Global warming and German agriculture: impact estimations using a restricted profit function

Günter Lang

Angaben zur Veröffentlichung / Publication details:

Lang, Günter. 1999. “Global warming and German agriculture: impact estimations using a restricted profit function.” Augsburg: Volkswirtschaftliches Institut, Universität Augsburg.

Global Warming and German Agriculture

Impact Estimations Using a Restricted Profit Function

Günter Lang*
University of Augsburg
March 1999

Abstract

This study uses the concept of shadow prices for measuring the impacts of climate change. Estimation of a restricted profit function rather than a cost or a production function increases the explanatory power of the agroclimate approach because of an endogenous output structure. Using low aggregated panel data on Western German farmers, the results imply that the agricultural production process is significantly influenced by climate conditions. By linking this model with a climate-change scenario, a remarkable positive shadow value is found for the German agricultural sector. Interestingly, the spatial distribution of the gains shows no concentration on those regions, which currently suffer from insufficient temperature. Finally, the importance of an endogenous output structure is confirmed by the finding that the desired product mix will drastically change.

JEL classification:

Q12, Q25

Keywords:

Climate change; impact study; agriculture; restricted profit function

* PD Dr. Günter Lang, University of Augsburg, Department of Economis, D-86135 Augsburg, Germany, e-mail guenter.lang@wiso.uni-augsburg.de. I'm greatly indebted to the German federal ministry of agriculture and the German weather service for providing the data set. Helpful comments from Hans-Helmut Bünning and Peter Welzel are gratefully acknowledged.

Introduction

Human activities are currently raising the atmospheric concentrations of important greenhouse gases like carbon dioxide or methane. As a consequence, the majority of natural scientists suspect a substantial climate change for the near future, if that didn't already occur. Of course, this externality is an important challenge for national policy and international coordination. To deal efficiently with the threat of greenhouse warming, environmental policies have to balance the costs of reducing emissions against the impacts of a changing climate. This is a demanding task for for economists, however, because the costs of slowing global warming as well as potential impact costs have to be estimated and compared.

To the current state of knowledge, one of the most affected sectors is agriculture. The reason for this dependence is a direct biological relationship between crop growth and climate conditions. From their exhaustive literature analysis, *Pearce et al. (1996)* conclude that globally about one fifth of all damages will occur in agriculture. Together with damages from sea level rise, increasing mortality and increasing energy demand, food production is ranking at the top of the vulnerable sectors.

These estimations are often very rough, however, because highly aggregated studies suffer from the fact that national or regional differences are not sufficiently taken into account. For example, international productivity differences, socioeconomic environments, or the climate microstructures within a country are neglected. Consequently, as the *IPCC*[1] states in its latest report, future work regarding the impacts of climate change on agriculture should be focused on regional models, which carefully pay attention to local features *(Reilly, 1996, p. 455).*

This study is following this direction of research and attempts to evaluate the economic consequences of climate change on German agriculture. As in contrast to the US (see e.g. *Adams et al, 1993, Easterling et al., 1992, Mendelsohn et al., 1994, Dixon et al., 1994*), currently only a few papers give predictions for the second-largest agricultural sector in the EC. For an exception see *Wolf (1994)* with estimations for regional wheat production in Europe.

To measure the relationship between climate conditions and farming, at least three different approaches can be used: Greenhouse experimental studies (see e.g. *Strain and Cure, 1985*), hedonic methods (see e.g. *Mendelsohn et al., 1994*), and agroclimatic models. As for the latter, they can be

---

[1] International Panel on Climate Change.

differentiated into calibrated simulation models of crop growth and statistical-empirical models, which combine real world agroeconomic data with climate information to evaluate the most appropriate relationship (see *Carter et al., 1998*, for this distinction).

This study follows the statistical-empirical approach by relying on microfounded production theory. More specifically, by using a restricted profit function, inputs as well as outputs are treated as endogenous. This allows for optimal adaptation of the farmers to the new climate conditions. Low-aggregated micro data in panel structure serves as empirical background, with the sample covering the whole area of (Western) Germany. All farm data is linked with climate information on the relevant region and time period. Finally, the simulation results from a complex atmosphere-ocean model are used as global warming scenario(see *Kattenberg et al., 1996*, for an overview).

Model Specification

Each farmer is assumed to behave like a profit-maximizer within a competitive environment, i.e. m^d input as well m^s output quantities are endogenous, whereas the corresponding prices are considered as exogenous. Given the state-controlled intervention system for the majority of agricultural products, this assumption seems to depict the real world situation quite well. The number of variable netputs is therefore summing up to $m = m^d + m^s$. Aside from the netput price vector $p = (p_1, \ldots, p_m)'$, each farmer is facing a set of (likewise exogenous) climate variables $z = (z_1, \ldots, z_q)'$, which are allowed to influence crop yields and therefore profits p .

As functional representation of the restricted profit function (see *McFadden, 1978*, for an exhaustive discussion), the following form is employed:

$$\pi(p,z) = a_0 + \sum_{i=1}^{m} a_i p_i^{\frac{1}{2}} + \sum_{i=1}^{m}\sum_{j=1}^{m} a_{ij}\left(p_i p_j\right)^{\frac{1}{2}} + \sum_{k=1}^{q} b_k z_k^{\frac{1}{2}} + \sum_{i=1}^{m}\sum_{k=1}^{q}\sum_{l=1}^{q} b_{ikl} p_i \left(z_k z_l\right)^{\frac{1}{2}} \tag{1}$$

This locally-flexible, twice-continuously-differentiable „generalized Leontief form“ is much less restrictive than the Cobb-Douglas or the CES because of non-constant substitution elasticities.

To ensure symmetry and linear homogeneity in netput prices, the following restrictions have to be imposed:

$$\begin{aligned} &a_0 = 0 \qquad a_i = 0 \;\; i = 1,\ldots,m \qquad b_k = 0 \;\; k = 1,\ldots,q \\ &a_{ij} = a_{ji} \qquad b_{ikl} = b_{ilk} \end{aligned} \tag{2}$$

For the present study with $m = 10$ netputs and $q = 3$ climate indicators, the implementation of (2) is reducing the number of free parameters to 115.

Aside from linear homogeneity, economic theory is claiming convexity in netput prices. One can use the Cholesky-factorization introduced by *Lau (1978)*, or an eigenvalue-procedure (*Talpaz et al., 1989*) to impose this important property. The latter is using the fact that all eigenvalues of a positive semidefinite matrix are non-negative. Therefore by adding a non-linear restriction of the form

$$\min(eig[H(b, p^0)]) \geq 0\,, \tag{3}$$

with $H(b, p^{\upsilon})$ representing the Hesse matrix of the restricted profit function, local convexity for the price vector p^{υ} is ensured. *b* is denoting the parameter vector.

Typically, p^{υ} is chosen as a vector with mean values of all netput prices. As *Talpaz et al. (1989)* have shown, the eigenvalue-procedure is under certain circumstances more favorable than a Cholesky-factorization because of its greater robustness. For studies with the number of netputs being greater than six, the Cholesky-factorization may fail. Because this is case in the current study, an eigenvalue-procedure had been imposed.

For an efficient use of the existing information, Hotelling’s Lemma is used to derive *m* netput equations:

$$\rho_i = y_i p_i = \frac{\partial \pi(p,z)}{\partial p_i} p_i = \sum_{j=1}^{m} a_{ij}\left(p_i p_j\right)^{\frac{1}{2}} + \sum_{k=1}^{q}\sum_{l=1}^{q} b_{ikl}\left(z_k z_l\right)^{\frac{1}{2}} \qquad i = 1,\ldots,m \tag{4}$$

ρ_i is representing the profit-maximizing DM-value for all variable netputs, with negative values characterizing inputs. Total profits of an individual firm are therefore given by the sum over ρ_i. Additive error terms, which are assumed to be normal distributed and contemporaneously correlated, are appended to the revenue equations (4).

To determine the parameters of the profit function (1), *m* revenue equations (4) are estimated jointly by maximum likelihood (for the likelihood function see *Greene, 1997, pp. 682ff.*). This powerful method increases the number of observations by the *m*-fold, without increasing the number of parameters to be estimated. The profit function itself has to be deleted, because the sum of the error terms from *m* revenues are equal to the error term of the profit function for every firm. Otherwise the variance-covariance matrix of the error terms would be singular.

One of the most important implications of a flexible functional form like (1) is that it allows for analytical simplification tests. In this paper, the basic assumption is that climate affects the production possibilities of crops and therefore the netput quantities. As can be seen from (1), a wide range of interactions between the *p*- and the *z*-variables are possible. To test for the basic assumption, three simplification tests are conducted:

a) The climate environment is without any relevance for the agricultural production process. This far-reaching hypothesis is identical with the restrictions

$$b_{ikl} = 0 \quad \forall i = 1,\ldots,m;\ k,l = 1,\ldots,q \tag{5}$$

b) The climate environment affects the production process, but there are no interactions between the variables in the *z*-vector. This less-restrictive hypothesis requires that the following restrictions are implemented:

$$b_{ikl} = 0 \quad \forall i = 1,\ldots,m;\ k,l = 1,\ldots,q;\ k \neq l \tag{6}$$

c) Relative output quantities are independent from input prices and climate conditions (output-separability). Hence climate conditions would influence the aggregated output level, but not the output mix. More formally, this restriction can be written as (*Livernois and Ryan, 1989*)

$$\frac{\partial \left(\dfrac{\partial p / \partial p_i}{\partial p / \partial p_j} \right)}{\partial p_k} = 0 \quad \text{and} \quad \frac{\partial \left(\dfrac{\partial p / \partial p_i}{\partial p / \partial p_j} \right)}{\partial z_k} = 0 \quad . \tag{7}$$

$$\forall p_i, p_j \in p^s, i \neq j; \quad \forall p_k \in p^d;\ \forall k = 1,\ldots,q$$

The superscripts *s* and *d* indicate output prices and input prices, respectively. All necessary parameter restrictions for output-separability are given in *Table A- 1*.

If the results should indicate that a statistically significant impact of climate exists, its economic importance has to be determined. This is the problem of finding a monetary value for the *z*-variables (public goods). Since the profit function gives the willingness to pay for a certain combination of *p* and *z* values, two different states of *z* can easily be compared, however. Differences in π due to a change in *z* indicate a different willingness to pay for certain *z*-environments. These shadow-values can take a positive („public good“) or a negative („public bad“) sign.

Within the framework of global warming, the shadow value of future climate is of central interest. Define z^0 as a vector with the current climate conditions, z^1 as a vector representing the projected climate. Given the present netput price structure as point of reference, the shadow value of climate change can then be measured as

$$s^{z^0 z^1} = \pi\left(p, z^1\right) - \pi\left(p, z^0\right). \tag{8}$$

Slight modifications of (8) allow for the monetary valuation of the change in just one single climate variable or of the relationship between simultaneous changes in *p* and in *z*. The latter could be of interest if global warming reduces world food supply and increases food prices (*Kane et al., 1992*).

If one is interested in the reactions of the netput quantities, the following formula can be used:

$$\Delta y_i^{z^0 z^1} = \frac{\hat{y}_i^1 - \hat{y}_i^0}{\hat{y}_i^0} = \frac{\partial \pi\left(p, z^1\right) \big/ \partial p_i - \partial \pi\left(p, z^0\right) \big/ \partial p_i}{\partial \pi\left(p, z^0\right) \big/ \partial p_i} \qquad i = 1, \ldots, m \tag{9}$$

$\Delta y_i^{z\,z}$ is the percentage reaction of netput i to a change from z^0 to z^1.

Data

The data used for estimation of the outlined model consist from three parts: Agroeconomic variables measuring netput quantities and prices, real weather data representing the current micro climate, and (third) projections about future climate conditions. All agroeconomic data were obtained from the German federal ministry for agriculture, whereas the German weather service provided all necessary weather data. Finally, as for the simulation of future climate, the 2xCO_2-projection[2] of the Geophysical Fluid Dynamics Laboratory (*GFDL*) was used.

Information about netput quantities and prices are available for five different types of farmers, which are again differentiated into 41 regions (see *Figure 4* for the geographical demarcation). The five types represent different kinds of specialization like fattening or the production of vegetables and fruit. For every region and every specialization the netput structure of a representative farmer is given. Taking further into account that some kinds of specialization in certain regions do not exist and the panel length is five periods (1990 to 1994), the total number of observations is 803.

As for the number of netputs, four inputs and six outputs can be differentiated. Following the proposal of the ministry for agriculture, the price for labor of the mainly self-employed farmers is based on the concept of opportunity costs. Land prices are assumed as rents to be paid in a particular region. All input prices are considering factor specific subsidies (e.g. for land), all output prices are taking product specific subsidies into account. *Table 1* presents detailed information about these ten netputs.[3]

Climatic data is available from a sample of weather stations in Western Germany. Because some of the weather stations are not relevant for agricultural production, in a first step all irrelevant stations (e.g. on mountains) were deleted. For the remaining 75 stations, the available information was condensed to three climate variables, which are relevant for crop growth: a) Effective temperature sum (*ETS*) as an indicator for the thermal situation, b) the Thornthwaite’s moisture index (*MI*) as an indicator for the availability of moisture, and c) the number of frost days (*FROST*) during April to September as an indicator for the length of the growing period. Finally, in order to link the agroeconomic information which is organized by 41 regions and the climate data which is existing for 75 stations, an assignment following the principle of spatial proximity was conducted. See *Lang (1999)* for a detailed description of the climate data and the assignment problem.

As mentioned before, the climate change scenario was adopted from the *GFDL* model. For central Europe an average temperature increase in the order of 2°C, accompanied by a 10% higher precipitation, is expected. Simulation models, which could offer spatial more disaggregated scenarios, do in general not exist. To maintain the regional heterogeneity of climate, all differences between the current and the future climate are added to every weather station (*Smith and Tirpak, 1990*). Information about the current climate conditions as well as about the expected conditions can be found in *Table 1*.

---

[2] Climate conditions given a doubling of the greenhouse gases against the base year 1958.

[3] See *Lang (1999)* for an exhaustive description of the data.

Table 1: Description of the data set

		mean	**std. dev.**	**minimum**	**maximum**
inputs	labor (full-time persons)	1.64	0.28	0.99	4.16
	-price ('000 DM/person)	30.80	1.07	22.87	35.85
	capital ('000 DM)	407.91	109.68	135.79	934.68
	-price	0.14	0.03	0.06	0.34
	land (ha)	36.91	15.14	3.49	94.17
	-price ('000/ha)	0.47	0.47	0.01	8.76
	material ('000 DM)	70.89	34.61	5.46	228.50
	-price	0.98	0.06	0.86	1.33
outputs	grain ('000 DM)	34.02	21.23	0.00	119.80
	-price	0.96	0.10	0.69	1.62
	sugarbeet ('000 DM)	6.89	11.91	0.00	84.16
	-price	1.02	0.09	0.72	1.39
	potatoes ('000 DM)	4.42	12.51	0.00	122.69
	-price	1.07	0.44	0.45	4.73
	oilseed ('000 DM)	6.28	7.41	0.00	61.52
	-price	0.91	0.10	0.64	2.17
	vegetables, fruit, wine ('000 DM)	17.10	43.16	0.00	273.72
	-price	0.84	0.15	0.65	1.09
	cattle ('000 DM)	130.21	75.12	0.00	561.26
	-price	0.95	0.09	0.75	1.53
current climate	*ETS* (effective temperature sum)	1918.0	265.5	1283.4	2700.5
	MI (moisture index)	133.9	47.3	51.1	347.7
	FROST	5.0	3.5	0	27
GFDL scenario	*ETS* (effective temperature sum)	2441.5	275.7	1816.1	3306.3
	MI (moisture index)	133.4	37.5	62.9	325.4
	FROST	1.9	3.0	0	19.7

number of observations: 803; DM-values in prices from 1990.

Empirical results

Parameter estimates for the profit function (1) were obtained by maximum likelihood estimation of $m = 10$ revenue functions (4). All linear restrictions given by (2) and the non-linear restriction (3) for maintaining convexity were imposed.[4] Putting together, 8030 observations are available for the determination of 115 free parameters. The program code was written in GAUSS. As can be seen from *Table A- 2*, where the estimation results are presented, about 50% of all parameters exhibit a significance level of at least 90%. Parameter describing the input behavior are in general more reliable than those for the output side.

To begin with the empirical analysis of the results, likelihood-ratio tests were run to check over the statistical relevance of the three climate variables. More specifically, the system of revenue equations was re-estimated with additional restrictions according to the three hypotheses specified above. The results, given in *Table 2*, allow a clear interpretation: Since all three hypotheses are highly significant rejected, the influence of climate conditions on agricultural production can be considered as sure. Furthermore, not only output levels, but also the output mix is affected by the regional climate.

---

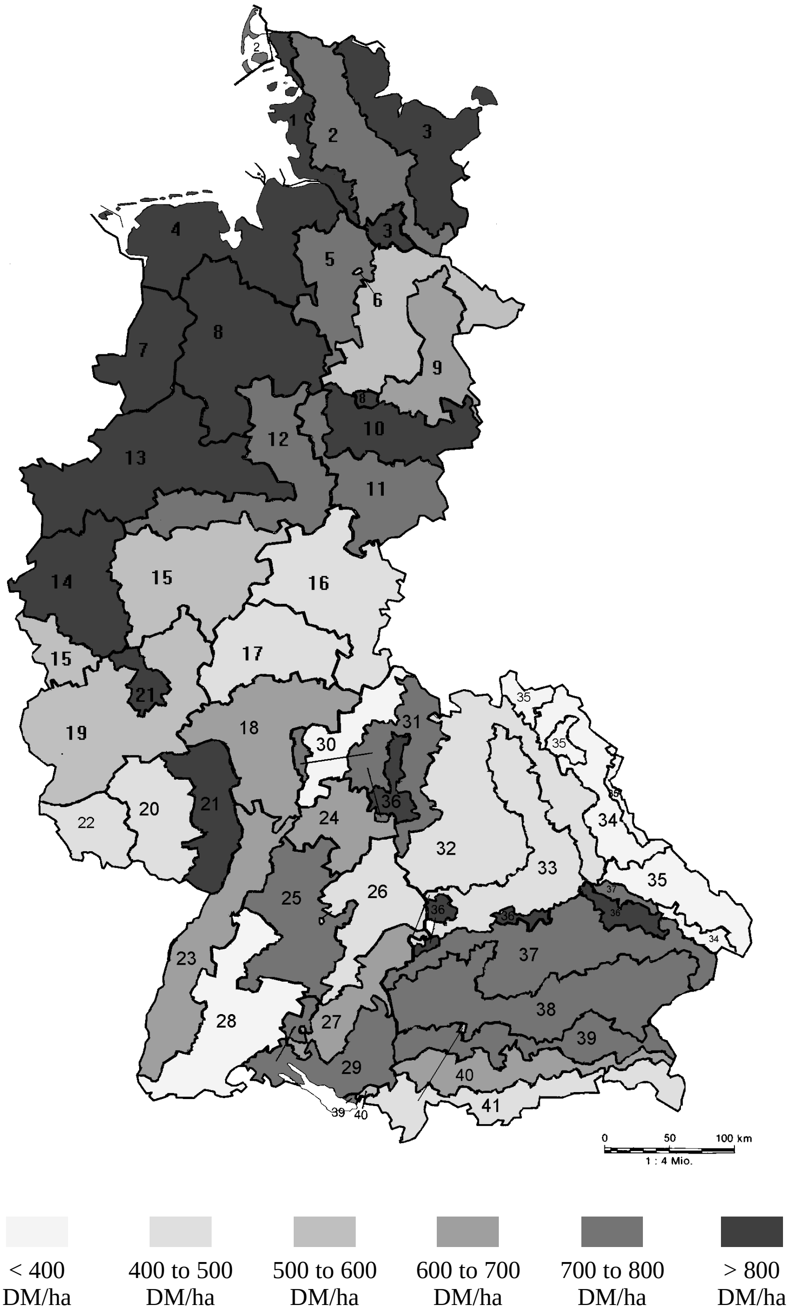
[4] In the empirical implementation the eigenvalue condition was somewhat weakened to the condition that all resulting own-price elasticities are negative for inputs and positive for outputs. Otherwise the profit function would adopt a „too convex" behavior with clearly implausible characteristics (see *Diewert and Wales, 1987*, for a similar argument).

Table 2: Likelihood-ratio-tests on simplified model structures

hypothesis	l_{LR}	degrees of freedom	$c^{2}_{0.10}$	$c^{2}_{0.01}$	result
a) climate conditions are irrelevant	708.88	60	74.40	88.38	reject
b) no interactions between climate variables	133.42	30	40.26	50.89	reject
c) output-separability	599.64	60	74.40	88.38	reject

l_{LR} as value of the likelihood-ratio statistics; c^{2} gives the critical chi-square values.

Figure 1: Shadow values of climate change by regions



Estimations for current netput prices. Climate change scenario from *GFDL*-model.

Turning to the economic interpretation of the parameter estimates, the shadow values of climate change are calculated on the basis of equation (8). For reasons of better comparison, the shadow values are divided by the desired quantity of land, which gives us „DM per ha". The results indicate a strong positive impact of global warming on the German agriculture: Given the current level of netput prices, every region and every kind of specialization can expect higher profits. At the average, the per-ha increase amounts to about DM 700, which is summing up to about DM 25000 per farm. This result implies that the increasing availability of warmth and the decreasing number of frost days during April to September will drastically improve the conditions for crop growth.

Geographical details on the distribution of shadow prices is depicted in *Figure 1*. As can be seen, there are remarkable differences between the regions in Western Germany. Benefits for farmers in the northern and the south-eastern part of Germany are in general greater than for those in central Germany. Interestingly, differences in netput prices turned out to be more important for the level of shadow values than the current climate condition: Producers in regions 28, 34 or 35, which heavily suffer from insufficient warmth, will gain less than the average farmer because of relative low output prices.

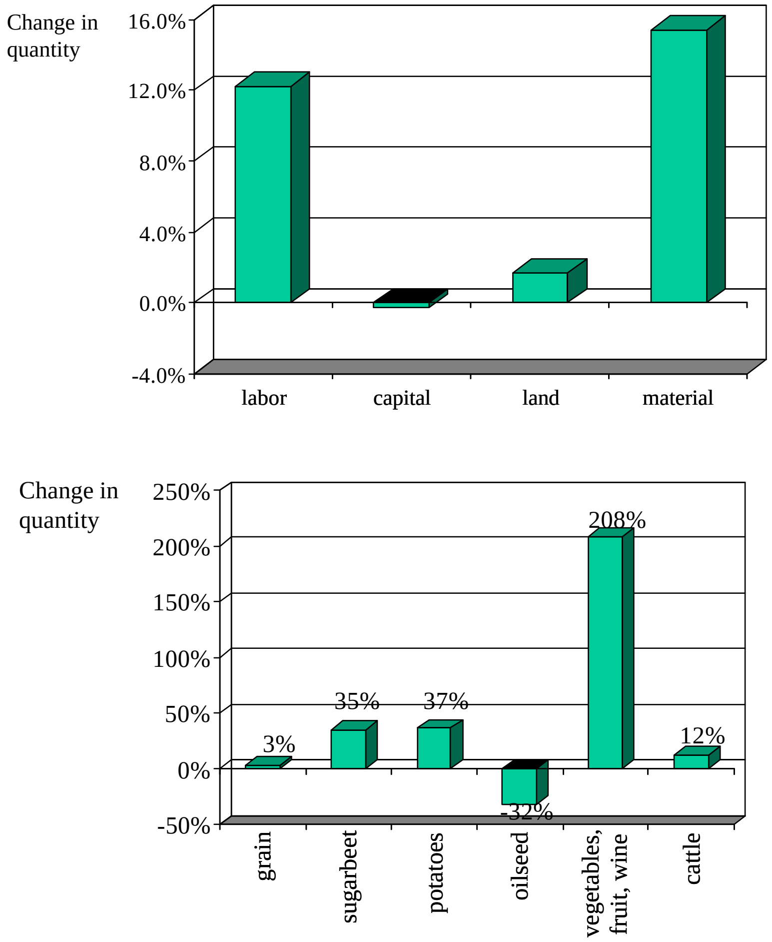
Aggregating this result for the whole agricultural sector, the positive impact of global warming sums up to about DM 7.6 billion (in 1990 prices). Relating this value to gross farm revenues, the annual benefit is about 12% of the present output value. Compared to the US, where most studies (see e.g. *Cline, 1992, Mendelsohn et al., 1994, Pearce et al., 1996, Smith and Tirpak, 1990)* show a negative to a slightly positive impact (-12% to +1%), the German agricultural sector turns out to be more positive affected.

As predicted by the output-separability test, not only the absolute levels, but also the relative structure of inputs and outputs heavily depends on climate conditions. *Figure 2* is providing the desired netput changes from the global-warming scenario. As can be seen, the currently very important products grain and cattle are estimated to enjoy only a small output increase. Instead, the labor-intensive production of vegetables, fruit and wine will expand drastically because of the higher temperature. From a methodological point of view, these results clearly support models with endogenous output mixes. By ignoring theses adaptation possibilities, the estimated damages and benefits are too large and too small, respectively (see also *Mendelsohn et al., 1994,* on that point).

Note that the predicted change in the output mix is based on relative, not on absolute advantages within the climatic framework. This can be demonstrated by the important product grain, which shows a climate change induced increase of just 3%. *Figure 3,* which is providing the desired grain output per unit of land for all relevant temperature (*ETS*) - moisture (*MI*) combinations, confirms that surprising result: Highest output levels per hektar can be expected for a dry and cold climate. But why is this the case, as - from a biological point of view - growth conditions for grain are improving with higher temperature?[5]

The answer on this question can be found in the climate-induced behavior of the other products. If the production possibilities of all products are enhancing, the farmer may decide to switch some land input from grain to sugarbeet, because the profit increase is larger. Consequently, the grain output is increasing less than proportional or even decreasing.

Figure 2: Change in netput quantities due to climate change

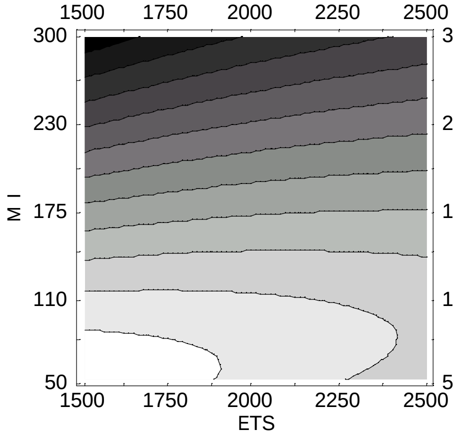


All calculations for a representative farmer and current netput prices. Climate change scenario from *GFDL*-model.

---

[5] For very high temperatures, barley and wheat will be substituted by corn.

Figure 3: Desired grain production in different temperature-moisture scenarios



Desired grain output per unit of land. Darker isocontours represent lower output.

Conclusion

The empirical results of this study indicate that the German agricultural sector, historically one of the biggest loser of structural change, could significantly gain from global warming. On a per-hektar basis, the mean shadow value is estimated at about DM 700, with the lower range being at DM 200, the upper range at DM 1200. Summing up for Western Germany, the aggregate benefit stands at DM 7.6 billion or 12% of the present production value. Furthermore, the desired output-mix will change drastically towards temperature-sensitive products, which are typically labor-intensive. Since the global projections for the agricultural output are negative, these findings suggest that the competitive viability of the German farming sector will substantially increase. Of course, further research is necessary to test for the robustness of this result.

Finally, it is important to note that no general conclusions on an environmental policy can be drawn from this study. Global warming will affect all countries and many market and non-market sectors. There are winners and losers from global warming - but to the current knowledge the winners couldn't compensate the losers. It may be the case, however, that with an appropriate consideration of adaptation options the enormous damages estimated by calibrated crop-yield studies on world agriculture have to be revisited. The expected worldwide loss in food production could be less drastic if a variable input and output structure is taken into account.

References

Adams, R.M., Fleming, R.A., Chang, C.C., McCarl, B.A., Rosenzweig, C. (1993), A Reassessment of the Economic Effects of Global Climate Change on U.S. Agriculture, Report for the U.S. Environmental Protection Agency, Washington DC.

Carter, T., Konijn, N.T., Watts, R. (1988), The Choice of First-Order Impact Models, in: *Parry, M.L., Carter, T.R. (eds.),* The Impact of Climatic Variations on Agriculture, Volume 1: Assessments in Cool Temperate and Cold Regions, Dordrecht: Kluwer Academic Publishers, pp. 97-123.

Cline, W.R. (1992), The Economics of Global Warming, Washington: Institute for International Economics.

Diewert, W.E., Wales, T.J. (1987), Flexible Functional Forms and Global Curvature Conditions, Econometrica 55, pp. 43-68.

Dixon, B.L., Hollinger, S.E., Garcia, P., Tirupattur, V. (1994), Estimating Corn Yield Response Models to Predict Impacts of Climate Change, Journal of Agricultural and Resource Economics 19, pp. 58-68.

Easterling, W.E., McKenney, M.S., Rosenberg, N.J., Lemon, K.M. (1992), Simulations of Crop Response to Climate Change: Effects with Present Technology and currently available Adjustments, Agricultural and Forest Meteorology 59, pp. 75-102.

Kane, S., Reilly, J., Tobey, J. (1992), An Empirical Study of the Economic Effects of Climate Change on World Agriculture, Climatic Change 21, pp. 17-35.

Kattenberg, A., Giorgi, F., Grassl, H., Meehl, G.A., Mitchell, J.F.B., Stouffer, R.J., Tokioka, T., Weaver, A.J., Wigley, T.M.L. (1996), Climate Models – Projections of Future Climate, in: *Houghton, J.T., Filho, L.G.M., Callander, B.A., Harris, N., Kattenberg, A., Maskell, K. (eds.),* Climate Change 1995: The Science of Climate Change, Second Assessment Report of the Intergovernmental Panel on Climate Change I, Cambridge: Cambridge University Press, pp. 285-357.

Lang, G. (1999), Globaler Klimawandel und Agrarsektor, Schriften zur angewandten Wirtschaftsforschung 80, Tübingen: Mohr-Siebeck.

Lau, L. (1978), Testing and Imposing Monotonicity, Convexity and Quasi-Convexity Constraints, in: *Fuss, M., McFadden, D. (eds.),* Production Economics: A Dual Approach to Theory and Applications, Amsterdam: North-Holland, pp. 409-453.

Livernois, J.B., Ryan, D.L. (1989), Testing for Non-Jointness in Oil and Gas Exploration: A Variable Profit Function Approach, International Economic Review 30, pp. 479-504.

Mendelsohn, R., Nordhaus, W.D., Shaw, D. (1994), The Impact of Global Warming on Agriculture: A Ricardian Analysis, The American Economic Review 84, pp. 753-771.

McFadden, D. (1978), Cost, Revenue, and Profit Functions, in: *Fuss, M., McFadden, D. (eds.),* Production Economics: A Dual Approach to Theory and Applications, Vol. 1, Amsterdam: North-Holland, pp. 1-110.

Pearce, D.W., Cline, W.R., Achanta, A.N., Fankhauser, S., Pachauri, R.K., Tol, R.S.J., Vellinga, P. (1996), The Social Costs of Climate Change: Greenhouse Damage and the Benefits of Control, in: *Bruce, J.P., Lee, H., Haites, E.F. (eds.),* Climate Change 1995: Economic and Social Dimensions of Climate Change, Second Assessment Report of the Intergovernmental Panel on Climate Change III, Cambridge: Cambridge University Press, pp. 181-224.

Reilly, J. (1996), Agriculture in a Changing Climate: Impacts and Adaptation, in*: Watson, R.T., Zinyowera, M.C., Moss, R.H. (eds.),* Climate Change 1995: Impacts, Adaptations and Mitigation of Climate Change, Second Assessment Report of the Intergovernmental Panel on Climate Change II, Cambridge: Cambridge University Press, pp. 427-467.

Smith, J.B., Tirpak, D.A. (1990), The Potential Effects of Global Climate Change on the United States, New York: Hemisphere Publishing Corporation.

Strain, B.R., Cure, J.D. (1985), Direct Effects of Increasing Carbon Dioxide on Vegetation, Washington: US-Department of Energie (DOE/ER-0238).

Talpaz, H., Alexander, W.P., Shumway, C.R. (1989), Estimation of Systems of Equations Subject to Curvature Constraints, Journal of Statistical Computation and Simulation 32, pp. 201-214.

Wolf, J. (1993), Effects of Climate Change on Wheat Production Potential in the European Community, European Journal of Agronomics 2, pp. 281-292.

Appendix

Figure 4: Spatial distribution of production areas and weather stations

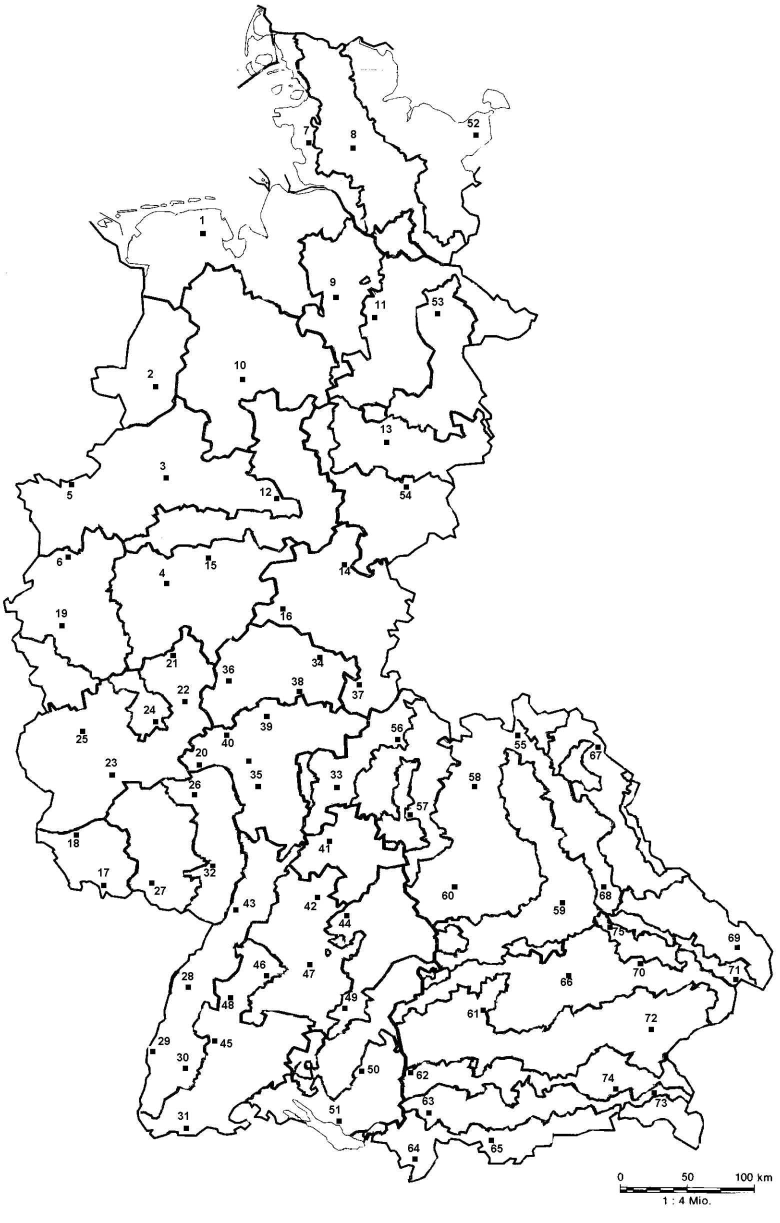


Table A- 1: Parameter restrictions for output-separability

$$\frac{\partial\left[\dfrac{\partial p/\partial p_i}{\partial p/\partial p_j}\right]}{\partial p_k}=\frac{\partial\left[\dfrac{\hat{y}_i}{\hat{y}_j}\right]}{\partial p_k}=$$

$$=\frac{\left[\frac{1}{2}a_{ik}\left(p_i p_k\right)^{-\frac{1}{2}}\right]\hat{y}_j-\left[\frac{1}{2}a_{jk}\left(p_j p_k\right)^{-\frac{1}{2}}\right]\hat{y}_i}{\hat{y}_j^2}=0$$

$$\forall p_i, p_j \in p^s \quad i \neq j, \quad \forall p_k \in p^d$$

and

$$\frac{\partial\left[\dfrac{\partial p/\partial p_i}{\partial p/\partial p_j}\right]}{\partial z_k}=\frac{\partial\left[\dfrac{\hat{y}_i}{\hat{y}_j}\right]}{\partial z_k}=$$

$$=\frac{\left[b_{ikk}+\sum_{l=1,l\neq k}^{q}b_{ikl}z_k^{-\frac{1}{2}}z_l^{\frac{1}{2}}\right]\hat{y}_j-\left[b_{jkk}+\sum_{l=1,l\neq k}^{q}b_{jkl}z_k^{-\frac{1}{2}}z_l^{\frac{1}{2}}\right]\hat{y}_i}{\hat{y}_j^2}=0$$

$$\forall p_i, p_j \in p^s \quad i \neq j, \quad \forall k = 1,\ldots,q$$

Table A- 2: Estimation Results

	labor	**capital**	**land**	**material**	**grain**
labor	0.0092^{***} *(0.0004)*	-0.0230^{***} *(0.0019)*	0.0030 *(0.0020)*	0.0060^{**} *(0.0025)*	0.0022 *(0.0034)*
capital		0.2644^{***} *(0.0027)*	-0.0111^{***} *(0.0011)*	0.1613^{***} *(0.0017)*	0.0284^{***} *(0.0018)*
land			-0.0000 *(0.0012)*	0.0159^{**} *(0.0063)*	-0.0133^{***} *(0.0028)*
material				0.1160^{***} *(0.0021)*	-0.0481^{***} *(0.0021)*
grain					0.0502^{***} *(0.0067)*

Asymptotic standard errors in parentheses. ***, ** and * denote a significance level of 99%, 95% and 90%, respectively (two-sided).

Number of observations: 8030

Table A- 2 (continued)

	sugarbeet	**potatoes**	**oilseed**	**vegetables, ...**	**cattle**
labor	-0.0098***	0.0018	0.0001	-0.0007	-0.0181***
	(0.0002)	*(0.0036)*	*(0.0029)*	*(0.0007)*	*(0.0010)*
capital	-0.0025***	-0.0041	-0.0094**	0.0407***	-0.3728***
	(0.0004)	*(0.0036)*	*(0.0046)*	*(0.0002)*	*(0.0005)*
land	0.0001	0.0011***	-0.0033**	0.0129***	-0.0256***
	(0.0013)	*(0.0004)*	*(0.0014)*	*(0.0015)*	*(0.0017)*
material	0.0218***	-0.0022	-0.0072***	-0.0060**	-0.2086***
	(0.0025)	*(0.0109)*	*(0.0021)*	*(0.0023)*	*(0.0093)*
grain	-0.0033	0.0032	0.0060**	-0.0227***	0.0701***
	(0.0037)	*(0.0078)*	*(0.0026)*	*(0.0034)*	*(0.0058)*
sugarbeet	0.0076**	-0.0014	-0.0040	-0.0098**	0.0061
	(0.0046)	*(0.0117)*	*(0.0049)*	*(0.0042)*	*(0.0225)*
potatoes		-0.0042	0.0030	0.0001	-0.0055
		(0.0147)	*(0.0108)*	*(0.0086)*	*(0.0143)*
oilseed			0.0151	-0.0039	0.0101
			(0.0270)	*(0.0302)*	*(0.0165)*
vegetables, fruit, wine				-0.0214	-0.0143
				(0.0848)	*(0.0121)*
cattle					0.4231
					(0.3616)

Table A- 2 (continued)

	ETS ´ ETS	***ETS ´ MI***	***ETS ´ FROST***	***MI ´ MI***	***MI ´ FROST***
labor	-0.0051	0.0019	-0.0004	-0.0041	0.0011
	(0.0068)	*(0.0013)*	*(0.0012)*	*(0.0055)*	*(0.0018)*
capital	0.1151^{***}	-0.0584^{***}	-0.0838^{***}	-0.0218^{***}	0.1399^{***}
	(0.0006)	*(0.0032)*	*(0.0007)*	*(0.0008)*	*(0.0038)*
land	0.0157^{***}	-0.0101	-0.0102	-0.0023	0.0164^{***}
	(0.0017)	*(0.0136)*	*(0.0076)*	*(0.0018)*	*(0.0030)*
material	0.0690^{***}	-0.0816^{***}	-0.0210^{***}	0.0702^{***}	0.0389^{***}
	(0.0068)	*(0.0089)*	*(0.0024)*	*(0.0040)*	*(0.0141)*
grain	-0.0263^{***}	0.0259^{***}	0.0075	-0.0273^{***}	-0.0152^{***}
	(0.0049)	*(0.0060)*	*(0.0236)*	*(0.0042)*	*(0.0069)*
sugarbeet	-0.0015	0.0053	0.0023	-0.0051	-0.0044
	(0.0089)	*(0.0124)*	*(0.0076)*	*(0.0127)*	*(0.0076)*
potatoes	-0.0012	0.0044	0.0019	-0.0028	-0.0024
	(0.0368)	*(0.0185)*	*(0.0101)*	*(0.0396)*	*(0.0135)*
oilseed	-0.0055	0.0029	0.0009	-0.0053	-0.0007
	(0.0245)	*(0.1475)*	*(0.0197)*	*(0.0227)*	*(0.0089)*
vegetables, fruit, wine	0.1628	-0.1200	-0.0313	0.1027	0.0461
	(0.1350)	*(0.0997)*	*(0.1547)*	*(0.1040)*	*(0.0695)*
cattle	-0.1561	0.1653	0.0499	-0.1170	-0.0920
	(0.1412)	*(0.1846)*	*(0.1981)*	*(0.0754)*	*(0.0585)*

Table A- 2 (continued)

	FROST ´ FROST
labor	-0.0017
	(0.0016)
capital	-0.0363***
	(0.0047)
land	-0.0030
	(0.0019)
material	-0.0086**
	(0.0035)
grain	0.0060
	(0.0094)
sugarbeet	0.0029
	(0.0111)
potatoes	0.0009
	(0.0267)
oilseed	-0.0008
	(0.0152)
vegetables,	-0.0171
fruit, wine	*(0.1227)*
cattle	0.0286
	(0.4036)