StartClim2010.D

Integrated precautionary and adaptation measures for the Marchfeld region

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Sustainable Economic Development,
BOKU

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Kurzfassung

Dürre zählt zu einem der wichtigsten agrarmeteorologischen Risiken und soll in den mittleren und höheren Breiten in den nächsten Dekaden zunehmen (IPCC, 2007). Daher ist es wichtig (i) den Zusammenhang zwischen Dürreereignissen und Ertragsschwankungen österreichweit quantitativ zu analysieren und (ii) die ökonomischen sowie umweltbedingten Effekte sowie negativen Externalitäten verschiedener Anpassungsmaßnahmen in der landwirtschaftlichen Pflanzenproduktion zu untersuchen. Basierend auf einem historischen Klimadatensatz (1975-2007) wurden moderate und extreme Dürreszenarien für Österreich erstellt, welche eine Zunahme der trockenen Tage für die Periode 2008-2040 abbilden. Die Analyse dieser Dürreszenarien ergab für die untersuchten Kulturarten (Mais, Winterweizen und Gerste) bei standardisierten Bewirtschaftungsverfahren ohne Bewässerung einen signifikanten Rückgang der Erntemengen von 60% bis 90%.

Vor allem im Marchfeld, einem der wichtigsten aber auch trockensten Pflanzenbaugebiete in Österreich, ist Beregnung von Gemüse sowie anderen hochwertigen Produkten bereits heute unabdingbar. Mit häufigeren Dürreereignissen nimmt die Bedeutung von Beregnungssystemen zu – eine mögliche Anpassungsmaßnahme an den Klimawandel – aber auch die Notwendigkeit Grundwasserressourcen zu schonen. Die Sprinklerberegnung kann eine profitable Anpassungsmaßnahme für die Region Marchfeld sein, denn die Pflanzenerträge können im Vergleich zu einem Bewirtschaftungsverfahren ohne Bewässerung beinahe verdoppelt werden. Jedoch kann diese Anpassungsmaßnahme den Druck auf die regionale Trinkwasserversorgung beträchtlich erhöhen. Das wassereffizientere aber auch wesentlich aufwendigere Tröpfchenberegnungssystem wird aus rein wirtschaftlichen Überlegungen eher keine Verbreitung finden – es sei denn, Ausstattungskosten werden subventioniert. Unseren Untersuchungen nach wird die Bereitschaft in eine Tröpfchenberegnungsanlage zu investieren durch die Einführung eines marktpolitischen Instruments wie Wasserpreise nicht erhöht. Stattdessen verringern Wasserpreise die Wahrscheinlichkeit überhaupt in eines der beiden Beregnungssysteme zu investieren.

Abstract

Drought is one of the major agro-meteorological risks to agriculture, which is expected to increase in the middle and high latitudes in the next decades (IPCC, 2007). Hence, it is important to (i) quantitatively analyze the relationship between drought events and fluctuations in crop yields, and (ii) to investigate the economic and environmental effects as well as negative externalities of possible adaptation measures in agricultural production. Based on different drought scenarios for Austria, we find a significant decrease in crop yields of 60% to 90% (for corn, winter wheat and barley) in case of rain-fed crop production.

Especially in the Pannonian region Marchfeld, which is one of the most important as well as driest crop production areas in Austria, irrigation of vegetables and other high quality products is indispensable already today. The importance of irrigation systems to adapt to climate change as well as the necessity to sustain groundwater resources increases with more frequent drought events. Sprinkler irrigation can be a profitable adaptation measure in the Marchfeld region as crop yields are distinctly increased compared to a management without irrigation. But it could also considerably enhance the pressure on regional groundwater aquifers. We find that investing in more water-efficient but also more expensive drip irrigation systems is unlikely unless subsidies for equipment cost are granted. Even the implementation of water prices would not increase the probability to adopt a drip irrigation system, but rather decrease the probability to invest into either of the two irrigation systems.

D-1 Introduction

Drought is known as one of the major agro-meteorological disasters as it can occur with high frequency, covers large areas and can cause big losses to agricultural production and economy (Zhang, 2004; Brázdil et al., 2009). A meteorological drought is commonly defined as deficits in precipitation over a defined period and region as compared to climatological average values. Furthermore, agricultural droughts are the resulting impact of lacking water supply for agricultural crops, leading to reduction of annual crop yields in the affected regions. Increasing temperatures can lead to a higher evapotranspiration causing a higher soil moisture deficit. This effect can be intensified, especially when precipitation amounts are decreasing. Thus throughout Europe some areas will be affected by more extreme drought events with uncertainty on extent and spatial distribution. Already during the period 1901-2005, a warming trend (+0.90°C) has been observed throughout Europe, which has been accelerating in the last 30 years (Alcamo et al., 2007). For the next decades, several Regional Climate Models (RCMs) project a larger warming trend in winter than in summer in Northern Europe and a larger warming trend in summer than in winter in the Central and Southern Europe (Christensen and Christensen, 2007).

Regarding the development of precipitation it is generally assumed that annual precipitation sums will decrease in Southern Europe but increase in Northern Europe (IPCC, 2007). For Central Europe, it is often predicted that precipitation rates may decline in summer but increase in winter (Jacob et al., 2008; Thaler et al., 2008; Eitzinger et al., 2009). Additionally, for Central and Southern Europe, it has been estimated that areas under water stress can increase from 19% in 2007 to 35% in 2070 (IPCC, 2007). Nevertheless, the uncertainty about precipitation scenarios is always larger than the uncertainty about temperature scenarios, because temperature is a spatially homogeneous variable while precipitation is not (Randall et al., 2007). The spatial pattern of precipitation is fairly irregular and therefore highly variable (Tebaldi et al., 2004; IPCC, 2007; Eitzinger et al., 2009). Overall, the risk of drought is expected to increase in middle as well as high latitudes (IPCC, 2007). For instance, Brázdil et al. (2009) have analyzed droughts in the Czech Republic in the period 1881-2006 based on different drought indices and have confirmed a statistically significant tendency to more intensive dry episodes in the investigated region.

Regarding Austria, future climate scenarios show an increase in average annual temperatures by approximately 1.6 C° between 2008 and 2040 (Strauss et al., 2010). Similar results have been derived by a RCM for Central Europe (Jacob et al., 2008). Thaler et al. (2008) suggest that precipitation rates in Eastern Austria are likely to decrease in summer and increase in winter periods.

These climatic changes will affect agriculture in numerous ways (Olesen and Bindi, 2002; Eitzinger et al., 2009). On the one hand, higher mean temperatures can increase the length of the potential growing season and more ambient CO_2 in the atmosphere can increase the resource efficiency of plants. On the other hand, higher temperatures will induce higher evaporation rates, and most likely also increase heat stress and enhance the duration to maturity of certain species. This could potentially reduce crop yield quality and quantities. In addition, it is expected that the frequency and occurrence of extreme weather events such as intensive rainfalls, hail, or drought may increase in a warmer climate. More intensive rain showers could negatively affect soil erosion as Klik and Eitzinger (2010) have shown in a case study for the region Weinviertel in Lower Austria. Changes in pest and disease problems are not expected so far (Olesen and Bindi, 2002), but monitoring is highly recommended (Eitzinger et al., 2009).

Consequently, it is important to (i) quantitatively analyze the relationships between fluctuations in crop yields and drought occurrence as well as to assess the potential damage and direct loss due to drought; and (ii) investigate integrated adaptation measures for agricultural production which are economically and environmentally sound.

Thus, chapter D-3 focuses on the development of different drought scenarios for Austria followed by biophysical impact studies on crop production at the national level. The drought scenarios are based on a daily climate change dataset with spatial resolution of 1 km² developed by Strauss et al. (2010). To produce this dataset, linear regression and bootstrapping methods have been used to project regional climate scenarios in Austria for the period 2008-2040 with consideration of spatio-temporal correlations. In the chapters D-4 and D-5, we perform analyses of adaptation strategies for the Pannonian region Marchfeld, which is one of the most important and the driest agricultural production regions in Austria. In chapter D-4, we assess the economic and environmental performance of a selected set of potential adaption measures, which could mitigate possible negative effects of climate change and especially more frequent drought events. A comprehensive list of adaptation measures can be found in the recently released first draft of the Austrian 'National Adaptation Strategy' (BMLFUW, 2010). We aim to contribute to this strategy by analyzing the economic and environmental effects of adaptation measures (i.e. irrigation and fertilization measures) in the Marchfeld region. Therefore, we investigate how the choice of management measures would change under drier climatic conditions (e.g. -20% of annual precipitation sums as described in Strauss et al. (2010), and in section D-3.1.2). We further focus on the changes in regional producer surplus, percolation water, nitrogen leaching and organic carbon content in the topsoil. We have found that sprinkler irrigation is effective in reducing economic cost of climate change, but exerts considerable pressure on regional groundwater aquifers. Consequently, we also investigate the possibility of adopting more water-efficient drip irrigation systems for agricultural production in the region.

In chapter D-5, we investigate a farmer's decision whether to adopt a sprinkler irrigation system or a more water-saving drip irrigation system. In this analysis, we assume a decreasing precipitation trend (reaching -20% of annual precipitation sums in the year 2040 compared to the values in the period 1975-2007; cp. Strauss et al., 2010) and uncertainty about the occurrence of annual precipitation patterns. We also investigate how these decisions change on different soil types and when policy measures (water pricing and equipment subsidies on drip irrigation systems) are introduced. We apply a stochastic dynamic programming approach.

We use the biophysical process simulation model EPIC (Environment Policy Integrated Climate; Williams, 1995; Izaurralde et al., 2006), which simulates important biophysical processes in agricultural land use management. EPIC simulates among others crop yields, nitrate leaching and topsoil organic carbon contents for different weather scenarios, site conditions, and crop management variants in Austria. The simulation outputs are mainly based on five thematic datasets addressing biophysical modeling aspects: (i) land use data, (ii) topographical data, (iii) soil data, (iv) cropland management data, and (v) climate data. The climate data is provided by the statistical climate model for Austria developed by Strauss et al. (2010) and by the drought model introduced in chapter D-3.

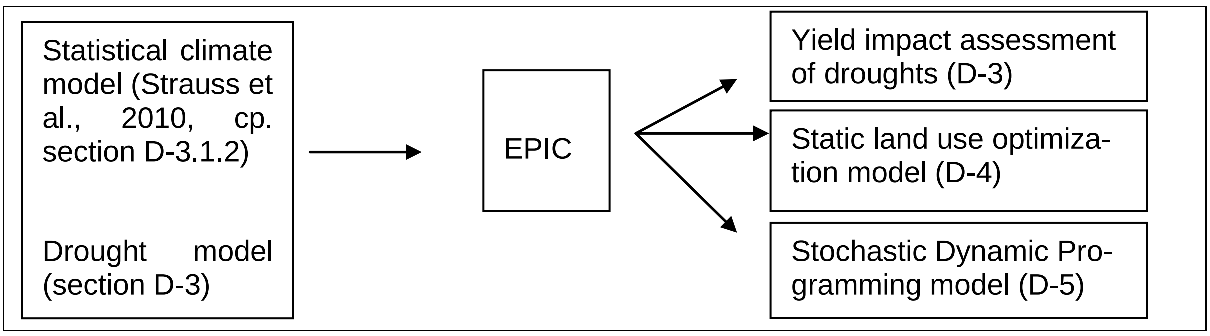

Fig. D-1.1: The modeling framework (own representation)

The modeling framework is illustrated in Fig. D-1.1. EPIC has already been applied and validated for the Marchfeld region (Schmid et al., 2004; Schmid et al., 2007; Cepuder et al., 1997; Hofreither et al., 2000; Liebhard et al., 2004; and Strauss et al., 2011).
The different analyses of our report will be submitted to international scientific journals by acknowledging the StartClim2010 program.

D-2 The region Marchfeld

The region Marchfeld is our case study region in the chapters D-4 and D-5. It is a part of the Vienna Basin and is influenced by a semi-arid climate with cold winters with frequently strong frost events and little snow fall as well as hot and dry summers. Marchfeld is one of the most important as well as the driest crop production areas in Austria (Schmid et al., 2004). Over the period 1975-2007, the average annual precipitation sum was 531 mm; for the vegetation period from April to September the average monthly precipitation sum was only 331 mm (Strauss et al., 2010). Consequently, irrigation of vegetables and high quality products is indispensable and the importance of irrigation will increase with more frequent drought events. The total arable area is about 65,000 ha. Around 60,000 ha support irrigation, of which 30% are regularly irrigated.[1] The arable area is cultivated by approximately 1900 farmers (Schmid et al., 2004). Currently, two types of sprinkler irrigation systems are used in Marchfeld: hand-moved sprinkler irrigation and the travelling-gun system (“Rain-star”).[2] Cereals, root crops and vegetables comprise the main agricultural products of the region. Livestock production is only marginal.

About 312 soil types can be differentiated in Marchfeld (Anonymous, 1972). These have been categorized into five soil types, according to the amount of total available soil water capacity in 1.2 cm soil depth and humus content in the topsoil (BFW, 2009). In one of the following analysis (chapter D-5) we concentrate on the most frequent soil type (soil 1), a Chernozem from fine sediment and loess formation with available soil water capacity of 196 mm as well as topsoil humus contents of 2.6%. Soil 1 represents approximately 49% of the region. Soil 2 is a Para-Chernozem with 59 mm available soil water capacity and 1.4% topsoil humus content, representing 14% of the region (Schmid et al., 2004; BFW, 2009).

In the region Marchfeld, intensive agriculture expanded from the 1970s onwards, and led to a decrease of the annual groundwater level by around 2 to 3 m from the 1970s to the 1990s (Stenitzer and Hoesch, 2005). As a response, the Marchfeld channel (*Marchfeldkanal*) was built to recharge and secure groundwater aquifers. High precipitation rates in the past five years (MAREV, 2011) have caused groundwater levels to increase considerably by 2 m since 2006 (Office of the Federal State of Lower Austria, 2011). This has now made it necessary to implement remediation measures as many housing cellars have been inundated[3]. Nevertheless, a situation similar to the 1970s could occur again if precipitation rates were to decline and irrigation measures increase as a response.

Nitrate pollution of groundwater is a serious environmental concern in Marchfeld. The legal threshold levels of 45 mg/l for groundwater and 50 mg/l for drinking water are exceeded at most gauge stations in the Marchfeld region. The region is therefore a groundwater rehabilitation zone (Federal state low of Lower Austria: LGBl. Nr. 6950/22-0). Fig. D-2.1 shows the slight increase of annual mean nitrate concentration levels of groundwater in Marchfeld from 1993 to 2004, and that they are, on average, always above the groundwater threshold level. Intensive agricultural production is said to be the major cause for these high nitrate pollution levels (Umweltbundesamt, 2006).

Excessive irrigation can influence nitrate pollution as it changes the ratio between percolation and nitrate leaching and consequently concentration levels. Also, with increasing percolation, nitrates can be leached into the groundwater and can contaminate drinking water. Stenitzer (2004) reports a runoff and percolation of irrigation water of ~73% for

[1] www.marchfeldkanal.at; accessed in February 2011

[2] see footnote 1

[3] www.regionmarchfeld.at

high quality crop cultivation in Marchfeld. Drip irrigation systems allow for a better application of water into the plant root zones, with little runoff and percolation. These systems may also increase evapotranspiration and crop yields (Ward and Pulido-Velazquez, 2008), which could increase the potential for the adoption of drip irrigation in the Marchfeld in the future.[4]

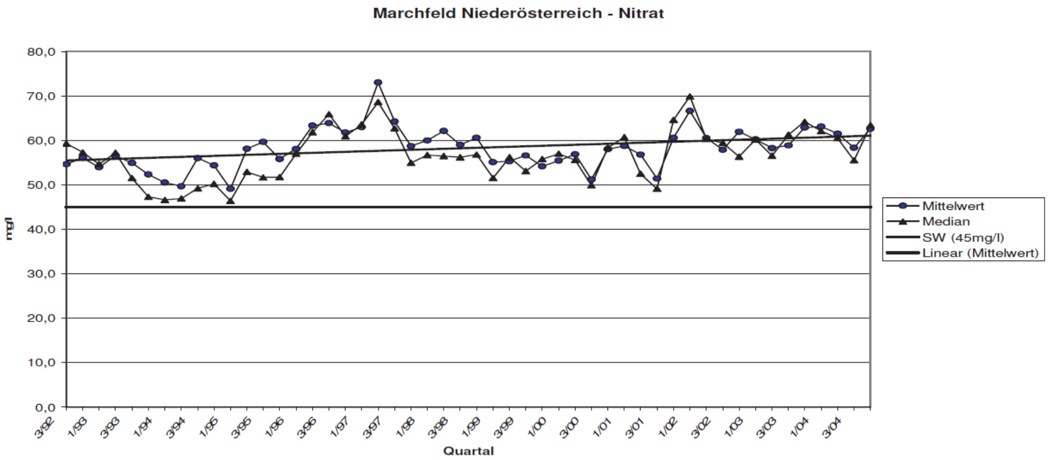

Fig. D-2.1: Nitrate concentration levels in groundwater in Marchfeld (Umweltbundesamt, 2006, p.41)
Note: Triangles represent median values; circles represent mean values; and the bold line gives the linear trend of mean values.

Strauss et al. (2011) found that higher average temperatures negatively affect crop yields due to higher evaporation rates in the Marchfeld region. Less water availability can reduce crop yields and consequently profits. Thaler et al. (2008) have assessed the effects of climate change on winter wheat, spring barley and maize in Marchfeld. Their findings suggest that winter wheat yields could increase, especially due to higher CO_2 concentrations, but yields for maize and spring barley would stagnate or decrease. The effects are highly sensitive to the soil water storage capacity.
Farmers can respond to these climatic changes by applying agronomic adaptation measures that mitigate possible negative effects and/or exploit possible new opportunities. Olesen et al. (2011), Olesen and Bindi (2002) and to a similar extent also Eitzinger (2010) differentiate between autonomous adaptation measures that can be implemented in the short-term (e.g. soil conserving tillage practices; cultivation of more stress-resistant and thermophile crops; adjustment of crop rotations, livestock breeding, fertilizer and pesticide use as well as sowing and harvesting dates; risk mitigation through insurance or storage) and planned adaptation measures with a long-term horizon (e.g. changes in land use and land allocation; improved irrigation infrastructure; new land management techniques with focus on water-efficiency; breeding of more stress resistant crops; improved monitoring systems; risk diversification and mitigation; increasing storage capacities; adoption of new production systems; measures that decrease evaporation rates). Other categorizations of agricultural adaptation measures are also available, see for example Iglesias et al. (2007) who differentiate between managerial, infrastructural and technical measures. Adaptation measures that affect water availability are assumed to be among the most important ones (Olesen et al., 2011). This will be especially true for regions that already have low annual precipitation sums, such as the Marchfeld. In these regions, irrigation is seen as an effective measure to secure crop production and income (Eitzinger et al., 2009).

[4] www.marchfeldkanal.at; accessed in February 2011

D-3 Drought scenarios for Austria[5]

Depending on the disciplinary perspective, drought can be defined in several ways, for instance, soil moisture drought and water stress of vegetation; or hydrological drought, which is described by the analysis of stream-flow, lake, or reservoir level data. The most commonly used definition of drought is the 'meteorological drought'. It is defined as deficits in precipitation over a defined period and region as compared to the climatological average values. The most important weather parameter in relation to drought events is precipitation which is – when being small or zero in a certain period - the primary cause of drought in Central Europe. But also temperature, wind speed and humidity can intensify drought impacts (Brázdil et al., 2009). Agricultural drought is described as a result of lacking water supply for agricultural crops leading to reduction of annual yields. In order to specify agricultural drought, comprehensive knowledge about crop cultivation and management is needed.[6] The definition of 'agricultural drought events' is specified by, for example, daily rainfall and crop water consumption in Yurekli and Kurunc (2006), the deficiency or absence of precipitation during the growing season or by long dry spells in Zhang (2004), and the number of consecutive days during which the actual evapotranspiration to potential evapotranspiration ratio (*AE/PE*) remains below a threshold value in Richter and Semenov (2005).

There exist many studies dealing with drought events and their impacts on agricultural production. For instance, Brázdil et al. (2009) have documented for the Czech Republic consistently lower crop yields for spring barley, winter wheat, forage crops on arable land, and hay from meadows in years with drought episodes compared to years without droughts. Also the drought of the Songliao Plain in China between spring to autumn of 1989 caused a large reduction of total maize production (Zhang, 2000). Zhang (2000) has shown that probability and spatial distribution of drought occurrence are closely connected with the rainfall during growing season of the crop and aridity index as climatic factors. Furthermore, the extent of risk of drought disaster to crop production is mainly decided by occurrence frequency, duration and intensity of drought disaster, spatial extent of damage caused by drought (i.e., the area affected by drought) and regional production level of the specific crop (Yang and Zhang, 1996). According to the theories of physical geography and field investigation, the possibility of drought disaster occurrence on different landforms and types of soil is different. Generally, the types of soil in which drought disaster can easily occur are mountain burozem, plain burozem, chestnut soil, chernozem, grassmarshland chernozem and grassmarsh soil (Zhang, 2004). Drought has a tendency to occur often (Zhang, 2000), and its degrees of damage on maize production have increased recently with global warming.

Only few studies have investigated the impacts of increased frequency of extreme events on production (e.g. crop yield) and the implications for risk management (e.g. diversification, regulations within the crop management practices). Therefore, we have developed drought scenarios based on a daily climate change dataset for Austria with spatial resolution of one km² developed by Strauss et al. (2010). Both the drought scenarios and the climate change dataset are described in more detail in section D-3.1.2 and D-3.1.3.

In this chapter, we use weather data for the period 1975-2008 from Strauss et al. (2010) to define a drought index for Austria. This index shows the daily proportion of dry area in Austria following a Beta-distribution. A Beta-distribution can, for example, be used to

[5] Paper prepared for submission to an international scientific journal by Franziska Strauss and Erwin Schmid (University of Natural Resources and Life Sciences, Vienna (BOKU), Institute for Sustainable Economic Development, Feistmantelstraße 4, 1180 Vienna, Austria) and Elena Moltchanova (University of Canterbury, Department of Mathematics and Statistics, Private Bag 4800, Christchurch 8140, New Zealand)

[6] http://edo.jrc.ec.europa.eu/php/index.php?action=view&id=16; June 2011

describe the distribution of an unknown probability value. The parameters of the Beta-distribution have been manipulated for the development of different drought scenarios. These drought scenarios together with other site specific data (e.g. topographical data, soil types, crop management variants, land use data) are input to the EPIC model (see chapter D-1), which simulates many biophysical processes and impacts on e.g. crop yields, soil parameters and stress factors. The eastern territory of Austria (e.g. the Marchfeld region) is one of the most important agricultural production regions, but also one of the driest compared to the West and the South of Austria, and therefore more vulnerable to an increased frequency of drought events. As crop yield variation is mostly due to the water availability (Ewert et al., 2002), the effects of increasing drought events from 2011 to 2040 have been investigated on different crops i.e. corn, spring barley and winter wheat using EPIC output data. A major aim of this study is to assess the crop yield impacts of increased drought events and to analyze the crop resistance against droughts as well as the need for irrigation. Moreover, we aim to provide a basis for adaptation strategies to mitigate the negative effects of extreme drought events.

D-3.1 Data and model framework

D-3.1.1 Climatological data

The climate data set for Austria (Strauss et al., 2010) has been used, which includes daily time series of solar radiation, maximum temperature, minimum temperature, precipitation, relative humidity and wind speed from 1975 to 2007. It is based on spatially interpolated climatologies of temperature and precipitation with high resolution which have been combined to define clusters with homogenous climate characteristics ('climate clusters'). For each climate cluster, a weather station with daily time series was selected to represent the long-term (inter-annual) and short-term (daily) variability. The criteria for climate cluster classification i.e. mean annual precipitation sums and mean annual temperatures for the period 1961-1990 are taken from the ÖKLIM dataset (Auer et al., 2000) and listed in Tab. D-3.1.

Tab. D-3.1: Criteria of climate cluster classification using mean annual precipitation sums and mean annual temperatures averaged over the period 1961-1990 (cp. Strauss et al., 2010).

Precipitation [mm]	class	Temperature [°C]	class
≤500	500	≤ 0	0
>500 to ≤600	600	>0 to ≤2.5	1
>600 to ≤700	700	>2.5 to ≤4.5	3
>700 to ≤800	800	>4.5 to ≤5.5	5
>800 to v900	900	>5.5 to ≤6.5	6
>900 to ≤1000	1000	>6.5 to ≤7.5	7
>1000 to ≤1250	1250	>7.5 to ≤8.5	8
>1250 to ≤1500	1500	>8.5 to ≤9.5	9
>1500	2000	>9.5 to ≤10.5	10
		>10.5 to ≤11.5	11
		>11.5 to ≤12.5	12
		>12.5	13

The 60 climate clusters established by our classification procedure are shown in Fig. D-3.1 for the period 1975-2007 (compared to the original period 1961-1990 the mean annual temperatures increased by approximately 0.7 °C when using the calculated linear temperature trend of 0.05 °C per year). As an example, the climate cluster 509 (precipitation class 500 + temperature class 9) represents annual precipitation sums lower than 500 mm and mean annual temperatures between 8.5 °C and 9.49 °C.

The historical mean annual temperature classes range between 0 and 10 (only small parts of Vienna and the West of the Neusiedlersee had mean annual temperatures above 10 °C in the period 1975-2007), where the class 0 contains all regions with mean annual temperature of 0 °C or less. The mean annual precipitation classes range from 500 to 2000, where the 500 class contains all regions with precipitation sums below 500 mm, and the 2000 class contains all regions with precipitation sums above 1500 mm (Tab. D-3.1). The highest annual precipitation sums are in the mountainous regions of the West and the South as well as in the northern foothills of the Alps. The lowest annual precipitation sums are in the flat areas of the East, the northeast and the southeast of Austria. We are especially interested in impacts of increased drought events in these regions.

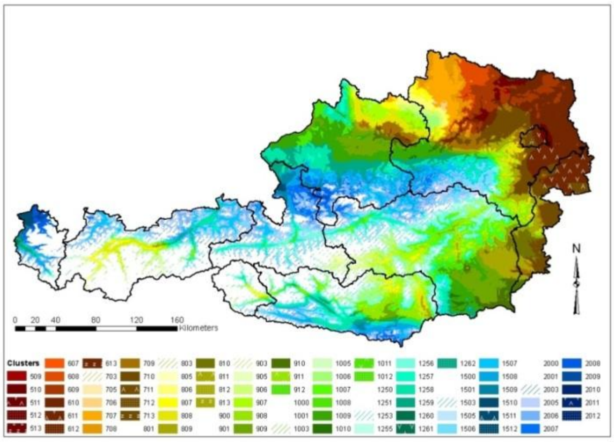

Fig. D-3.1: The Austrian climate clusters in the period 1975-2007 (cp. Strauss et al., 2010).

D-3.1.2 Statistical climate model (cp. Strauss et al., 2010)

Strauss et al. (2010) have compiled a dataset based on linear regression and bootstrapping methods to project regional climate scenarios in Austria for the period 2008-2040. One assertion is that the local weather variations and the development of regional climates in the next three decades could be better captured in a statistical climate change model – compared to RCMs - by using historical meteorological data. The representation of spatial frames and variability are important in climate modeling, because regions often show a wide range of different climate patterns. For instance, the Lower Austrian region could climatologically be described as a dry continental lowland climate in the northeast, as a continental highland climate in the northwest, as a transition climate in the foothills of the Alps, and as a very humid and snowy mountain climate in the northern congestion of the Alps (Fig. D-3.1). Small-scale climate patterns have been considered in the regional climate modeling of Strauss et al. (2010).

The authors calculated a mean linear temperature trend of 0.05 °C per year for Austria using a homogenized dataset from 1975 to 2007, which corresponds to a temperature increase of 1.65 °C in 33 years. Unlike temperature, no clear long-term trends have been discernible in the precipitation data, which is in agreement with the IPCC report for the annual precipitation sums in the Alpine region (IPCC, 2007). Consequently, Strauss et al. (2010) have assumed that there is no trend in precipitation for any of the climate clusters for the next three decades. But some reservation may still be appropriate, because some RCMs show a shift of precipitation amounts from the summer to the winter, and others show an increase in the inter-annual variability (IPCC, 2007). All stations in Austria show a clear decadal variability in the annual precipitation sum which has a magnitude of ±10%. To take into account the possibility of such decadal variabilities and any possible shifts in the seasonal precipitation distribution, several differing assumptions for alternative precipitation scenarios have been made in Strauss et al. (2010), and some of the resulting precipitation scenarios (e.g. -20% of annual precipitation sum) have been used in the chapters D-4 and D-5.

D-3.1.3 Drought index

Based on the historical daily climate dataset for Austria from 1975 to 2007, we have developed a drought index $DI_{d,A}$ for each day d in the period 1975-2007 for Austria A (see Fig. D-3.2):

$$DI_{d,A} = M[dd,cl] * Area_{cl}/Area_{A} \quad (1)$$

where $M[dd,cl]$ is a matrix containing all dry days dd in a climate cluster cl, and a dry day means that the daily precipitation sum is 0 mm, $Area_{cl}$ is the area of the respective climate cluster in km², and $Area_{A}$ is the area of Austria in km².

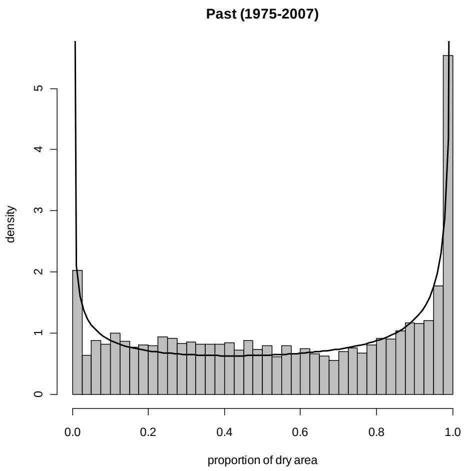

Fig. D-3.2: Empirical Beta-distribution (black line) with the parameters 0.60 and 0.45 and the underlying measured proportion of dry days in the period 1975-2007.
Note: 0 means that the whole Austrian area is wet; 1 means that the whole Austrian area is dry.

The empirical distribution of our drought index follows a Beta-distribution (Fig. D-3.2). The Beta-distribution is a family of continuous probability distributions defined on the interval (0, 1) parameterized by two positive shape parameters, typically denoted by α and β. The domain of the Beta-distribution can be viewed as a probability, and in fact the Beta-distribution is often used to describe the distribution of an unknown probability value. The Beta-density function can take on different shapes depending on the values of the two parameters α and β.
We have developed different drought scenarios for Austria (Fig. D-3.3). The first scenario assumes a continuation of the empirical Beta-distribution as observed in the past (scenario 1 with parameters 0.60 and 0.45; further denoted as 'base run scenario'), in the second and third scenarios, we have increased the sampled proportion of dry days in Austria according to changed parameters of the Beta-distribution (scenario 2 with parameters 0.75 and 0.50; scenario 3 with parameters 2.5 and 0.50). Thus, with scenario 2 a situation where the whole country is dry occurs more often compared to the base run scenario resulting in an increase of drought events. Scenario 3 describes an even more extreme increase of drought events. The proportion of dry days when the entire country is wet is effectively zero.
The spatial correlations have been considered in our drought scenarios by applying a bootstrap procedure and sampling an entire set of daily records at a time. For each climate cluster we have bootstrapped the days according to the underlying Beta-distribution under consideration of the respective month. Moreover, the daily information

on all parameters (precipitation, maximum and minimum temperatures, solar radiation, relative humidity, and wind speed) has been kept so that the daily correlations remain the same as in the past. However, we assume that temporal correlations over a longer period than one day will change.

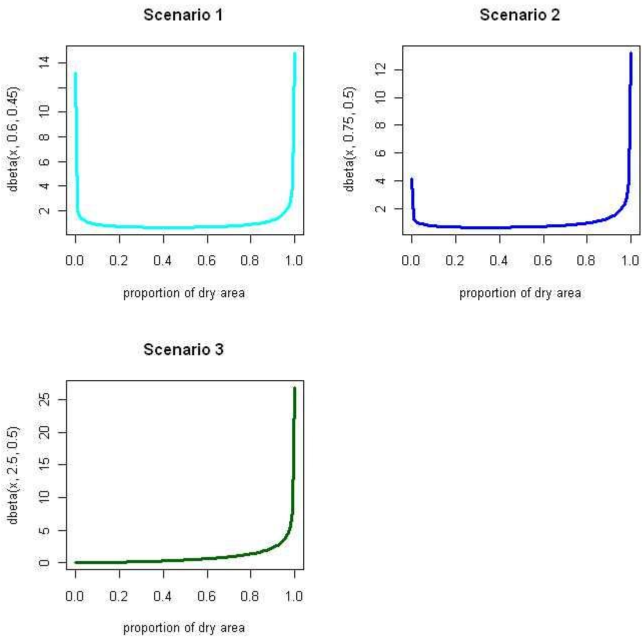

Fig. D-3.3: Drought scenarios 1, 2 and 3 by different parameters in Beta-distribution.

The impact assessment of increased drought events has been conducted by analyzing simulation output of the biophysical process model EPIC (see chapter D-1) and is shown in the following section.

D-3.2 Results

D-3.2.1 Drought scenarios in Austria

We have investigated the annual mean values of precipitation, maximum and minimum temperatures, and found that mean annual precipitation sums of Scenario 3 are lowest compared to Scenario 1 and 2 (Fig. D-3.4), and mean annual maximum temperatures are rising most in Scenario 3 (Fig. D-3.5), whereas mean annual minimum temperatures of Scenario 3 are often lower than in Scenario 1 and 2 (Fig. D-3.6).

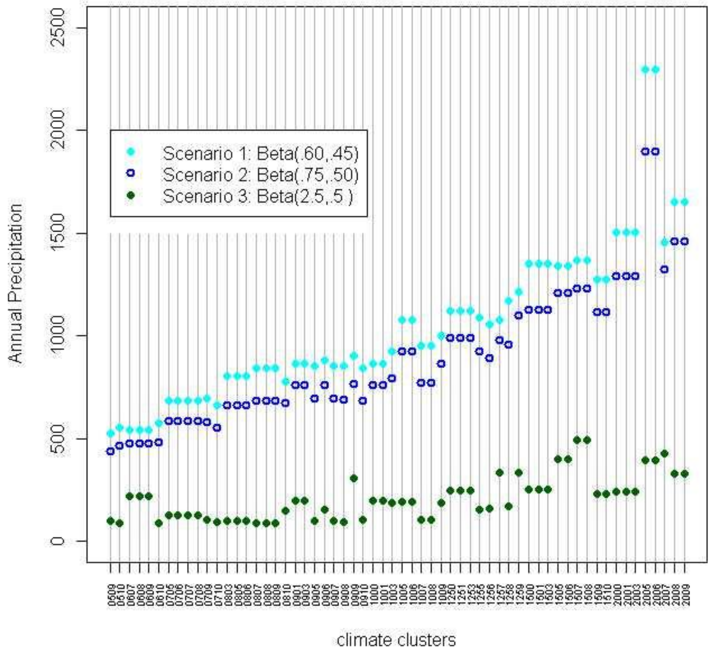

Fig. D-3.4: Mean annual precipitation sums in mm for the three drought scenarios and 60 climate clusters in Austria in the period 2008-2040.

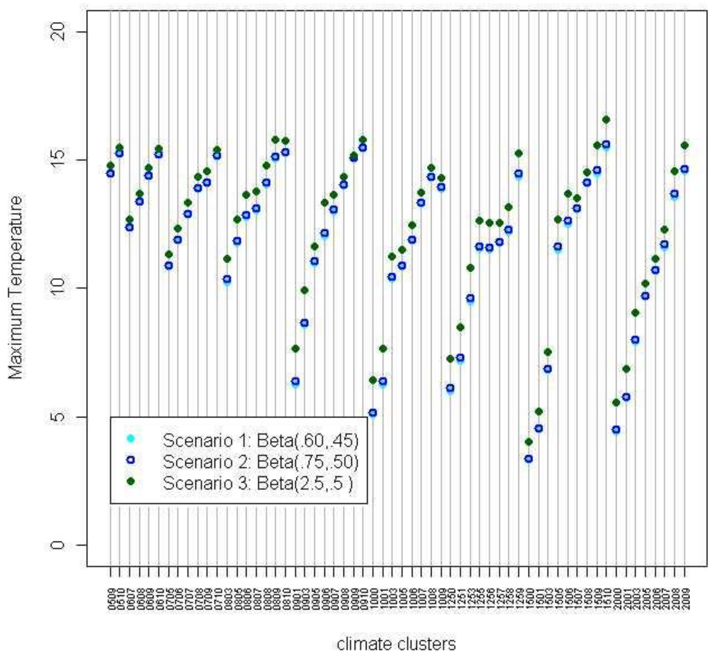

Fig. D-3.5: Mean annual maximum temperatures in °C for the three drought scenarios and 60 climate clusters in Austria in the period 2008-2040.

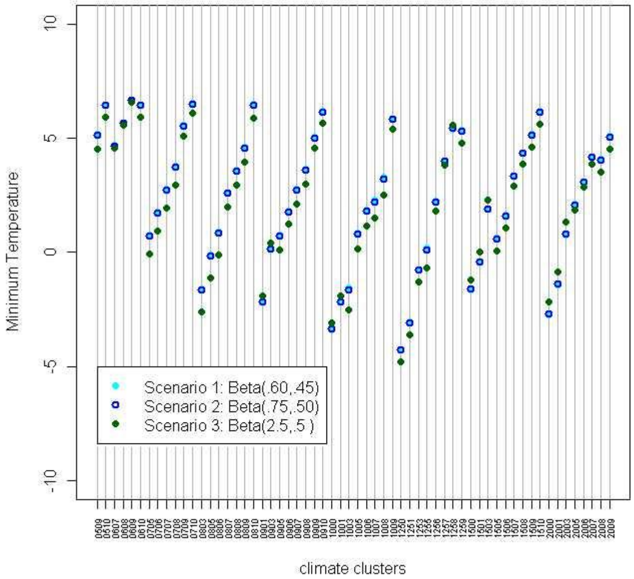

Fig. D-3.6: Mean annual minimum temperatures in °C for the three drought scenarios and 60 climate clusters in Austria in the period 2008-2040.

We have further analyzed in which months the most severe decrease of precipitation sum occurs compared to the past period 1975-2007. Fig. D-3.7 shows for three selected climate clusters that the decrease of precipitation sum is higher in the summer half year (between 20% and 30%) compared to the winter half year (small decreases or increases between 2% and 4%).

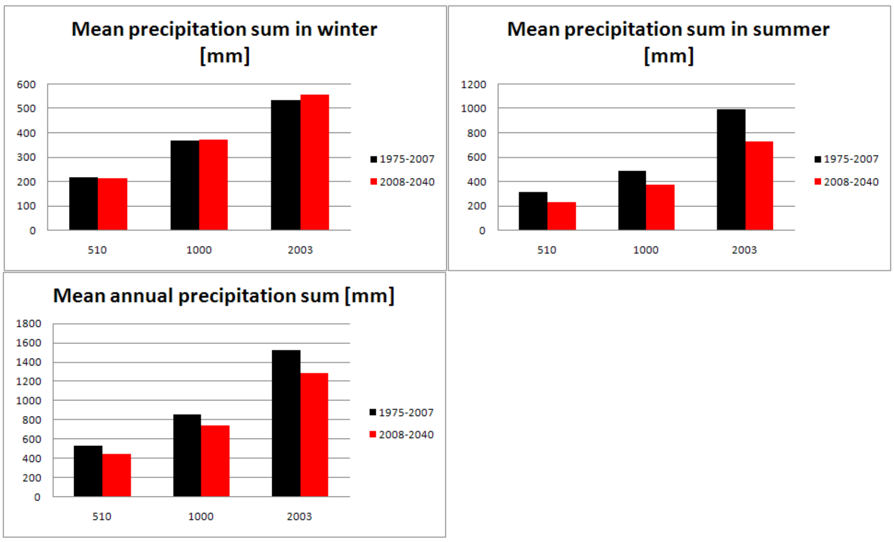

Fig. D-3.7: Winter, summer and annual precipitation sums for three different climate clusters (510, 1000, 2003) in the periods 1975-2007 and 2008-2040.

D-3.2.2 Impacts of droughts on the agricultural production

We have simulated the impacts of increased drought events, as represented by our drought scenarios 2 and 3, on crop yields by comparing percentage changes in crop yields between the base run scenario and the two drought scenarios. Crop yields have been simulated with EPIC for corn, winter wheat and spring barley. Fig. D-3.8 shows the percent differences of simulated corn yields between drought scenario 2 (or drought scenario 3) and the base run scenario in Austria. In many parts of the country, and especially in the eastern lowlands, corn yields decrease with more intense and frequent drought events, as expected. In these regions, the annual precipitation sums of the past period 1975-2007 were low compared to other regions, and a continued decrease in precipitation amount leads to water being the most limited factor. However, in the foothills of the Alps and in the South-East of Austria corn yields can increase by up to 30%. In these regions, enough water is available for the crop and the increase in temperature leads to an increase of crop yields, as corn is a thermophile plant. The percentage changes are different when comparing results of scenario 3 with results of our base run scenario. The number of regions where the reduced precipitation amount becomes a limiting factor for corn production increase substantially. Compared to the base run scenario, corn yields with drought scenario 3 decrease by 60% to 90%. Regions with increases in corn yields almost completely disappear. The results for winter wheat (Fig. D-3.9) as well as for spring barley (Fig. D-3.10) are similar to the results shown with corn yields.

Our results are confirmed with other research results. For instance, Brázdil et al. (2009) have analyzed drought effects on different crops in the Czech Republic from 1881 to 2006. They have found lower impacts on winter wheat production than on spring barley production. This is due to a better developed root system and earlier onset of growth in the spring for the former. At the national level, areas that are located at higher elevations with higher precipitation sums tend to be less vulnerable to droughts.

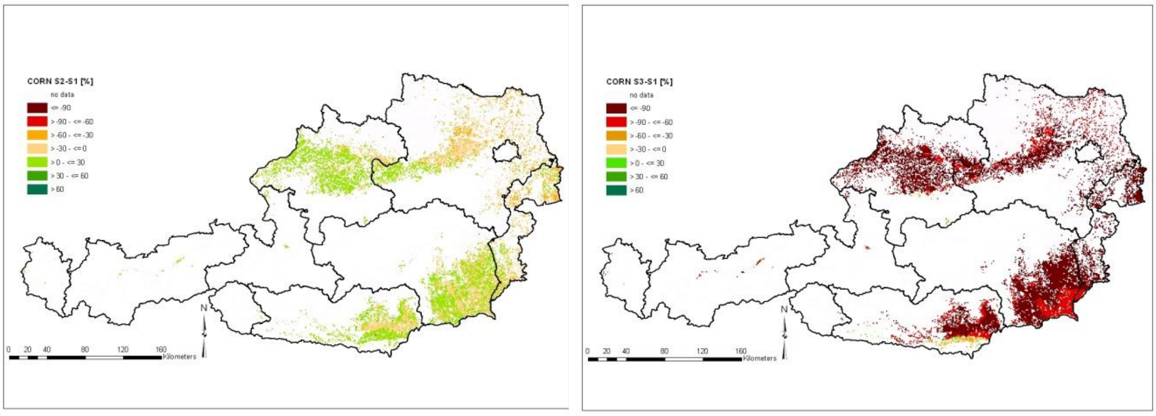

Fig. D-3.8: Difference in corn yield between drought scenario 2 (left) / drought scenario 3 (right) and the base run scenario [%]

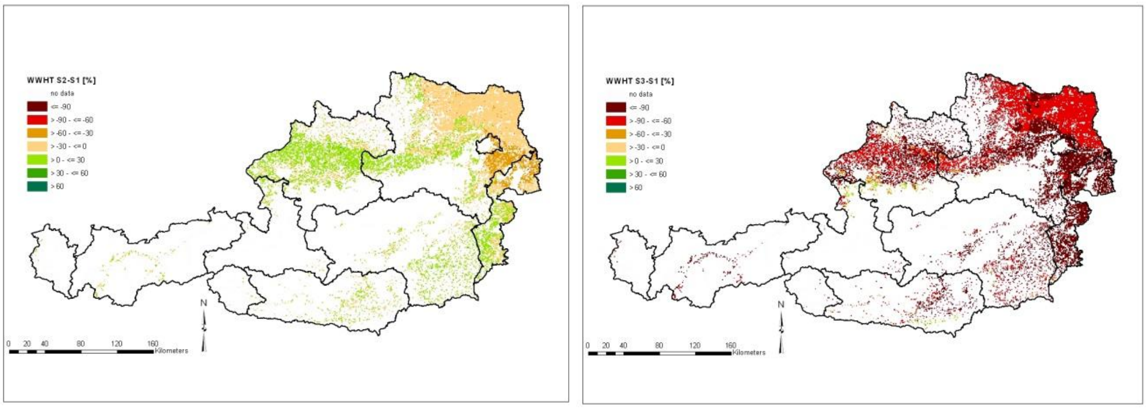

Fig. D-3.9: Difference in winter wheat yield between drought scenario 2 (left) / drought scenario 3 (right) and the base run scenario [%]

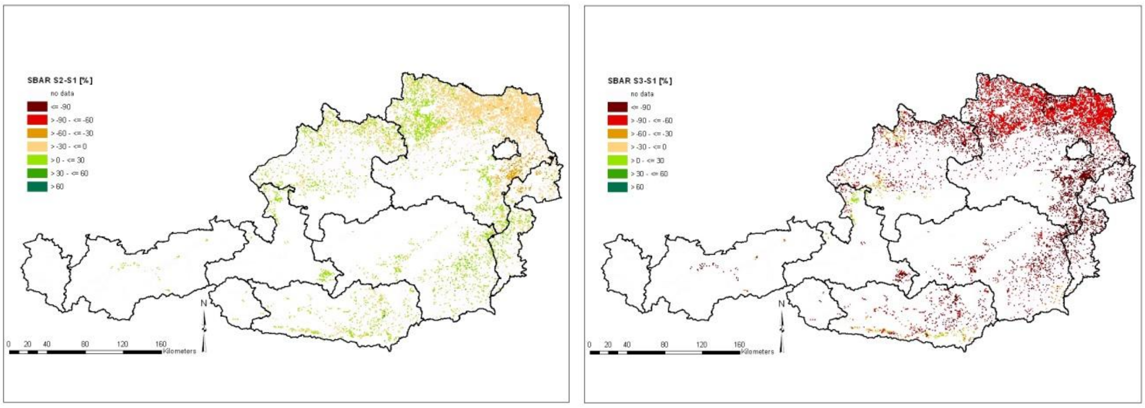

Fig. D-3.10: Difference in spring barley yield between drought scenario 2 (left) / drought scenario 3 (right) and the base run scenario [%]

D-3.3 Summary and conclusions

Different drought scenarios for Austria have been developed using a drought index following a Beta-distribution. The first scenario assumes a similar frequency and occurrence of drought events which leads to similar climatic conditions in the period 2008-2040 compared to the period 1975-2007. In drought scenario 2, we have significantly increased our drought index, leading to more dry conditions in Austria compared to the period 1975-2007. In drought scenario 3, the climatic conditions are extreme. A day where the whole country is wet does not occur anymore.

We have assessed crop yield impacts of increased drought events on a national level by comparing simulated crop yields with EPIC (cp. chapter D-1) between the three drought scenarios. The comparisons between drought scenarios 2 and 1 indicate a substantial crop yield decrease for corn, winter wheat and spring barley, especially in the North-East of Austria, which is one of the driest regions. Comparisons between drought scenarios 3 and 1 indicate decreases in crop yields between 60% and more than 90% throughout most of the country.

The developed drought scenarios as well as the crop yield impact simulations of increased drought events will be further analyzed in a scientific paper which will be submitted to an international journal.

Acknowledgements

This study has been part of the EU project ccTAME (http://www.cctame.eu/) as well as of the StartClim2010 research project ‘Integrated precautionary and adaptation measures for the Marchfeld region’ of the BMWF, BMWFJ, BMLFUW and ÖBf (http://www.austroclim.at/index.php?id=startclim2010).

D-4 Integrative model analysis of adaptation measures in the Marchfeld region[7]

We assess the economic and environmental effects of selected adaptation measure in the Marchfeld region. Thus, we aim to contribute to the Austrian ‘National Adaptation Strategy’ which provides a comprehensive list of adaptation measures in agriculture (Eitzinger et al., 2009; BMLFUW, 2010). In this study we focus on two different kinds of adaptation measures: drip and sprinkler irrigation and adjustment of fertilization rates. We investigate how the choice of management measures can change under warmer and drier climatic conditions, similar to those described in section D-3.1.2. Ideally, adaptation strategies should be effective and sustainable. Operationally and with regard to our regional analysis, this could mean that adaptation measures in Marchfeld should mitigate the negative effects of climate change or make use of new opportunities so that:

- regional income increases / is sustained / or the loss is minimized;
- the environment is not polluted above a legal threshold level (e.g. nitrate concentrations);
- natural resources (e.g. soil and water) are preserved for future generations.

Hence we focus on the changes in regional producer surplus, percolation water, and nitrogen leaching, organic carbon in the topsoil and irrigation water use.
We present a regional land use optimization model that integrates biophysical outputs from EPIC (see chapter D-1). This integrative model analysis allows us to simulate both the choices of farmers adapting to changes in climatic conditions and the environmental consequences of their respective land use and management choices.
This chapter is structured as follows: First, we provide an overview of our data input. Second, we describe our methodological approach. Third, we show the results of our model runs. At the end we summarize and discuss possible implications of our results.

D-4.1 Data

Our case study takes place in the agriculturally important region Marchfeld (cp. chapter D-2). Our analysis accounts for the arable land in the region (~61604 hectares). Marchfeld is subdivided into its municipalities and each municipality is further divided into homogenous response units (HRU). HRU share similar topographical characteristics such as altitude, inclination and soil types. Hence, they can be used as an interface between biophysical and economic simulation models (Schmid et al., 2005).
Climate data from Strauss et al. (2010) are used to simulate the effects of climate change in Marchfeld for the period 2031 to 2040 (cp. section D-3.1.2). We include two climate change scenarios. Scenario A is characterized by a temperature increase of 1.6 °C compared to the reference period 1996-2005 and a similar distribution of precipitation, and Scenario B is characterized by a temperature increase of 1.6 °C as well but a decrease of annual precipitation sums by 20%. These climate data together with soil, topographical and crop management data are fed into the biophysical process model EPIC (cp. chapter D-1). EPIC can simulate outcomes for – inter alia – crop yield, biomass, percolation and nitrogen leaching and organic carbon in the topsoil. The outcomes are per hectare and will be compared to the reference scenario 1996-2005.
Farming systems and tillage practices are assumed to be conventional. In order to allow farmers to adapt to climate change we included five different crop management options:

[7] Some parts of this chapter were taken from the short paper “Integrative model analysis of adaptation measures in the Marchfeld region” prepared for the 21st congress of the Austrian Society of Agricultural Economics, 4th to 6th October 2011, Bozen, Italy by Mathias Kirchner, Franziska Strauss, Christine Heumesser und Erwin Schmid (University of Natural Resources and Life Sciences, Vienna (BOKU), Institute for Sustainable Economic Development, Feistmantelstrasse 4, 1180 Vienna, Austria)

- Standard: standard fertilizer measures
- Reduced: reduced fertilizer rates
- Low: low fertilizer rates (no commercial fertilizer)
- Drip: drip irrigation
- Sprinkler: sprinkler irrigation

Furthermore, the data set includes 22 different crop rotation systems. Each crop rotation system has been simulated for a length of ten years (i.e. the length of each period) and they comprise various combinations of the 21 crops i.e. alfalfa, barley, red clover, corn, corn silage, durum wheat, beans, fallow, field peas, oats, potatoes, sugar beet, soybean, sunflower, timothy hay, triticale, winter rape, winter rye, and winter wheat.

Average annual crop prices for the period 1998-2005 are calculated based on price data from Statistics Austria (2011). In order to account for support policies (e.g. single farm payment), we assume a general policy premium of 300 €/ha/a. Variable costs of production such as maintenance and fuel cost, purchase of seeds, pesticides and fertilizers as well as service and insurance costs are derived from the standard gross margin catalogue (BMLFUW, 2008) and from own data sources. Variable costs for both sprinkler and drip irrigation (i.e. labor and electricity consumption) as well as their respective annual capital costs are also taken into account[8]. We hold crop prices and production costs constant in both periods in order to better identify the effect of climate change on the environmental outcomes.

D-4.2 The regional land use model

We have developed a linear regional land use optimization model that integrates the biophysical outcomes from EPIC (cp. chapter D-1). We conduct a comparative static analysis by running the model for each scenario. Land use choices are made for all municipalities and HRU in the Marchfeld region. Management choices comprise crop rotation systems and crop management measures. Our land use model will obtain an optimal land use and management portfolio for both periods. Through the linkage with EPIC, we can immediately obtain the biophysical outcomes for the optimal production portfolios. The economic and environmental outcomes are presented in section D-4.3 and discussed in section D-4.4.

The regional land use model has been solved by using the software package GAMS (General Algebraic Modelling System; www.gams.com). GAMS is an optimization software package that is ideally suited for both linear and non-linear modelling problems. Its programming language is concise and easy to use and it allows integrating data from different sources (e.g. EPIC). Its applications in agricultural economics range from small scale farm modelling to general equilibrium models.

The model equations are outlined below i.e. (1) to (4.3):

$$\max\left\{ \mathbf{RPS} = \sum_{r,h,c,m} \left(\mathbf{ProdChoice}_{r,h,c,m} * \mathbf{Gross\ Margin}_{r,h,c,m} \right) \right\} \qquad (1)$$

$$\sum_{c,m} \left(\mathbf{ProdChoice}_{r,h,c,m} * \mathbf{Land}_{r,h,c,m} \right) \leq \mathbf{Total\ Land}_{r,h} \qquad \forall\, r,h \qquad (2)$$

$$\sum_{x} \left[\left(\mathbf{MixChoice}_{r,h,x} \right] * \mathbf{Mixes}_{r,h,c,x} \right) \leq \sum_{m} \left(\mathbf{ProdChoice}_{r,h,c,m} \right) \qquad \forall\, r,h,c \qquad (3.1)$$

$$\sum_{m} \left(\mathbf{ProdChoice}_{r,h,c,m} \right) \leq \sum_{x} \left(\mathbf{MixChoice}_{r,h,x} * \sum_{c} \mathbf{Mixes}_{r,h,c,x} \right) \qquad \forall\, r,h \qquad (3.2)$$

[8] More detailed information on crop prices, variable production costs and the costs of irrigation measures are in the Appendix A-1 and A-2.

$$\sum_{r,h,c,m}\left(\mathbf{ProdChoice}_{r,h,c,m} * \mathbf{PRKN}_{r,h,c,m}\right) \Big/ \mathbf{Total\ Land} \leq \mathbf{MaxPRKN} \quad (4.1)$$

$$\sum_{r,h,c,m}\left(\mathbf{ProdChoice}_{r,h,c,m} * \mathbf{PRK}_{r,h,c,m}\right) \Big/ \mathbf{Total\ Land} \geq \mathbf{MinPRK} \quad (4.2)$$

$$\sum_{r,h,c,m}\left(\mathbf{ProdChoice}_{r,h,c,m} * \mathbf{OCPD}_{r,h,c,m}\right) \Big/ \mathbf{Total\ Land} \geq \mathbf{MinOCPD} \quad (4.3)$$

The objective function (1) of our land use model maximizes regional producer surplus (RPS) subject to municipalities (r) and HRU (h). The choices are crop rotation systems (c) and management measures (m). RPS is the sum of the product of production choices (ProdChoice) and average annual gross margins (GrossMargin). We define gross margin as total revenues minus total direct production costs. Total direct production costs comprise of variable costs as well as annual capital costs of irrigation systems. Revenues are a function of crop yields times the respective crop prices. 'Land' is the land use parameter for the production choices. Each production choice is made per hectare. 'Total Land' is arable land available per municipality and HRU.

The balance equations (3.1) and (3.2) ensure a convex set of alternative crop rotation system mixes. This allows us to model observed and constructed crop rotation system shares and should ideally yield more realistic and less extreme results. 'Mixes' is the parameter for available mixes (x) by municipality and HRU. It contains the percentage fraction of crop rotation systems in each municipality and HRU. The choice of mixes can range from one to nineteen depending on how many crop rotation systems have been observed.

We also use the model including constraints on nitrogen (4.1) and percolation (4.2) as well as on soil organic carbon content (4.3). The parameters 'PRKN', 'PRK' and 'OCPD' are obtained from the EPIC model and give nitrogen leaching (kg/ha), percolation (mm) and topsoil organic carbon content (t/ha) per production choice, respectively. We constrain these environmental outcomes to average annual outcomes per hectare. Nitrogen leaching should not exceed 0.78 kg/ha, while percolation water and topsoil organic carbon content should not decrease to a level lower than 24 mm and 60 t/ha, respectively. These levels correspond approximately to the average output levels for the period 1996-2005 if the model is run without these constraints. This allows us to simulate how management choices might change in the future if environmental externalities are being taken into account.

D-4.3 Results

In this section we present some results from our model application. First, we will give an overview of the results from the EPIC model. Secondly, we present the results from our regional land use model and compare the outcomes of the different periods.

D-4.3.1 EPIC results

Tab. D-4.1 depicts some selected simulation results from EPIC for each scenario and the five different management measures. One can see that less fertilization as well as irrigation measures yield lower nitrate concentration levels than compared to standard fertilization. The effects on topsoil organic carbon content are rather small. Crop yields increase with irrigation measures but decrease if less fertilizer is applied. The effect of irrigation on crop yields, compared to standard fertilization, is highest in Scenario B. An analysis of variance shows that the choice of management measures significantly influences the average annual outcomes for PRKN, PRK, NO3 and crop yields at a confidence level of 1% in all scenarios. There are also considerable differences in the amount of water use between the irrigation measures with drip irrigation being more water use efficient than sprinkler irrigation.

Tab. D-4.1: Statistical analysis of EPIC results.

	Standard		Low		Reduced		Drip		Sprinkler	
	Mean	St.D.	Mean	St.D.	Mean	St.D.	Mean	St.D.	Mean	St.D.
1996-2005 Reference Scenario										
PRK (mm)	23.9	43.1	24.2	43.11	24.2	43.29	34.3	53.1	33.4	51.7
PRKN kg/ha)	1.0	4.5	0.7	2.8	0.9	3.8	0.9	3.4	0.8	3.2
NO3 (mg/l)	7.0	19.8	4.4	13.5	6.0	17.9	6.0	15.9	5.8	15.8
OCPD (t/ha)	59.7	18.7	60.6	18.9	59.7	18.7	60.0	18.6	60.0	18.6
Crop Yield (t/ha)	5.4	2.8	4.5	2.4	5.2	2.7	6.1	3.3	6.1	3.2
Water use (mil. m^3)	0.0	0.0	0.0	0.0	0.0	0.0	36.5	38.6	48.7	45.2
Irrigation (mm)	0.0	0.0	0.0	0.0	0.0	0.0	59.2	62.7	79.1	73.4
2031-2040 Scenario A										
PRK (mm)	18.4	40.4	18.5	40.6	18.5	40.5	26.4	48.9	25.7	47.5
PRKN (kg/ha)	1.4	6.1	0.9	3.8	1.2	5.1	1.0	3.7	0.9	3.5
NO3 (mg/l)	9.6	28.5	5.9	19.3	8.2	25.3	7.1	20.1	6.8	19.8
OCPD (t/ha)	59.0	18.5	59.8	18.8	59.0	18.5	59.5	18.5	59.6	18.5
Crop Yield (t/ha)	4.7	2.6	4.0	2.2	4.6	2.5	6.3	3.4	6.3	3.4
Water use (mil. m^3)	0.0	0.0	0.0	0.0	0.0	0.0	63.7	40.9	79.3	42.9
Irrigation (mm)	0.0	0.0	0.0	0.0	0.0	0.0	103.3	66.4	128.8	69.6
2031-2040 Scenario B										
PRK (mm)	6.2	20.2	6.3	20.4	6.2	20.3	8.9	24.7	9.2	25.5
PRKN (kg/ha)	1.1	5.7	0.7	3.7	0.9	4.9	0.7	3.5	0.7	3.5
NO3 (mg/l)	11.3	44.6	7.1	31.5	10.1	40.8	7.6	30.0	7.6	29.7
OCPD (t/ha)	57.9	18.3	58.8	18.5	57.8	18.3	58.8	18.3	58.9	18.3
Crop Yield (t/ha)	3.3	2.1	3.1	1.9	3.3	2.1	6.0	3.2	6.0	3.1
Water use (mil. m^3)	0.0	0.0	0.0	0.0	0.0	0.0	88.9	37.3	102.9	35.5
Irrigation (mm)	0.0	0.0	0.0	0.0	0.0	0.0	144.4	60.6	167.0	57.6

Average annual outcomes will change considerably in the 2031-2040 climate change scenarios (see Fig. D-4.1). The EPIC data indicate that percolation will decrease by around 23% with Scenario A and by even more than 70% with Scenario B. This is most likely the result of less precipitation and higher evapotranspiration rates. Nitrogen leaching increases for standard, low and reduced fertilization by more than 35% and 60% with Scenario A and B, respectively. With irrigation measures, nitrogen leaching increases by around 14% with Scenario A and actually decreases by around 10% with Scenario B. In all cases nitrate concentration levels rise significantly. The changes in soil organic carbon are rather marginal. With Scenario A, average crop yields decline by more than 10% unless irrigation measures are applied. Then crop yields could increase slightly by around 3% on average. Drought negatively affects the average crop yields. Crop yields decline by 30% with fertilization measures but only slightly with irrigation measures.

Water use will increase under climate change. With Scenario A, the increases are 75% for drip irrigation and 63% for sprinkler irrigation. A decrease of annual precipitation sums by 20% clearly enhances the need for water. Drip irrigation will use 144% more water and sprinkler irrigation 111%. Notably, the increases for water use are always higher for drip irrigation. Hence, the relative water-efficiency of drip irrigation declines with climate change. While sprinkler irrigation needs on average 25% more water than drip irrigation in 1996-2005 this difference drops to 20% with climate change scenario A and to only 14% with climate change scenario B. According to paired t-tests, the differences between all annual environmental outcomes of the periods is highly significant (with $\alpha = 0.01$).

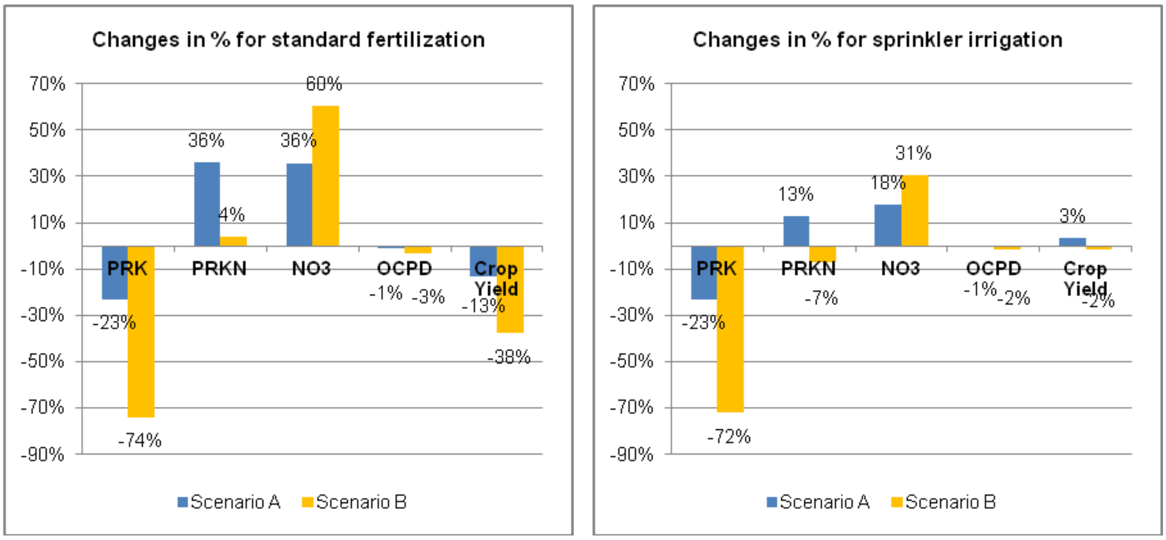

Fig. D-4.1: Relative changes in average annual environmental outcomes with standard fertilization (left) and with sprinkler irrigation (right) compared to the reference period 1996-2005.

The results for average annual crop yields and gross margins for selected crops are shown in Tab. D-4.2. Irrigation measures lead to the highest crop yields compared to all other management measures, especially in the climate change scenarios. For example, compared to standard fertilization corn yields could increase by 36% in 1996-2005 and by even 73% and 157% with Scenario A and Scenario B, respectively. The effects on corn yields are big, whereas on summer barley, carrots and potatoes they are small, but still statistically significant at a 1% confidence level. In addition, irrigation will also significantly decrease average annual crop yield variability. Not surprisingly, less fertilization usually decreases crop yields compared to standard fertilization. For example, a low fertilizer system would cause winter wheat yields to drop by 20% in the reference scenario and Scenario A, and by 10% in Scenario B. Management measures can also affect crop revenues, but these effects vary between crops. Notably, drip irrigation will, on average, always yield less revenue than sprinkler irrigation.

Climate change will affect the outcomes for the selected crops significantly (see Fig. D-4.2 and D-4.3). Less precipitation and higher temperatures will decrease average annual yields for corn, summer barley, carrots and potatoes under all management measures. Interestingly, only winter wheat yields can increase in both scenarios A and B if irrigation measures are applied. It can be observed that irrigation measures clearly mitigate the negative effects of climate change on crop yields.

Annual average gross margins for all crops and management measures will decline with climate change. A decrease of annual precipitation sums by 20% will further enhance the loss in gross margins. All changes between the periods are statistically significant at a 1% confidence level.

Tab. D-4.2: Average annual crop yields and gross margins for winter wheat (WWHT), corn (CORN), summer barley (SBAR), carrots (CRRT) and potatoes (POTA).

		Standard		Low		Reduced		Drip		Sprinkler	
		Mean	Std	Mean	Std	Mean	Std	Mean	Std	Mean	Std
1996-2005 Reference Scenario											
WWHT	t/ha	6.0	1.1	4.8	1.1	5.8	1.0	6.5	0.5	6.5	0.4
CORN	t/ha	6.9	2.0	6.2	1.7	6.9	1.9	9.3	0.7	9.4	0.8
SBAR	t/ha	4.3	0.8	3.5	0.7	4.1	0.7	4.6	0.4	4.6	0.4
CRRT	t/ha	3.5	0.5	3.4	0.5	3.4	0.5	3.6	0.3	3.6	0.3
POTA	t/ha	3.5	0.6	3.2	0.6	3.5	0.6	3.6	0.4	3.7	0.4
WWHT	€/ha	490	132	417	128	505	124	94	216	251	121
CORN	€/ha	458	245	432	213	486	239	95	169	315	149
SBAR	€/ha	407	99	340	92	403	92	27	202	161	108
CRRT	€/ha	1596	432	1526	413	1589	426	1253	376	1436	303
POTA	€/ha	339	309	251	286	319	302	-135	332	71	276
2031-2040 Scenario A											
WWHT	t/ha	5.1	1.8	4.1	1.5	5.0	1.7	7.3	0.7	7.4	0.7
CORN	t/ha	5.3	1.9	4.8	1.5	5.3	1.9	9.1	0.8	9.1	0.9
SBAR	t/ha	3.9	0.8	3.4	0.8	3.8	0.8	4.2	0.5	4.3	0.5
CRRT	t/ha	3.1	0.7	3.0	0.6	3.1	0.6	3.4	0.3	3.5	0.3
POTA	t/ha	3.2	0.6	3.0	0.6	3.2	0.6	3.4	0.5	3.4	0.5
WWHT	€/ha	384	217	332	179	405	209	-4	123	228	119
CORN	€/ha	260	232	267	190	294	231	25	118	239	134
SBAR	€/ha	358	104	332	102	364	99	-105	181	93	116
CRRT	€/ha	1301	563	1237	542	1298	557	1002	348	1241	321
POTA	€/ha	191	325	128	318	176	320	-368	283	-126	264
2031-2040 Scenario B											
WWHT	t/ha	3.5	1.7	3.1	1.5	3.5	1.7	7.1	0.8	7.1	0.9
CORN	t/ha	3.2	1.3	3.2	1.3	3.2	1.3	8.6	0.8	8.4	1.2
SBAR	t/ha	2.9	1.0	2.6	0.8	2.8	1.0	4.1	0.5	4.2	0.5
CRRT	t/ha	2.4	0.7	2.4	0.7	2.4	0.7	3.3	0.3	3.4	0.3
POTA	t/ha	2.5	0.7	2.4	0.7	2.5	0.7	3.2	0.5	3.3	0.5
WWHT	€/ha	194	201	221	173	223	199	-78	108	132	132
CORN	€/ha	12	164	61	158	43	165	-75	117	125	152
SBAR	€/ha	229	132	234	103	240	129	-232	151	-9	121
CRRT	€/ha	727	615	693	602	732	610	812	319	1095	299
POTA	€/ha	-180	363	-156	344	-189	358	-542	266	-254	260

The EPIC data suggests that one is to expect a significant drop in regional producer surplus and higher nitrate concentration levels in the future. These effects are amplified in Scenario B. The results also support the common assumption of a non-linear relationship between agro-ecosystems and climate (Fallon and Betts, 2010). But the actual environmental and economic outcomes will of course depend on farmers' actual land use and management choices. The regional land use optimization model, tries to identify these choices, under the assumption that farmers act rationally (i.e. they make decisions so that their profit is maximized subject to constraints). The next section presents these model results.

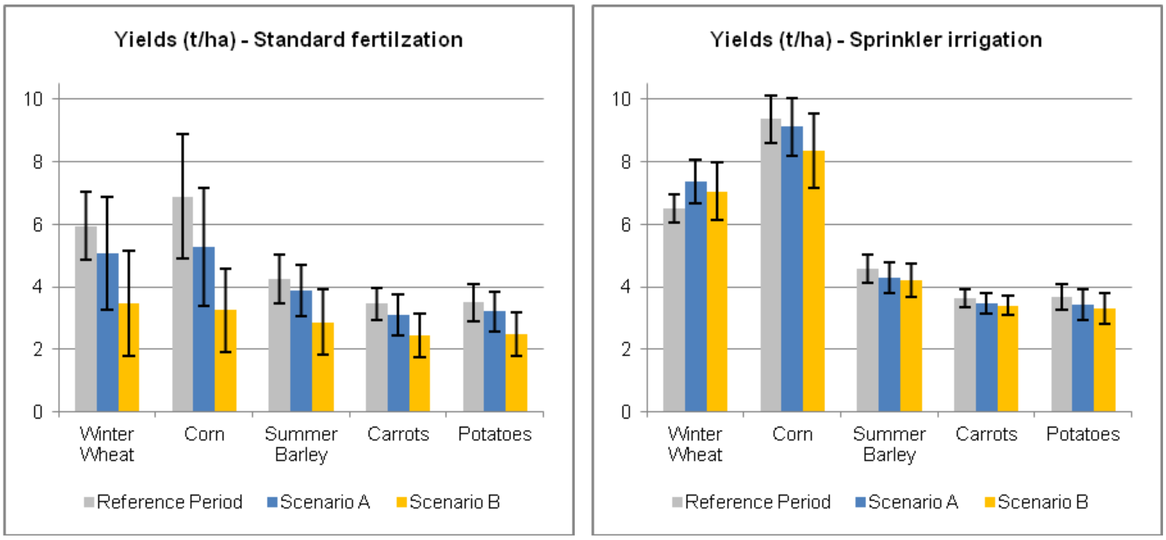

Fig. D-4.2: Average annual crop yields with standard fertilization (left) and sprinkler irrigation (right).

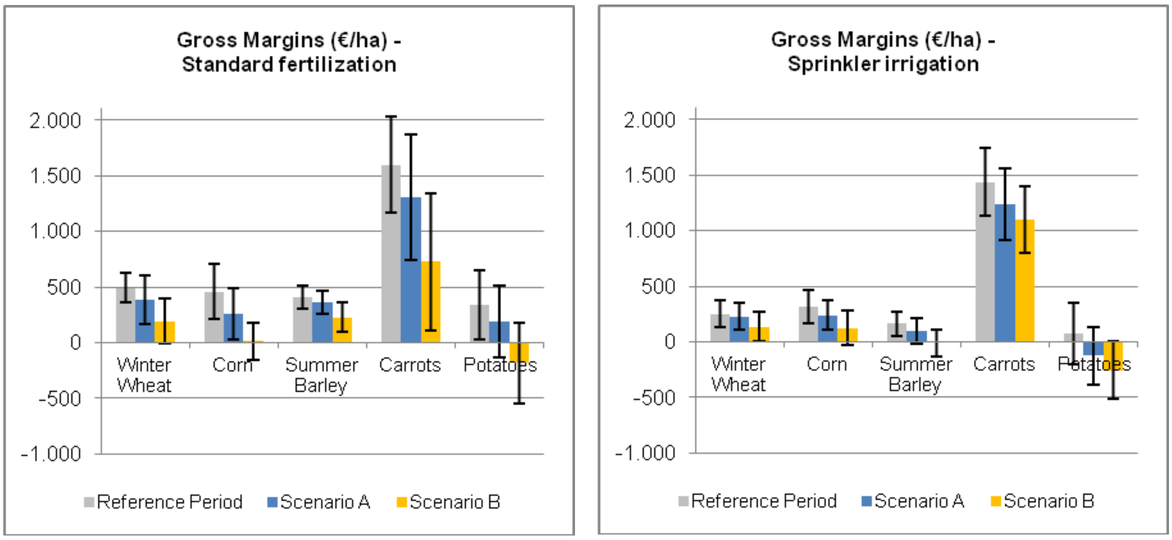

Fig. D-4.3: Average annual gross margins with standard fertilization (left) and sprinkler irrigation (right).

D-4.3.2 Regional land use model results

This section presents and discusses the results of the regional land use model. We compare the average annual outcomes of the climate change scenarios to the reference scenario 1996-2005. The climate change scenarios have been run once without any environmental regulation and once constrained to the average annual environmental outcomes of the reference scenario (see section D-4.2). The minimum constraint on percolation runoff had to be relaxed by half to just 12 mm for Scenario B due to the extreme overall decrease in percolation water under all management measures (see section D-4.3.1). Otherwise, the model would have been infeasible. Hence, we can also analyse how farmers would react to climate change if they were to take into account the environmental effects of production.

Tab. D-4.3 depicts the shares of the five management measures in each scenario (reference scenario, Scenario A, and Scenario B). In the reference scenario, standard and reduced fertilization measures are the most dominant measures in the region. Climate change increases the relative share of sprinkler irrigation measures substantially and reduces the share of standard fertilization to a low level. With climate change scenario A, irrigation measures comprise 43% or 56% of the total share of management measures. The changes are even more pronounced with Scenario B. With 20% less precipitation, the share of sprinkler irrigation increases to 85% or 84%. This is not unexpected, given the earlier results of the EPIC data in section D-4.3.1. There will also be a slight increase in the share of low fertilization with Scenario B.

Tab. D-4.3: Management shares in each scenario.

	1996-2005	2031-2040			
		Scenario A		Scenario B	
		Unregulated	Constrained	Unregulated	Constrained
Standard	43.9%	9.9%	6.3%	0.3%	0.0%
Low	1.7%	1.1%	1.8%	5.8%	10.5%
Reduced	50.3%	45.6%	36.2%	9.3%	0.9%
Drip	0.0%	0.0%	0.0%	0.0%	4.8%
Sprinkler	4.0%	43.4%	55.7%	84.7%	83.7%

The economic and environmental results are shown in Tab. D-4.4. The changes with regard to 2031-2040 are illustrated in Fig. D-4.4 and D-4.5. In both climate change scenarios, regional producer surplus will decline considerably. If production is constrained by environmental targets the decrease in regional producer surplus is slightly higher than in the unregulated case. While regional producer surplus decreases by around 13% or 14% with Scenario A, it will drop by 30% or 39% with Scenario B. In contrast, crop production will increase with climate change. If production is unregulated crop production increases by 5% and 7% with Scenario A and Scenario B, respectively. If environmental outputs are constrained, crop production will only increase by only 1% with Scenario B, but by almost 7% with Scenario A.

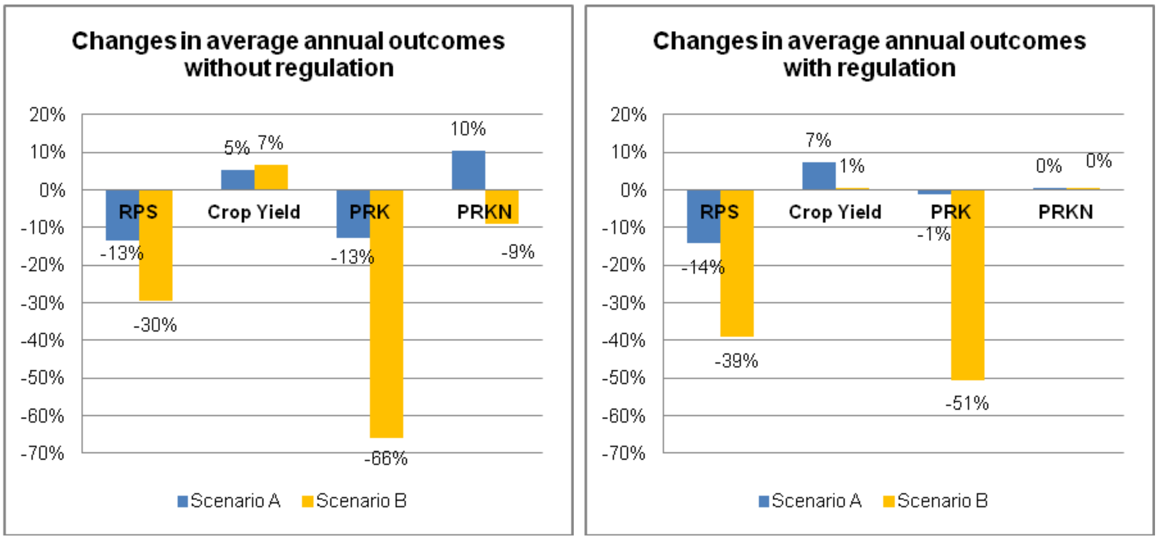

Fig. D-4.4: Relative changes in environmental and economic outcomes without (left) and with (right) regulation.

It is very interesting to see that average annual producer surplus decreases while average annual crop production actually increases. Applying more irrigation measures makes it possible to increase crop production in most instances, but higher variable costs lead to a net loss in producer surplus. Although drip irrigation could also increase average annual crop production (see section D-4.3.1) its application is most of the time more costly than sprinkler irrigation. The large decline in crop production makes standard fertilization much less profitably in any scenario of the period 2031-2040. Hence, in our regional model sprinkler irrigation - and to a small extent also low fertilization - seems to be a cost-efficient adaptation measure to climate change in Marchfeld compared to all other management measures considered.

Tab. D-4.4: Regional land use model results.

	1996-2005		2031-2040							
			Scenario A				Scenario B			
			Unregulated		Constrained		Unregulated		Constrained	
	Mean	Std	Mean	Std	Mean	Std	Mean	Std	Mean	Std
RPS (Mill. €/a)	48.06	8.93	41.65	6.98	41.18	6.97	33.83	6.63	29.18	5.30
RPS (€/ha/a)	780.20	144.95	676.08	113.36	668.88	113.19	549.13	107.69	474.06	86.19
Crop Production (t/ha/a)	5.78	0.62	6.08	0.68	6.20	0.62	6.16	0.73	5.81	0.60
PRK (mm/a)	24.36	9.61	21.20	14.33	24.02	15.51	8.31	7.37	12.01	9.98
PRKN (kg/ha/a)	0.78	0.72	0.86	0.84	0.78	0.80	0.71	0.84	0.78	1.02
NO_3 (mg/l)	14.36	10.37	21.46	17.49	17.00	14.95	46.17	38.88	32.43	27.19
OCPD (t/ha/a)	60.16	0.87	59.88	0.83	60.04	0.81	59.29	0.89	60.06	0.94
Water use (Mill. m³)	3.90	0.60	42.71	5.45	53.36	6.40	93.16	7.98	95.01	8.18
Irrigation (mm)	6.33	0.97	69.34	8.85	86.68	10.40	151.23	12.96	154.36	13.28

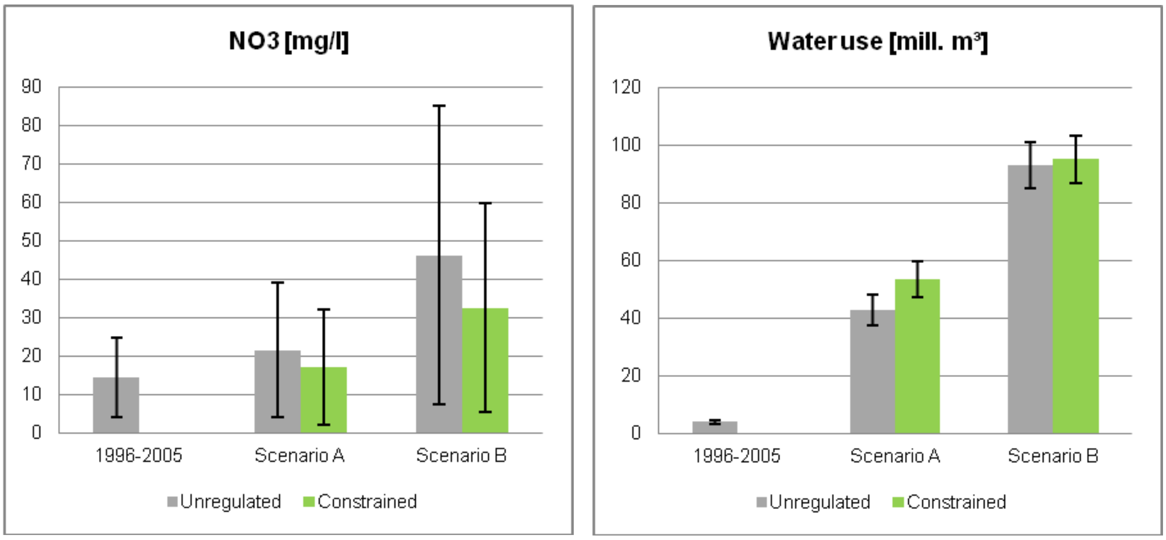

Fig. D-4.5: Changes in average annual nitrate concentrations (left) and water use (right).

Our model results further indicate that climate change will significantly affect the environmental outcomes. If environmental outputs are unregulated, percolation will decrease by 13% and 66% with Scenario A and Scenario B, respectively. At the same time nitrogen leaching increases with Scenario A by 10% and decreases by 9% with Scenario B. The percolation and nitrogen leaching ratios are thus changed in a way that increases nitrate concentration by almost half in Scenario A and by more than 200% in Scenario B. Nitrate concentration levels will also rise even if percolation and nitrogen leaching are constrained. This is due to annual variations of these outcomes (environmental outputs are constrained to average annual outcomes per period). Nevertheless, the environmen-

tal constraints do mitigate the effect on nitrate concentrations moderately. Changes in topsoil organic carbon contents are mostly small.
Bigger changes can also be observed for irrigation water use. In the reference scenario, ca. 4 million m³ water are used for irrigation measures. With climate change, water use for irrigation purposes could increase to around 50 million m³ with Scenario A and to more than 90 million m³ with Scenario B. Given that total groundwater uptake in Marchfeld by agriculture, industry and municipalities amounted to 50 million m³ in 2001 (Mötz and Neudorder, 2002) such an increase in water use would exert high pressure on groundwater reserves in Marchfeld.

D-4.4 Summary and conclusions

We have developed and applied a regional land use optimization model in order to analyse the performance of a selected set of management options on environmental and economic criteria such as regional producer surplus, crop yields, nitrate concentrations and irrigation water use. We have integrated data from the biophysical simulation model EPIC in order to be able to quantitatively analyse the environmental effects of land use and management choices. Climate change data from Strauss et al. (2010) have been used for our scenario analysis (cp. section D-3.1.2). We have compared the reference period 1996-2005 to two different climate change scenarios for the period 2031-2040. In the climate change scenario A annual precipitation sums will be unchanged while they will decrease by 20% in the climate change scenario B.
Our climate change scenario analysis indicates that it could lead to substantial increases in water use for irrigation, higher nitrate concentration levels, and to decreases in regional producer surpluses. All effects will be considerably bigger, if precipitation decreases by 20% in 2031-2040. Crop production could potentially increase slightly due to widespread application of irrigation measures in 2031-2040. Regulating the stream of environmental outputs such as nitrogen leaching and percolation yield as well as topsoil organic carbon content would decrease nitrate concentrations significantly but also increase both the loss in producer surplus and irrigation water use.
In the climate change scenarios, sprinkler irrigation becomes one of the most profitable management measures. Its share increases to more than 40% with Scenario A and to even more than 80% with Scenario B. This makes it the most cost-efficient adaptation measure in our regional model. However, more irrigation means more water use and, as our model results indicate, this could exert pressures on the regional groundwater aquifer. In addition, EPIC results show that - no matter what management measure is being applied - nitrate concentration will likely rise in both climate change scenarios.
While sprinkler irrigation is effective in reducing the economic costs of climate change, it will also considerably increase the pressure on the regional groundwater aquifer. Together with increased nitrate concentration levels this will most likely increase the costs of irrigation and drinking water extraction and/or treatment in Marchfeld. Hence, water pricing or subsidies for more water-efficient irrigation measures such as drip irrigation should also be included in future model runs, as it has been done for the investment model in chapter D-5. Nevertheless, while drip irrigation is said to be the most water-efficient irrigation measures available (Eitzinger et al., 2009) our EPIC data suggest that the difference in water use compared to sprinkler irrigation diminishes the warmer and drier the climate becomes. This is due to our EPIC model specifications implying thresholds for annual irrigation, which are earlier reached with sprinkler irrigation than with drip irrigation. In future studies, it will therefore be appropriate to identify and include a wider range of adaptation measures that positively affect water availability, such as conservation tillage, windbreak hedges, or precision farming. It may also be worthwhile to allow for a combination of irrigation and fertilization measures in order to mitigate the increase in nitrate concentration levels as well as alternative land use options (e.g. energy crops).

Acknowledgements

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D-5 Investment in irrigation systems under weather uncertainty[9]

In the regional land use model (see chapter D-4), we found sprinkler irrigation to be an effective adaptation measure to reduce the economic cost of climate change. At the same time, it was found to exert considerable pressure on the regional groundwater aquifer. In this chapter, we investigate a farmer's decision to invest into a sprinkler or more water-efficient drip irrigation system under precipitation uncertainty until the year 2040 and how this decision is affected by common policy measures such as imposing water pricing or equipment subsidies. In contrast to the previous chapter, the management strategies drip and sprinkler irrigation systems are combined with optimal application of nitrogen fertilizer. To achieve sustainable water management strategies, the European Water Framework Directive promotes a set of policy options such as appropriate water pricing and the implementation of metering to support volume-based charging, ensuring that agricultural subsidies are linked to more efficient water use, and investing in technologies that increase water use efficiency (EEA, 2009). In particular, drip irrigation systems have proven to increase crop water productivity i.e. increasing yields and decreasing the amount of water used (e.g. Cetin and Bilgel, 2002; Fedaku and Teshome, 1998 in Luquet et al., 2005). Currently, the most common obstacle to invest into drip irrigation systems is related to the investment costs, which are often not affordable for low or even medium income farmers (Vidal et al., 2001; in Luquet et al., 2005). Investment decisions in production equipment are additionally complicated, as farmers are confronted with uncertainty about production conditions, amongst others due to climatic or seasonal factors such as rainfall or frost events (Tozer, 2009), and subsequent uncertainty as to whether investment remains profitable. With these problems in mind, we aim to model an agriculturalist's decision to invest in a sprinkler irrigation system or in an even more water-efficient drip irrigation system under uncertainty about the evolution of precipitation on two alternative soil types. Firstly, we assess the optimal timing to invest in the planning period 2009-2040. Secondly, we investigate how investment decisions are affected by policy measures, such as the introduction of water prices and subsidies. Our case study focuses on the region Marchfeld in Austria (see chapter D-2). Currently, only sprinkler irrigation systems are used in Marchfeld, but as drip irrigation systems allow for a precise application of water it might be viable to adopt drip irrigation systems in the Marchfeld in the future.[10]

We use agro-ecological data from the biophysical process simulation model EPIC (cp. chapter D-1) as well as weather parameters from a statistical climate model for Austria (Strauss et al., 2010). We apply a stochastic dynamic programming approach, which provides a framework to analyze investment decisions under uncertainty about e.g. production conditions, irreversibility of capital investment and the possibility to wait and postpone investment to a later point in time into one model framework (e.g. Dixit and Pindyck, 1994; Pindyck, 1980).

This chapter is structured as follows. In section D-5.1, we introduce the data and case study area. This is followed by a brief introduction of the analysis method. In section D-5.3, we provide results indicating the optimal timing to invest in either a drip or sprinkler irrigation system in case of no policies, water prices and equipment subsidies. In section D-5.4, we conclude.

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9 Paper prepared for presentation at the EAAE 2011 Congress Change and Uncertainty. Challenges for Agriculture, Food and Natural Resources; August 30 to September 2, 2011; ETH Zurich, Zurich, Switzerland by Christine Heumesser, Franziska Strauss, Erwin Schmid (University of Natural Resources and Life Sciences, Vienna (BOKU), Institute for Sustainable Economic Development, Feistmantelstrasse 4, 1180 Vienna, Austria) and Sabine Fuss, Jana Szolgayová (International Institute for Applied Systems Analysis (IIASA), Ecosystems Services And Management, Schlossplatz 1, A-2361 Laxenburg, Austria)

10 www.marchfeldkanal.at; accessed in February 2011

D-5.1 Data

Our study area is the Marchfeld region in Austria, which is one of the most important field crop production areas as well as driest areas in Austria. We use the biophysical process simulation model EPIC (cp. chapter D-1). We simulate biophysical impacts of five crops (winter wheat- included in two different crop rotations -, sugar beets, potatoes, corn, and carrots) which cover more than 50% of the agricultural land. We assume conventional tillage practices i.e. ploughing. The production inputs nitrogen fertilizer and irrigation water are automatically determined by the EPIC model and thus regarded as simulation outputs. The assignment of fertilizer and irrigation water amounts is subject to certain assumptions: 90% of the crop growth period is water and nitrogen stress-free; total annual nitrogen application rates are limited to 170 kg/ha; and the maximum annual irrigation volume allowed for each crop amounts to 500 mm. Crop production is simulated for two soil types in Marchfeld (cp. chapter D-2).
Precipitation data is taken from the statistical climate model for Austria presented in section D-3.1.2. Several precipitation scenarios have been generated to account for the range of possible precipitation patterns. These include higher or lower annual precipitation sums as well as unchanged annual precipitation sums with seasonal redistribution. In the following analysis, we use weather data of one of the most extreme precipitation scenario, which portrays a decrease in annual precipitation sums of - 5% until 2016, -10% until 2024, -15% until and 2032, and - 20% until 2040 (Strauss et al., 2010). These values have been verified by the literature. For instance, Christensen and Christensen (2007) employ various General Circulation Models (GCMs) and Regional Climate Models (RCMs) by using different emission scenarios (A2 and B2; IPCC, 2007) as well as different resolutions, ensemble members and parameterizations for some European regions simulating increases or decreases in seasonal precipitation sums of ~60% until 2100 depending on the assumptions made. In our study, the bootstrapping resulted in 300 ‘weather scenarios’, which depict the uncertainty of annual precipitation sums in the stochastic dynamic programming model. As the weather data are a direct input to the EPIC model, we obtain for each year and each EPIC output variable 300 realizations. In Tab. D-5.1, we provide the mean and standard deviation of dry matter crop yield and irrigation quantities as well as profits (for details on profit calculation cp. section D-5.2[11]) over the time period 2009-2040 and over the 300 realizations provided for each year. Variable production costs (BMLFUW, 2008), and mean commodity prices from 2005-2009 are used to calculate annual profits. Capital costs of irrigation systems were surveyed from producers (personal communication with Fa. Bauer; Fa. Parga).
The crop yields are declining compared to the past (1975-2007). The summary statistics in Tab. D-5.1 show that irrigation in the period 2009-2040 leads to a decrease in crop volatility, except for potatoes. Irrigation also results in higher average dry matter crop yields compared to the case of no irrigation. Sprinkler irrigation systems require more irrigation water inputs, but drip irrigation yields the lowest average profits. Only for the production of carrots and sugar beets, sprinkler irrigation yields higher average profits than the scenario without irrigation. Notably, the annual capital cost of a drip irrigation system, which are assumed to operate for 15 years, is 400 €/ha/a for carrots and 233 €/ha/a for all other crops, whereas the annual capital cost for sprinkler irrigation is 213 €/ha/a for all crops. Notable differences in labor hour requirements per ha occur to install or run the respective irrigation system (drip irrigation: 30 h/ha/a; sprinkler irrigation: depending on irrigation amounts applied to the fields; variation between on average 1 h/ha/a for winter wheat and 6 h/ha/a for sugar beets).

[11] Information used for the profit calculation is reported in the Appendix A-3.

Tab. D-5.1: Summary statistics of crop yields, irrigation water and profits for each crop and irrigation system.

		SOIL 1					
		No irrigation		Sprinkler		Drip	
		μ	σ	μ	σ	μ	σ
Corn		6.2	1.2	7.9	0.5	7.9	0.5
Carrots		5.4	0.6	5.5	0.4	5.5	0.4
Potatoes	Yields t/ha/a	7.0	0.8	7.1	0.8	7.1	0.8
Sugar beets		7.8	1.2	10.1	0.6	10.3	0.5
Winter wheat 1		4.7	0.8	4.8	0.8	4.8	0.8
Winter wheat 2		4.9	0.8	5.1	0.7	5.1	0.8
Corn				127	51	113	45
Carrots				39	36	34	32
Potatoes	Irrig.			53	37	47	32
Sugar beets	mm/ha/a			162	56	143	49
Winter wheat 1				35	35	32	31
Winter wheat 2				36	35	32	31
Corn		130	163	9.4	84.8	-249	70.2
Carrots		8321	1100	8351	843	7909	825
Potatoes	Profit €/ha/a	2347	515	2112	512	1815	514
Sugar beets		48	198	60.0	104	-167	86.1
Winter wheat 1		460	175	204.2	168	-100	169
Winter wheat 2		516	160	281	141	-22	142

		SOIL 2					
		No irrigation		Sprinkler		Drip	
		μ	σ	μ	σ	μ	σ
Corn		4.6	1.3	7.5	0.5	7.5	0.5
Carrots		3.5	0.8	5.2	0.5	5.3	0.4
Potatoes	Yields t/ha/a	5.3	0.9	6.6	0.8	6.7	0.8
Sugar beets		6.2	1.2	9.8	0.7	10.0	0.6
Winter wheat 1		3.0	1.1	4.7	0.7	4.7	0.7
Winter wheat 2		3.0	1.1	4.9	0.7	5.0	0.7
Corn				254.6	45	229.1	42.4
Carrots				147.9	43	132.0	36.1
Potatoes	Irrig.			162.9	38	144.5	32.3
Sugar beets	mm/ha/a			279.9	35	262.4	39.8
Winter wheat 1				141.4	40	126.0	34.8
Winter wheat 2				141.7	40	126.3	34.9
Corn		-81.9	163	-115.2	789	-319.4	64.5
Carrots		4712	1648	7590.5	920	7357.5	863.2
Potatoes	Profit €/ha/a	1233	577	1748.3	501	1530.8	501.0
Sugar beets		-216	194	-57.9	111	-229.7	88.8
Winter wheat 1		107	221	120.1	145	-132.2	144.2
Winter wheat 2		127	221	186.2	135	-65.0	133.9

Note: The mean (μ) and standard deviation (σ) is calculated over the years 2009-2040 and over 300 weather scenarios provided for each year. Yield t/ha/a and irrigation mm/ha/a stem from EPIC outputs, profit is our own calculation.

D-5.2 Method

In the stochastic dynamic programming model, the farmer decides in each year of the planning period whether to invest into a drip or sprinkler irrigation system and whether to operate the installed system. Investment in irrigation systems is a long-term investment. We assume that a farmer bases his investment decision on his expectation about how annual precipitation will develop over the years 2009-2040. We further assume that in each year 300 possible annual precipitation sums, $P_{t} \sim U(\rho_{t}^{1}, \ldots, \rho_{t}^{300})$, can occur with equal probability. Once the system has been installed, the farmer can decide whether to operate the irrigation system or not from the following year onwards depending on his daily information about rainfall. To formulate the decision problem we

denote x_t the state of the system in year t. x_t can take the values from the set $X_t = \{0, 1, 2\}$, where 0 implies that until period t no irrigation system has been built; 1 that drip irrigation has been built; and 2 that sprinkler irrigation has been built prior to period t. The investment decision in year t is denoted as a_t, chosen from the set $A_t = \{0,1, 2\}$, where 0 means that no investment is made in the respective period; 1 that drip irrigation is adopted; and 2 that sprinkler irrigation is adopted. The set of feasible actions depends on the state of the system: in case a system has already been installed no further investment is possible. This constraint is expressed by $x_t a_t = \mathbf{0}$. The state of the system in the next year is determined by the current state and the investment decision in the current year, $x_{t+1} = x_t + a_t$. In the first period of the model no irrigation system is built, $x_1 = \mathbf{0}$. The operational decision, $u_t \in \{0, x_t\}$, can take the values $\{0,1, 2\}$, with 1 representing that the drip system is switched on, 2 that sprinkler irrigation is switched on and 0 meaning that the previously installed irrigation system is not in use. The constraint $u_t \in \{0, x_t\}$ indicates that the system has been built before period t, but can only be operated from period t onwards.
The annual profits consist of revenue from crop cultivation less the costs of crop production, which includes cost specific for each crop and specific for each irrigation system. More precisely, the operational profits in period t, $\pi(u, \rho_t^i)$, depend on the operational decision and the annual precipitation sums (equation 1), and the annualized capital cost, $c(x_t + a_t)$, depend on the state in period t after the investment decision has been made (equation 2):

$$\pi(u, \rho_t^i) = y(u, \rho_t^i) \cdot p^c - (c_{Lh} \cdot c + Varc) - q^{\uparrow}e\,(u, \rho_{\downarrow}(t)^{\uparrow}i) \cdot p^{\uparrow}e - i\,Lh(u, \rho_{\downarrow}(t)^{\uparrow}i) \cdot c) - q^{\uparrow}n\,(u, \rho_{\downarrow}(t)^{\uparrow}i) \cdot p^{\uparrow}n) \quad i = 1, \ldots, 300 \tag{1}$$

$$c(x_t + a_t) = aCapc(x_t + a_t) + a_{well(x_t+a_t)} \tag{2}$$

The components of the operational profit include parameters assumed constant over time: p_i^c, the constant commodity price; c, the hourly wage; p^e, cost of electricity per kWh; p^n, the price of fertilizer; and $Varc_i$, the variable cost accrued per crop including reparation cost, fuel cost, liming cost, boron cost, cost of herbicide, fungicide, pest management and sowing cost. The remaining components vary by operational decision and the respective annual precipitation sum, determining amongst other the required quantity of irrigation water and nitrogen fertilizer. This includes the yield revenue, $y(u, \rho_t^i)$; and the labor requirement per crop, c_{Lh_i}. The variable cost of using the irrigation system include energy cost, determined by the quantity of energy used by the irrigation system, $q_i^e(u_t, \rho_t^i)$. The annual labor requirement for irrigation activity is given by $i_{Lh_i}(u_t, \rho_t^i)$ and the annual amount of nitrogen fertilizer used, $q_i^n(u_t, \rho_t^i)$. As annual operational profits depend on changes in precipitation, any deviations in investment behavior must be due to changes in precipitation. The annualized fixed cost of the respective irrigation systems is the sum of the annualized capital cost, $aCapc(x_t + a_t)$, and the annualized cost of building a well, $a_{well(x_t+a_t)}$.
The problem of the agent can be formulated as an optimization problem of timing his investment decisions, a_t, and choosing operational action, u_t, so that the expected sum of profits over the planning period is maximized (equation 3). The discount rate is

given by r and $e^{-r \cdot t}$ is the discount factor, by which future profits received in time t must be multiplied to obtain the present value.

$$\max_{a_t, u_t} \left\{ E \left[\sum_{t=1}^{31} e^{-r \cdot t} \cdot \left(\pi(u_t, P_t) - c(x_t + a_t) \right) \right] \right\} \tag{3}$$

$$s.t.$$

$$x_{t+1} = x_t + a_t \qquad t = 1, \ldots, 31$$
$$x_1 = 0$$
$$a_t \in \{0,1,2\} \qquad t = 1, \ldots, 31$$
$$x_t a_t = 0 \qquad t = 1, \ldots, 31$$
$$u_t \in \{0, x_t\} \qquad t = 1, \ldots, 31$$
$$P_t \sim U(\rho_1(t)^{1}, \ldots, \rho_1(t)^{300}) \qquad t = 1, \ldots, 31$$

The formulated problem is a standard stochastic optimal control problem in discrete time on a finite horizon and thus can be solved by the backward dynamic programming. The optimal investment and operational decision in each year are then obtained recursively by solving the Bellman equation, using the terminal condition that in the terminal period the value of the investment takes the value zero:

$$V_{32}(x, i) = 0 \qquad for \ \forall x \in \{0,1,2\} \quad \forall i \in \{1, \ldots, 300\} \tag{4}$$

$$V_t(x, i) = \max_{\substack{a,u: ax=0 \\ u \in \{0, x_t\}}} \left[\pi(u, \rho_t^i) - c(x+a) + e^{-r} \cdot \frac{\sum_{j=1}^{300} V_{t+1}(x+a, j)}{300} \right] \tag{5}$$

$$[a_t(x,i), u_t(x,i)] = \underset{\substack{a,u: ax=0 \\ u \in \{0, x_t\}}}{\operatorname{argmax}} \left[\pi(u, \rho_t^i) - c(x+a) + e^{-r} \cdot \frac{\sum_{j=1}^{300} V_{t+1}(x+a, j)}{300} \right] \tag{6}$$

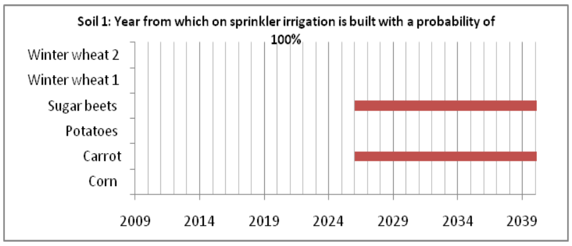
$$for \ \forall x \in \{0,1,2\} \quad \forall i \in \{1, \ldots, 300\} \quad t = 31, 30, \ldots, 1$$

The right hand side of the Bellman equation can be decomposed into the sum of immediate profits, $\pi(u, \rho_t^i) - c(x+a)$, which the agents receives upon investment in each precipitation scenario, and the expected discounted continuation value, $e^{-r} \cdot \frac{\sum_{j=1}^{300} V_{t+1}(x+a, j)}{300}$, which is assessed over the 300 possible precipitation scenarios occurring in each year. The expected discounted continuation value is evaluated for the state the agent is in, which changes according to the investment actions the agent undertakes. Thus, the agents aims to find in each year and each precipitation scenario, the combination of investment $a_t(x, i)$ and operational actions $u_t(x, i)$, which maximizes his immediate profit and discounted expected continuation value of his actions (equation 6).
The solution of the recursive optimization is a multidimensional matrix, which contains the optimal investment action, $a_t(x, i)$, and the optimal operational action , $u_t(x, i)$, for every state x , each precipitation scenario ρ_t^i and t . To analyze this outcome we calculate the cumulative probabilities of an action occurring in or prior to a specific year. The probability that an irrigation system is chosen is calculated separately for each crop. We use the software Matlab for all operations.

D-5.3 Results

Scenario 1 – No policies

For both soil types, we find that the probability to invest in a drip irrigation system at any point in time is zero for all crops. High capital cost or high operation cost respectively seem to render the adoption of drip irrigation unattractive. In contrast, the cumulative probability to invest into sprinkler irrigation is positive for sugar beets and carrots on soil 1, and for all crops, except corn, on soil 2 (Fig. D-5.1). On soil 1, the probability that sprinkler irrigation is adopted for production of carrots and sugar beets is 100% in year 2024. This result is not surprising as for both crops sprinkler irrigation yields higher profits than drip irrigation system or no irrigation. According to our climate scenarios, year 2025, marks a decrease in annual precipitation sums by 15% on all randomly drawn precipitation sums. On the less fertile soil type, our analysis reveals a 100% probability that sprinkler irrigation is adopted for the production of carrots, potatoes and sugar beets already in year 2009. We also find a 100% probability that sprinkler irrigation is adopted for the production of winter wheat of crop rotation system 1 in year 2023 and for winter wheat of crop rotation system 2 already in year 2015.The combination with sugar beets and carrots in crop rotation system 2 induces an earlier adoption of sprinkler irrigation for winter wheat. The results are not surprising, as the employment of sprinkler irrigation yields the highest average profits for the production of carrots, and minimizes average losses for the production of sugar beets, respectively.



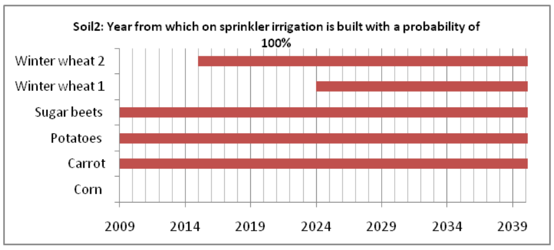


Fig. D-5.1: Year from which on sprinkler irrigation is adopted with a probability of 100%, on fertile soil 1 (left) and on less fertile soil 2 (right).
Note: own calculation.

Scenario 2 – Water Pricing Policies

We introduce water prices from 0.2€ to 2€ per mm of irrigation water used, reflecting increasing levels of water scarcity. We analyse whether these increased operational costs of sprinkler irrigation have a positive impact on the adoption of drip irrigation systems. Our results reveal that drip irrigation is never adopted. At the same time we observe that increasing water prices either delay the adoption of sprinkler irrigation for some crops, or make the adoption not profitable at all (Tab. D-5.2).

Tab. D-5.2: Year in which sprinkler irrigation systems is adopted with a probability of 100%, for the scenario without policies and 4 alternative water pricing policy scenarios.

	SOIL 1						SOIL 2					
	Corn	Carrot	Potatoes	Sugar beets	Winter wheat 1	Winter wheat 2	Corn	Carrot	Potatoes	Sugar beets	Winter wheat 1	Winter wheat 2
No policy	-	2024	-	2024	-	-	-	2009	2009	2009	2023	2015
0.20 €	-	2024	-	-	-	-	-	2009	2009	2009	-	-
0.50 €	-	2024	-	-	-	-	-	2009	2009	2023	-	-
1 €	-	2024	-	-	-	-	-	2009	2009	-	-	-

2 €	-	2028	-	-	-	-	-	2009	2009	-	-	-

Note: own calculation.

On the more fertile soil type, already water prices of 20 cent/mm decrease the probability to adopt sprinkler irrigation for the production of sugar beets to zero. For carrot production, even with water prices of 1€/mm the optimal timing to adopt sprinkler irrigation systems remains unchanged until the year 2024. Only water prices of 2 €/mm delay the optimal timing of investment to the year 2028 instead of 2025. On the less fertile soil type, the probability to adopt sprinkler irrigation in year 2009 for production of carrots and potatoes remains unchanged for all water pricing scenarios. In contrast, the optimal timing to adopt sprinkler irrigation for the production of sugar beets with a probability of 100% is delayed to the year 2023 with water prices of 50 cent/mm. For the production of winter wheat in both crop rotations systems, the introduction of water prices reveals that sprinkler irrigation is adopted in year 2039 with 43% for winter wheat in crop rotation system 1, and 39% in year 2039 for winter wheat of crop rotation system 2. From a water resource point-of-view, the decreasing probability of adopting an irrigation system could imply a favorable development as groundwater resources can recover from exploitation; on the other hand, without irrigation, less crop outputs per hectare are produced.

Scenario 3 – Equipment subsidies for drip irrigation systems

We introduce a range of subsidy rates – as proportion of 10% to 90% of drip irrigation capital cost – to analyze how the investment decision is affected. The results are provided in Tab. D-5.3. We find that on Soil 1, subsidies of 10% to 60% do not change the optimal investment plan. The optimal timing to invest into sprinkler irrigation for the production of carrots and sugar beets remains a 100% in year 2024. For the production of carrots, subsidies of 70% of drip irrigation capital cost lead to a 100% probability to adopt drip irrigation in year 2020. Subsidies of 80% also lead to an adoption of drip irrigation for sugar beets in year 2024 and in 2011 for the production of carrots. With subsidies of 90% of capital costs, the year 2009 becomes the optimal timing to invest in drip irrigation for the production of carrots and sugar beets. At the same time, the probability to adopt sprinkler irrigation decreases to zero for both crops. For the less fertile soil type 2, we find that subsidies from 10-50% of capital cost do not affect the optimal investment strategy of all crops. With subsidies of 60%, there is a 100% probability to adopt drip irrigation in year 2009 for the production of carrots; and with subsidies of 70%, there is a 100% probability to adopt drip irrigation for the production of sugar beets in year 2009. A subsidy of 80% also makes the investment in drip irrigation optimal for production of winter wheat of crop rotation system 1 in year 2022. With a subsidy of 90%, the probability to adopt drip irrigation for the production of carrots, potatoes, sugar beets, and winter wheat from the second crop rotation system is a 100% already in year 2009. For the production of corn, the investment probability is a 100% in year 2029 and for winter wheat of crop rotation system 1 in year 2015.

Tab. D-5.3: Year in which drip and sprinkler irrigation systems are adopted with a probability of 100% for the scenario without policies and 7 alternative irrigation subsidy policy scenarios.

	SOIL 1											
	Corn		Carrots		Potatoes		Sugar beets		Winter wheat 1		Winter wheat 2	
	Drip	Spri.	Drip	Spri.	Drip	Spri.	Drip	Spri.	Drip	Spri.	Drip	Spri.
No policy	-	-	-	2024	-	-	-	2024	-	-	-	-
10%	-	-	-	2024	-	-	-	2024	-	-	-	-
30%	-	-	-	2024	-	-	-	2024	-	-	-	-
50%	-	-	-	2024	-	-	-	2024	-	-	-	-
60%	-	-	-	2024	-	-	-	2024	-	-	-	-
70%	-	-	2020	-	-	-	-	2024	-	-	-	-
80%	-	-	2011	-	-	-	2024	-	-	-	-	-
90%	-	-	2009	-	-	-	2009	-	-	-	-	-

SOIL 2												
	Corn		Carrots		Potatoes		Sugar beets		Winter wheat 1		Winter wheat 2	
	Drip	Spri.	Drip	Spri.	Drip	Spri.	Drip	Spri.	Drip	Spri.	Drip	Spri.
No policy	-	-	-	2009	-	2009	-	2009	-	2023	-	2015
10%	-	-	-	2009	-	2009	-	2009	-	2023	-	2015
30%	-	-	-	2009	-	2009	-	2009	-	2023	-	2015
50%	-	-	-	2009	-	2009	-	2009	-	2023	-	2015
60%	-	-	2009	-	-	2009	-	2009	-	2023	-	2015
70%	-	-	2009	-	-	2009	2009	-	-	2023	-	2015
80%	-	-	2009	-	-	2009	2009	-	2022	-	-	2015
90%	2019	-	2009	-	2009	-	2009	-	2015	-	2009	-

D-5.4 Summary and conclusions

A more sustainable water management in agriculture can be achieved by employing irrigation systems which minimize irrigation water inputs per unit of output. We employ a stochastic dynamic programming model to investigate a farmer's investment decision to adopt either a sprinkler, or a more water-efficient drip irrigation system under uncertainty about future precipitation patterns and for production on a more and less fertile soil type. Until 2040, a downward trend in annual precipitation sums is assumed and for each year, 300 possible annual precipitation sums can materialize with equal probability. We investigate how farmers' investment decisions are influenced by the introduction of water pricing policies and the provision of subsidies on capital cost of drip irrigation systems. The analysis is performed separately for the production of five typical crops found in the agricultural region Marchfeld in Austria on two alternative soil types. We use simulation outputs from the biophysical process model EPIC and precipitation data from a statistical climate model (Strauss et al., 2010). There are notable differences in production between both soil types. Average annual crop yields are always higher on the more fertile soil type. On the more fertile soil type, production under sprinkler irrigation achieves the highest average annual profits for carrots and sugar beets and for both crops we find that investment in sprinkler irrigation takes place in year 2025. In contrast, on the less fertile soil type sprinkler irrigation yields the highest average annual profits for all crops, except corn. Investment in sprinkler irrigation is optimal for the production of carrots, sugar beets and potatoes in year 2009 and for winter wheat of crop rotation system 1 and 2, in year 2023 and 2015, respectively. For production on both soil types we find that drip irrigation seems not to be an investment option when no policies are considered. When water prices are introduced, the probability to adopt drip irrigation remains zero and the probability to adopt the sprinkler irrigation system decreases for many crops on both soil types. From a resource point-of-view, less irrigation allows groundwater resources to recover from over exploitation. On the other hand, rain-fed production produces less crop output than irrigated production, which can also be undesirable. Considering the introduction of subsidies around 70%-90% of the capital costs of drip irrigation results in an earlier adoption of drip irrigation systems for carrots and sugar beets on the more fertile soil type and for all crops on the less fertile soil types. As subsidies in this extent can weigh heavily on the national budget, it should be determined whether a shift to drip irrigation is sufficiently productive for all crops and soil types. Additionally, it needs to be determined how a shift to drip irrigation and a subsequent higher groundwater level can minimize costs in other sectors, e.g. a household's cost to extract groundwater for consumption. It would also need further investigations whether water-efficient irrigation technologies are appropriate for agricultural needs, the capacities of the operating systems and farmers.

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D-6 Conclusions

The literature shows a trend towards an increase of more intense drought events in Central Europe (e.g. Christensen et al., 2007; Brázdil et al., 2009; Fallon and Betts, 2010). Therefore, we have developed a high resolution climate dataset for Austria including more frequent drought events. Three different drought scenarios have been computed by manipulation of the distribution of a drought index representing the dry area in Austria for each day in the past period from 1975 to 2007 (chapter D-3).

In our report, we further provide high resolution biophysical data on crop yields, topsoil organic carbon content, nitrate leaching and others for Austria. These data can be used for many different studies (on a national level or case study analyses) as presented in the different chapters, e.g. the analysis of drought impacts on agricultural production (D-3), the integrated land use optimization model which assesses possible adaptation measures (D-4) or the investment in irrigation systems under weather uncertainty (D-5). In the latter two chapters, we focus on the Marchfeld region located in the eastern lowlands of Austria, which is one of the most important agricultural production regions, but at the same time one of the driest regions with approximately 500 mm of annual precipitation sum (cp. chapter D-2).

Our model results of the integrated land use optimization model indicate that climate change will lead to substantial increases in water use, to higher nitrate concentration levels, and to decreases in regional producer surplus. All effects will be considerably enhanced if precipitation sums decrease by 20% in 2031-2040 compared to 1996-2005. Crop production could potentially slightly increase due to widespread application of irrigation measures in 2031-2040. Regulating the stream of environmental outputs such as nitrate leaching and percolation yield as well as topsoil organic carbon content would decrease nitrate concentrations significantly but increase both the loss in producer surplus and irrigation water use.

We found that sprinkler irrigation is effective in reducing the economic costs of climate change, but it will also considerably increase pressure on the regional groundwater aquifer. Together with increased nitrate concentration levels this will most likely increase the costs of irrigation and drinking water extraction and/or treatment in Marchfeld. The total water amounts used by drip irrigation are smaller than for sprinkler irrigation in all scenarios used. We have further investigated a farmer's investment decision in drip and sprinkler irrigation systems under weather uncertainty until 2040 and how this decision changes when policy measures such as water pricing and equipment subsidies are introduced. We have also accounted for adjustment of nitrogen fertilizer application if drip/sprinkler or no irrigation water is applied. We find that investment in sprinkler irrigation is optimal for the production of carrots and sugar beets on a fertile soil type and for the production of all crops on less fertile soil type. However, drip irrigation seems not to be an investment option when no policies are considered. By introducing water prices, the probability to adopt drip irrigation remains zero and the probability to adopt the sprinkler irrigation system decreases for many crops. Considering the introduction of subsidies around 70%-90% of the capital costs of drip irrigations results in an earlier adoption of drip irrigation systems for carrots and sugar beets on the more fertile soil type and for all crops on the less fertile soil type. As subsidies in this extent can heavily weigh on the national budget it should be determined whether a shift to drip irrigation is sufficiently productive for all crops and soil types. Also, water-efficient irrigation technologies must be appropriate for agricultural needs, the capacities of the operating systems and farmers.

Nevertheless, while drip irrigation is said to be the most water-efficient irrigation measures available (Eitzinger et al., 2009) our EPIC simulations suggest that the difference in water use compared to sprinkler irrigation diminishes the warmer and drier the climate becomes. This is due to our EPIC model specifications implying thresholds for annual irrigation, which are earlier reached with sprinkler irrigation than with drip irrigation. In future studies, it will therefore be appropriate to identify and include a wider range of adaptation measures that positively affect water availability, such as conservation tillage, windbreak hedges or precision farming. It may also be worthwhile to allow for a combination of irrigation and fertilization measures as well as alternative land use tions (e.g. energy crops). We can make available our climate and biophysical data for the following StartClim projects.

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Table of Figures and Tables

Figures

Tables

Appendix

Appendix A-1: Crop Budgets for chapter D-4

Crops	Average Prices in €/t 1998-2005	Dry matter content	Total Variable Costs[1] in €/ha
Alfalfa	109.16	0.85	373.91
Barley	91.24	0.85	353.03
Red clover	119.94	0.85	433.14
Sweet clover	119.94	0.85	466.44
Corn	104.28	0.85	529.14
Carrots	171.70	0.20	1575.86
Corn silage	20.00	0.35	395.31
Durum wheat	133.32	0.85	360.81
Farm beans	91.20	0.85	317.61
Fallow land	55.01	0.85	120.85
Field peas	98.85	0.85	319.86
Oats	93.57	0.85	330.68
Potatoes	102.33	0.20	1594.75
Summer barley	108.42	0.85	346.72
Sugar beet	46.76	0.20	1025.67
Soybean	196.31	0.85	353.43
Sunflower	184.87	0.85	426.17
Timothy hay	109.16	0.85	466.44
Triticale	85.74	0.85	350.36
Winter rape seed	178.52	0.85	337.45
Winter rye	97.60	0.85	333.16
Winter wheat	101.58	0.85	373.13

[1]Variable costs comprise of costs of maintenance; input costs, such as oil, seeds, pesticides and fertilizers; as well as insurance and services costs

Appendix A-2: Selected examples of annual irrigation costs included in chapter D-4

Irrigation Systems	Irrigation	Labor Costs[1]	Energy Costs	Capital Costs	Total Costs
		€/ha/a			
Sprinkler	30mm	11.1	4.35	213.33	228.78
Drip	30mm	300.0	3.30	233.33	536.63
Sprinkler	80mm	29.6	11.59	213.33	254.52
Drip	80mm	300.0	8.81	233.33	542.14
Sprinkler	150mm	55.5	21.74	213.33	290.57
Drip	150mm	300.0	16.51	233.33	549.84

[1]Labor costs for sprinkler irrigation depend on irrigation time whereas drip irrigation requires 30h of labor input per year and hectare regardless of irrigation time. An hourly wage of 10€/h was assumed.

Appendix A-3: Summary statistics and information on data source for each crop and irrigation system (for chapter D-5).

		Capital cost[1] €/ha/a	Irrigation Labor hours in h/ha/a[2] (mean)		Electricity cost[3] (mean)		Av. crop price 2005-2009 €/t	Variable costs[4] in €/ha	Labor hours/ crop in h/ha/a	dry/wet Conver-sion coeff.
			Soil 1	Soil 2	Soil 1	Soil 2				
Corn	Sprinkler		5	9	18	36	121.8	512	15.1	1.17
	Drip	233	30	30	12	24				
Carrots	Sprinkler	213	1	5	5	21	236	1566	58.7	8.3
	Drip	400	30	30	4	14				
Potatoes	Sprinkler	213	2	6	7	23	126.6	1501	56.4	5
	Drip	233	30	30	5	15				
Sugar Beets	Sprinkler	213	6	2	23	39	32.8	885	27.2	5
	Drip	233	30	30	15	28				
Winter wheat	Sprinkler	213	1	5	5	20	183	359.5	6.2	1.17
	Drip	233	30	30	3	13				
Source		personal communication with production firm Windisch, G., Firma Bauer; Wannemacher, F., Fa. PARGA; 06/2010; own calculations					Statistic Austria (03/2010)	BMLFUW 2008	BMLFUW 2008	guess-timates

Note: The mean is calculated over 300 precipitation scenarios and the years 2009-2040.

[1] Annualized capital cost are calculated for the expected life of the irrigation system, which is 15 years for both irrigation systems (Source: Wannemacher, F.; personal communications Prof. Breuer, 05/2010)

[2] Irrigation labour hours describe the hours needed to install and run respective irrigation system. Labor hours for sprinkler irrigation depend on irrigation amount, e.g. 1.1h/ha per irrigation activity. Per irrigation activity 50mm are applied to field: irrigation amount/50mm * 1.11h/ha

[3] Both irrigation systems have a water use of $60m^3/h$. Sprinkler has consumption of electricity of 12 kWh and drip irrigation of 9.8kWh. The average annual electricity price is assumed to be 0.065 €/kWh(Source: Statistic Austria). The duration of irrigation can be calculated as: duration irrigation = irrigation quantity m^3/water use per hour; duration of irrigation * electricity consumption per hour * electricity price €/kWh.

[4] Variable costs include costs for fuel, sowing, herbicides, fungicides, pest management, reparation, liming, boron and other