Adaptation is gaining attention as an inevitable answer to the challenges posed by climate change. The increasingly uncertain climatic conditions to which actors are exposed are becoming a constraint for their well-being. This paper looks at diversification as a key factor in reducing risk and means of coping with an uncertain climate. The aim of this work is to identify combinations of agricultural crops that reduce current and future climate related risks in the Guadiana River Basin. The Guadiana is a transboundary river between Spain and Portugal. The paper uses the variance of the revenue of agricultural crops as a proxy for climate risk, associating minimum variance with a region that is well adapted to the climatic conditions. The paper assesses risks as a function of the key agricultural crops and the climatic conditions that the Guadiana is subjected to. Crop yields under different climatic conditions are simulated by linking climate scenarios from General Circulation Models to the regional crop simulation model CropSyst. Borrowing from economic theory, the paper shows what cropping patterns reduce climate related risk. Crops with yields that have a low correlation provide the highest potential to reduce climate risks. Comparing model simulations of the scenario period 1961-1990 to the period 2071-2100, results suggest that the climate will have modest effects on the average crop yield, but will significantly reduce the variance of crop yields and change crop yield correlation. This changes the cropping pattern that provides the highest risk security.

Keywords: diversification, risk, climate impacts, adaptation, crop yield simulation

1 Introduction

Adaptation is increasingly seen as an inevitable answer to the challenges posed by climate change (IPCC, 2001). A challenge for people is to maintain well-being under the uncertain environmental conditions that they are exposed to. Recognising climate change implies coping with uncertainty about the future. Faced with the limits of predicting future environmental conditions, some academics have moved away from trying to identify adaptation options for specific scenario years. Instead they look for activities and adaptation strategies that are robust in terms of their performance under a range of possible future conditions (e.g. Gleick, 2003).

Literature in the research domains of agriculture and biodiversity have provided arguments that diverse systems are more robust and better able to cope with future risk. For example, research on diversified cropping systems has illustrated the great importance of diversity for reducing crop failure (Vandermeer 1989, Altieri 1994). It has been shown that minimizing risk while investing in crop production can be achieved by developing a portfolio of crop types that have low covariance with respect to the risk to which they are subjected. Tonhasca and Byrne (1994) investigated the effect of crop diversification on mitigating pests, whereas others have assessed the influence of the diversity of landscape structures in agriculture on sustainability of yields and biodiversity (e.g Thies and Tscharntke, 1999). Furthermore, crop diversity has been used in a range of African settings as an indicator of both ecosystem resilience and a strategy for food security (Blocka and Webb, 2001; Unruh, 2004). Fraser et al. (2005) use the theory on panarchy (Gunderson & Holling, 2001) to further elaborate a theoretical framework on the importance of portfolio management and diversification for reducing vulnerability in agro-environmental systems. Figge (2004) argues that not only the number of species determines biodiversity but the degree of diversification as well. In social sciences diversity is
related to innovation and learning (Olsson et al., 2006; Ostrom, 2005). In economic research Frenken et al. (2004) show that unrelated variety in regional knowledge across economic sectors dampens unemployment growth. In the area of financial services, planning and investing under uncertainty has been commonly employed. An approach that is widely used to determine investment strategies under uncertainty is Modern Portfolio Theory (Markovitz, 1952). It shows how different investments can be combined in a portfolio with a lower risk than the risk of the individual investments.

Although diversification is commonly studied in agricultural and economic research to meet demand fluctuations (Isik, 2006), fewer attempts are made to quantify the benefits of diversification in relation to coping with climate change (Aerts et al., 2007; Aerts & Werners, in prep). This paper studies diversification as an adaptation strategy to stabilise farmer income and reduce climate related risks. By doing so it aims to contribute to the quest for methods to identify land use patterns that are less vulnerable to climate change. Agriculture is explored as large land user that is at risk from climate change. Using results from crop simulations the paper aims to illustrate a method that could be extended to other land uses. More specifically this paper aims to assess whether crop diversification can reduce climate related risks at present and in the future. It shows in a quantitative example how to compare the correlation and variance of different crops to find more robust cropping patterns.

The paper illustrates how portfolio theory encourages to systematically discussing the relationship between the revenue and risk of individual crops and the revenue and risk of a mixed cropping pattern. This paper looks at diversification as an adaptation strategy to cope with an uncertain environment. The paper seeks to examine diversification not as a magic bullet that is always required, but as an attribute of agro-environmental systems with consequences for the way the system performs. The paper shows that under some conditions diversification can reduce climate related risks; under other conditions it can add to them. Results suggest that climate change modifies the variance and correlation of crop revenues. A re-evaluation of cropping patterns can provide higher risk security.

This paper has three main components. First the methods are introduced for modelling crop yield and assessing robust cropping patterns under climate change. Secondly, the results are presented for selected crop types, comparing baseline years with future scenarios. Thirdly, conclusions are presented and extensions of the research are discussed that could be pursued in future research.

This paper presents the first results of an investigation towards robust land use patterns. By including an overview of possible future research directions in Section 4, the paper explicitly calls for discussion and feedback from participants of the ICCC 2007 and other readers. The authors hope that the dialogue at the ICCC will mutually enrich our work, towards a more sustainable and adaptive future.

2 Method

2.1 Study area: the Guadiana river basin

Crop yields are simulated for the Guadiana river basin. The Guadiana is a transboundary river between Spain and Portugal (see Figure 1). The river basin has the typical semi-arid climate of Southern Europe. Climate change is expected to increases the pressure on the available water resources and thus the conflict between agriculture/irrigation and the environment. Groundwater reserves are already being threatened by salinisation and by overexploitation. A number of important ecosystems lie within the Guadiana basin. In the Portuguese part of the basin the Alqueva dam –the largest artificial lake of Europe- is being developed. Water allocation is still uncertain. Opportunities include those for tourism and for farming to change cropping patterns and increase irrigation. In the Spanish Upper Guadiana basin, groundwater development has substantially increased the livelihoods of the people in this area, but is over exploited at present. In the drought susceptible Guadiana river basin adaptation will be of vital importance to address the needs of farming, nature, forestry, fire risk reduction, human water use, and economic development. Although the methodology presented in this paper is applied to the
Guadiana basin it can be readily extended to the other regions to determine the potential benefits of diversification in reducing climate related risks.

![Study area: the Guadiana river basin (left: Iberian Peninsula with country borders; right: Portuguese and Spanish provinces in the river basin)](image)

### 2.2 Simulating present and future crop yield and revenue under climate change

To assess the impact of climate change on crop yields, crop yields are simulated over a baseline period (1961-1990) and a future period (2071-2100) by driving a crop growth simulation model (CropSyst) with outputs of a high-resolution regional circulation model (HIRHAM). CropSyst (Cropping Systems Simulation Model) is a multi-year, multi-crop, daily time step crop growth simulation model, developed with emphasis on a friendly user interface (Stöckle et al, 2003). The model simulates the soil water budget, soil-plant nitrogen budget, crop canopy and root growth, crop phenology, dry matter production, yield, residue production and decomposition, and erosion.

The model allows the user to specify management parameters such as sowing date, cultivar genetic coefficients (photoperiodic sensitivity, duration of grain filling, maximum LAI, etc.), soil profile properties (soil texture, thickness, water and nitrogen initial content), fertilizer and irrigation management, tillage and atmospheric CO2 concentration. The core of crop growth simulation is the determination of unstressed (potential) biomass growth based on crop potential transpiration and on crop intercepted photosynthetically active radiation. This potential growth is then corrected by water and nitrogen limitations to determine actual daily biomass gain. The simulated yield is obtained as the ratio between actual total biomass accumulated at physiological maturity and the harvest index (HI=harvestable yield/aboveground biomass).

Daily meteorological input data (minimum & maximum temperature, rainfall and solar radiation) were provide by the model HIRHAM (Extra High resolution) (12.5 km resolution) for two time slices: 1961-'90 (baseline period) and 2071-2100 (future period) for the SRES A2 scenario. For each grid point defined by the HIRHAM model in the Guadiana basin, soil properties (texture & thickness) were extracted from the European Soil Database (ESDB)\(^1\). The concentration of CO\(_2\) was set to 350 ppm for the baseline period and 700 ppm in the future scenario A2 after SRES (2000) and IPCC (2001).

**Selection of crops for the simulation**

The present study simulates main annual crops (rain fed and irrigated) cultivated in the Guadiana basin. To test and present the methodology of crop diversification this study focuses on durum wheat, barley, maize, sorghum and sunflower (Table 1). Criteria for crop selection include data availability, prevalence in the region, low inter-annual yield correlation, crops with independent yields, a mix of irrigated and rain fed crops, a simple relation between yield and farmer’s income, and experience with crop modelling in CropSyst.

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\(^1\) “ESDBv2 Raster Archive - a set of rasters derived from the European Soil Database distribution version 2 (published by the European Commission and the European Soil Bureau Network, CD-ROM, EUR 19945 EN)”
Although olive plantations and vineyard are well represented in the area, these were not yet included in the analysis. These crops have a multi year cropping cycle and climate impacts on crop yield depend on the history of several years. In addition quality aspects have to be taken into account when assessing the revenue of these crops, which is outside the scope of this study. Also outside the present scope is the complex agroforestry system of dehesa, supporting the production of a large variety of products such as cork, fodder, firewood, meat and honey. The integration of these more complex crops that are typical for the area will be an aim in future research.

### Crop Characteristics

<table>
<thead>
<tr>
<th>Crop</th>
<th>Characteristics</th>
<th>C3/ C4 Typical yield [t/ha]</th>
<th>Typical fraction of total crop</th>
<th>Av. Price [€/kg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Durum wheat</td>
<td>Temperate regions offer the most suitable growth conditions. Well adapted to different soil types. In temperate climate usually rain fed. The growth phases most sensitive to drought are shooting, flowering, caryopsis filling. Sensitive to water logging.</td>
<td>C3 PT: 1.7 (Soft) ES: 2.7</td>
<td>PT: 20% ES: 16%</td>
<td>0.15</td>
</tr>
<tr>
<td>Barley</td>
<td>More drought resistant than wheat. Under water limiting conditions it offer higher yields. High temperature tolerance in drought conditions.</td>
<td>C3 PT: 1.6 ES: 2.9</td>
<td>PT: 1.5% ES: 5%</td>
<td>0.30</td>
</tr>
<tr>
<td>Sunflower</td>
<td>Heat tolerant without extra maintenance. Rain fed in the study area.</td>
<td>C3 PT: 0.6 ES: 0.9</td>
<td>PT: 5.4% ES: 10%</td>
<td>0.23</td>
</tr>
<tr>
<td>Sorghum</td>
<td>Typical in sub-humid semi-arid areas. Requires high temperature. In comparison to maize, sorghum is less sensitive to seasonal climatic variation and water stress. In the study area it is grown both rain fed and irrigated.</td>
<td>C4 PT: no data ES: 8.0</td>
<td>PT: no data ES: 0.1%</td>
<td>0.14</td>
</tr>
<tr>
<td>Maize</td>
<td>Water is the main limiting factor in an arid climate: the yield strongly depends on irrigation possibilities. In the study area maize is almost entirely irrigated.</td>
<td>C4 PT: 9.4 ES: 9.5</td>
<td>PT: 6.1% ES: 4%</td>
<td>0.15</td>
</tr>
</tbody>
</table>

Sources: a) Ministerio de Agricultura, Pesca y Alimentacion Spain; b) EUROSTAT
1) Photosynthesis type; 2) Typical values for Portuguese part (PT; Alentejo region, Source b)) and Spanish part (ES; Source a)) of river basin.

Table 1: Crop characteristics of the simulated crops

As mentioned above, CropSyst allows choosing various parameters for the simulation including crop management options. Table 2 shows the key simulation parameters for the selected crops. The earliest starting date is the date before which sowing does not occur. The sowing date is the date at which the mean temperature has been equal or higher then the optimal sowing temperature for 5 consecutive days. Nitrogen fertilization was set at 150 kg/ha, applied at sowing time (50%) and at anthesis (50%).

The simulations of the crops sorghum and maize include irrigation. In the simulations, crops are irrigated when the plant available water is lower then the maximum allowable depletion in the soil (depletion depth). This threshold is expressed as percentage of maximum field water content. In future simulations, the irrigation will be applied according to usual water management in the area.

<table>
<thead>
<tr>
<th>Crop</th>
<th>Earliest starting date</th>
<th>Optimal sowing temperature [°C]</th>
<th>Fertilization [Kg nitrate/ha]</th>
<th>Irrigation</th>
<th>Depletion depth [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Durum wheat</td>
<td>01/01</td>
<td>7°</td>
<td>150</td>
<td>No</td>
<td>-</td>
</tr>
<tr>
<td>Barley</td>
<td>01/01</td>
<td>7°</td>
<td>150</td>
<td>No</td>
<td>-</td>
</tr>
<tr>
<td>Sunflower</td>
<td>01/03</td>
<td>10°</td>
<td>150</td>
<td>No</td>
<td>-</td>
</tr>
<tr>
<td>Sorghum</td>
<td>15/03</td>
<td>11°</td>
<td>150</td>
<td>Yes</td>
<td>0.35</td>
</tr>
<tr>
<td>Maize</td>
<td>15/03</td>
<td>11°</td>
<td>150</td>
<td>Yes</td>
<td>0.35</td>
</tr>
</tbody>
</table>

Table 2: Parameters for the simulation of different crops
Crop revenue

To compare crops, gross crop revenue is calculated by multiplying crop yield with an average crop price. Table 1 lists the crop prices used. In the remaining of this paper revenue refers to gross revenue. The estimation of crop revenue will be improved in future work. Estimates of net revenue (income) will include the costs of irrigation, fertilization, subsidies, labour, seeds and possibly price dynamics.

2.3 Assessing crop variance, correlation and robust cropping patterns under climate change

This paper builds on Modern Portfolio Theory (MPT) to identify cropping patterns with low climate related risks. MPT quantifies how different investments can be combined into a portfolio that has a lower risk than the investments individually. Given different possibilities for investment, MPT allows assessing what combination of investments has the lowest risk to realise a certain revenue (most stable income). MPT can be applied when four conditions are met (Elton and Gruber, 1995; Fraser et al., 2005): (1) there is more than one possible investment at any given time, (2) these investments are subject to risk, (3) there is information about the historical and / or expected revenue of the investments and (4) the same external conditions do not affect all investments equally. These conditions are met when deciding on a cropping pattern. Table 3 compares the terminology used in portfolio theory with the terminology used in agricultural management used in this paper.

<table>
<thead>
<tr>
<th>Terminology</th>
<th>Definition in MPT</th>
<th>Application in this paper</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Investment</strong></td>
<td>Items within a portfolio (also called asset)</td>
<td>Different crop types</td>
</tr>
<tr>
<td><strong>Portfolio</strong></td>
<td>Set of investments held by a person or an organization</td>
<td>Cropping pattern of different crops grown in an area (grid cell of 12.5 x 12.5 km)</td>
</tr>
<tr>
<td><strong>Correlation</strong></td>
<td>A measure of the degree to which assets are equally affected by external conditions</td>
<td>A measure of the degree to which crops are equally affected by climate change</td>
</tr>
<tr>
<td><strong>Diversification</strong></td>
<td>Dividing the investment into a variety of (partly-) uncorrelated assets</td>
<td>Growing different crops in an area (grid cell)</td>
</tr>
<tr>
<td><strong>Revenue ( \bar{R} )</strong></td>
<td>Total revenue (or return) is a measure of the combined income gain (or loss) from a portfolio.</td>
<td>Mean annual revenue earned from the crops grown (price times yield per acre) over a 30 year simulation period.</td>
</tr>
<tr>
<td><strong>Risk ( V )</strong></td>
<td>The uncertain outcome of an investment. Risk is measured by the standard deviation or variance of portfolio revenue</td>
<td>Risk is defined as the variance of the revenue in an area (grid cell) over 30 years (1961-1990 or 2071-2100)</td>
</tr>
<tr>
<td><strong>Efficient frontier</strong></td>
<td>Portfolios on the efficient frontier are optimal in both offering maximal expected revenue for a given level of risk and minimal risk for a given revenue</td>
<td>Cropping patterns on the efficient frontier are optimal in both offering maximal expected revenue for a given level of risk and minimal risk for a given revenue</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Table 3: Terminology used in this paper compared to MPT</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Generally, investments (crops types) are characterized by expected revenue (mean revenue) and risk (variance of revenue). It is assumed that farmers aim to maximise crop revenue and minimise the probability of low revenue (risk). They prefer crops with higher expected revenue and/or lower risks.</td>
</tr>
</tbody>
</table>

Following MPT (Harvey, 1995), the expected mean revenue \( \bar{R}_{cropping \_ pattern} \) of a cropping pattern with \( n \) different crops (with expected revenue \( \bar{R}_i \)) each grown at a share \( X_i \) can be estimated:

\[
\bar{R}_{cropping \_ pattern} = \sum_{i=1}^{n} \bar{R}_i \times X_i
\]  

(1)

with \( \bar{R}_i \) the expected revenue the individual crop \( i \). Here defined as the average of the annual crop yield over the simulation period.
The risk $V_{cropping \_pattern}$ of a cropping pattern is represented by the variance $V_i$ of its revenues, which can be estimated with the formula:

$$V_{cropping \_pattern} = \sum_{i=1}^{n} X_i^2 V_i + 2 \sum_{i=1}^{n} \sum_{j=i+1}^{n} X_i X_j \sigma_{ij}$$  \hspace{1cm} (2)

With $X_i$ the share of the individual crops in the cropping pattern, $V_i$ the variance of the revenue of crop $i$ over the simulation period and $\sigma_{ij}$ the covariance of the revenue of the crops $i$ and $j$ over the simulation period ($\sigma_{ij} = \frac{1}{N} \sum_{k=1}^{N} (R_{ik} - \bar{R}_i)(R_{jk} - \bar{R}_j)$).

The covariance between two crops is positive when revenues between the crops are positively related and negative when revenues between the crops are negatively related. The interpretation of the actual number of the covariance is difficult. Therefore, it is better to calculate the correlation between two crops, which lies between -1 and 1. A negative correlation between two crops $i$ and $j$ indicates that when the revenue of crop $i$ turns out to be above its expected value, then the revenue of crop $j$ is likely to be below its expected value, and vice versa. A positive correlation suggests that when $i$’s revenue is above (below) its expected value, then $j$’s will also be above (below) its expected value. The correlation between two crops $i$ and $j$ is defined as:

$$\rho_{ij} = \frac{\sigma_{ij}}{\sqrt{V_i V_j}}$$  \hspace{1cm} (3)

With $V_i$ and $V_j$ the variances of the revenue of the crops $i$ and $j$ over the simulation period.

From equation (2) follows that the variance of a cropping pattern is less than the weighted sum of the variances of the individual crops when the correlation between the crops is less than 1. In other words, diversification is beneficial as long as there is less than perfect positive correlation between the revenue of crops.

Crop diversification for two crops is illustrated in Figure 2. The figure plots the expected revenue and variance of a hypothetical cropping pattern. The curved lines are obtained by changing the share of the two crops in the cropping pattern from only A (point A) to only B (point B). The different curves correspond to different values for the correlations $\rho$ between the two crops.

**Figure 2: Expected revenue of cropping patterns of two crops for different correlations between the crops revenues (after Ross et al, 2002)**

A farmer can develop different cropping patterns by varying the share of crop A and B (points located more to the left represent cropping patterns with higher proportions of crop A, which has a smaller expected revenue and risk than crop B). The diversification effect applies to the curved lines, where the correlation is smaller than unity. The lower the correlation between the two crops, the more bent is the curve indicating that the same revenue can be earned at lower risk. The point MinV (minimum
variance), which is located on each of these curves, represents the minimum variance cropping pattern. The share of crop A at in the cropping pattern with MinV is:

\[ X_{A, \text{MinV}} = V_B - \sigma_{AB} / V_A + V_B - 2\sigma_{AB} \]  

(4)

The backward bending always occurs if \( \rho \leq 0 \), but may or may not occur if \( \rho > 0 \). Obviously, no farmer wants to grow crops with an expected revenue below the minimum variance cropping pattern. Therefore, the so-called efficient frontier representing all efficient cropping patterns for a given correlation lies between MinV and B.

Following MPT and its extension the Capital Asset Pricing Model (Sharpe, 1964) the optimal combination of risky investments (or Tangent Portfolio) can be calculated after introducing a risk free revenue. The risk-free revenue is the revenue that it is assumed can be obtained without risk, for example by putting the money in the bank that would otherwise be invested in crops. It defines the minimum revenue an investor will accept. Thus the share of crop A in the optimal cropping pattern OptCP with two crops is (see also Figure 2 & Harvey, 1995):

\[ X_{A, \text{OptCP}} = \frac{(R_A - R_{\text{risk-free}}) V_B -(R_B - R_{\text{risk-free}}) \sigma_{AB}}{(R_A - R_{\text{risk-free}}) V_B + (R_B - R_{\text{risk-free}}) V_A - (R_A + R_B - 2R_{\text{risk-free}}) \sigma_{AB}} \]  

(5)

When risk and revenue for individual crops are known as well as the correlation coefficients between these crops, MPT allows for quantitatively determining the cropping pattern at MinV, efficient frontiers and the optimal cropping pattern OptCP for a given risk free revenue \( R_{\text{risk-free}} \) such as plotted Figure 2.

3 Results

3.1 Crop yields, revenue and variance

Table 4 lists the average crop yield, crop revenue and standard deviation (square root of the variance) in the simulation periods: i) Climate baseline year (1961-1990) and ii) Scenario A2 (2071-2100)). The standard deviation is included because it is easier to compare to crop yield and revenue than the variance. The standard deviation presented here is the average over the grid cells. Crop yields and revenue fall with in the typical range for the region (see also Table 1). It is recalled that revenue refers to gross revenue. Since it does not include the cost of irrigation, care has to be taken when comparing non irrigated and irrigated crops.

<table>
<thead>
<tr>
<th>Crop</th>
<th>Yield [kg/ha]</th>
<th>Revenue [euro/ha]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Durum wheat</td>
<td>2124 ± 995</td>
<td>2118 ± 858</td>
</tr>
<tr>
<td>Barley</td>
<td>2143 ± 945</td>
<td>2154 ± 840</td>
</tr>
<tr>
<td>Sunflower</td>
<td>996 ± 497</td>
<td>1034 ± 444</td>
</tr>
<tr>
<td>Sorghum</td>
<td>10985 ± 1263</td>
<td>9262 ± 1199</td>
</tr>
<tr>
<td>Maize</td>
<td>10145 ± 1055</td>
<td>8702 ± 959</td>
</tr>
</tbody>
</table>

Table 4: Average crop yield and revenue ± standard deviation (Climate baseline year (1961-1990) / Scenario A2 (2071-2100))

For the non-irrigated C3 crops (durum wheat, barley and sunflower) average crop yield does not change significantly between the two simulation periods. Temperature and water stress are found to be counterbalanced by carbon fertilization. In addition temperature stress is compensated by starting the growth season earlier. Average crop yield of the irrigated C4 crops (sorghum and maize) decreases. Temperature stress is not counterbalanced by carbon fertilization.
Variance decreases for all crops, mostly because the variance of the rainfall during the growth cycle in the A2 scenario is lower than in the climate baseline years. In addition the influence of atmospheric carbon concentration on crop yields grows. The carbon concentration typically has a much lower inter-annual variation than rainfall or temperature.

3.2 Correlation of crops

Table 5 lists the correlation of revenue of the different crops in the simulation periods i) Climate baseline year (1961-1990) and ii) Scenario A2 (2071-2100)). Because the correlation matrix is symmetric, only the upper half is shown.

<table>
<thead>
<tr>
<th>Correlation</th>
<th>Durum wheat</th>
<th>Barley</th>
<th>Sunflower</th>
<th>Sorghum</th>
<th>Maize</th>
</tr>
</thead>
<tbody>
<tr>
<td>Durum wheat</td>
<td>1</td>
<td>0.96 / 0.97</td>
<td>0.58 / 0.72</td>
<td>0.34 / 0.19</td>
<td>0.32 / 0.14</td>
</tr>
<tr>
<td>Barley</td>
<td>1</td>
<td>0.57 / 0.71</td>
<td>0.33 / 0.20</td>
<td>0.32 / 0.16</td>
<td></td>
</tr>
<tr>
<td>Sunflower</td>
<td>1</td>
<td>0.48 / 0.26</td>
<td>0.46 / 0.23</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sorghum</td>
<td></td>
<td></td>
<td></td>
<td>1</td>
<td>0.94 / 0.93</td>
</tr>
<tr>
<td>Maize</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1</td>
</tr>
</tbody>
</table>

Table 5: Correlation of crop yields (Climate baseline year (1961-1990) / Scenario A2 (2071-2100))

The correlation of crops that have a high correlation at present remains high in the future. Barley and wheat are an example of two crops that respond very similarly to climatic conditions and are highly correlated. The correlation between the non-irrigated C3 crops (durum wheat, barley and sunflower) increases from the baseline scenario to the future A2 scenario. This indicates that the future climate affects crops more similar than the present climate. In other words, the future climate regime is more uniformly suitable (or unfavourable) for the different non-irrigated crops studied here. This is especially true for crop combinations with sunflower. The medium correlation of sunflower and barley or durum wheat at present is largely explained by their different growth seasons. Barley and durum wheat are spring crops, whereas sunflower is a summer crop that is sown later. Temperature rise in the future scenario allows for earlier sowing of sunflower. Thus the growth cycle of sunflower will have a larger overlap with the growth cycle of barley and durum wheat, adding to the correlation.

The correlation between the non-irrigated C3 crops and the irrigated C4 crops (sorghum and maize) declines. Already the non-irrigated C3 crops are differently impacted by climatic conditions than the irrigated C4 crops. In the future this difference will increase. The yield reduction in the previous section already indicated that the non-irrigated C3 crops and the irrigated C4 crops are affected differently.

At present crop revenue is calculated by multiplying crop yield with an average crop price. This way the correlation of crop types depends on the yield and its variance only. It does not depend on price.

3.3 Diversification with barley and sunflower

This section illustrates how diversification of cropping patterns can reduce climate related risk. Results are presented spatially of a cropping pattern with two crops: barley and sunflower. These crops were chosen because they have a medium correlation (see Table 5), suggesting a benefit from diversification. In the Guadiana basin, barley is considered an alternative for sunflower because of its higher drought tolerance. Both crops are rain fed. For combining a rain fed with an irrigated crop the cost of irrigation ought to be taken into account, which is outside the scope of the present paper.

Figure 3 illustrates spatially the share of barley in a cropping pattern of barley and sunflower that has the lowest variance in crop revenue (Equation 4). Figure 4 illustrate the share of barley in the optimal cropping pattern OptCP of barley and sunflower (Equation 5). Figure 4 shows the results for a risk free revenue of 105, assuming a 5% return on investment can be achieved risk free. The optimal cropping pattern is relatively insensitive to the assumed risk free revenue. In both figures the results for the
climate baseline years are on the left and for the A2 climate scenario on the right. Each dot in the figure represents a 12.5km grid cell.

![Figure 3](image1.png)

**Figure 3**: Share of barley when combining it with sunflower to give the lowest variance in total crop revenue (left: climate scenario baseline years 1961-1990; right: climate scenario A2 2071-2100)

![Figure 4](image2.png)

**Figure 4**: Share of barley when combining it with sunflower to give the optimal revenue – variance ratio for total crop revenue (left: climate baseline years 1961-1990; right: climate scenario A2 2071-2100)

Figure 3 shows that at present a combination of sunflower and barley with a high share of sunflower has the lowest variance in revenue. In the central to eastern region a larger share of barley yields the lowest revenue variance. In the future climate scenario, increasing the share of barley will in most locations stabilise revenue. This is especially true for the central and eastern part of the river basin and the southwestern part of Extremadura. Although the cropping patterns in Figure 3 minimise revenue fluctuations and thus have lowest risk, this risk reduction comes at a cost. The revenue of barley per hectare is higher than that of sunflower. Farmers may choose to take a higher risk at a higher expected revenue. Figure 4 shows that at present the optimal cropping pattern according to MPT (equation 5) has a higher share of barley than the cropping pattern with the lowest variance (Figure 3). In the future climate scenario, the optimal cropping pattern raises the share of barley further.

Table 6 lists the average crop revenue and its standard deviation for barley, sunflower, the cropping pattern with the lowest variance and the optimal cropping pattern. It illustrates how diversification reduces the variance of crop revenue and risk. Although the variance of the individual crops reduces in the future scenario, the minimum variance is not reduced. Barley and sunflower are stronger correlated in the future which reduces the benefits of diversification. Table 6 includes the average share of barley in the different cropping patterns, confirming the trend visualised spatially in Figure 3 and Figure 4. The climate change scenario suggests that when comparing barley and sunflower a higher share of barley can provide higher risk security in the future.

<table>
<thead>
<tr>
<th>Revenue [euro/ha]</th>
<th>Barley</th>
<th>Sunflower</th>
<th>Cropping pattern MinVar</th>
<th>Optimal cropping pattern</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Base: 1961-1990</strong></td>
<td>276 ± 122</td>
<td>227 ± 113</td>
<td>231 ± 90 (share barley 0.22)</td>
<td>246 ± 96 (share barley 0.47)</td>
</tr>
<tr>
<td><strong>A2: 2071-2100</strong></td>
<td>278 ± 108</td>
<td>236 ± 101</td>
<td>245 ± 90 (share barley 0.29)</td>
<td>262 ± 96 (share barley 0.64)</td>
</tr>
</tbody>
</table>

Table 6: Average crop revenue ± standard deviation of cropping patterns with different shares of barley
4 Discussion, Conclusions & Future work

4.1 Crop diversification, revenue, variance and correlation

Whenever people can decide between different activities and the revenue on the individual activities is subjected to risk, portfolio theory can be used to develop robust sets of activities. These conditions hold for land use planning that aims to cope with climate change and for crop management in particular. The Guadiana river basin example shows that crops can be combined to reduce climate related risks. It shows how Modern Portfolio Theory (MPT) can help in developing more robust cropping patterns that generates the highest revenue under an acceptable risk (uncertainty). Although the example is relatively simple, it confirms that MPT encourages discussing systematically the relationship between the revenue and risk of individual crops (or other activities) and the revenue and risk of complete cropping patterns (or other land uses). It also shows how important it is to understand the correlation of the revenue of different crops. Comparing model simulations of the scenario period 1961-1990 to the period 2071-2100, results suggest that climate change will have modest effects on the average crop yield, but will significantly reduce the variance of crop yields and change crop yield correlation. This changes the cropping pattern that provides the highest risk security. As such MPT is a valuable tool to learn and re-evaluate cropping patterns once more information about climate risks becomes available. The method can incorporate information from many different data sources.

Apart from revenue and variance, the choice for a particular cropping pattern depends obviously on more factors than those mentioned in the Guadiana river basin case. For example, the costs differences of growing different crops are neglected for reasons of simplicity. As are price fluctuations and other not climate related uncertainties. In addition crop selection depends on the risk perception of farmers and the risk they are willing to accept. Personal preferences and experience also play a role in crop selection. In this light, the method illustrated in this paper assesses the potential benefits of diversification in reducing climate risks. It does not represent the full mechanism underlying crop selection. The comparison to real cropping patterns will produce important additional information.

Other limitations of the method are that MPT assumes that:

- Revenues are normally distributed and well represented by their average value, variance and covariance. This may not be the case for climate change impacts and large impacts (3 to 6 standard deviations from the average) may occur more frequently than the normal distribution would expect.
- Variance of returns is an adequate measurement of risk.
- Given a certain expected return investors will prefer lower risk (lower variance) to higher risk.
- All investors have access to the same information and agree about the risk and expected revenue of all investments. Hence all investors have the same expectations about security returns for any given time period. This is unlikely in the case of expectations about climate impacts.
- Risk-free rates exist with limitless borrowing capacity and universal access.

4.2 Future work

Model results will be compared to real cropping patterns to assess the potential benefit resulting from diversification as well as the barriers to take advantage of changes in cropping pattern. To allow for the evaluation of real cropping patterns different crop types will have to be included in the presented methodology. In view of the current agriculture pattern of the Guadiana River Basin citrus, olives and vineyards will be assessed in the future. This analysis can include real data as well as model results from models other than CropSyst. Further calibration of both CropSyst results and the calculated cropping patterns with observed data is suggested, focussing on regional differences and spatial patterns.

Special attention will go out to the traditional dehesa system that combines oak plantations with cattle grazing and the production of many related products. It is the main agro-forestry system in large part
of the basin that has adapted to the prevailing climatic conditions over centuries. Highly diversified in itself it offers a challenging topic for further research.

Future work could take into account crop management options that enable adaptation to climate change, such as irrigation techniques and changes in the timing of planting and crop handling. Stakeholders in the region expressed interest in the benefits of diversification with non-agricultural activities such as tourism. Dissemination of the potential of these options will be part of future research.

The concept of diversification fits well in current climate change and vulnerability research (e.g. Adger, 2004; O’Brien et al., 2004), which focuses more on reducing vulnerability. The risk-revenue ratio might be an appropriate proxy for vulnerability and adaptive capacity of land use systems. So far this paper adopts an anthropocentric utilitarian point of view: systems are valuable because humans expect a future benefit. The inclusion of values of systems beyond the human use is still to be considered.

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