Integrative model analysis of adaptation measures to a warmer and drier climate

Eine integrative Modellanalyse von Anpassungsmaßnahmen an ein wärmeres und trockeneres Klima

Mathias KIRCHNER, Franziska STRAUSS, Christine HEUMESSER and Erwin SCHMID

Summary

We assess the economic and environmental consequences of alternative adaptation measures to a warmer and drier climate in the crop production region Marchfeld in Austria. Our integrated model analysis reveals that increasing temperatures without changes in precipitation patterns (compared to the period 1976-2005) may be slightly beneficial for agricultural producers in the Marchfeld, at least until 2040. However, we also find that if drought events become more frequent, this may exert high pressure on groundwater resources as farmers are likely to irrigate most of the arable land. Furthermore, this could decrease producer surpluses due to the additional costs of irrigation.

Keywords: integrative model analysis, chance constrained programming, adaptation measures, climate change, Marchfeld

Zusammenfassung

Wir untersuchen die ökonomischen und umweltrelevanten Konsequenzen von pflanzenbaulichen Anpassungsmaßnahmen an ein wärmeres und trockeneres Klima in der Region Marchfeld in Österreich. Unsere integrative Modellanalyse zeigt, dass eine Erhöhung der Durchschnittstemperaturen ohne Änderungen im Niederschlagsregime (Referenzperiode 1976-2005) zumindest bis 2040 leichte Vorteile für landwirtschaftliche Produzenten bringen könnte. Wenn in Zukunft jedoch Dürreereignisse häufiger eintreten, kann es aufgrund der Zunahme an Beregnungsmaßnahmen zu größeren

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Entnahmen von Grundwasser kommen. Im Weiteren hätte dies zur Folge, dass auf Grund der zusätzlichen Produktionskosten mit geringeren Produzentenrenten zu rechnen ist.

Schlagworte: Integrative Modellanalyse, Chance Constrained Programmierung, Anpassungsmaßnahmen, Klimawandel, Marchfeld

1. Introduction

Farmers are used to adapt to changing climate conditions. However, the rate of climatic changes has accelerated in the last decades (TRNKA et al., 2011). The case study region Marchfeld may be especially prone to changes in precipitation patterns. Its climate is characterised as semi-arid with average annual precipitation sums of around 500 mm. In particular, summer months can be very hot and dry, and irrigation of vegetables and high quality products is indispensable. Currently, about 30% of arable land is regularly irrigated (MARCHFELDKANAL, 2012).

A statistical climate change model developed by STRAUSS et al. (2012) assumes that average annual temperatures in Austria will increase by approximately 1.5 °C until 2040. Predictions about changes in precipitation patterns are usually much more uncertain than those for temperatures and vary across regions as well as with the respective climate model used. For Central Europe (and thus also Marchfeld), it is generally assumed that precipitation rates may decline in summer but increase in winter (TRNKA et al. 2011; THALER et al., 2012).

An increase in temperatures together with such a decline in rainfall in summer may result in more water stress during crop growth. For example, STRAUSS et al. (2011) find that higher average temperatures alone may already decrease crop yields and thus profits in Marchfeld. As a response, farmers may increase irrigation amounts. Measures that affect water availability are assumed to be among the most important adaptation measures in agriculture (OLESEN et al., 2011).

In Marchfeld, agricultural production has been intensified since the 1970ies. This has led to detrimental effects on the environment such as volatile groundwater levels (STENITZER and HOESCH, 2005) and high levels of nitrate contamination in groundwater (UMWELTBUNDESAMT, 2011) – both of which are likely to be affected by climate change.

Therefore, we analyse the economic and environmental performance of alternative adaptation measures. We have developed a regional land use optimization model that integrates outputs from the biophysical process model EPIC (Environmental Policy Integrated Climate) which uses inputs of the statistical climate change model for Austria (STRAUSS et al., 2012) in order to investigate changes in the optimal mix of management measures, such as irrigation and fertilization under warmer and drier climatic conditions. We then assess the consequences of these changes on regional producer surplus, water use, nitrogen emissions and topsoil organic carbon content.

The paper is structured as follows: in section 2, we present our data and methodology. Results are shown in section 3. The implications of our results on regional policy are discussed in section 4.

2. Data and Method

In the Marchfeld region, total cropland amounts to about 61,600 ha. For our analysis, the cropland is divided into municipalities and homogenous response units (HRUs). HRUs share similar natural characteristics such as elevation, slope and soil types. Hence, they can be used as an interface between biophysical and economic simulation models in order to account for the natural heterogeneity in production and emission (SCHMID et al., 2005) and represent our units of analysis.

The biophysical process model EPIC was used for simulating, inter alia, dry matter crop yields, nitrogen emissions and topsoil organic carbon contents. The outcomes primarily depend on land use, HRUs, crop management, and climate data. We have used climate data developed by STRAUSS et al. (2012) in order to derive our climate scenarios. Two climate change scenarios (2011-2040), Scenario A and Scenario B, have been compared to a historical reference (Past Scenario: 1976-2005). In both climate change scenarios, temperatures increase by 1.5 °C until 2040. However, in Scenario A we assume that precipitation patterns of the past remain unchanged; while in Scenario B annual precipitation sums decrease by 20% (i.e. our 'drought' scenario).

For the calculation of regional producer surplus for each scenario and management option we use average annual crop prices for the period 1998-2005 (STATISTIK AUSTRIA, 2011). We also assume a decoupled premium of 300 €/ha/a. Variable costs of production are derived from the standard gross margin catalogue (BMLFUW, 2008). Variable costs of irrigation as well as their respective annual capital costs are also taken into account (own calculations). Crop prices and production costs are constant in both periods in order to isolate the effect of climate change on the choice of management measures.

The management options include different fertilization rates (standard, reduced and low) and whether to use sprinkler irrigation or not. Furthermore, we include 22 different crop rotation systems which comprise various combinations of 21 crops (e.g. barley, corn, durum wheat, beans, potatoes, sugar beet, sunflower, winter rape, winter wheat) at municipality level.

We have developed a regional land use optimization model that integrates the biophysical outcomes from EPIC. In addition to the climate scenarios, we analyse two different model settings: The Base Model omits environmental constraints while the Chance Constrained Model is subject to environmental regulations (hereafter called ER model) including probabilistic constraints on targets for nitrate emissions and topsoil organic carbon content. We further use the resulting optimal land use and management portfolios to conduct a comparative static analysis. The general model outline is given below:

$$\max \; f(d, X) = \sum\nolimits_c \left(d_c X_c\right) \tag{1}$$

$$s.t. \; \sum\nolimits_c \left(a_{jc} X_c\right) \le b_j \quad \forall j \tag{2}$$

$$\Pr\left[\; \sum\nolimits_c \left(n_c X_c\right) \le N \;\right] \ge \alpha \tag{3}$$

$$\Pr\left[\; \sum\nolimits_c \left(k_c X_c\right) \ge K \;\right] \ge \alpha \tag{4}$$

$$\sum\nolimits_m \left(\theta_m M_{cm}\right) \le X_c \quad \forall c \tag{5}$$

$$\sum\nolimits_c \left(X_c\right) \le \sum\nolimits_m \left(\theta_m \sum\nolimits_c M_{cm}\right) \tag{6}$$

$$X_c \ge 0 \tag{7}$$

The objective function (1) maximises average annual regional producer surplus, where X_c is the choice variable and d_c the gross margin parameter. The index c represents production choices, i.e. on land use, crop rotations, fertilization rates, and irrigation measures. Inequality (2) constrains the choice variable to available resource endowments (b), such as land and, in the ER model, also to irrigation water use, both denoted by the index j. The Leontief technology matrix to convert resources into crop products is represented by a. The parameters for total nitrogen emissions (n) and topsoil organic carbon contents (k) are subject to uncertainties. A simple method of including such uncertainties is the use of chance constrained programming (Zhu et al., 1994; Moghaddam and DePuy, 2011). Inequalities (3) and (4) represent such a probabilistic constraint for nitrogen emissions and topsoil organic carbon content, respectively. These constraints shall not be violated at a given level of probability, denoted by α (we use 95%). While total nitrogen emissions should not exceed a certain maximum (N), a minimum of topsoil organic carbon content should be maintained (K). Assuming that the distribution of the random variables is normal, the chance constraint (3) (and (4) respectively) can be reformulated as (Zhu et al., 1994):

$$\sum_c \left(\overline{n_c} X_c\right) + K_\alpha \sqrt{\sum_c \left(\sigma^2{}_c X^2{}_c\right)} \leq N \qquad (8)$$

where $\overline{n}$ is the arithmetic mean of total nitrogen emissions and K_α is a constant that depends on the distribution of the random variable and the level of probability. The term $(\sum_c (\sigma_c^2 X_c^2))^{(1/2)}$ is the standard deviation of $\sum_c (\overline{n_c} X_c)$. Hence, one obtains a deterministic value which incorporates the uncertainty of the parameter for a certain level of confidence. Moghaddam and DePuy (2011) refer to it as a 'safety term'. The average annual threshold levels are 100 kg/ha for total nitrogen emissions, 60 t/ha for topsoil organic carbon, and 100 mm for irrigation. Water access is unlimited in the Base model.

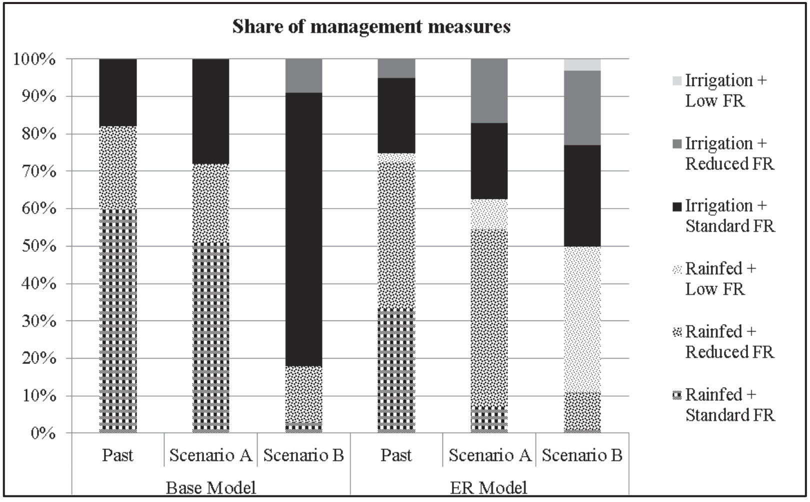
Finally, constraints (5) and (6) ensure a convex set of alternative crop rotation system mixes, where θ is the choice variable for the crop rotation mix and M the parameter for available mixes denoted by m.

The Base model and the ER model are solved for two climate change scenarios, scenario A and B, and for past observation (1975-2005) using the software GAMS (General Algebraic Modeling System). The linear solver CPLEX has been used for the Base model and the non-linear solver CONOPT for the ER model.

3. Results

Figure 1 illustrates the optimal mix of management measures to a changing climate. The first three columns from the left indicate how farmers may adapt without being forced to meet environmental targets (i.e. the Base model). In all climate scenarios, standard fertilization rates are widely applied (more than 70% in all scenarios) while low fertilization rates are not profitable at all. The application of sprinkler irrigation increases from 18% to 28% in Scenario A and to 82% in Scenario B. Hence, irrigation seems to be a cost-efficient adaptation measure to a warmer and drier climate.

Fig. 1: Optimal shares of crop management measures by scenarios and model settings



Note: 'FR' refers to fertilization rates.

Source: Own calculations

The last three columns show how farmers' choices may change when they have to meet environmental targets (i.e. the ER model). Here, the application of sprinkler irrigation in the Past Scenario and Scenario A is higher than in the Base model. The EPIC simulations indicate that irrigation reduces, on average, nitrogen emissions. Hence, farmers have an incentive to increase their irrigation share when nitrogen emission targets are binding. In Scenario B, the constraint on irrigation water use becomes binding which in turn leads to an increase in the application of lower fertilization rates.

The main average annual economic and environmental outcomes of the optimal crop management choices are presented in Table 1. The Base model results indicate that, on the one hand, Scenario A seems to provide new opportunities for farmers. Average annual regional producer surplus as well as crop production increase slightly by 5% and 4%, respectively (compared to the Past Scenario). However, nitrogen emissions increase significantly (6%), topsoil organic carbon decreases marginally and water use is increased by more than half. On the other hand, a drier climate (Scenario B) seems to pose challenges on farmers. Crop production can be enhanced by increasing irrigation amounts. Nevertheless, regional producer surplus drops by 7% due to the additional costs associated with irrigation. Nitrogen emissions do not change substantially but topsoil organic carbon decreases slightly (2%). The biggest environmental effect can be found in water use. In a drier climate, water withdrawals may quadruple.

Tab. 1: Average annual economic and environmental results

	Base Model			**ER Model**		
	Past	***Sc. A***	***Sc. B***	***Past***	***Sc. A***	***Sc. B***
Regional PS (mill €)	58.07	60.84	53.72	56.79	58.27	47.66
	28%	*28%*	*32%*	*26%*	*27%*	*30%*
Crop production (t/ha)	5.79	6.04	6.41	5.85	6.06	5.33
	9%	*10%*	*6%*	*8%*	*9%*	*11%*
Total nitrogen emission (kg/ha)	101.29	106.93	101.15	95.41	95.52	95.43
	37%	*36%*	*38%*	*38%*	*39%*	*37%*
Topsoil organic carbon (t/ha)	58.75	58.26	57.69	60.18	60.19	60.22
	3%	*3%*	*3%*	*3%*	*3%*	*3%*
Sprinkler irrigation amounts (mm)	30.44	48.95	163.61	40.89	62.89	100.00
	29%	*27%*	*25%*	*31%*	*28%*	*25%*
Total agricultural water use (mill m^3)	18.75	30.16	100.79	25.19	38.74	61.60

Note: The percentages values in italic are coefficients of variation; PS refers to producer surplus.
Source: Own calculations.

The ER model shows that, compared to the Base model, mitigating environmental degradation leads to only small losses in producer surplus in both the Past Scenario and Scenario A, with the latter still being the most profitable of all Scenarios. The losses in producer surplus are much more profound in Scenario B, especially due to the constraint on water use. Interestingly, if average nitrogen emissions are constrained to 100 kg/ha in 95% of all states, the actual average levels are much lower than 100 kg/ha. This is due to the high variations of nitrogen emission levels which in turn leads to a large 'safety term'.

Contrary, topsoil organic carbon contents are only slightly above 60 t/ha. Compared to the Base model water use in the ER model is much higher in the Past Scenario and Scenario A, but lower in Scenario B, as the constraint becomes binding. Nevertheless, the increase in water use is still substantial in the latter case.

Observed data on irrigation amounts in Marchfeld correspond quite well to our estimations for the Past Scenarios (20 to 40 mill m^3; whereby 90% is withdrawn from groundwater bodies and only 10% from surface waters; see MARCHFELDKANAL, 2012). However, THALER et al. (2012) report more conservative increases in water demand for winter wheat in Marchfeld than we do for comparable climate scenarios until 2050. Nevertheless, in Scenario B total regional water use (which is total agricultural water use plus ca. 25 mill m^3 water withdrawals by industries and municipalities) far outweighs the natural groundwater recharge rate plus the contribution of the Marchfeldkanal (ca. 56 and 10 mill m^3, respectively, according to NEUDORFER, 2012). Groundwater recharge rates are likely to decline substantially in the future due to climate change (FUCHS, 2005).

4. Conclusions

According to some climate projections, semi-arid regions in Central Europe such as the Marchfeld might become prone to more frequent drought occurrences in the near future (TRNKA et al. 2011, THALER et al. 2012). Thus, an evaluation of agricultural adaptation strategies is indispensable. In our study we have analysed the economic and environmental effects of selected adaptation measures, such as irrigation and fertilization.

Our integrative model analysis indicates that sprinkler irrigation seems to be a cost-efficient adaptation measure in a warmer and drier climate. If precipitation patterns remain unchanged, farmers may even expect to gain from an increase in temperatures, at least until 2040. However, if drought events become more frequent, widespread application of irrigation measures may considerably increase pressure on regional groundwater resources. This may negatively affect farmers, industry and municipalities due to higher extraction costs. While the supply of water may be regulated this will inevitably lead to a significant decline in producer surplus. A further trade-off exists in mitigating nitrogen emissions and maintaining topsoil organic carbon stocks. While it is a tedious if not impossible task to assess the economic benefits of mitigating these environmental externalities, one has to at least think of efficient ways of internalising them, e.g. through water pricing or subsidies for more efficient irrigation techniques. HEUMESSER et al. (2011) find that farmers in Marchfeld would require substantially high subsidies in order to invest in more water-efficient irrigation systems (i.e. drip irrigation). Given these findings, there may be a need for developing a regional water policy framework in order to avoid future conflicts and to contribute to a sustainable development of the region. Future studies should include the participation of relevant stakeholders as well as a wider range of possible adaptation measures, such as conservation tillage, windbreak hedges or precision farming.

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Affiliation

DI Mathias Kirchner, Mag.ª Franziska Strauss,
Mag.ª Christine Heumesser and Univ. Prof. DI Dr. Erwin Schmid
Institute for Sustainable Economic Development and
Doctoral School Sustainable Development
University of Natural Resources and Life Sciences
Feistmantelstraße 4, 1180 Vienna, Austria
Tel.: +43 1 47654 3667
eMail: mathias.kirchner@boku.ac.at, franziska.strauss@boku.ac.at,
christine.heumesser@boku.ac.at and erwin.schmid@boku.ac.at