benefit from larger field sizes. Differentiated Target levels are likely to decrease the share of AEZs taken out of production in Scenario 2.

Despite its limitations, this study provides some valuable insights based on a strong bio-economic analysis. Crop diversification has a major effect on climate-induced production risk. The trade-off between risk avoidance costs and a decrease in VaR showed that, especially in AEZs with moderate to low productivity levels, farms benefit from diversification.

How the obtained results align with the existing agricultural policy remains an interesting question. Under the new CAP (2023), the former crop diversification criterion is replaced by GAEC 7, which focuses on crop rotation as part of voluntary good agricultural and environmental conditions (GAECs) for farmers. Exceptions are made for organic farms, and farms below 10 hectares are assumed to fulfill GAEC 7 in all cases. In the previous CAP (2013), farms with arable land exceeding 30 hectares were required to cultivate at least three different crops, with the main crop covering no more than 75% of the land, and the combined two main crops not exceeding 95% of the arable land to meet the greening criterion [29]. The same criterion applies in the new CAP (2023), but with the additional requirement that farmers demonstrate how the measure "clearly helps preserve soil potential" [30].

This study highlights the importance of crop diversification as an adaption strategy to mitigate climate-induced production risks. In most areas of Brandenburg, the optimal approach for risk mitigation is the cultivation of approximately three crops simultaneously. Expanding crop diversification within GAECs beyond their soil preservation potential can contribute to enhancing economic farm resilience. As the measure has been least effective in highly productive areas, implementing a low subsidy targeting regions with lower gross margins could potentially enhance economic climate resilience at minimal risk avoidance costs. Site-specific case studies could provide deeper insight into the economic potential of crop diversification in such regions.

5. Conclusions

This study assessed the contribution of crop diversification and irrigation to economic resilience and the tradeoffs between maximizing the average gross margin and minimizing production risk. Two economic optimization scenarios were compared based on statewide simulated yield data. In Scenario 1, the average gross margin per hectare is maximized by selecting the most profitable crop rotation under local climate and soil conditions (AEZs) with consideration of future climate change. In Scenario 2, an implementation of the Target MOTAD (Minimization of Negative Deviation) model is used to minimize economic risk, taking climate-induced risks into account.

The results show that the Target MOTAD model leads to an increase in the number of crops grown annually in all AEZs. However, accounting for climate-induced future risk only leads to an increase in the irrigated area when high-value crops such as potatoes and beetroot were included in the crop rotations. The importance of diversification as a tool to reduce production risk was independent of the inclusion of high-value crops and the possibility of irrigation. The risk management effectiveness varied across the different AEZs. Diversification plays an important role in climate-resilient agricultural production and contributes most to economic resilience in areas with moderate to low productivity.

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